Soft Soil Stabilisation Using High Calcium Waste Material Fly Ash

Hassnen M. Jafer[1,2], W. Atherton[3], and F. Ruddock[3]

[1] Postgraduate Research Student, Liverpool John Moores University, School of the Built Environment, Henry Cotton Building,15-21 Webster Street, Liverpool, L3 2ET, UK
[2]University of Babylon, College of Engineering, Civil Engineering Department, Babil, Iraq.
[3] Liverpool John Moores University, School of the Built Environment, Peter Jost Enterprise Centre, Byrom Street, Liverpool, L3 3AF, UK

Email: H.M.Jafer@2014.ljmu.ac.uk

Abstract:

Civil engineering projects located in areas with soft soil present some of the most common problems in many parts of the world. Depending on the nature of the project, expensive solutions are sometimes used, which commonly involves the removal and replacement of the weak soils. Alternatively, ground improvement is now considered the best solution for such problems. Soil improvement can be achieved either by mechanical and/or chemical stabilisation. To reduce the use of cement and lime as the most traditional stabilizers applied to soft soils, sustainable waste materials have been increasingly used for soil stabilisation. This paper presents the results of a laboratory study on the stabilisation of silty clayey soil using a waste material fly ash (FA) with high calcium content produced from the incineration processes in domestic power stations. The FA used in this study has a high content of calcium oxide CaO and suitable content of silicon dioxide SiO_2 (more than 25%). These cementitious and pozzolanic properties are responsible for the self-cementing characteristics of this fly ash. An intermediate plasticity silty clayey soil with medium organic matter content has been used in this study. The effect of FA on the physical and engineering properties on the selected soil such as the consistency limits, compaction characteristics (optimum moisture content and maximum dry density), and soil strength (unconfined compressive strength (UCS)), has been investigated. Different percentages of fly ash were added to the soft soil (1.5, 3, 6, 9, 12, and 15%) to produce different admixtures. Improvement levels were evaluated dependant on the UCS tests carried out on specimens at different periods of curing (zero, 7, 14, and 28 days). Results indicated that the maximum dry density decreased and the optimum moisture content increased with the increase of the FA content. In terms of the UCS tests, the results yielded the optimum value of the FA used in this study to be 12.0%, as this percentage decreased the index of plasticity (IP) significantly. The results of this study indicated that the use of this waste material could produce a significant cementitious reaction when added to the soil, and it could be used as a supplementary cementitious material.

Key words: *Waste materials, high calcium fly ash, unconfined compressive strength, and soft soils.*

Introduction

Soft soil is one of the most problematic soils in civil engineering because of its high compressibility, the tendency to swell when its water content increases and its low compressive strength. Soil stabilisation is a technique introduced a number of years ago in order to render the soil capable of meeting the requirements of specific engineering projects (Kolias, et.al. 2005). More specifically, soil stabilisation is recommended to aid the engineer in being able to employ the natural soil of a project's site as an engineering material with specific properties, especially strength, volume stability, permeability and durability. Stabilisation of subgrade soil has traditionally relied on treatment with lime, cement, and special additives such as Pozzolanic materials. Overall, lime and Ordinary Portland cement (OPC) have been involved as binder materials in soil stabilisation which have the responsibility for the hydration reaction to bond the soil particles to each other as indicated in numerous of researches (Miura et al., 2002; Raoul, et al., 2010; Farouk and Shahien, 2013; and Önal, 2014).

The manufacture of 1 tonne of OPC assumes the consumption of 1.5 tonnes of quarry material, energy consumption of 5.6 GJ/tonne and a CO2 emission of approximately 0.9 tonne. Thus, cement manufacture represents 5% of total anthropogenic CO2 emission (O'Rourke et al., 2009). A growth of about 6.95 % annually has been recorded with a highest increase of 9.0 % in 2010, and 2011 with a slowdown to 3.0 % in 2012 to reach 3.7 billion tons (Merchant Research & consulting ltd, 2013). Overall, the global cement market is predicted to increase at 5% per year. Due to the high cost and negative environmental impact of cement production, researchers have been driven to find alternative materials to replace, or decrease the use of, OPC in the concrete industry. These materials are called supplementary cementitious materials (SCM). They are in general by-product materials and most of these are called pozzolans, which by themselves do not have any cementitious properties, but when mixed with cement, react to form cementitious compounds (National Ready Mix Concrete Association, 2000).

Pozzolanic materials such as micro silica fume (SF), rice husk ash (RHA), pulverised fuel ash (PFA), ground blast furnace slag (GBS), etc., which are regarded as waste materials, have been used individually for soil stabilisation. They improve some of physical and engineering properties of soft soils dependant on their specific surface area and fineness which causes in decrease the cohesion and increase the density for soft soils as indicated in recent research projects (Abd El-Aziz, et al., 2006; Lin et al., 2007; and Yadu and Tripathi, 2013)

On the other hand, many researchers have used waste materials as SCM in soil stabilisation to reduce the use of OPC and lime and to boost the hydration reactivity dependant on the pozzolanic reaction of these materials. RHA, palm oil fuel ash (POFA), ladle furnace slag (LFS), SF, and coal waste have been used as SCM in recent research projects (Brooks, 2010; Ahmed et al.,2011; Manso, et al., 2013; Fattah et al., 2014; and Modarres and Nosoudy, 2015).

The current study has used the waste material fly ash as self-cementing material in order to replace the traditional binder (OPC and lime) used in soft soil stabilisation completely. The level of improvement in the physical properties of the soft soil was evaluated dependant on the results obtained from consistency limits test and compaction parameters. Additionally, the development in the geotechnical properties of the soft soil stabilised with this waste material was investigated dependant on the results yielded from unconfined compressive strength test. UCS test was conducted on specimens of the soft soil treated with different amount of the FA (0.0, 1.5, 3, 6, 9, 12, and 15%) with different ages of curing (zero, 7, 14, and 28 days).

Materials

Soft Soil Sample

The soft soil used in this study was collected from a site located in High Town to the north of Liverpool. The soil samples were extracted from the riverbank of the estuary of River Alt from a depth about 30-50cm below ground level, then placed in sealed plastic packs 20-25kg each before the transferring to the laboratory. Figure 1 shows the site where the soil samples used in this study were extracted. The site in general is an alluvial plain and the soil's visible description is medium soft, dark grey clayey silt with traces of sand and the smell of algae.

Figure 1. Extraction Site

After transferring the soil samples to the laboratory, a soil specimen was taken to calculate the natural moisture content in accordance with BS EN ISO 17892-1:2014 (European Committee for Standardization, 2014), and the rest of the soil was air dried inside the lab to be prepared for other classification testing. The physical and geotechnical characteristics of the soft soil were determined in accordance to BS EN ISO 17892-4:2014 for particle size distribution and in accordance to BS 1377-2 and 4:1990 (British Standard, 1990) for Atterberg limits and compaction parameters respectively. The results are shown in Table 1, and Figure 2 shows the particle size distribution of the soft soil used in this study. According to the Unified Soil Classification System (USCS), and depending on the particle size distribution, LL, and IP, the soil in this research project is an intermediate plasticity silty clay with sand (CI).

Table 1. Main physical and engineering properties of the soft soil

Property	*Value*
Natural moisture content NMC %	*52.14*
Liquid Limit LL %	*44*
Index of Plasticity IP	*20.22*
Sand %	*13.08*
Silt %	*43.92*
Clay %	*43.00*
Specific Gravity (Gs)	*2.61*
γ_{dmax} g/cm^3	*1.57*
Optimum moisture content OMC %	*23*
pH	*7.78*
Organic matter content %	*7.95*
Unconfined Compressive Strength qu, kPa	*202*

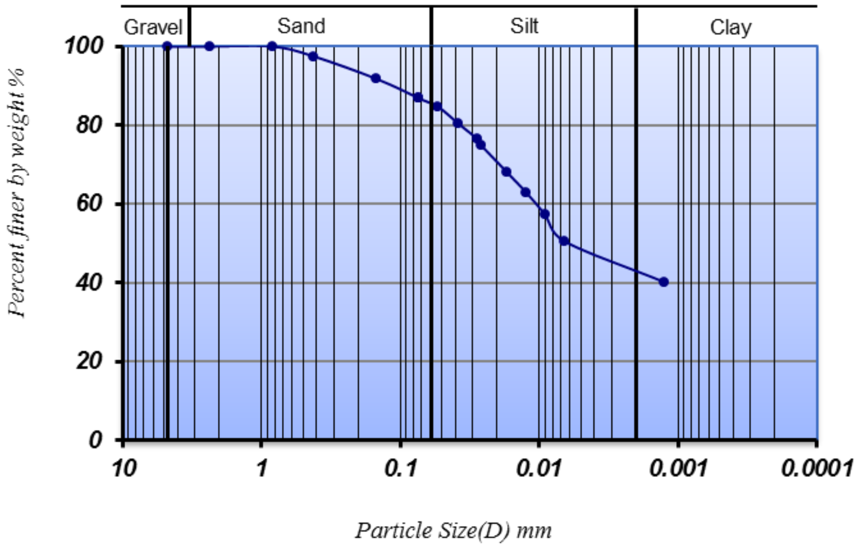


Figure 2. Particle size distribution of the soft soil

The Waste Materials Fly Ash (FA)

The fly ash used in this study is a waste powder material produced from the incineration processes in a domestic power generation station. It has high calcium content and a sufficient amount of silica. This material is slightly coarse in comparison to the Ordinary Portland Cement as shown in Figure 3. A Scanning electronic microscopy test (SEM) showed that the particles of this material have a coagulated and flocculated shape as shown in Figure 4. Particle size distribution of binder material has an undeniable effect on the compressive strength of stabilised soil. It was found that the finer the particles of fly ashes used in concrete with cement, the higher compressive strength obtained (Celik et al., 2008). Therefore; it is expected that the coarse particles of the FA could retard its performance during the hydration reactivity.

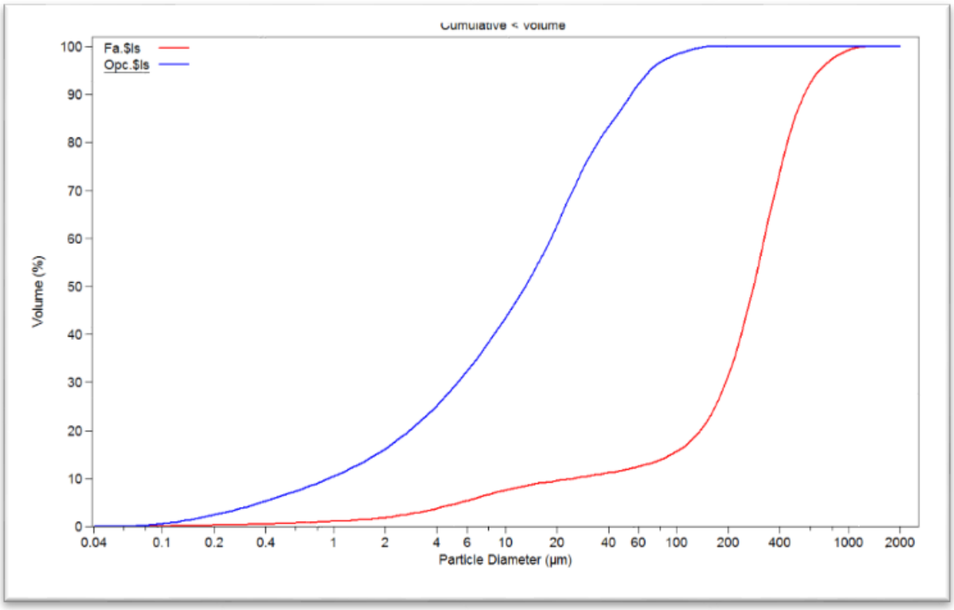


Figure 3. Comparison of cumulative particle size distribution of OPC and FA

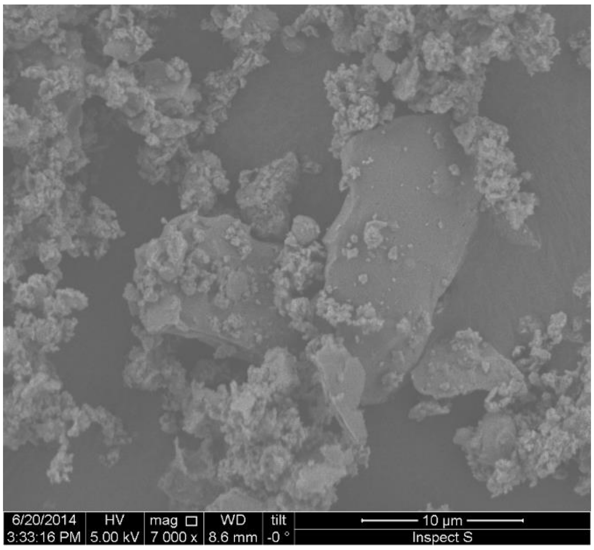


Figure 4. SEM image of the waste material used in this study

Experimental Work

Sample preparation and conditioning

Five different percentages of the FA (1.5, 3, 6, 9, and 12%) were added to the soft soil to determine its effect on the Atterberg limits of the soft soil. The unconfined compressive strength test was conducted according to BS 1377-7:1990 (British Standard, 1998) for untreated compacted soil and soil stabilised with the FA with 1.5, 3, 6, 9, 12, and 15% based on the dry weight of the soil. UCS values were determined by using a computerised and motorised triaxial machine but without applying any lateral load in the triaxial cell ($\sigma_3 = 0$). Remoulded specimens 38mm in diameter and 76mm in height, with specific densities and moisture contents (dependant on the maximum dry density (MDD) and optimum moisture content (OMC) obtained from compaction tests for each corresponding percentage of FA) were prepared using a constant volume mould, which was subjected to static load provided by a manual hydraulic jack as shown in Figure 5. After compaction, the specimens were extruded from the mould, weighed, then wrapped in cling film, sealed in well-sealed plastic bags, and stored for curing in the room at a temperature of 20 ± 2^{o}C. Four groups of specimens were prepared for four different curing periods (0, 7, 14, 28 days), and for each corresponding period of curing, two specimens were prepared for each percentage of FA for more reliable results.

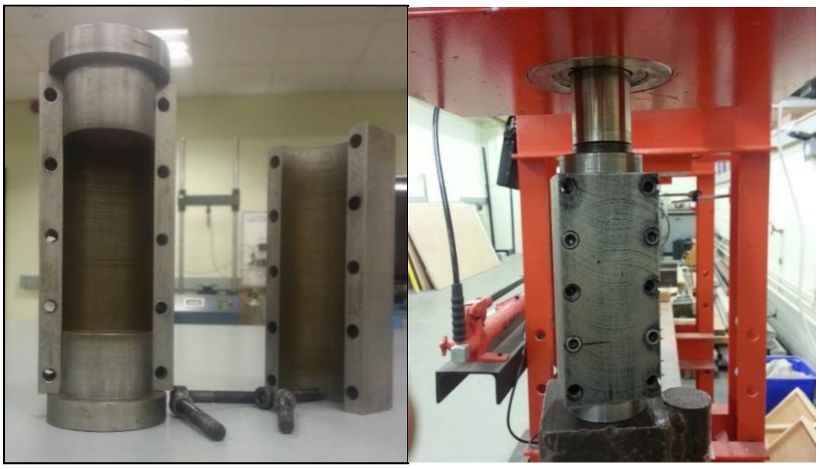


Figure 5. Constant volume mould and the hydraulic jack

Laboratory tests

Three fundamental tests were conducted to investigate the effect of the FA on the physical and engineering properties of the soft soil in this study. These tests were:

- Atterberg limits test - (Liquid Limit (LL), Plastic Limit (PL), and Index of Plasticity (IP)). These limits were determined in accordance to BS 1377-2:1990 (British Standard, 1990). A Cone Penetrometer device was used to find the LL.
- Standard Proctor compaction test - conducted in accordance to BS 1377-4:1990 (British Standard, 2002), 2000g of dry powdered soil was mixed with five different water contents. For each value of water content, soil paste was compacted in a standard mould using a 2.5kg rammer with three layers; each layer was subjected to 25 blows.
- Unconfined compressive strength test - carried out according to BS 1377-7:1990 (British Standard, 1998) on four groups for each corresponding percentage of FA which were tested in four different periods of curing (zero, 7, 14, and 28 days).

Results and Discussion

Atterberg Limits

Figure 6 shows the relationship between the Atterberg limits and the FA used in this study for the soft soil treated with 1.5, 3, 6, 9, and 12% of the waste material by the dry weight of the soft soil. From this figure, it can be seen that the FA has a positive effect in reducing the Index of Plasticity from 20 to below 14, and that LL values increased with the increase of the FA content. This reduction in soil plasticity is attributed to the process of exchange of cations between the soft soil and the FA (Gharib, et. al, 2012). Since Atterberg limits play an important role in soil identification and classification, and give an indication about soil behaviour in the presence of water such as the workability and expansion problem, the FA used in this study can increase the workability by increasing the LL, and decrease the swelling and shrinkage potential by decreasing IP.

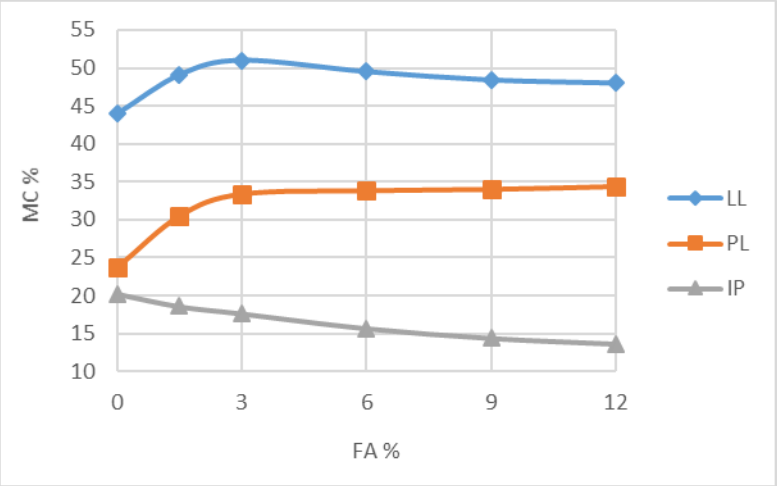


Figure 6. Effect of the FA on the Atterberg limits of the soft soil

Compaction parameters

The aim of this test is to find the maximum dry density and optimum moisture content for untreated soil and soil stabilised with different percentages of stabiliser material. The values obtained from this test are very important and they are considered to prepare the required specimens for several geotechnical experiments such as UCS, CBR, compressibility, triaxial test and swelling potential. Standard Proctor compaction tests were carried out on the soft soil using different percentages of the FA (0, 1.5, 3, 6, 9, 12, and 15%). The results of the compaction tests are shown in Figure 7. It can be observed easily that the MDD decreases and OMC increases with the continuous increase in FA content because of high water absorption of the FA.

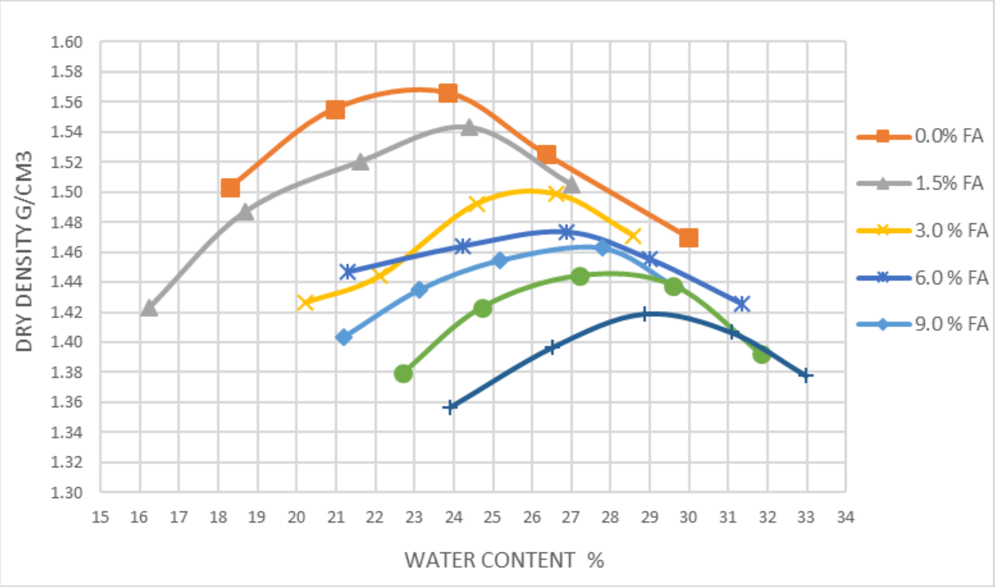
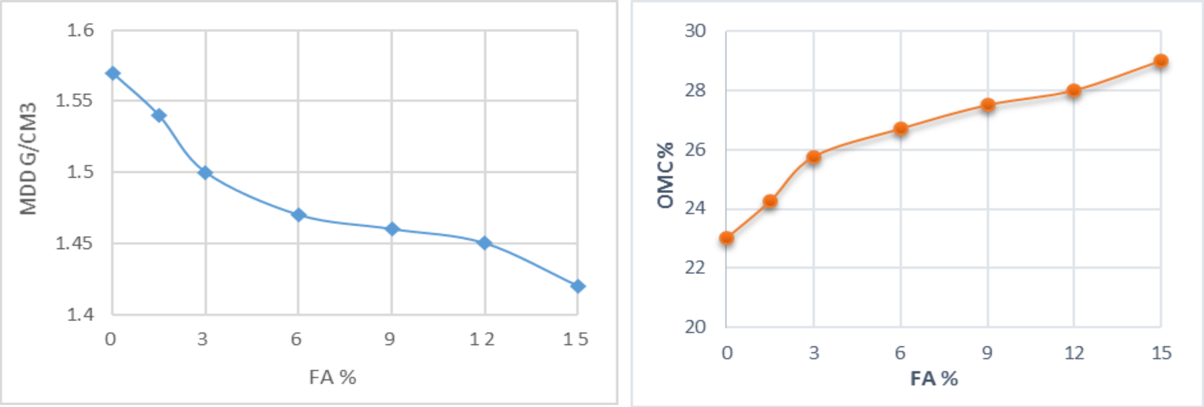


Figure 7. Effect of FA on the compaction parameters of the soft soil

Figures 8 a and b show the effect of the FA on the MDD and OMC for the soft soil respectively. From Figure 8a, it can be recognised that there is a significant decrease in MDD with the continuous increase with FA percentage to less than 1.45 g/cm^3 for soil treated with 15% of FA. OMC also recorded a dramatic increase with the increase of FA to reach approximately 29% at 15% FA as shown in Figure 8b. The results of compaction tests reflect the high water absorption of the FA. This could be beneficial because it leads to a decrease in the required compaction effort on site to achieve the desired degree of relative compaction.

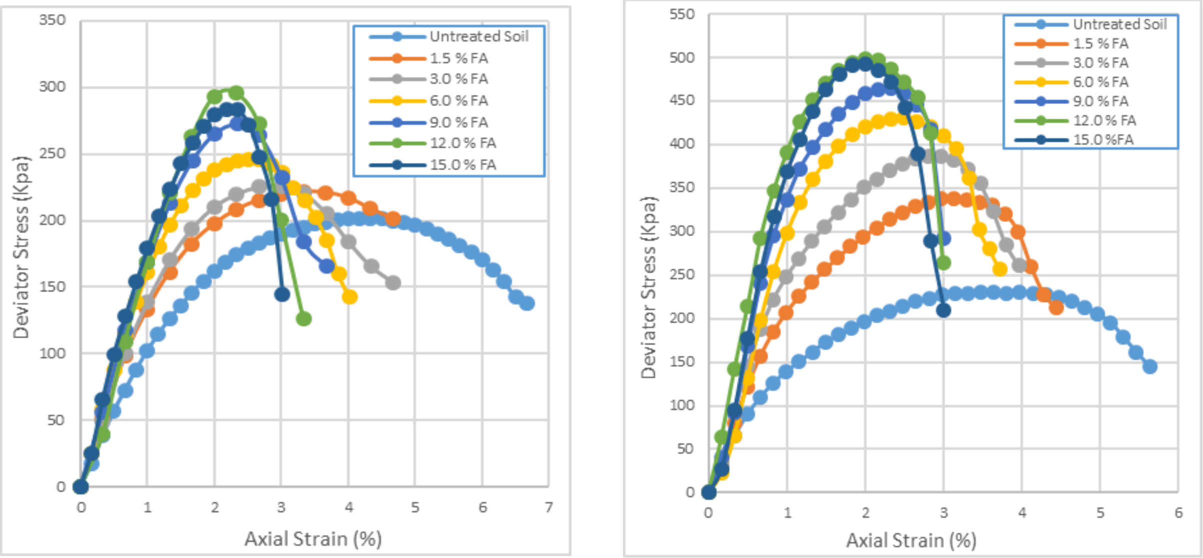


(a) **(b)**

Figure 8. (a) Effect of FA on the MDD, and (b) Effect of FA on OMC

Unconfined compressive strength test (UCS)

Figures 9 a and b show the laboratory results in the form of stress-strain diagrams from unconfined compressive strength tests for the soft soil treated with different percentages of the FA (1.5, 3, 6, 9, 12, and 15%) for zero days and 28 days curing respectively. It can be seen that the compressive strength increased with the increase of curing time for each corresponding percentage of FA. Overall, the results indicated a significant improvement in UCS of the soft soil treated with the FA; UCS increased from about 200kPa for the untreated soil to over 500kPa for the soil treated with 12% of FA after 28 days curing.



(a) (b)

Figure 9. Stress-strain relationship for soil treated with different contents of FA (a) zero day curing and (b) 28 days curing

The unconfined compressive strength values measured for different FA content with different curing periods are shown in figure 10. From this figure, it is clear that 12.0% of the FA implemented the maximum values of UCS for different curing times and the improvement in UCS for the soft soil can be recognised clearly after adding 9% of FA.

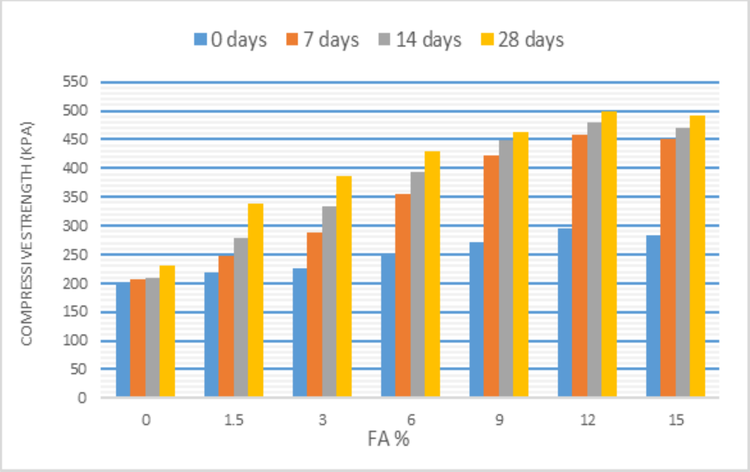


Figure 10. Relationship between UCS and FA percentage in different periods of curing

From another point of view, Figure 11 shows the development in UCS with the time of curing for untreated and treated soil with the optimum percentages of the FA. It can be seen that the UCS of the stabilised soil increased significantly through the time of curing from just under 300kPa for uncured specimens up to about 500kPa at 28 days of curing. It should be noted that there was a dramatic increase in UCS for stabilised soil with the optimum content of the FA for an earlier curing time (7 days curing), which provides about 90% of the total development of UCS. After this, the rate of UCS development began to plateau as shown in Figure 11. This indicates that the waste material used in this study has a fast curing property which means that it has the ability to stabilise the soft soil within short period.

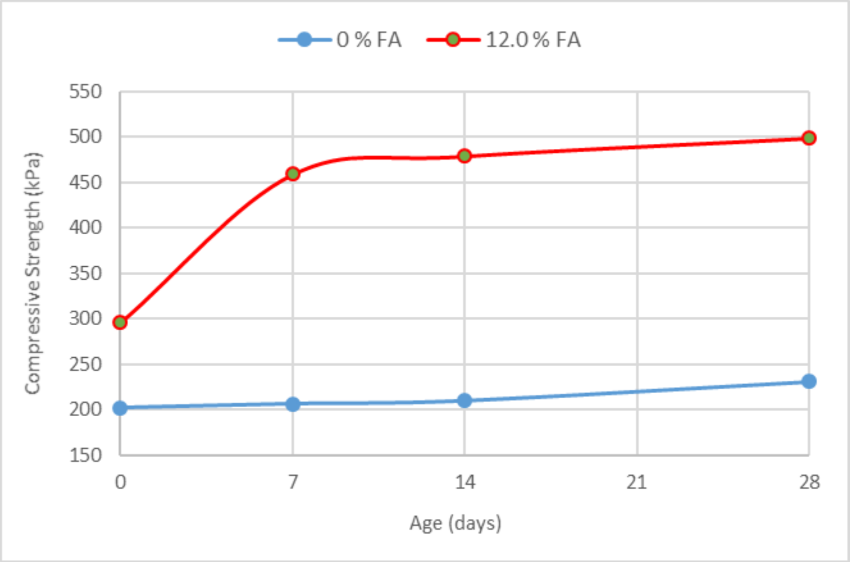


Figure 11. UCS development with curing time for soil stabilised with optimum FA

Conclusions

In conclusion, the effect of the waste material FA used in this study on the physical and engineering properties of the selected soft soil can be summarised as follows:

1. The FA has a positive effect on the physical properties of the soft soil. The results showed that IP was decreased by approximately 1/3 of its original value with the use of 12% FA, which would improve soil resistance against swelling and shrinkage effects.
2. Furthermore, MDD decreased and OMC increased with the increase of the FA, which would increase the workability of soil mixing in the field and decrease the required effort to achieve the desired degree of compaction for the soil.
3. The FA has significantly improved the unconfined compressive strength of the soft soil. The results showed that UCS was increased by approximately 250% with 12% FA after 28 days curing in comparison to UCS of untreated soft soil.
4. The waste material FA used in this study has the potential to be used as soft soil stabiliser and it has the ability to improve the physical and engineering properties within short periods of curing.

Recommendations

1. Depending on particle size distribution, the FA is a slightly coarse material, it is expected that it would produce a better results in soil stabilisation if it were to be ground using low energy grinding effort.
2. Study the effect of the FA on the other geotechnical properties of the soft soil such as the consolidation and California bearing ratio (CBR).

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