

1 *Effect of FA on the bearing capacity of stabilised Fine Sand*

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11 **ABSTRACT**

12 This paper is concerned with the role of fly ash (FA) content in CBR values of stabilized
13 sandy soil for geotechnical and geoenvironmental infrastructures. A series of laboratory tests,
14 particle size distribution and California Bearing Ratio (CBR) were performed. The literature
15 review demonstrates the shortage of research on stabilization of sandy material with fly ash.
16 The main focus of this paper is to establish the optimum quantity of FA content for
17 stabilization of this type of soil. A total of 14 distinctive variations of stabilized sand are
18 presented, with three different FA content (5%, 10% and 15%), three main curing periods, 1-
19 week, 2-week and 4-week durations and a constant cement content of 3%. Some samples
20 were only treated with cement 3% and 5%, with no addition of FA, so that the effect of
21 cement on this particular sand can be observed, and the contribution of the FA alone can be
22 understood. The obtained results are in line with the literature for other types of soil.

23
24 Keywords: **Geotechnical Engineering, Embankments, Strength and testing of materials**

27 **INTRODUCTION**

28

29 Coal-fired power plants around the world produce nearly 25% of the world's primary energy
30 needs, or in other words, 38% of the worldwide electricity is generated from these coal-fired
31 power plants (Barnes and Sear, 2006). Coal Combustion Products (CCPs) are the residues
32 generated in coal-fired power stations by burning coal as fuel. Fly ash (FA) constitutes about
33 80% of the total coal ash produced worldwide (Abmaruzzaman 2010). In general, most of the
34 FA produced is disposed of in a landfill, causing concerns for environmental agencies. An
35 increase in utilization of FA would lead to lower disposal rate, less land being used for
36 landfill and replacement of traditional base materials so that CO₂ emissions can be lowered.
37 This paper is focused on the utilization of FA only, as it has proved to be a more viable soil
38 stabilizer in comparison to bottom ash, due to its finer particle size.

39

40 The study is concerned with the influence of fly ash on stabilized sandy soil. Its effect is
41 investigated and analyzed through some laboratory tests, such as particle size distribution
42 (PSD) and California bearing ratio (CBR) test. In the first section of this paper, a revision of
43 previous relevant research is outlined, in the background, covering some general aspects of
44 FA, its sustainability, continued by ground improvement and soil stabilization. The aim of the
45 study presented in this paper is to examine the suitability of class F FA as a suitable material
46 for construction of embankments in geotechnical engineering projects.

47 **BACKGROUND**

48

49 Throughout the past decades, FA has been named as a problematic solid waste due to the
50 conventional disposal methods from thermal power plants and factories, as arable lands all
51 around the world have been contaminated and degraded. As the planet's fifth largest raw
52 material resource (Abmaruzzaman 2010), FA can be used as an alternative to conventional
53 materials in the construction of geotechnical and geoenvironmental infrastructures.

54 Diminishing and/or minimizing mining and quarrying for natural-occurring resources, and
55 instead using CCPs as a replacement, it can lead to sustainable and environmental gains.
56 Energy demand and emissions to the atmosphere can also be reduced by utilizing CCPs
57 (Barnes and Sear, 2006).

58

59 FA production, utilization and disposal rates in the UK from 1999 to 2013 are illustrated in
60 Figure 1. It can be seen that, from 1999 to 2003, landfill rates were higher than the utilization
61 rate, however, 2003 onwards it has been lower than the utilization rate. Although in 2010,
62 36% of the total FA produced was sent to landfill, this increased to 48% in 2012, while the
63 utilization amount remained at around 32 million tonnes, and then in 2013, the rate of landfill
64 dropped to 38%. The relative utilization and production of fly ashes differ noticeably from
65 one country to another (Figure 2). In the near future, the disposal of FA is believed to be too
66 costly if not banned (Abmaruzzaman 2010). This can be seen in Netherlands, where all the
67 FA must be utilized or exported since landfill is prohibited (Eijk et al., 2011).

68

69 Fly ash can be utilized for a variety of applications within the construction industry (Figure 3).
70 It can be seen that about 60% of the total FA produced in the United States is unutilized,
71 making it one of the highest unutilized rates worldwide. In addition, Figure 3 illustrates that
72 nearly 30% of the FA utilization in the US is used for the production of cement and concrete
73 products, while utilization for soil stabilization, which this study is focused on, accounts for
74 less than 0.5% of total production and about 1% in waste stabilization.

75

76 The reutilization of waste materials, such as FA, within the construction industry, and
77 particularly in Geotechnical Engineering, has a significant potential to minimize the amount
78 of disposed waste materials (Baykal et al., 2004; Cetin and Aydilek 2013). Celauro et al.,
79 (2012) stated that utilization of FA in the construction of road, railways and airports, due to
80 the volumes of materials used, would have a profound impact from the environmental point
81 of view on the surroundings. Cetin and Aydilek (2013) believe that the reutilization of the FA

82 in embankments construction can lead to several benefits:

- 83 • Lower solid waste disposal costs
- 84 • Minimizing damage to natural resources caused by excavating earthen materials
- 85 for construction
- 86 • Conserving production energy
- 87 • Providing sustainable construction
- 88 • Providing economic growth

89

90 **Ground Improvement and stabilization using FA**

91

92 Ground improvement can be defined ‘as the introduction of materials or energy to soils to
93 affect a change in performance of the ground such that it performs more reliably and can be
94 incorporated into the design process’ (Essler 2012). All around the world, the construction of
95 projects with very long design lives, such as embankments, retaining walls and bridges, is
96 made possible by improving the load-bearing capacity and stability of soils through ground
97 improvement techniques (Cofra 2005). It generally involves the enhancement of ground
98 properties, principally by strengthening or stiffening processes and compaction or
99 densification mechanisms, to achieve a specific geotechnical performance (Serridge and
100 Slocombe, 2012). In the recent past, the use of ground improvement has increased
101 significantly, down to more construction sites being located in areas of poor-quality ground,
102 redevelopment of existing sites and remediation of contaminated sites.

103

104 O’Flaherty and Hughes (2016) explain that modification of a soil is used to improve its
105 properties without causing much increase to its elastic modulus or tensile strength, while
106 stabilization is employed for achieving significant improvements in strength and stiffness.

107 Ground improvement through stabilization, is seen as an economical way of construction by
108 diminishing the number of soil exchanges (Hussian 2010).

109

110 One of the major methods used to solve the problems caused by weak soils is soil
111 stabilization by mixing with a cementitious binder. The most two common binders are lime
112 and cement. The stabilization is achieved by the soil particles being glued more chemically
113 than physically. Moreover, dealing with weak soils is one of the most important challenges in
114 the construction industry (Cristelo et al. 2013; Senol et al. 2006), in particular, in road and
115 highway construction or in geotechnical engineering (Fauzi et al. 2010; Senol et al. 2006).
116 Therefore it is vital to find methods of soil improvement techniques so that demands can be
117 met. Dockter et al. (1999) concluded that coal combustion FA has ‘excellent potential for use
118 in rammed earth construction as a low-cost alternative to Portland cement and other
119 stabilizers because of its pozzolanic properties’. Soil stabilization using FA benefits from the
120 enhancement of the compressive strength of the soft (Bergado et al. 1996; Prabakar et al.
121 2004). Additional benefits of soil stabilization may include:

- 122 • Improvement of permeability, soil resistance to the weathering process and traffic
123 usage (ASTM 1992, cited by Zaliha et al. 2013)
- 124 • Improvement of the shear strength, filter, drainage system (Parabakar et al. 2004)

125

126 Some of the advantages of ground improvement using wastes are to reduce the high cost of
127 building and to maintain the waste-disposal facilities while increasing the supply of
128 construction material from the waste (Porbaha and Hanzawa, 2001). In considering the
129 performance of new built embankments, other factors apart from the stability of the
130 embankment slope that should be considered: (Manceau et al. 2012)

- 131 • Failure of the embankment foundation
- 132 • Settlement of the foundation material
- 133 • Self-settlement of the embankment fill

134

135 Through chemical techniques, ‘stabilization can be done using chemical and emulsions since
136 they work as compaction aids, binders, water repellents and as well as modifying the soil
137 behaviour’ (Graves et al. 1988). The chemical reaction of soil particles and chemical
138 additives creates a strong bond between the soil grains, resulting in a stronger, more durable
139 and a better quality soil in comparison to an untreated soil. In the case of lime, the reactions
140 are mainly pozzolanic, and with cement, there are hydraulic. A hydraulic reaction needs only
141 water to react and increase in strength while a pozzolanic reaction requires water and a
142 pozzolanic material like soil (Janz and Johansson 2002). According to several authors
143 (Pacheco et al. 2012; Criado et al. 2007), alkaline-activated materials are, in general, better
144 performing than cement from a mechanical point of view and show increased durability and
145 stability. There are currently also many researchers and practitioners investigating in soil
146 stabilisation where triple binders were used, as in the present research where different
147 combinations of FA and cement with sandy material are tested (Auststab 2012).

148

149 Utilization of FA stabilization of the soil used in subgrade improves the stability of the
150 working platform, which is less susceptible to disturbance by moisture and construction
151 traffic (Mackiewicz and Ferguson 2005). Subgrade soil stabilization can save huge amounts of
152 money by reducing the thickness of pavement layers, in comparison to traditional methods,
153 which involve cutting out and replacing the unstable subgrade soil (Beeghly, 2003). Makusa
154 (2012) states the following limitations that stabilized soil-FA can have:

- 155 • Soil to be stabilized shall have less moisture content; therefore, dewatering may
156 be required.
- 157 • Soil-FA mixture cured below zero and then soaked in water are highly
158 susceptible to slaking and strength loss
- 159 • Sulfur contents can form expansive minerals in soil-fly ash mixture, which
160 reduces the long-term strength and durability.

161

162 According to Hossain (2010), soils with a 'liquid limit less than 40% and plasticity index
163 within the range 22-25% are most suitable for stabilization.' Nevertheless, it was concluded,
164 by the same author, that soils could be in consistence of these two conditions and still prove
165 suitable for stabilization (Hossain 2010). Thus, investigating the stabilization of different
166 types and combinations of stabilizers and soil types is essential.

167

168 Makusa (2012) reports that for a given degree of compaction, the maximum dry density is
169 usually lower for stabilized soil than for untreated soil. Also, the optimum moisture content
170 increases with increasing binders. This is believed to be the case, due the heat generated when
171 the binders begin their chemical reactions. According to Makusa (2012) the hydration
172 process in soils stabilized by cement occurs directly after water and cement come into contact.
173 Furthermore, the author states that in stabilized soils, 'enough moisture content is essential
174 not only for hydration process to proceed but also for efficient compaction' (Makusa 2012).

175

176 **Stabilization Activation**

177

178 Cement is one of the most common stabilizers utilized throughout the past decades. One of
179 the key factors, of utilizing cement in stabilizing soils, is that cement reaction is independent
180 of soil minerals, and it relies on the water that may be found in any soil. Soils stabilised with
181 cement could have the following improved properties (Makusa 2012):

- 182 • Decreased cohesiveness
- 183 • Decreased volume expansion or compressibility
- 184 • Increased strength

185

186 Class F FA can be only utilized in stabilization with the addition of an activator, like cement or
187 lime. According to Cristelo et al. (2012b), stabilized soil with cement-based binders achieved
188 a higher mechanical strength, when compared to soil stabilized with lime-based binders.
189 Another benefit of using cement as an activator for FA is that it can lead to lower leachate
190 of heavy metals and/or help in containing it (Kamon et al. 2000). The US air force has
191 developed a methodology (Figure 4), where suitable stabilizers are suggested based on soil
192 type (Little and Nair, 2009).

193

194 **Laboratory Testing**

195

196 An increasing amount of research resources is being directed to the study of FA utilization
197 and FA stabilization. In the studies, which FA was utilized to stabilize soil, a series of
198 laboratory tests were performed. The most common of these tests are:

- 199 • Particle Size Distribution (PSD) (Cristelo et al. 2011; Cristelo et al. 2012b)
- 200 • California Bearing Capacity (CBR) test (Hossain 2010; Koliass et al. 2005; Jackson et
201 al., 2007; Sato and Nishimoto, 2005)
- 202 • Compressive Strength (Arioz et al. 2013; Cristelo et al. 2012a; Kamon et al. 2000;
203 Koliass et al. 2005; Sato and Nishimoto, 2005)
- 204 • XRD Analysis (Arioz et al. 2013; Cristelo et al. 2012a; Koliass et al. 2005)

205

206 For the purpose of this paper, a series of PSD and CBR tests have been performed, based on
207 previous results of compaction tests (Mahvash et al, 2017). The results of numerous tests
208 found in the literature are summarised in Table 1. It can be seen that several researchers
209 (Cristelo et al. 2011; Koliass et al. 2005; Aydiyek and Arora, 2005; Santos et al. 2011; Cristelo
210 et al. 2012a; Cristelo et al. 2012b; Reyes and Pando, 2007; Sahu 2001; McCarthy et al. 2011)
211 reviewed the effect of FA (both class C and F) on ground improvement through soil
212 stabilization. This table also shows that majority of the tested soils have been clays with few

213 sandy samples. It can be suggested that, in general, for most of the soils, there is an increase
214 in the CBR value after the treatment, except one case in the study by Sahu (2001), where
215 there was a reduction in CBR, for the Kalahari Sand, from 40% to 10% when used 24% fly
216 ash, and down to 30% when 8% FA was used. In the study by Arora and Aydilek (2005), silty
217 sand was stabilized with 40% FA (Class F) content with two different activators, lime and
218 cement. Over a 4-week curing period, the samples stabilized with cement achieved an
219 Unconfined Compressive Strength (UCS) of 5.0 MPa, over twelve times higher than what
220 was achieved with lime. This result was in consistence with the conclusion obtained by other
221 authors, like Cristelo et al. (2012b), which also state that cement-based binders typically
222 produce significantly better and more consistent results when compared to lime-bases binders.
223 Thus, it can be suggested that cement is a more viable option as an activator than lime.

224

225 Additionally, results by Santos et al. (2011) illustrated that there is not a substantial
226 improvement when the FA contend raised from 40% to 60%, whereas there was a clear
227 improvement from 20% to 40% FA content. Meanwhile, in 2011, Cristelo et al. published the
228 results of an extensive research on soil improvement by utilizing Class F FA. The curing
229 periods took as long as a year and produced overwhelming results, with one sample (40% FA
230 – 365-day curing) achieving 43 MPa in UCS. In the same study, samples were also cured for
231 90 and 28 days, with UCS of 17 MPa and 8 MPa (40% FA) respectively. Therefore it can be
232 suggested, the longer the curing period, the higher the strength of the soil. Furthermore,
233 Cristelo et al. (2012a) compared stabilization with both class C and class F fly ash, using the
234 same FA content (20%) and equal curing periods (84-day), the class F stabilized samples had
235 about three times the strength compared to the samples stabilized with class C. It should be
236 noted that there were improvements in the physical strength of FA stabilized samples in every
237 study. Thus, it can be concluded again that the most successful stabilization, using Class F FA,
238 is obtained with cement as activator. Moreover, the curing period should be maximized. The
239 choice of activator differs in each study. These include: cement, lime, sodium hydroxide (SH)

240 and sodium silicate (SS). In some investigations, the authors used a mixture of SH and SS
241 (Cristelo et al. 2011, Cristelo et al. 2012a, Cristelo et al. 2012b),

242

243 Figure 5 shows various possible results for soil stabilization using FA, which has been
244 developed from Table 1. It can be concluded that further research requires to be carried out on
245 sand, clayey sand in particular, and furthermore on high plasticity silts. This paper is focused
246 on sand only.

247

248 **METHODOLOGY**

249

250 Comprehensive series of laboratory tests consisting of particle size distribution (PSD) and
251 CBR test were conducted on untreated soil samples and stabilized samples using different
252 proportions of FA and cement as activator. Each FA content was tested with at least three
253 samples created under the same conditions and procedures, so the obtained results can be
254 more reliable. There were three variations of FA content chosen for this study, 5%, 10% and
255 15% (as in Cristelo et al. 2011; Cristelo et al. 2012a) with three different curing periods, 1-
256 week, 2-weeks and 4-weeks. In this experimental study, a total of 14 CBR tests were
257 performed. The aim of this set of laboratory tests was to analyze the influence FA content on
258 the bearing capacity of the stabilized soil, by comparing stabilized soils against pre-treated
259 samples.

260

261 Cement, with a content of 3% was chosen an activator for this study. This value is selected as
262 an average based on previous studies (Kolias et al. 2005; Kaniraj and Havanagi, 1999). The
263 proposed tests were performed in accordance to British Standards, with at least two
264 representatives specimens for determination of the moisture content (BSI 1990a). It should be
265 noted that all the samples were compacted instantly after mixing, without any delays.

266

267 **Particle Size Distribution (PSD)**

268

269 The particle size distribution tests performed in this study to the untreated material were in
270 accordance with BS 1377-2 1990, Classification tests, the “Dry Sieving Method” (BSI 1990b).

271 The grading and uniformity of the soil can be evaluated using the classification graph.

272 O’Flaherty and Hughes (2016), state that the typical values for the C_c and C_u of even graded
273 soil is <1 and <6 , respectively. Meanwhile, soils with particles size range of 0.06mm to 2mm,

274 are classified as sand through British soil classification system (BSI 1990b).

275

276 **CBR**

277

278 As it is well known, the California Bearing Ratio (CBR) is obtained by measuring the
279 relationship between force and penetration when a cylindrical plunger is made to penetrate

280 the soil at a standard rate. In order to find the optimum values, the CBR tests were carried out
281 in accordance with BS 1377-4 1990, “Determination of the California Bearing Ratio” (BSI

282 1990c). A series of compaction tests (Proctor) were carried out first, to identify the optimal
283 water content for each FA content, and therefore all the CBR samples were compacted at

284 optimal conditions (Mahvash et al. 2017). The CBR tests were carried out in a modified CBR
285 mould with soil compacted in three layers and each layer subject to 72 blows from the 2.5kg

286 rammer (BSI 1990c). A surcharge of 2kg was also used in the CBR tests. All the samples
287 were mixed, compacted and sealed within 30 minutes. During the curing, the temperature

288 remained constant of around 21°C throughout. The samples were stored in airtight bags
289 during the curing period to keep its humidity constant.

290

291

292

293 **Resilience modulus and Unconfined Compressive Strength by correlations**

294

295 AASHTO is now favoring the resilient modulus dynamic stiffness test for characterizing the
296 strength of pavement material (Beeghly 2003). Resilient modulus (M_r) is the elastic modulus
297 utilized in mechanistic-empirical pavement analyses and design (Lav and Lav, 2014).
298 According to O’Flaherty and Hughes (2016), M_r is the fundamental subgrade strength
299 parameter needed as input to any rational or mechanistic pavement design process
300 (O’Flaherty and Hughes, 2016). For the purpose of this study, the correlation (Eq. 1) derived
301 by Transportation and Road Research Laboratory (TRRL) will be used to evaluate M_r values
302 (in kN/m^2) in correlation with the obtained CBR values (Coleri 2007; Buchanan 2007).

303
$$M_r = 17616.1 \text{ CBR}^{0.64} \quad (1)$$

304 Furthermore, another common factor in road design process is the Unconfined Compressive
305 Strength (UCS). A study by Behera and Mishara (2012) was carried out to correlate the CBR
306 and the UCS (MPa) on fly ash, lime mixture at 7 and 28-day curing periods (Behera and
307 Mishara, 2012, cited by Purwana and Nikraz, 2014). As a result, the following equations have
308 been derived to evaluate UCS values (in MPa), using the achieved CBR values.

309

310 7-Day
$$\text{UCS} = (\text{CBR} - 14.14) / 108.8 \quad (2)$$

311 14-Day
$$\text{UCS} = (\text{CBR} - 26.63) / 82.63 \quad (3)$$

312 28-Day
$$\text{UCS} = (\text{CBR} - 39.13) / 56.45 \quad (4)$$

313

314

315 **MATERIALS**

316 **Sand**

317

318 For the purpose of this study, the sand (Building Sand) was obtained from Civils & Lintels, a
319 UK supplier. The sand was delivered in polyethylene bags of 25kgs. The sand has a
320 maximum dry density of 1741 kg/m^3 and optimum moisture content of 13.4% at its original
321 state.

322

323 **Fly Ash**

324

325 The fly ash utilized in this study was obtained from a UK power station, Ratcliffe-on-Soar
326 power station in Nottingham. According to ASTM class F fly ashes contain at least 70% by
327 weight of Silicon dioxide (SiO_2) + Aluminium oxide (Al_2O_3) + Iron oxide (Fe_2O_3) (ASTM
328 2003, cited by Kelly 2015). The FA used in this study contains nearly 75% by weight of SiO_2
329 + Al_2O_3 + Fe_2O_3 . Thus, the FA in this research can be classified as Class F.

330

331 In order to produce more consistent samples, irregular and larger particles in the FA had to be
332 removed. The FA was oven dried and then passed through a 2.36mm sieve. Over 20% of the
333 total FA, as it was supplied, was greater than 2.36mm.

334

335

336

337 **Cement**

338

339 The cement used in this study is Ordinary Portland cement (OPC), obtained from a UK
340 supplier. The following conditions were obtained from the manufacturer data sheet (Lafarge
341 2012):

342

- 343 • Based on sustainable cement technology
- 344 • Consistent strength meeting all the conformity criteria in BS EN 197-1
- 345 • Manufactured from natural products

346

347 **RESULTS AND DISCUSSION**

348

349 After the analysis of the PSD for the soil (Figure 6), the coefficients of the sand were
350 evaluated, with a C_U value of about 2 and C_C value of just under 1 (0.98). This would classify
351 the soil as a poorly and/or even graded soil (O’Flaherty and Hughes, 2016). It can also be
352 seen from Figure 6 that the soil would classify as sand through British Standards (BSI 1990b).
353 Similar evaluation process proved the FA to be having grain size of similar to that of silt
354 and/or clay (Fig.7).

355

356 The results of CBR tests performed with different FA content, different curing periods and
357 cement content are presented in this section and discussed further. The results of all the CBR
358 tests performed for this study are tabulated in Table 2, where the denomination for each case
359 is also presented. It can be seen that the CBR values of all the stabilized samples were
360 increased in comparison to sand-only (S-0C-0FA), by a range of 76% to 1453%. CBR test

361 results achieved for each sample showed the mechanical strength of the material under each
362 condition.

363

364 Figure 8 demonstrates the effect of cement content on the CBR values. The untreated sand
365 sample had an average CBR value of 18% of the three samples. The results of the study show
366 that the influence of the addition of cement on the mechanical strength of cement only
367 stabilized samples is significant, multiplying the CBR value by a minimum factor of 2. The
368 highest strength gained was in the one week cured sample of 5% cement and no FA (S-5C-
369 0FA), achieving improvement in CBR value of 96.53%. Tests identified that the percentage
370 of cement positively increased the strength of the material dramatically, while curing period
371 (using 3% cement) had a smaller yet still positive impact on the materials strength.

372

373 Observing the CBR values of samples S-3C-0FA and S-5C-0FA, it can be seen that the CBR
374 value was increased from 41.43% to 96.53% by the addition of 2% of cement. Meanwhile,
375 the initial 3% addition of cement to S-0C-0FA sample, improved the CBR value by 23.4%.
376 Clearly, the chemical reactions between this particular sand and the cement have proved to be
377 profound. The results show that the use of cement in the stabilized mix has played a major
378 role in the improvement of the achieved CBR values. In this study, the addition of cement
379 was only for activating purposes. However, Koliias et al. (2005) also presented a similar
380 observation, where samples with 4% cement content (5% FA content) proved to be much
381 more viable than 2% cement content samples, where there was no significant improvement
382 post 14 days of curing. If the cement-only samples (in Fig.8 and S-3C-0FA7, S-3C-0FA14
383 and S-3C-0FA28 –in the figure 9 for 0% of FA) were to be isolated, it is evident that for
384 increasing curing periods the CBR values increase without the FA, reaching almost the
385 maximum expected level of bearing capacity after 28 days of curing. Similar behaviour was
386 also observed in previous studies (Sahu 2001, Koliias et al. 2005).

387

388 Moreover, figure 9 illustrates how FA percentage affects the bearing capacity achievable of
389 the stabilized soil. To analyze the effect of FA content, the samples with a mixture of 3%
390 cement addition are presented in this figure. The graph also shows the CBR values of samples
391 with no addition of FA, so that the effect of FA can be observed more accurately as, by
392 keeping the cement content constant, the FA content is the only variable affecting the possible
393 strength achieved. It can be seen that there is a reduction in CBR values, respect to 0% of FA,
394 as 5% FA is added to the cement-only samples for 2 and four weeks of curing, while the
395 reduction bears to its minimum for 10% of FA after one week of curing. For higher FA
396 content (i.e. 15%), CBR values seem to have an increasing trend.

397 Figure 10 presents the effect of the curing period on CBR values for the whole set of samples.
398 As it can be seen, the samples stabilized with 3% cement, have all produced a similar overall
399 trend, with an increase in CBR values as the curing periods expand. By keeping the FA and
400 cement content constant, the only variable between the samples is the curing time. Tests were
401 carried out for 1, 2 and 4 weeks curing periods. It is also remarkable that all the results of
402 CBR obtained for 0% of FA and 3% of cement follow the same discussed trend, and are
403 higher than those obtained for the different tested amounts of FA, although after 4 weeks of
404 curing the CBR are very similar to those for 15% of FA, while for 5 and 10% these values
405 keep the same increasing trend. For comparison, previous results obtained for the same
406 material, using 5% of cement and 10% of FA are also presented (Wood, 2016). From this
407 results it is clear that the effect of a higher proportion of cement on the bearing capacity is
408 quite remarkable, with an increasing trend with the curing time, far from achieving and
409 asymptotic value after the 4 weeks of curing, while for 3% of cement, the results do not seem
410 to indicate the same steep increasing trend for the week 4 as for 5% of cement, but a much
411 more moderated one, indicating that the activation reactions are almost complete after 28 days
412 for 3% of cement.

413 Figure 10 clearly shows the improvement in CBR values as an effect of a longer curing time
414 in all cases. The FA samples with 3% cement content range from a CBR value of 25.7% to

415 66.95% with a slight upward correlation between all, proving that as curing time is increased
416 so is the strength of the sample. The strongest sample was the four weeks, 10% FA and 5%
417 cement, achieving a CBR value of more than fourteen and half times the CBR achieved from
418 the sand in its original state.

419

420 As presented earlier in Table 2, the values of UCS and M_r were predicted using the
421 correlations stated earlier. It should be highlighted that these correlations are not intended to
422 yield very accurate results for these magnitudes, but at the same time, from them we can
423 obtain a possible range of values that would have been obtained through laboratory tests.

424 Figures 11 and 12, which illustrate the relationship between FA content and the M_r and UCS,
425 were derived from these values. It can be seen that in both figures, all the different curing
426 periods have produced the same behavior and are in correlation with each other. The highest
427 UCS value obtained was for the S-3C-15FA28 sample, with a value of 0.49 MPa, achieving
428 an improvement of over 12 times compared to the untreated sample. As included earlier in
429 Table 1, the UCS results of several studies, concerning with FA-soil stabilization were
430 discussed. In most of the cases, the UCS was at least increased by a factor of 4 over a 7-day
431 curing period. Despite the improved UCS values with FA stabilization, cement-only (3%
432 content) stabilized samples produced even higher UCS values in comparison to samples
433 stabilized with 3% cement. The obtained results for UCS are of the same range as reported by
434 previous experimental researches (Rezagholilou and Nikraz, 2015).

435

436

437 CONCLUSIONS

438

439 The main findings from the testing carried out in this research were that, as expected, the
440 bearing capacity, measured by means of the CBR value, is very much affected by the fly ash
441 percentage and curing time. However, it should be pointed out that for all the samples with

442 3% cement, the cement-only tests achieved higher CBR values than the ones with additional
443 5%, 10% and 15% FA content, in all three different curing times. The sample S-3C-15FA28
444 is the only variation, which obtained a marginally higher CBR than its equivalent cement only
445 sample (S-3C-0FA28), by 0.77% only, showing that curing period of 28 days, with 15% FA
446 content have a positive effect regarding bearing capacity, comparable to the 3% cement and
447 0% FA result. Nevertheless, based on the results of this study, this particular class F fly ash
448 and the sandy soil, appear to react in a more significant manner as the cement percentage is
449 increased, achieving higher CBR values with strong correlations with FA content and curing
450 period. This behaviour was also seen in testing performed in previous studies and was similar
451 to the effects of fly ash content on clayey soils.

452

453 Further analysis should be carried out with different the soil types to see how the soil affects
454 the achievable strength of that sample, particularly clayey sands, as very few researches have
455 been found in the literature for this kind of soil.

456

457 As a result of testing, it has proven that there is a potential application for fly ash to be used
458 successfully as a soil stabilizer, with accurate addition of cement. It increases the physical
459 characteristics and reduces the environmental burden of current solutions. Results show that
460 how much strength increase is achievable for sandy soils, and with more analysis could be
461 used for practical applications. This has the potential to be a sustainable use for the byproduct
462 of coal power stations. It potentially can provide a solution for energy companies to reducing
463 landfill costs, and with the ever-increasing cost of landfill could prove hugely beneficial
464 financially.

465

466 More research should surround the topic of variation in results between tests in the field and
467 laboratory tests. Having researched the literature the approach to close this gap is to leave the
468 sample for one to two hours after mixing to replicate the conditions of site. This, however,
469 does not seem like an accurate and engineered approach and should be reassessed to dictate a

470 more specific approach to the engineered practice.

Notation List

The following symbols are used in this paper:

C_c = Grading Coefficient

C_u = Coefficient of Uniformity

M_r = Resilient Modulus

SiO_2 = Silicon dioxide

Al_2O_3 = Aluminium oxide

Fe_2O_3 = Iron oxide

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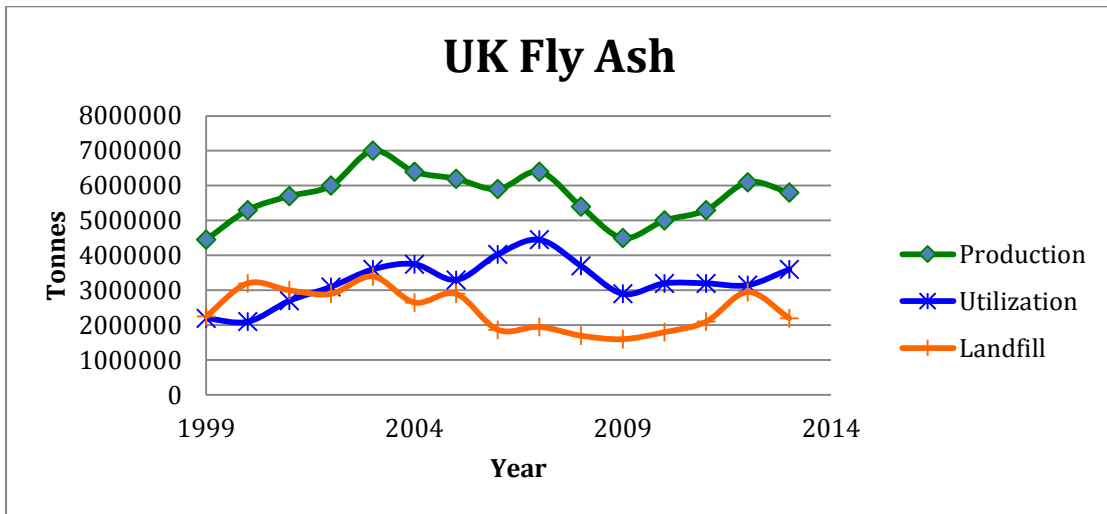


Fig. 1. UK FA production, utilization, and landfill values (after Carroll 2015; UKQAA 2016)

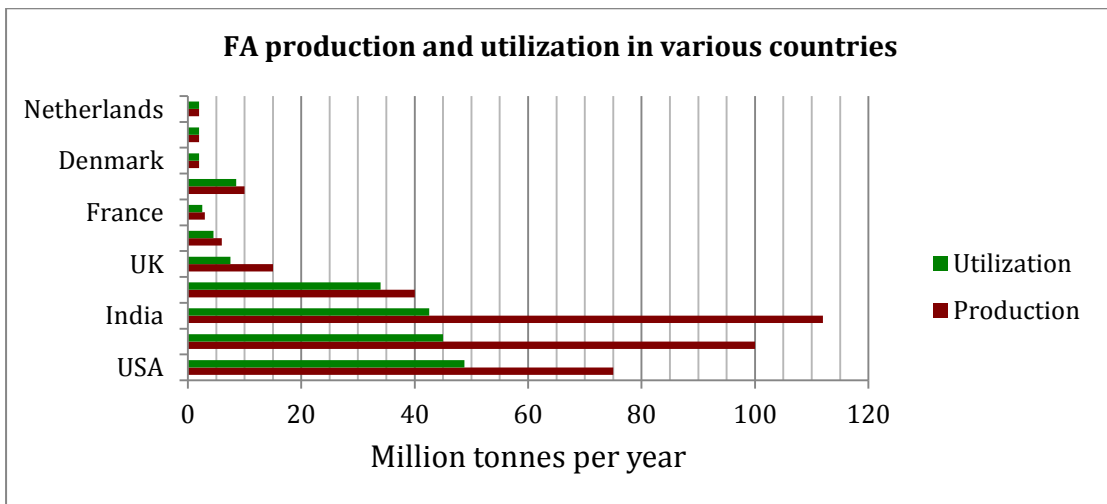


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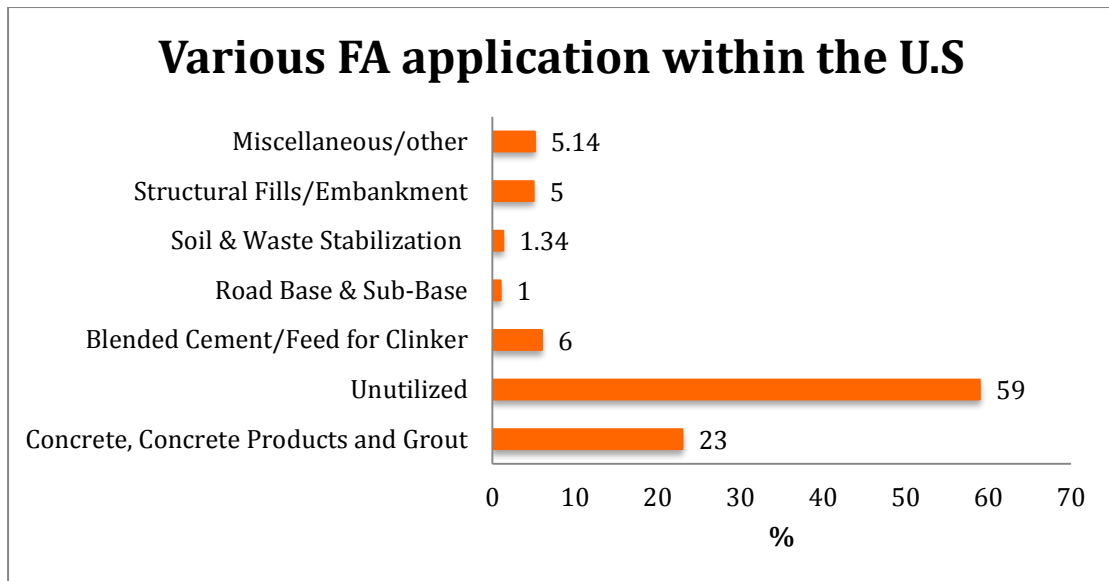


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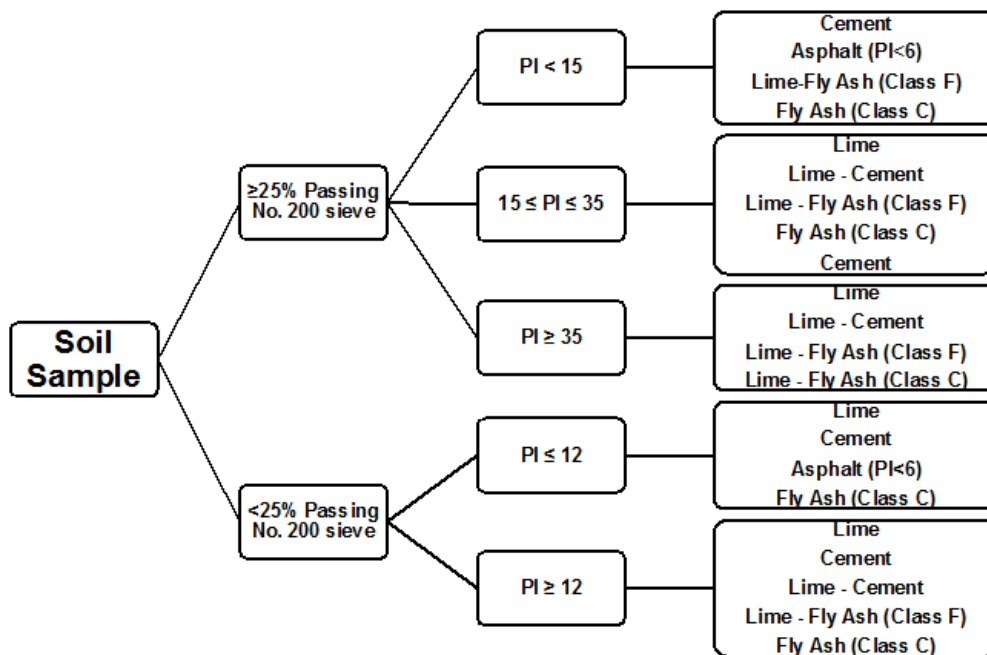
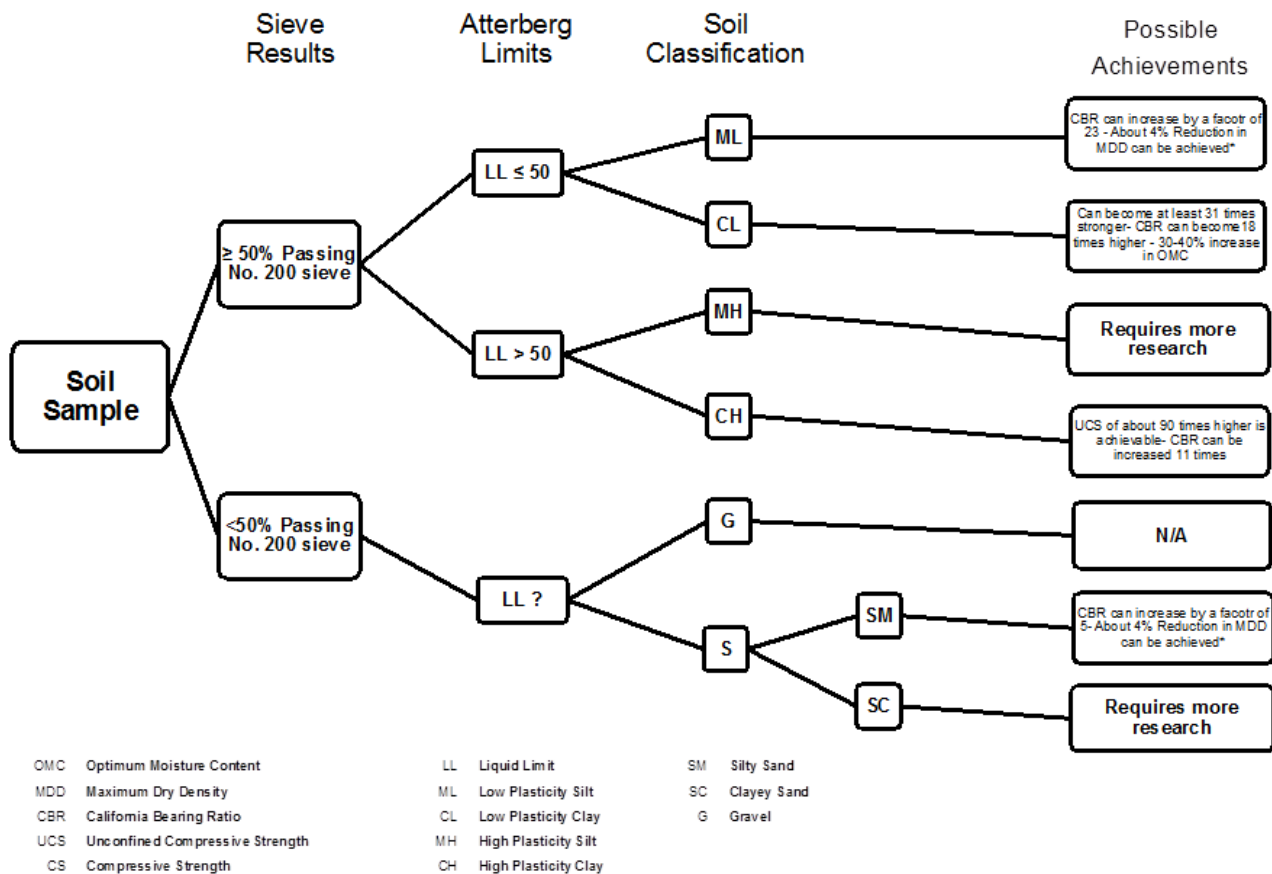


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Note: These results are possible with curing during of 12 to 13 weeks with Fly Ash content of 20% to 24%. *Cured for only seven days

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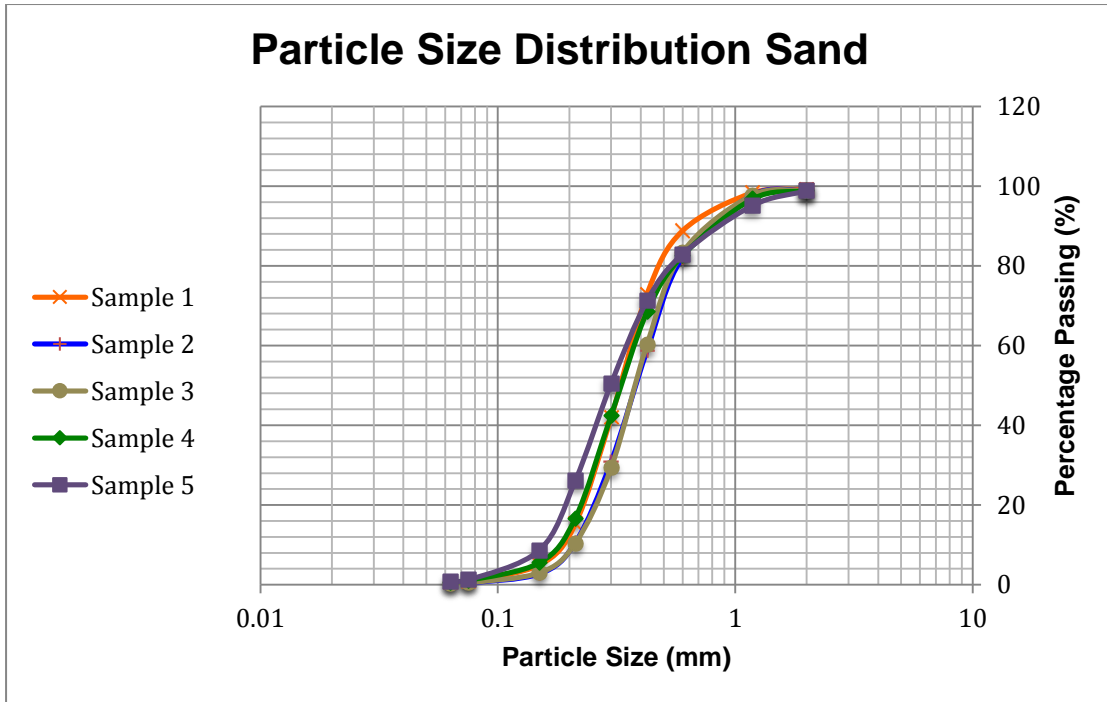


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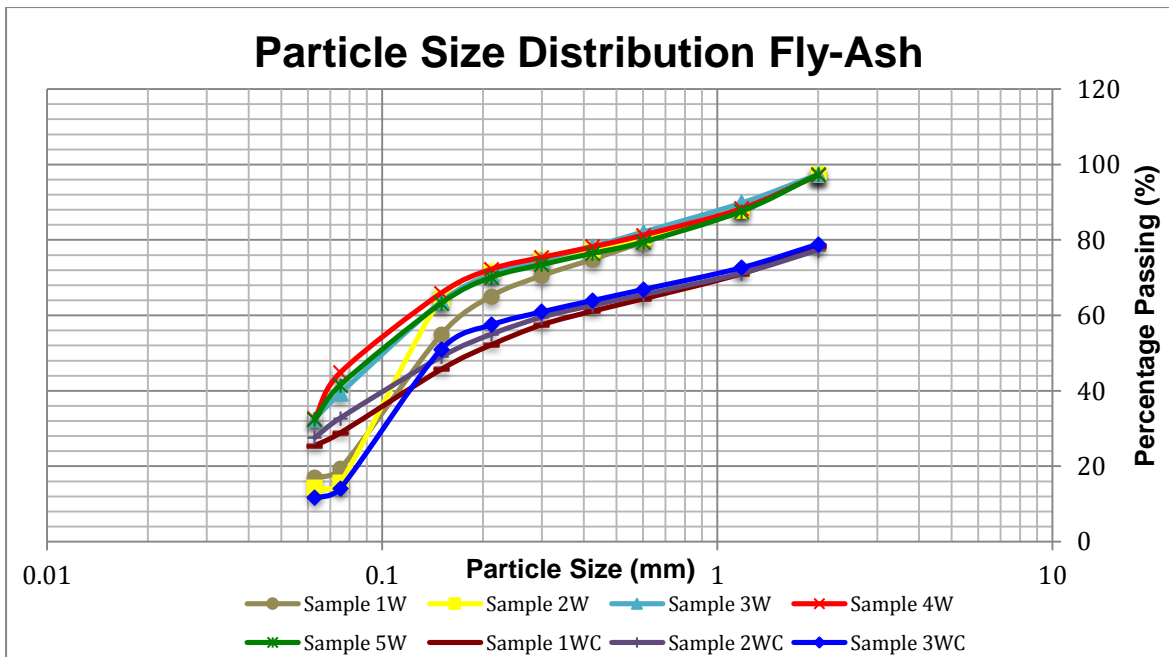


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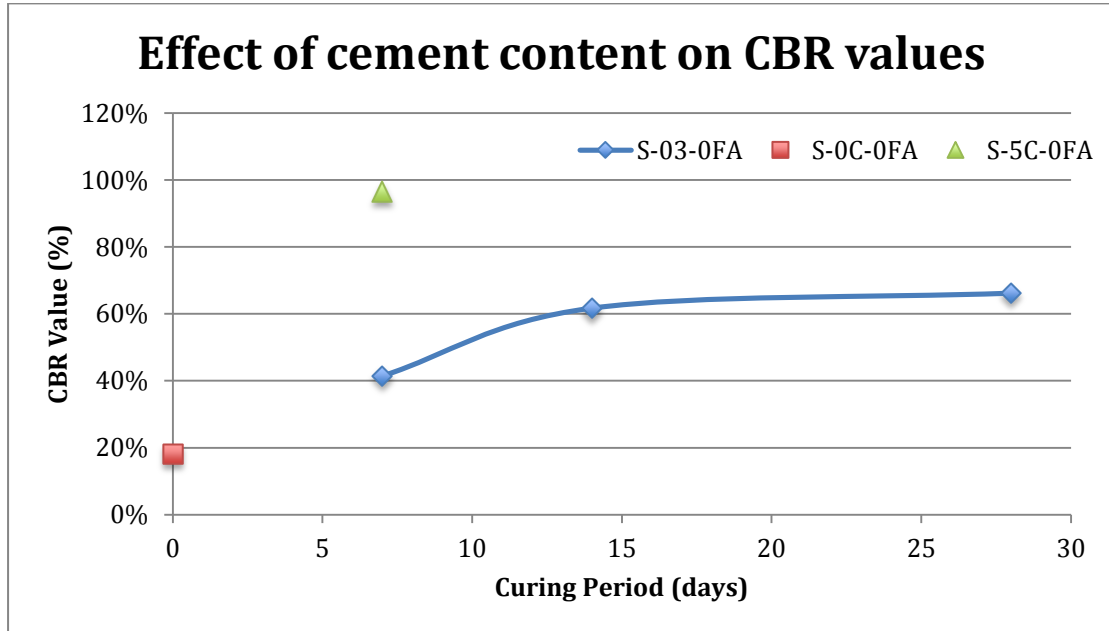


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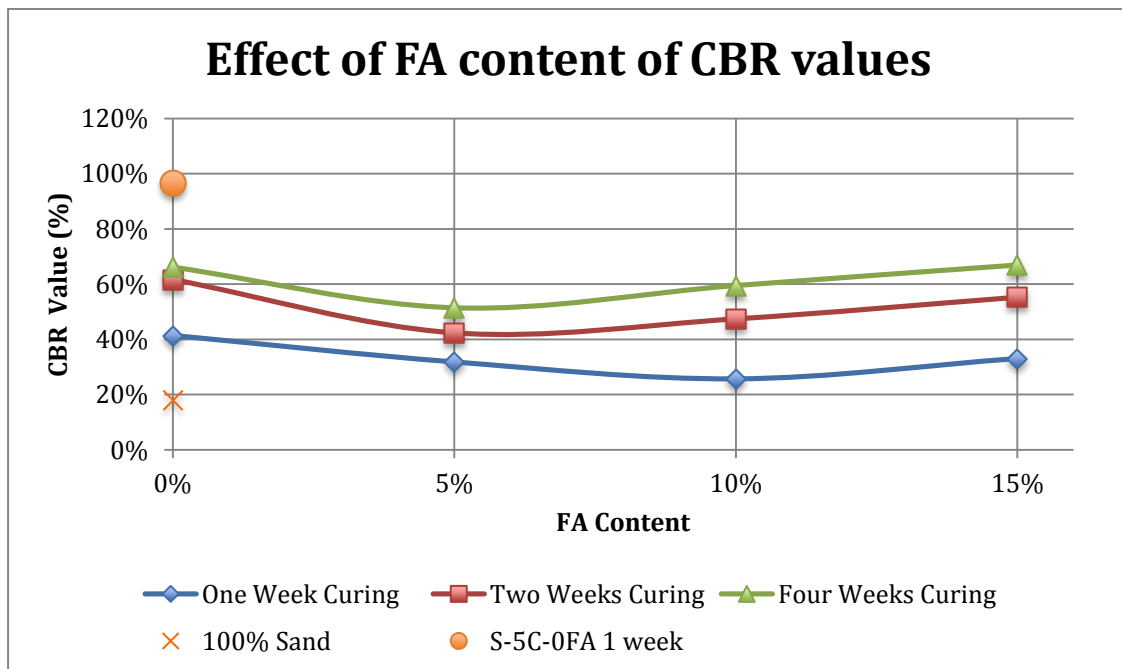


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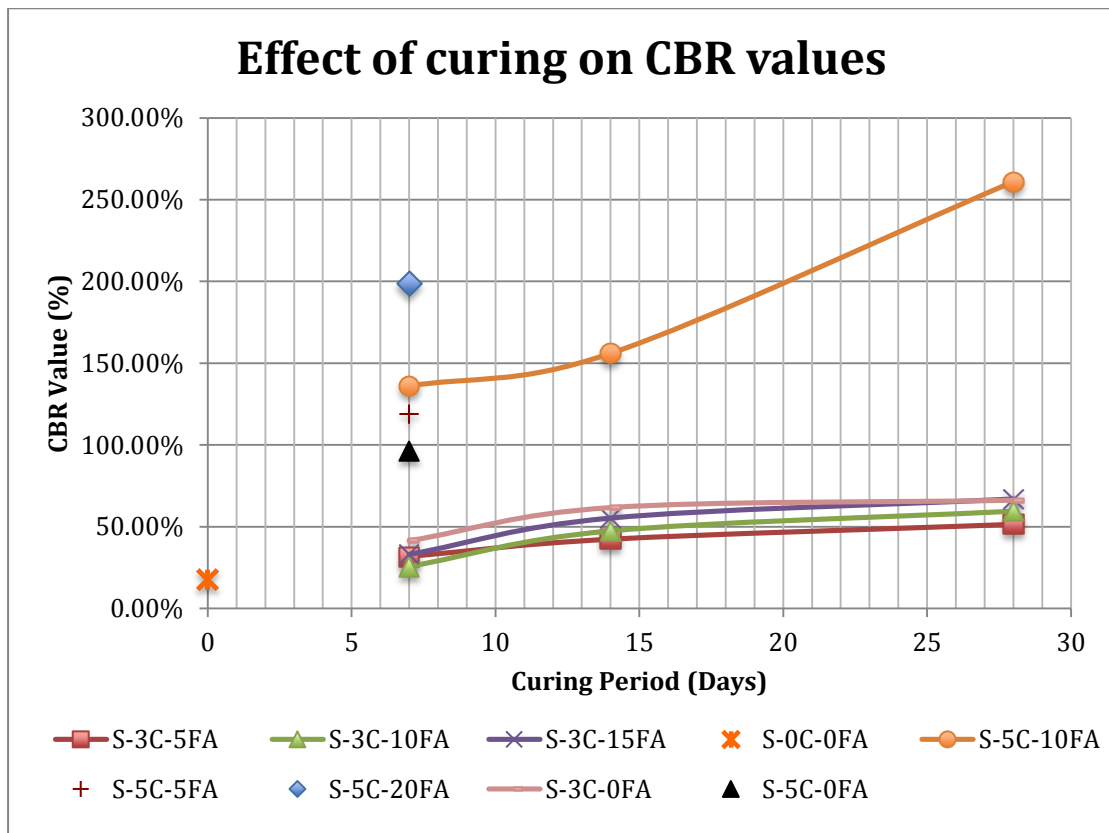


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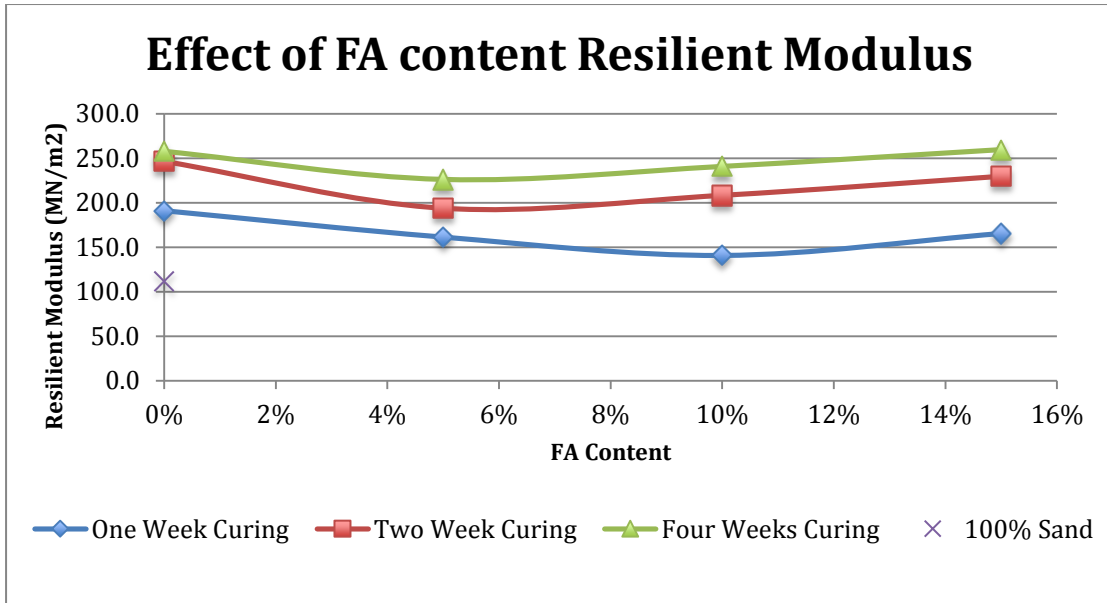


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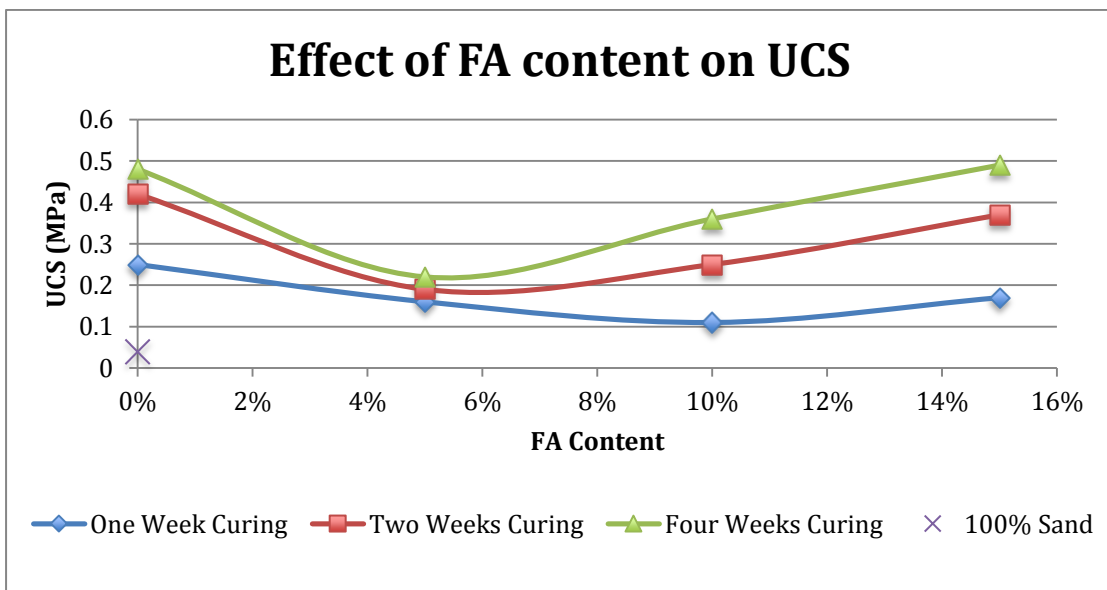


Fig 12. Effect of FA content on UCS

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Table 1. Results of soil stabilizing by using fly ash from nine different studies

Table 2. CBR, UCS and the M_r values of all the stabilized samples

Summary: Experiences of soil stabilization using Fly Ash

Fly Ash	Soil	Activator	Tests	Results		Source
				Before Treatment	After Treatment	
20% Fly Ash (FA)	Lean Clay	Cement	OMC	20% FA and 91-day curing	30%	Kolias et al. 2005
			CS	0.1 Mpa	3.1 Mpa	
			CBR	10%	185%	
			MDD	15.9 KN/m ³	13.1 KN/m ³	
20% Fly Ash (FA)	Lean Clay	Cement	OMC	20% FA and 28-day curing	30%	
			CS	0.1 Mpa	1.7 Mpa	
			CBR	10%	185%	
			MDD	15.9 KN/m ³	13.1 KN/m ³	
20% Fly Ash (FA)	Fat Clay	Cement	CS	20% FA and 91-day curing	1.75 Mpa	
			CBR	0.1 Mpa	110%	
20% Fly Ash (FA)	Fat Clay	Cement	CS	20% FA and 28-day curing	1.25 Mpa	
			CBR	0.1 Mpa	110%	
10% Fly Ash (FA)	Lean Clay	Cement	OMC	10% FA and 91-day curing	26%	
			CS	0.1 Mpa	1.9 Mpa	
			CBR	10%	140%	
			MDD	15.9 KN/m ³	14.1 KN/m ³	
10% Fly Ash (FA)	Lean Clay	Cement	OMC	10% FA and 28-day curing	26%	
			CS	0.1 Mpa	1.1 Mpa	
10% Fly Ash (FA)	Fat Clay	Cement	CBR	10% FA and 91-day curing	140%	
			MDD	15.9 KN/m ³	14.1 KN/m ³	
10% Fly Ash (FA)	Fat Clay	Cement	CS	10% FA and 28-day curing	0.7 Mpa	
			CBR	0.1 Mpa	60%	
10% Fly Ash (FA)	Fat Clay	Cement	CS	10% FA and 91-day curing	0.5 Mpa	
			CBR	0.1 Mpa	60%	

OMC Optimum Moisture Content
 MDD Maximum Dry Density
 CBR California Bearing Ratio
 UCS Unconfined Compressive Strength
 CS Compressive Strength
 SH Sodium Hydroxide
 SS Sodium Silicate

40%	Fly Ash Class F (FAF)	Silty Sand	Cement	MDD UCS	40% FAF and 28-day curing 15.46 kN/m ³ 5.0 Mpa
40%	Fly Ash Class F (FAF)	Silty Sand	Cement	MDD UCS CBR	40% FAF and 7-day curing 15.46 kN/m ³ 3.2 Mpa 140%
40%	Fly Ash Class F (FAF)	Silty Sand	Lime	MDD UCS	40% FAF and 28-day curing 15.36 kN/m ³ 0.4 Mpa
40%	Fly Ash Class F (FAF)	Silty Sand	Lime	MDD UCS CBR	40% FAF and 7-day curing 15.36 kN/m ³ 0.3 Mpa 36%

60%	Fly Ash (FA)	Low Plasticity Clay		OMC MDD CS	60% FA and 28-day curing 14% 17.9 kN/m ³ 28% 13.9 2.67 Mpa
40%	Fly Ash (FA)	Low Plasticity Clay		OMC MDD CS	40% FA and 28-day curing 14% 17.9 kN/m ³ 25% 14.6 kN/m ³ 2.65 Mpa
20%	Fly Ash (FA)	Low Plasticity Clay		OMC MDD CS	20% FA and 28-day curing 14% 17.9 kN/m ³ 23% 15.5 kN/m ³ 1.35 Mpa

20%	Fly Ash Class F (FAF)	Fat clays	SH & SS	UCS	20% FAF and 84-day curing 0.08 Mpa 8.6 Mpa
20%	Fly Ash Class F (FAF)	Fat clays	SH & SS	UCS	20% FAF and 28-day curing 0.08 Mpa 1.7 Mpa
20%	Fly Ash Class C (FAC)	Fat clays	SH & SS	UCS	20% FAC and 84-day curing 0.08 Mpa 2.8 Mpa
20%	Fly Ash Class C (FAC)	Fat clays	SH & SS	UCS	20% FAC and 28-day curing 0.08 Mpa 1.3 Mpa

10%	Fly Ash Class F (FAF)	Fat clays	SH & SS	UCS	10% FAF and 84-day curing 0.08 Mpa	4.2 Mpa	Cristelo et al. 2012b
10%	Fly Ash Class F (FAF)	Fat clays	SH & SS	UCS	10% FAF and 28-day curing 0.08 Mpa	0.6 Mpa	
10%	Fly Ash Class C (FAC)	Fat clays	SH & SS	UCS	10% FAC and 84-day curing 0.08 Mpa	1.9 Mpa	
10%	Fly Ash Class C (FAC)	Fat clays	SH & SS	UCS	10% FAC and 28-day curing 0.08 Mpa	1.1 Mpa	
25%	Fly Ash Class F (FAF)	Granitic Residual Soil	SH & SS	UCS MDD	25% FAF and 7-day curing 19.2 KN/m ³	17 Mpa	Reyes and Pando, 2007
20%	Fly Ash Class C (FAC)	High Plasticity Clay		MDD CS	20% FAC and 40-day curing 12.1 kN/m ³ 0.03 Mpa	0.96 Mpa	
20%	Fly Ash Class C (FAC)	High Plasticity Clay		MDD CS	20% FAC and 28-day curing 12.1 kN/m ³ 0.03 Mpa	0.9 Mpa	
10%	Fly Ash Class C (FAC)	High Plasticity Clay		MDD CS	10% FAC and 40-day curing 12.1 kN/m ³ 0.03 Mpa	0.56 Mpa	
10%	Fly Ash Class C (FAC)	High Plasticity Clay		MDD CS	10% FAC and 28-day curing 12.1 kN/m ³ 0.03 Mpa	0.45 Mpa	Sahu, 2001
24%	Fly Ash (FA)	Kalahari Sand		OMC MDD CBR	24% FA and 7-day curing 5% 17.3 KN/m ³ 40%	7% 14.7 KN/m ³ 10%	
24%	Fly Ash (FA)	Calcrete		OMC MDD CBR	24% FA and 7-day curing 15.60% 17.2 KN/m ³ 40%	17% 16.3 KN/m ³ 90%	

24%	Fly Ash (FA)	Silty Sand	OMC MDD CBR	24% FA and 7-day curing 9% 19.0 KN/m ³ 80%	9% 18.2 KN/m ³ 470%
24%	Fly Ash (FA)	Black Cotton Soil	OMC MDD CBR	24% FA and 7-day curing 20% 15.1 KN/m ³ 0%	23.50% 14.8 KN/m ³ 25%
24%	Fly Ash (FA)	Low Plasticity Silt	OMC MDD CBR	24% FA and 7-day curing 12% 19.8 KN/m ³ 10%	12.30% 18.9 KN/m ³ 230%
8%	Fly Ash (FA)	Kalahari Sand	OMC MDD CBR	8% FA and 7-day curing 5% 17.3 KN/m ³ 40%	5% 16.8 KN/m ³ 30%
8%	Fly Ash (FA)	Calcrete	OMC MDD CBR	8% FA and 7-day curing 15.60% 17.2 KN/m ³ 40%	19.90% 16.4 KN/m ³ 60%
8%	Fly Ash (FA)	Silty Sand	OMC MDD CBR	8% FA and 7-day curing 9% 19.0 KN/m ³ 80%	8.80% 18.6 KN/m ³ 315%
8%	Fly Ash (FA)	Black Cotton Soil	OMC MDD CBR	8% FA and 7-day curing 20% 15.1 KN/m ³ 0%	22.70% 15.3 KN/m ³ 5%
8%	Fly Ash (FA)	Low Plasticity Silt	OMC MDD CBR	8% FA and 7-day curing 12% 19.8 KN/m ³ 10%	11.90% 19.6 KN/m ³ 40%
40%	Fly Ash Class F (FAF)	Sandy Clay	SH & SS UCS	40% FAF and 365-day curing	43 Mpa
40%	Fly Ash Class F (FAF)	Sandy Clay	SH & SS UCS	40% FAF and 90-day curing	17 Mpa

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40%	Fly Ash Class F (FAF)	Sandy Clay	SH & SS	UCS	<u>40% FAF and 28-day curing</u> 8 Mpa
20%	Fly Ash Class F (FAF)	Sandy Clay	SH & SS	UCS	<u>20% FAF and 365-day curing</u> 24 Mpa
20%	Fly Ash Class F (FAF)	Sandy Clay	SH & SS	UCS	<u>20% FAF and 90-day curing</u> 5 Mpa
20%	Fly Ash Class F (FAF)	Sandy Clay	SH & SS	UCS	<u>20% FAF and 28-day curing</u> 3.5 Mpa
<hr style="border-top: 1px dashed red;"/>					
24%	Fly Ash -a	Oxford Clay	Lime	OMC MDD UCS	<u>24% FA and 90-day curing</u> 25% 26.90% 14.9 KN/m ³ 14.3 KN/m ³ 0.3 Mpa 1.9 Mpa
24%	Fly Ash -b	Oxford Clay	Lime	OMC MDD UCS	<u>24% FA and 90-day curing</u> 25% 28.10% 14.9 KN/m ³ 13.7 KN/m ³ 0.3 Mpa 1.5 Mpa
24%	Fly Ash -a	Oxford Clay	Lime	OMC MDD UCS	<u>24% FA and 28-day curing</u> 25% 26.90% 14.9 KN/m ³ 14.3 KN/m ³ 0.3 Mpa 1.4 Mpa
24%	Fly Ash -b	Oxford Clay	Lime	OMC MDD UCS	<u>24% FA and 28-day curing</u> 25% 28.10% 14.9 KN/m ³ 13.7 KN/m ³ 0.3 Mpa 1.2 Mpa
12%	Fly Ash -a	Oxford Clay	Lime	OMC MDD UCS	<u>12% FA and 90-day curing</u> 25% 26.70% 14.9 KN/m ³ 14.4 KN/m ³ 0.3 Mpa 1.7 Mpa
12%	Fly Ash -b	Oxford Clay	Lime	OMC MDD UCS	<u>12% FA and 90-day curing</u> 25% 27.40% 14.9 KN/m ³ 14.0 KN/m ³ 0.3 Mpa 1.4 Mpa
12%	Fly Ash -a	Oxford Clay	Lime	OMC MDD UCS	<u>12% FA and 28-day curing</u> 25% 26.70% 14.9 KN/m ³ 14.4 KN/m ³ 0.3 Mpa 1.3 Mpa

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12% FlyAsh -b	Oxford Clay	Lime	12% FA and 28-day curing
		OMC	25%
		MDD	27.40%
		UCS	14.0 KN/m ³
			0.3 Mpa

Table 1. Results of soil stabilizing by using fly ash from nine different studies

Table 2. CBR, UCS and the M_r values of all the stabilized samples

Sample	Code	Curing Period (days)	CBR (%)	UCS (MPa)	M_r (MPa)
Sand	S-0C-0FA	0	18.03	0.04	112.1
Sand+3%Cement	S-3C-0FA7	7	41.43	0.25	191.0
Sand+3%Cement	S-3C-0FA14	14	61.7	0.42	246.4
Sand+3%Cement	S-3C-0FA28	28	66.18	0.48	257.7
Sand+5%Cement	S-5C-0FA	7	96.53	0.76	328.2
Sand+3%Cement+5%FA	S-3C-5FA7	7	31.82	0.16	161.3
Sand+3%Cement+5%FA	S-3C-5FA14	14	42.36	0.19	193.7
Sand+3%Cement+5%FA	S-3C-5FA28	28	53.94	0.22	226.1
Sand+5%Cement+5%FA¹	S-5C-5FA7	7	120.03	0.97	377.3
Sand+3%Cement+10%FA	S-3C-10FA7	7	25.7	0.11	140.7
Sand+3%Cement+10%FA	S-3C-10FA14	14	47.43	0.25	208.2
Sand+3%Cement+10%FA	S-3C-10FA28	28	59.5	0.36	240.8
Sand+5%Cement+10%FA¹	S-5C-10FA7	7	136.9	1.13	410.4
Sand+5%Cement+10%FA¹	S-5C-10FA14	14	156.7	1.57	447.5
Sand+5%Cement+10%FA¹	S-5C-10FA28	28	262.01	3.95	621.8
Sand+3%Cement+15%FA	S-3C-15FA7	7	33.08	0.17	165.4
Sand+3%Cement+15%FA	S-3C-15FA14	14	55.27	0.37	229.7
Sand+3%Cement+15%FA	S-3C-15FA28	28	66.95	0.49	259.7
Sand+5%Cement+20%FA¹	S-5C-20FA	7	198.54	1.69	520.6

(¹After Wood 2016)