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Mahvash-Mohammadi, Siavash, Lopez-Querol, Susana and Bahadori-Jahromi, Ali ORCID: https://orcid.org/0000-0003-0405-7146 (2017) Effect of fly ash on the bearing capacity of stabilised fine sand. Proceedings of the ICE - Ground Improvement. ISSN 1755-0750

http://dx.doi.org/10.1680/jgrim.17.00036

Effect of FA on the bearing capacity of stabilised Fine Sand

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ABSTRACT

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

Keywords: Geotechnical Engineering, Embankments, Strength and testing of materials

INTRODUCTION

Coal-fired power plants around the world produce nearly 25% of the world's primary energy needs, or in other words, 38% of the worldwide electricity is generated from these coal-fired power plants (Barnes and Sear, 2006). Coal Combustion Products (CCPs) are the residues generated in coal-fired power stations by burning coal as fuel. Fly ash (FA) constitutes about 80% of the total coal ash produced worldwide (Abmaruzzaman 2010). In general, most of the FA produced is disposed of in a landfill, causing concerns for environmental agencies. An increase in utilization of FA would lead to lower disposal rate, less land being used for landfill and replacement of traditional base materials so that CO_2 emissions can be lowered. This paper is focused on the utilization of FA only, as it has proved to be a more viable soil stabilizer in comparison to bottom ash, due to its finer particle size.

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

BACKGROUND

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

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

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

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

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

- Lower solid waste disposal costs
- Minimizing damage to natural resources caused by excavating earthen materials for construction
- Conserving production energy
- Providing sustainable construction
- Providing economic growth

Ground Improvement and stabilization using FA

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

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

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

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

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

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

- Failure of the embankment foundation
- Settlement of the foundation material
- Self-settlement of the embankment fill

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

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

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

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

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

Stabilization Activation

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

- Decreased cohesiveness
- Decreased volume expansion or compressibility
- Increased strength

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

Laboratory Testing

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

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

For the purpose of this paper, a series of PSD and CBR tests have been performed, based on previous results of compation tests (Mahvash et al, 2017).. The results of numerous tests found in the literature are summarised in Table 1. It can be seen that several researchers (Cristelo et al. 2011; Kolias et al. 2005; Aydilek and Arora, 2005; Santos et al. 2011; Cristelo et al. 2012a; Cristelo et al. 2012b; Reyes and Pando, 2007; Sahu 2001; McCarthy et al. 2011) reviewed the effect of FA (both class C and F) on ground improvement through soil stabilization. This table also shows that majority of the tested soils have been clays with few sandy samples. It can be suggested that, in general, for most of the soils, there is an increase in the CBR value after the treatment, except one case in the study by Sahu (2001), where there was a reduction in CBR, for the Kalahari Sand, from 40% to 10% when used 24% fly ash, and down to 30% when 8% FA was used. In the study by Arora and Aydilek (2005), silty sand was stabilized with 40% FA (Class F) content with two different activators, lime and cement. Over a 4-week curing period, the samples stabilized with cement achieved an Unconfined Compressive Strength (UCS) of 5.0 MPa, over twelve times higher than what was achieved with lime. This result was in consistence with the conclusion obtained by other authors, like Cristelo et al. (2012b), which also state that cement-based binders typically produce significantly better and more consistent results when compared to lime-bases binders. Thus, it can be suggested that cement is a more viable option as an activator than lime.

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

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

METHODOLOGY

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

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

Particle Size Distribution (PSD)

The particle size distribution tests performed in this study to the untreated material were in accordance with BS 1377-2 1990, Classification tests, the "Dry Sieving Method" (BSI 1990b). The grading and uniformity of the soil can be evaluated using the classification graph. O'Flaherty and Hughes (2016), state that the typical values for the C_c and C_U of even graded soil is <1 and <6, respectively. Meanwhile, soils with particles size range of 0.06mm to 2mm, are classified as sand through British soil classification system (BSI 1990b).

CBR

As it is well known, the California Bearing Ratio (CBR) is obtained by measuring the relationship between force and penetration when a cylindrical plunger is made to penetrate the soil at a standard rate. In order to find the optimum values, the CBR tests were carried out in accordance with BS 1377-4 1990, "Determination of the California Bearing Ratio" (BSI 1990c). A series of compaction tests (Proctor) were carried out first, to identify the optimal water content for each FA content, and therefore all the CBR samples were compacted at optimal conditions (Mahvash et al. 2017). The CBR tests were carried out in a modified CBR mould with soil compacted in three layers and each layer subject to 72 blows from the 2.5kg rammer (BSI 1990c). A surcharge of 2kg was also used in the CBR tests. All the samples were mixed, compacted and sealed within 30 minutes. During the curing, the temperature remained constant of around 21^{o}C throughout. The samples were stored in airtight bags during the curing period to keep its humidity constant.

Resilience modulus and Unconfined Compressive Strength by correlations

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

$$M_r = 17616.1\ CBR^{0.64} \qquad (1)$$

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

7-Day $$UCS = (CBR-14.14)/108.8 \qquad (2)$$

14-Day $$UCS = (CBR-26.63)/82.63 \qquad (3)$$

28-Day $$UCS = (CBR-39.13)/56.45 \qquad (4)$$

MATERIALS

Sand

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

Fly Ash

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

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

Cement

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

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

RESULTS AND DISCUSSION

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

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

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

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

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

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

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

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

As presented earlier in Table 2, the values of UCS and M_r were predicted using the correlations stated earlier. It should be highlighted that these correlations are not intended to yield very accurate results for these magnitudes, but at the same time, from them we can obtain a possible range of values that would have been obtained through laboratory tests. Figures 11 and 12, which illustrate the relationship between FA content and the M_r and UCS, were derived from these values. It can be seen that in both figures, all the different curing periods have produced the same behavior and are in correlation with each other. The highest UCS value obtained was for the S-3C-15FA28 sample, with a value of 0.49 MPa, achieving an improvement of over 12 times compared to the untreated sample. As included earlier in Table 1, the UCS results of several studies, concerning with FA-soil stabilization were discussed. In most of the cases, the UCS was at least increased by a factor of 4 over a 7-day curing period. Despite the improved UCS values with FA stabilization, cement-only (3% content) stabilized samples produced even higher UCS values in comparison to samples stabilized with 3% cement. The obtained results for UCS are of the same range as reported by previous experimental researches (Rezagholilou and Nikraz, 2015).

CONCLUSIONS

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

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

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

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

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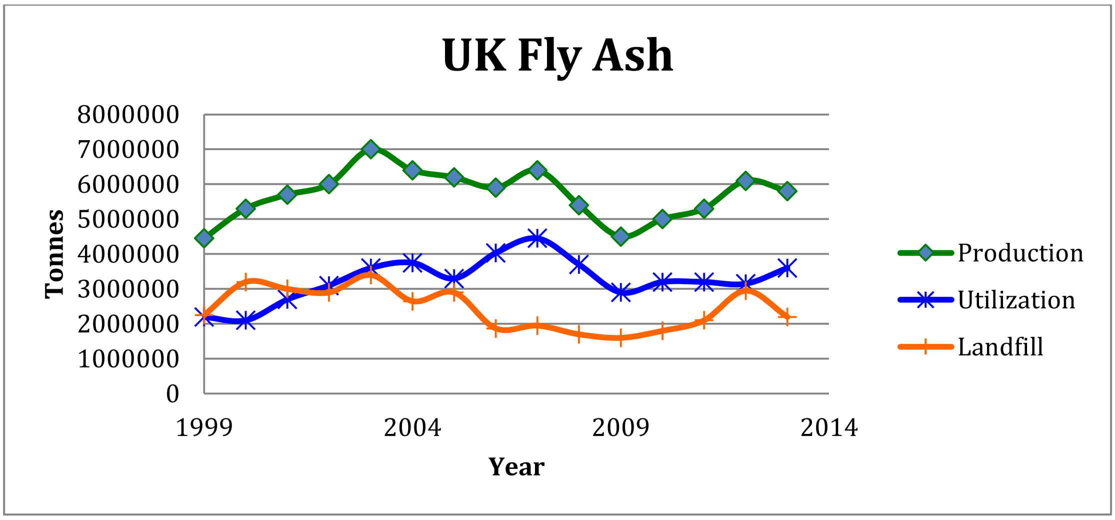
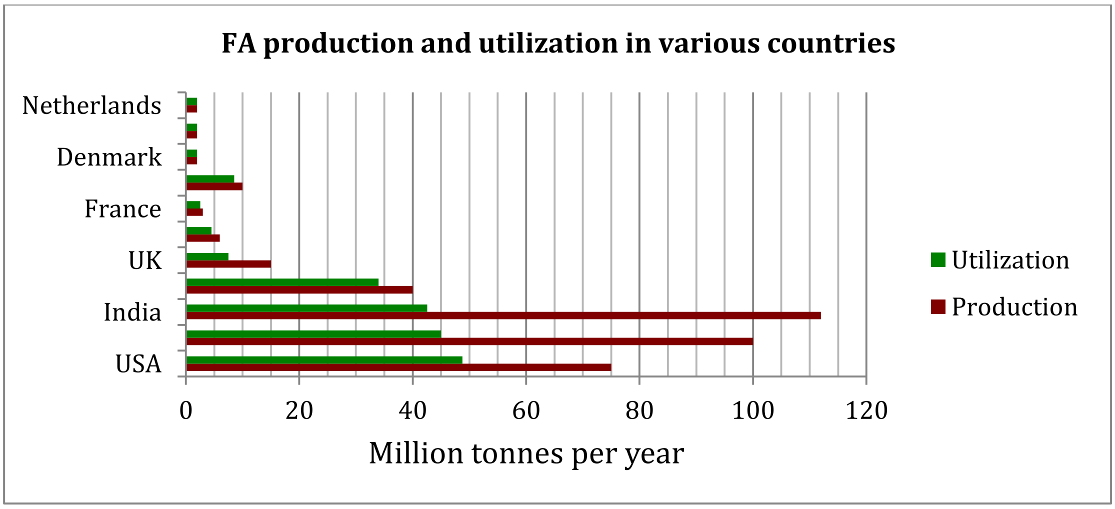


Fig. 1. UK FA production, utilization, and landfill values (after Carroll 2015; UKQAA 2016)



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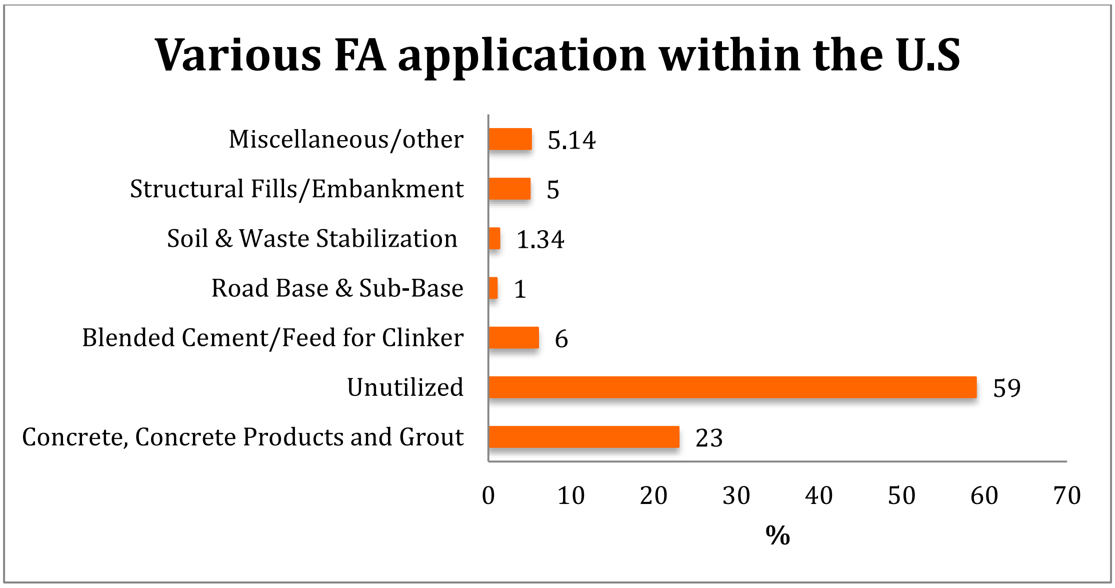

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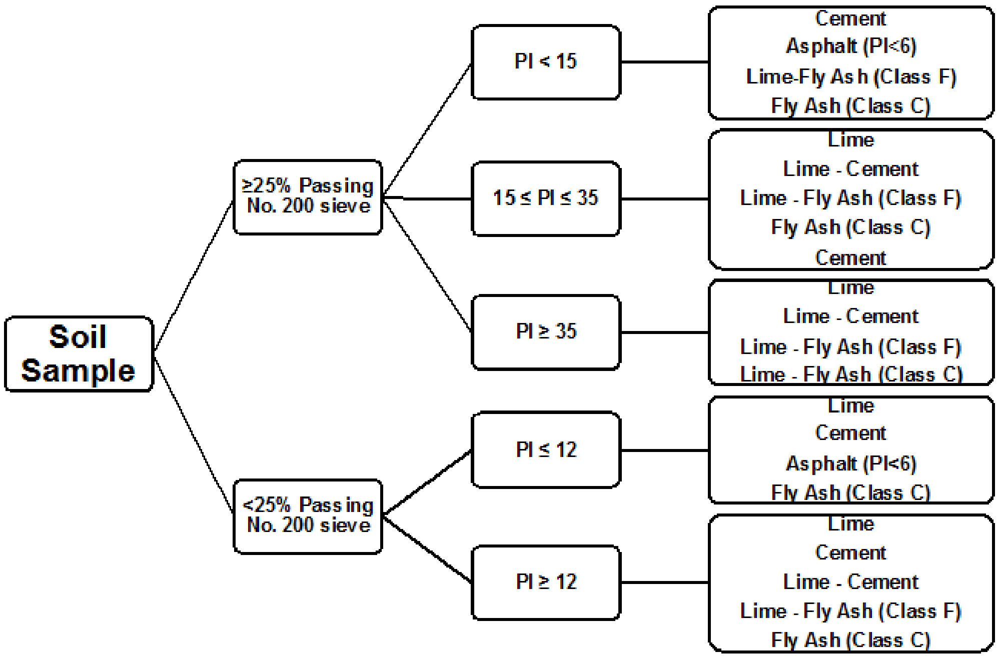

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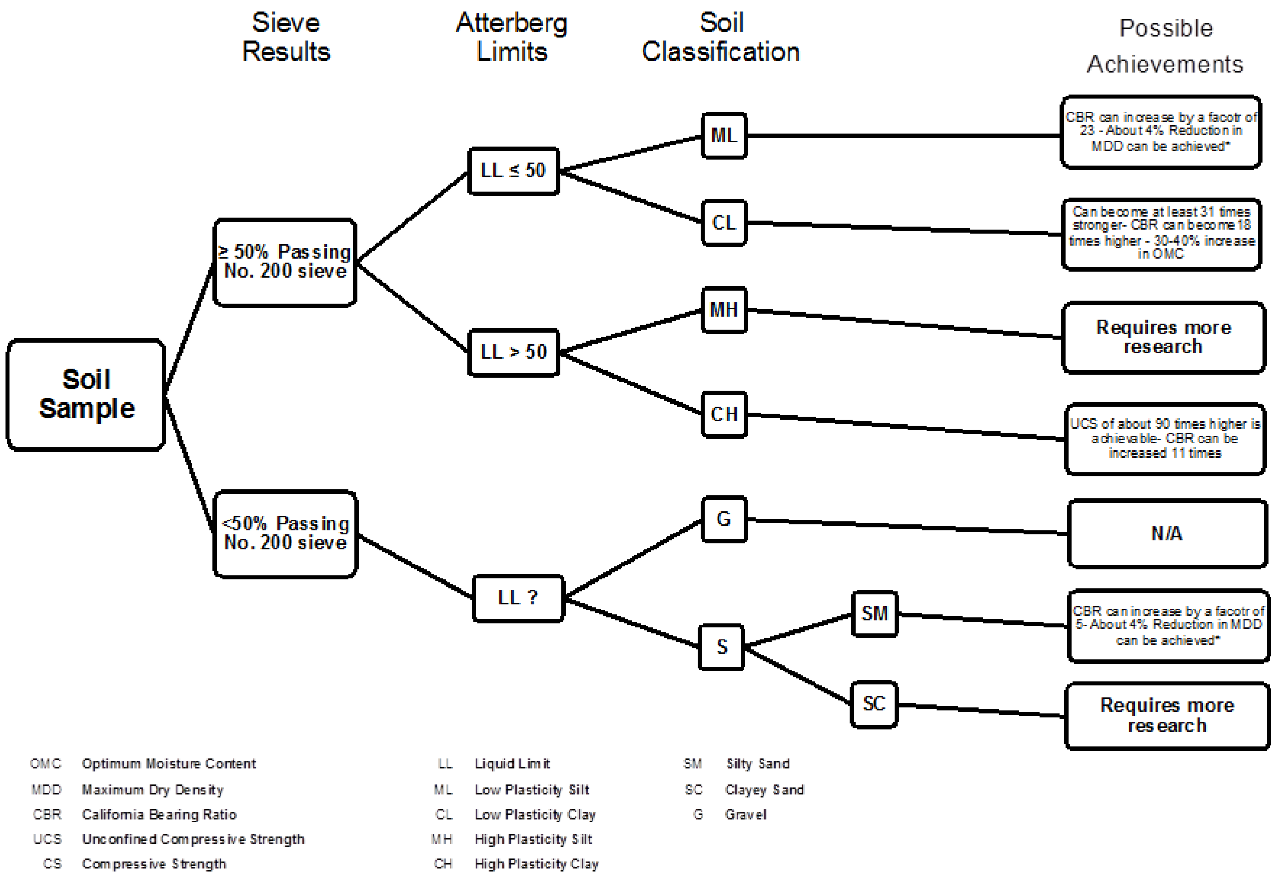
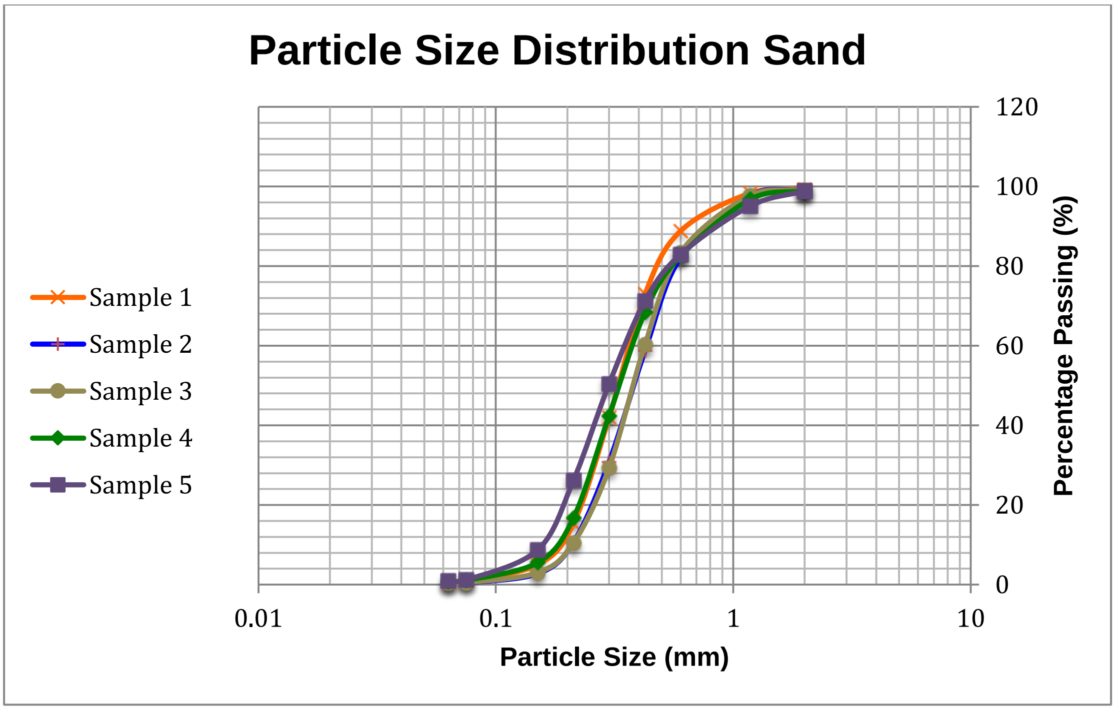


Note: These results are possible with curing during of 12 to 13 weeks with Fly Ash content of 20% to 24%. *Cured for only seven days

Fig. 5. Various Possible Results of Soil Stabilization Using Fly Ash



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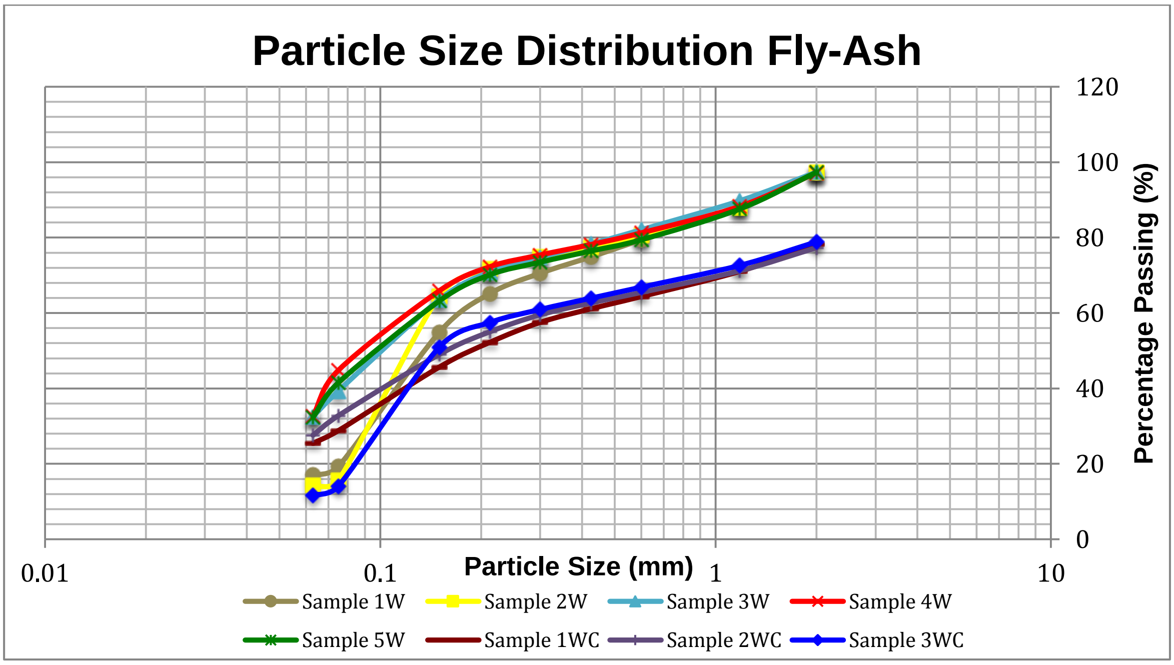

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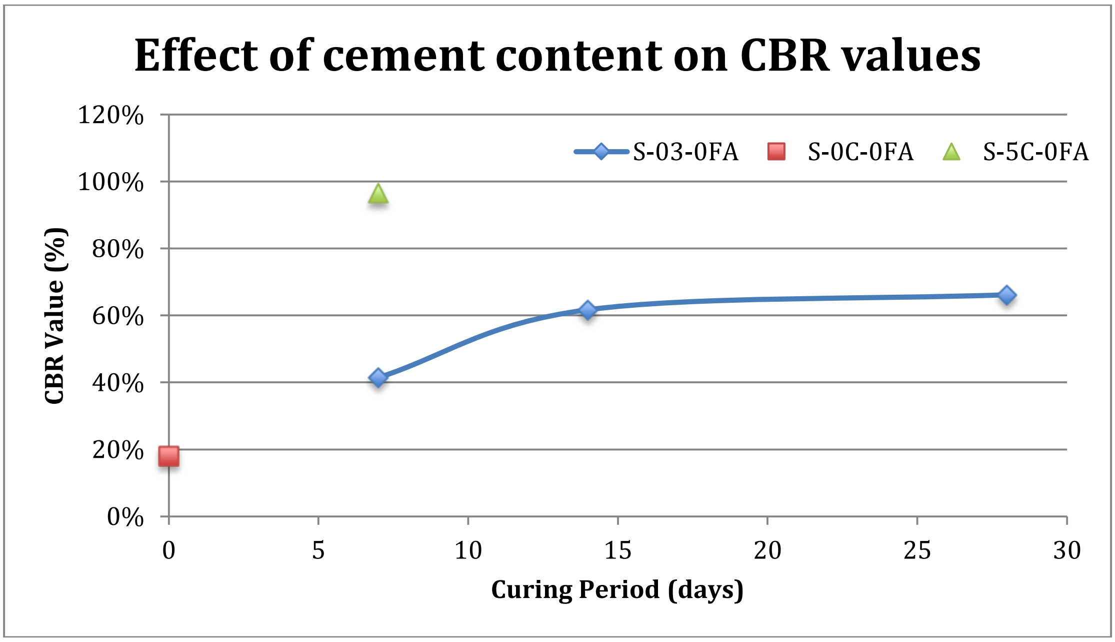
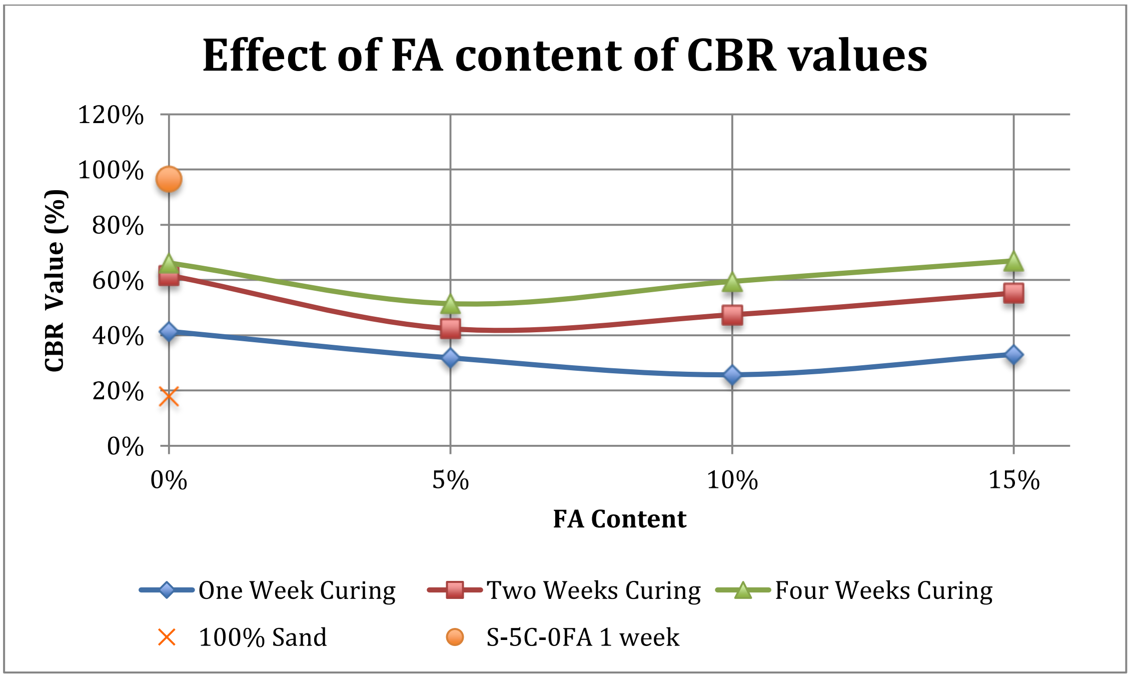


Fig 8. Effect of cement content on CBR values untreated sand and sand + cement.



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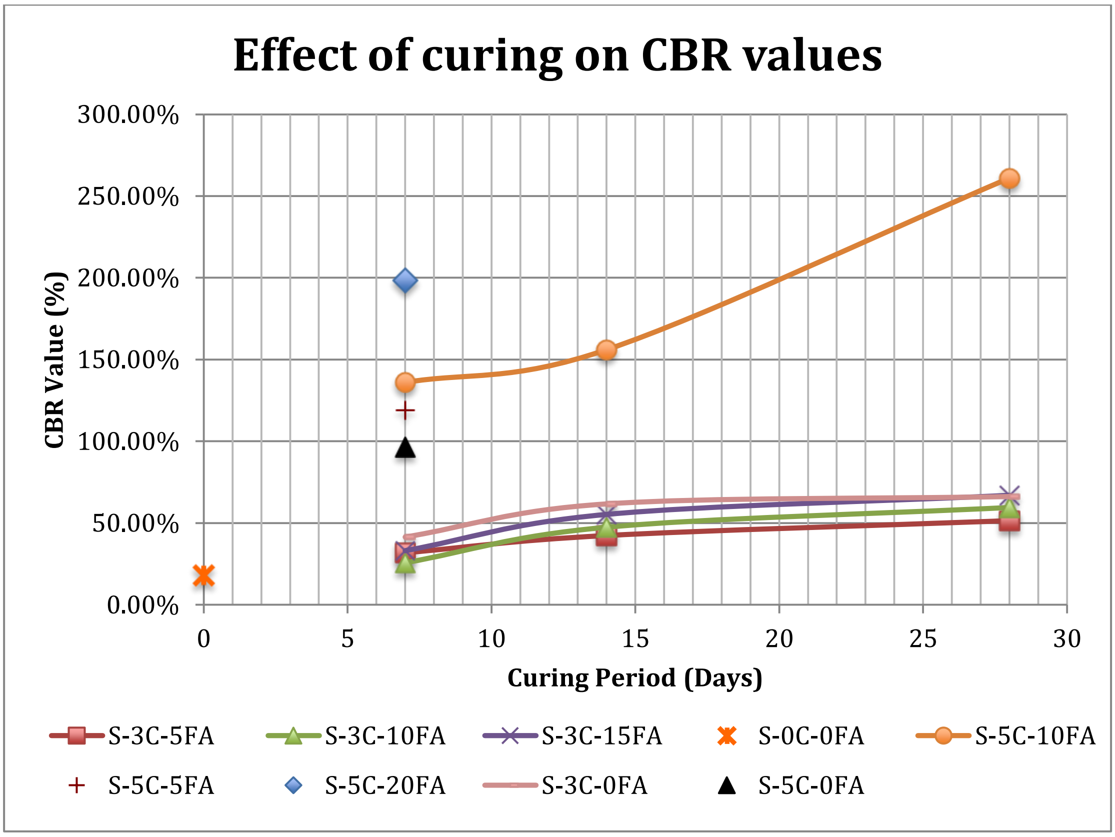

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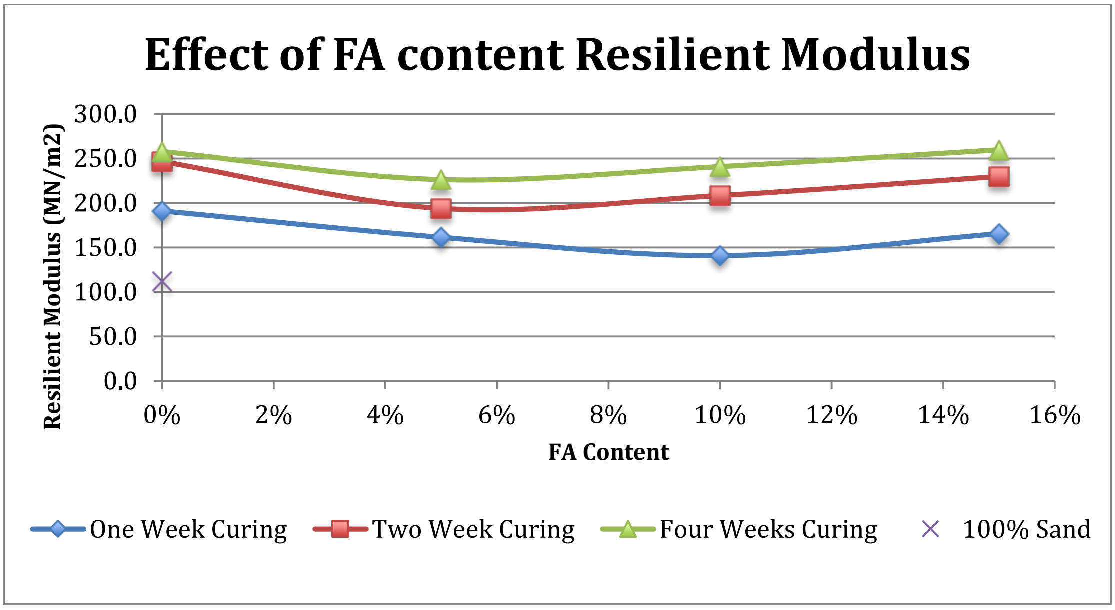

Fig 11. Effect of FA content on Resilient Modulus

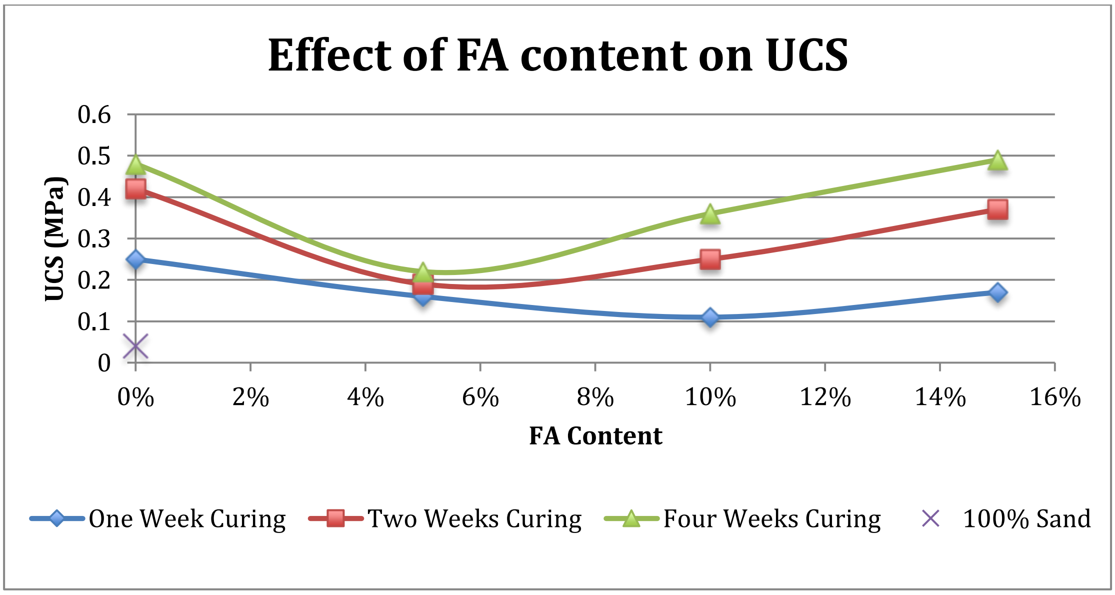

Fig 12. Effect of FA content on UCS

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Summary: Experiences of soil stabilization using Fly Ash

	Fly Ash	Soil	Activator	Tests	Results: Before Treatment	Results: After Treatment	Source
20%	Fly Ash (FA)	Lean Clay	Cement		20% FA and 91-day curing		Kolias et al. 2005
				OMC	22%	30%	
				CS	0.1 Mpa	3.1 Mpa	
				CBR	10%	185%	
				MDD	15.9 KN/m3	13.1 KN/m3	
20%	Fly Ash (FA)	Lean Clay	Cement		20% FA and 28-day curing		
				OMC	22%	30%	
				CS	0.1 Mpa	1.7 Mpa	
				CBR	10%	185%	
				MDD	15.9 KN/m3	13.1 KN/m3	
20%	Fly Ash (FA)	Fat Clay	Cement		20% FA and 91-day curing		
				CS	0.1 Mpa	1.75 Mpa	
				CBR	10%	110%	
20%	Fly Ash (FA)	Fat Clay	Cement		20% FA and 28-day curing		
				CS	0.1 Mpa	1.25 Mpa	
				CBR	10%	110%	
10%	Fly Ash (FA)	Lean Clay	Cement		10% FA and 91-day curing		
				OMC	22%	26%	
				CS	0.1 Mpa	1.9 Mpa	
				CBR	10%	140%	
				MDD	15.9 KN/m3	14.1 KN/m3	
10%	Fly Ash (FA)	Lean Clay	Cement		10% FA and 28-day curing		
				OMC	22%	26%	
				CS	0.1 Mpa	1.1 Mpa	
				CBR	10%	140%	
				MDD	15.9 KN/m3	14.1 KN/m3	
10%	Fly Ash (FA)	Fat Clay	Cement		10% FA and 91-day curing		
				CS	0.1 Mpa	0.7 Mpa	
				CBR	10%	60%	
10%	Fly Ash (FA)	Fat Clay	Cement		10% FA and 28-day curing		
				CS	0.1 Mpa	0.5 Mpa	
				CBR	10%	60%	

OMC **Optimum Moisture Content**
MDD **Maximum Dy 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		40% FAF and 28-day curing		Aydilek and Arora, 2005
				MDD		15.46 kN/m3	
				UCS		5.0 Mpa	
40%	Fly Ash Class F (FAF)	Silty Sand	Cement		40% FAF and 7-day curing		
				MDD		15.46 kN/m3	
				UCS		3.2 Mpa	
				CBR		140%	
40%	Fly Ash Class F (FAF)	Silty Sand	Lime		40% FAF and 28-day curing		
				MDD		15.36 kN/m3	
				UCS		0.4 Mpa	
40%	Fly Ash Class F (FAF)	Silty Sand	Lime		40% FAF and 7-day curing		
				MDD		15.36 kN/m3	
				UCS		0.3 Mpa	
				CBR		36%	
60%	Fly Ash (FA)	Low Plasticity Clay			60% FA and 28-day curing		Santos et al. 2011
				OMC	14%	28%	
				MDD	17.9 kN/m3	13.9	
				CS		2.67 Mpa	
40%	Fly Ash (FA)	Low Plasticity Clay			40% FA and 28-day curing		
				OMC	14%	25%	
				MDD	17.9 kN/m3	14.6 kN/m3	
				CS		2.65 Mpa	
20%	Fly Ash (FA)	Low Plasticity Clay			20% FA and 28-day curing		
				OMC	14%	23%	
				MDD	17.9 kN/m3	15.5 kN/m3	
				CS		1.35 Mpa	
20%	Fly Ash Class F (FAF)	Fat clays	SH & SS		20% FAF and 84-day curing		Cristelo et al. 2012a
				UCS	0.08 Mpa	8.6 Mpa	
20%	Fly Ash Class F (FAF)	Fat clays	SH & SS		20% FAF and 28-day curing		
				UCS	0.08 Mpa	1.7 Mpa	
20%	Fly Ash Class C (FAC)	Fat clays	SH & SS		20% FAC and 84-day curing		
				UCS	0.08 Mpa	2.8 Mpa	
20%	Fly Ash Class C (FAC)	Fat clays	SH & SS		20% FAC and 28-day curing		
				UCS	0.08 Mpa	1.3 Mpa	

10%	Fly Ash Class F (FAF)	Fat clays	SH & SS		10% FAF and 84-day curing			
				UCS	0.08 Mpa	4.2 Mpa		
10%	Fly Ash Class F (FAF)	Fat clays	SH & SS		10% FAF and 28-day curing			
				UCS	0.08 Mpa	0.6 Mpa		
10%	Fly Ash Class C (FAC)	Fat clays	SH & SS		10% FAC and 84-day curing			
				UCS	0.08 Mpa	1.9 Mpa		
10%	Fly Ash Class C (FAC)	Fat clays	SH & SS		10% FAC and 28-day curing			
				UCS	0.08 Mpa	1.1 Mpa		
25%	Fly Ash Class F (FAF)	Granitic Residual Soil	SH & SS		25% FAF and 7-day curing		Cristelo et al. 2012b	
				UCS		17 Mpa		
				MDD	19.2 KN/m3			
20%	Fly Ash Class C (FAC)	High Plasticity Clay			20% FAC and 40-day curing		Reyes and Pando, 2007	
				MDD	12.1 kN/m3			
				CS	0.03 Mpa	0.96 Mpa		
20%	Fly Ash Class C (FAC)	High Plasticity Clay			20% FAC and 28-day curing			
				MDD	12.1 kN/m3			
				CS	0.03 Mpa	0.9 Mpa		
10%	Fly Ash Class C (FAC)	High Plasticity Clay			10% FAC and 40-day curing			
				MDD	12.1 kN/m3			
				CS	0.03 Mpa	0.56 Mpa		
10%	Fly Ash Class C (FAC)	High Plasticity Clay			10% FAC and 28-day curing			
				MDD	12.1 kN/m3			
				CS	0.03 Mpa	0.45 Mpa		
24%	Fly Ash (FA)	Kalahari Sand			24% FA and 7-day curing		Sahu, 2001	
				OMC	5%	7%		
				MDD	17.3 KN/m3	14.7 KN/m3		
				CBR	40%	10%		
24%	Fly Ash (FA)	Calcrete			24% FA and 7-day curing			
				OMC	15.60%	17%		
				MDD	17.2 KN/m3	16.3 KN/m3		
				CBR	40%	90%		

24%	Fly Ash (FA)	Silty Sand			24% FA and 7-day curing		
				OMC	9%	9%	
				MDD	19.0 KN/m3	18.2 KN/m3	
				CBR	80%	470%	
24%	Fly Ash (FA)	Black Cotton Soil			24% FA and 7-day curing		
				OMC	20%	23.50%	
				MDD	15.1 KN/m3	14.8 KN/m3	
				CBR	0%	25%	
24%	Fly Ash (FA)	Low Plasticity Silt			24% FA and 7-day curing		
				OMC	12%	12.30%	
				MDD	19.8 KN/m3	18.9 KN/m3	
				CBR	10%	230%	
8%	Fly Ash (FA)	Kalahari Sand			8% FA and 7-day curing		
				OMC	5%	5%	
				MDD	17.3 KN/m3	16.8 KN/m3	
				CBR	40%	30%	
8%	Fly Ash (FA)	Calcrete			8% FA and 7-day curing		
				OMC	15.60%	19.90%	
				MDD	17.2 KN/m3	16.4 KN/m3	
				CBR	40%	60%	
8%	Fly Ash (FA)	Silty Sand			8% FA and 7-day curing		
				OMC	9%	8.80%	
				MDD	19.0 KN/m3	18.6 KN/m3	
				CBR	80%	315%	
8%	Fly Ash (FA)	Black Cotton Soil			8% FA and 7-day curing		
				OMC	20%	22.70%	
				MDD	15.1 KN/m3	15.3 KN/m3	
				CBR	0%	5%	
8%	Fly Ash (FA)	Low Plasticity Silt			8% FA and 7-day curing		
				OMC	12%	11.90%	
				MDD	19.8 KN/m3	19.6 KN/m3	
				CBR	10%	40%	
40%	Fly Ash Class F (FAF)	Sandy Clay	SH & SS		40% FAF and 365-day curing		Cristelo et al. 2011
				UCS		43 Mpa	
40%	Fly Ash Class F (FAF)	Sandy Clay	SH & SS		40% FAF and 90-day curing		
				UCS		17 Mpa	

40%	Fly Ash Class F (FAF)	Sandy Clay	SH & SS		40% FAF and 28-day curing		
				UCS		8 Mpa	
20%	Fly Ash Class F (FAF)	Sandy Clay	SH & SS		20% FAF and 365-day curing		
				UCS		24 Mpa	
20%	Fly Ash Class F (FAF)	Sandy Clay	SH & SS		20% FAF and 90-day curing		
				UCS		5 Mpa	
20%	Fly Ash Class F (FAF)	Sandy Clay	SH & SS		20% FAF and 28-day curing		
				UCS		3.5 Mpa	
24%	Fly Ash -a	Oxford Clay	Lime		24% FA and 90-day curing		McCarthy et al. 2011
				OMC	25%	26.90%	
				MDD	14.9 KN/m3	14.3 KN/m3	
				UCS	0.3 Mpa	1.9 Mpa	
24%	Fly Ash -b	Oxford Clay	Lime		24% FA and 90-day curing		
				OMC	25%	28.10%	
				MDD	14.9 KN/m3	13.7 KN/m3	
				UCS	0.3 Mpa	1.5 Mpa	
24%	Fly Ash -a	Oxford Clay	Lime		24% FA and 28-day curing		
				OMC	25%	26.90%	
				MDD	14.9 KN/m3	14.3 KN/m3	
				UCS	0.3 Mpa	1.4 Mpa	
24%	Fly Ash -b	Oxford Clay	Lime		24% FA and 28-day curing		
				OMC	25%	28.10%	
				MDD	14.9 KN/m3	13.7 KN/m3	
				UCS	0.3 Mpa	1.2 Mpa	
12%	Fly Ash -a	Oxford Clay	Lime		12% FA and 90-day curing		
				OMC	25%	26.70%	
				MDD	14.9 KN/m3	14.4 KN/m3	
				UCS	0.3 Mpa	1.7 Mpa	
12%	Fly Ash -b	Oxford Clay	Lime		12% FA and 90-day curing		
				OMC	25%	27.40%	
				MDD	14.9 KN/m3	14.0 KN/m3	
				UCS	0.3 Mpa	1.4 Mpa	
12%	Fly Ash -a	Oxford Clay	Lime		12% FA and 28-day curing		
				OMC	25%	26.70%	
				MDD	14.9 KN/m3	14.4 KN/m3	
				UCS	0.3 Mpa	1.3 Mpa	

12%	FlyAsh -b	Oxford Clay	Lime		12% FA and 28-day curing	
				OMC	25%	27.40%
				MDD	14.9 KN/m3	14.0 KN/m3
				UCS	0.3 Mpa	1.2 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%FA[1]	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%FA[1]	S-5C-10FA7	7	136.9	1.13	410.4
Sand+5%Cement+10%FA[1]	S-5C-10FA14	14	156.7	1.57	447.5
Sand+5%Cement+10%FA[1]	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%FA[1]	S-5C-20FA	7	198.54	1.69	520.6

([1]After Wood 2016)