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Assessing the Potential of a Waste Material for Cement Replacement and the Effect of Its Fineness in Soft Soil Stabilisation

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Abstract**—**This paper represents the results of experimental work to investigate the suitability of a waste material (WM) for soft soil stabilisation. In addition, the effect of particle size distribution (PSD) of the waste material on its performance as a soil stabiliser was investigated. The WM used in this study is produced from the incineration processes in domestic energy power plant and it is available in two different grades of fineness (coarse waste material (CWM) and fine waste material (FWM)). An intermediate plasticity silty clayey soil with medium organic matter content has been used in this study. The suitability of the CWM and FWM to improve the physical and engineering properties of the selected soil was evaluated dependant on the results obtained from the consistency limits, compaction characteristics (optimum moisture content (OMC) and maximum dry density (MDD)); along with the unconfined compressive strength test (UCS). Different percentages of CWM were added to the soft soil (3, 6, 9, 12 and 15%) to produce various admixtures. Then the UCS test was carried out on specimens under different curing periods (zero, 7, 14, and 28 days) to find the optimum percentage of CWM. The optimum and other two percentages (either side of the optimum content) were used for FWM to evaluate the effect of the fineness of the WM on UCS of the stabilised soil. Results indicated that both types of the WM used in this study improved the physical properties of the soft soil where the index of plasticity (IP) was decreased significantly. IP was decreased from 21 to 13.64 and 13.10 with 12% of CWM and 15% of FWM respectively. The results of the unconfined compressive strength test indicated that 12% of CWM was the optimum and this percentage developed the UCS value from 202kPa to 500kPa for 28 days cured samples, which is equal, approximately 2.5 times the UCS value for untreated soil. Moreover, this percentage provided 1.4 times the value of UCS for stabilized soil-CWA by using FWM which recorded just under 700kPa after 28 days curing.

Keywords**—**Soft soil stabilisation, waste materials, fineness, and unconfined compressive strength.

I. Introduction

THE most common defects in soft soils are their low compressive strength, high compressibility, and the tendency to swell when water content increases. These attributes cause the soil to be classified as a problematic soil. The accepted traditional method of soft soil mitigation is to replace the soft soil with stronger materials. Due to the high cost of this method, researchers have been motivated to search for alternative methods, and one of these methods includes the process of soil stabilisation. Soil stabilisation is a procedure presented several decades ago in order to render the soils engineering properties suitable to meet the requirements of specific engineering projects [1]. More specifically, soil stabilisation is recommended to help the engineer in being able to reuse the natural soil that exists on site as an engineering material with specific properties, especially strength, volume stability, permeability and durability [2]. Stabilisation of soft soil has conventionally been achieved by mixing soft soils with lime, cement, and/or special additives such as Pozzolanic materials. However, there are numerous research projects involving lime and Ordinary Portland Cement (OPC) as binder material in soft soil stabilisation. Lime and OPC have been used mainly as preferable binder materials and it has the ability to bond soil particles to each other resulting in a strong material as indicated in [3]-[6], [2].

The manufacture of 1 tonne of OPC consumes 1.5 tonnes of raw material with energy consumption of 5.6 GJ/tonne and CO_2 emission of approximately 0.9 tonne. Moreover, it was found that cement manufacture represents 10% of total global CO_2 emissions [7]. 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. However, the global cement market is predicted to increase at 5% per year [8]. Due to the high cost and harmful 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 some of these are called pozzolans, which by themselves do not have any cementitious properties, but when mixed with cement, react to form cementitious compounds.

Many researchers have used different types of by-product or waste materials such as palm oil fly ash (POFA), sawdust ash (SDA), rice husk ash (RHA), calcium carbide residue (CCR), pulverised fuel ash (PFA), ground blast furnace slag (GBS), silica fume (SF), etc., for soil stabilisation. They used these materials as pozzolanic material to improve the physical properties of week soils dependant on their specific surface area and fineness which causes a decrease in the cohesion and

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increase the density for soft soils, as well as improved soil strength against swelling and shrinkage stresses [9]-[15].

On the other hand, waste materials are used sometimes as SCM in soil stabilisation to reduce the use of OPC and lime and to enhance the hydration reactivity. These materials such as RHA, POFA, ladle furnace slag (LFS), SF, and coal waste have suitable pozzolanic reaction and/or a self-cementing property which when mixed with OPC as SCM can provide better results both in the concrete industry and soil stabilisation as indicated in recent research projects [16]-[19], [2].

The specific surface area and the particle size distribution of OPC as well as the candidate materials have an undeniable effect on the compressive strength of stabilised soil. It was found that the finer the particles of fly ash used in concrete with cement, the higher compressive strength obtained [20]. It was proven that the increasing in surface area due to finer particles, provides more available surface of binder material for hydration reaction which in turn improves the engineering properties of stabilised soils especially durability and compressive strength [21], [22].

This study represents the laboratory experimental work to investigate the potential of a self-cementing waste material fly ash to be used as SCM in soil stabilisation, as well as to investigate the effect of fineness and PSD on the performance of this waste material in soft soil stabilisation. The waste material was used in two different grades of fineness (CWM and FWM) with percentages 0, 3, 6, 9, 12, and 15% by the dry weight of the stabilised soil to find their effect on the Atterberg limits. Along with compaction parameters and UCS, the same percentages used in Atterberg limits tests were used for CWM, while 9, 12, and 15% were added with respect to FWM. All specimens of UCS test were cured for different periods of time (zero, 7, 14, and 28 days).

II. Materials

A. Soil Sample

The soil used in this study was brought from the banks of the River Alt which is located in High Town to the north of Liverpool city centre in the UK. The soil samples were extracted from a depth ranging between 30 and 50cm below the ground level, then placed in heavy duty plastic bags with approximately 25kg in each, then sealed carefully before the sending to the laboratory. Fig. 1 shows the site where the soil samples stabilised in this study were taken from. 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.

In the laboratory, all the required experimental work was conducted to identify physical, chemical, and engineering properties of the selected soil. The natural moisture content (NMC) was determined when the soil arrived at the laboratory, and then the remaining soil was air dried inside the lab to be prepared for other experiments.

The physical and geotechnical characteristics of the soft soil were determined in accordance to BS EN ISO 17892-4:2014 for particle size distribution [23], and in accordance to BS 1377-2 and 4:1990 [24] for Atterberg limits and compaction parameters respectively. The particle size distribution results of the selected soil is shown in Fig. 2, while the main physical and geotechnical properties are listed in Table I. 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 intermediate plasticity silty clay with sand (CI).

Fig. 1 Site of Extraction

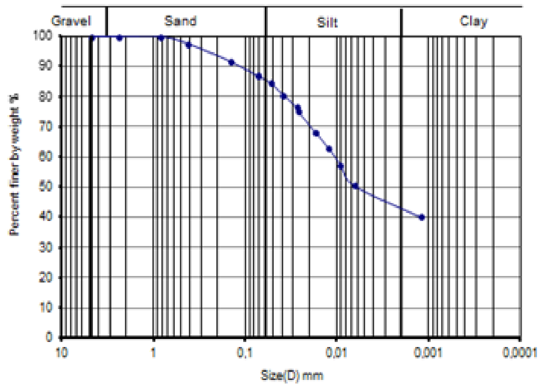


Fig. 2 Particle Size Distribution Curve

TABLE I
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)	2.57
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

g/cm^3= gram/cubic centimetre, kPa = kilopascal.

B. Waste Material (WM)

The waste material used in this study is a powder material resulting from the incineration processes for a particular type of waste material in a domestic power generation station. This waste material is produced in two different grades of fineness (coarse (CWM) and fine (FWM)) but both of two states have the same chemical composition. In comparison to the PSD of OPC, both kinds of the waste material used in this study are coarser than the OPC as shown in Fig. 3.

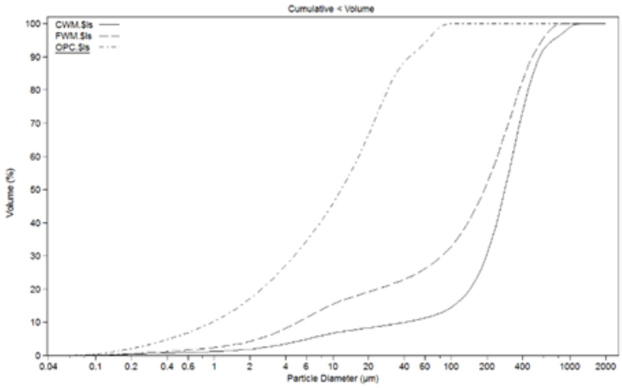


Fig. 3 Particle Size Distribution of the Waste Material Compared with OPC

From another point of view, Table II shows the statistical data of the waste material used in this study in comparison to those for OPC. The big difference between d_{10} for FWM and OPC and d_{10} for CWM can be easily recognised. Later, both types of the waste material became coarser than OPC.

Figs. 4 and 5 show the images of scanning electronic microscopy tests (SEM) for CWM and FWM respectively. From Fig. 4, the large size particles inside the highlighted area can be seen which are not found in Fig. 5 for FWM. However, the particle shape for this waste material can be considered as coagulated particles.

TABLE II
VOLUME STATISTICS FOR BOTH STATES OF THE WASTE MATERIAL USED IN THE STUDY

Item	CWM	FWM	OPC
d_{10} (μm)	24.67	5.069	0.936
d_{50} (μm)	279.3	189.6	13.08
d_{90} (μm)	553.9	481.6	54.29
Mean (μm)	300.3	218.3	21.10
Median (μm)	279.3	189.6	13.08

μm = Micrometre

III. EXPERIMENTAL WORKS

A. Sample Preparation and Conditioning

The soil samples were prepared for Atterberg limits testing by adding five different percentages of the both kinds of WM 0, 3, 6, 9, 12, and 15% by the dry weight of soil. The water was added directly to the mixture to make the stabiliser-soil paste then the paste was tested straight away according to BS 1377-2:1990 [24].

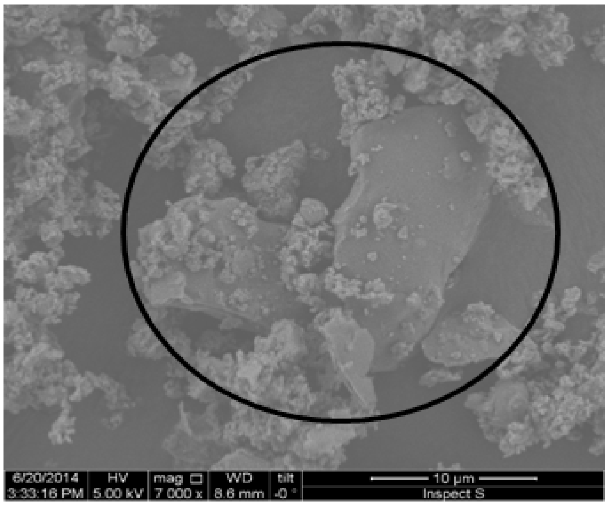


Fig. 4 SEM Image of CWM

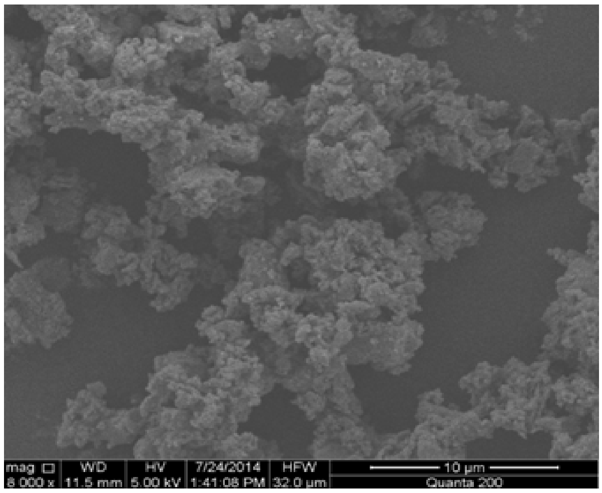


Fig. 5 SEM Image of FWM

With respect to the specimens for UCS testing, 0, 3, 6, 12, 15% by the dry weight of CWM were added to the soft soil to find the optimum content. Then 9, 12, and 15% of FWM were added to the soil to find the effect of fineness on the performance of WM used in this study. A computerised and motorised triaxial machine was used to conduct the UCS testing and the values of UCS were determined by applying vertical load only and eliminating the lateral stress in triaxial cell ($\sigma 3 = 0$). The constant volume mould shown in Fig. 6 was used to prepare specimens of 38mm in diameter and 76mm in height with specific densities dependant on MDD and OMC calculated from compaction test for each corresponding percentage of the added WM. The specimens were compacted inside the constant volume mould by using a manual hydraulic jack then extruded out of the mould and weighed (Fig. 7), wrapped in cling film, enclosed in well-sealed plastic bags, and stored for curing at a temperature of 20 ± 2^oC. Treated soil specimens with each corresponding percentage of both kinds of WM were prepared for each period of curing (0, 7, 14, and 28 days) for more reliable results.

Fig. 6 Constant Volume Mould Used to Prepare the Soil Specimens for UCS Tests

Fig. 7 Hydraulic Compaction and Weighing of a Specimen during Specimens Preparation

B. Laboratory Tests

Three major experiments were conducted to investigate the effect of CWM and FWM on the physical and engineering properties of the soft soil in this study. These tests were:

- Atterberg limits testing - (Liquid Limit (LL), Plastic Limit (PL), and Index of Plasticity (IP)). These limits were determined in accordance to BS 1377-2:1990 [24]. LL tests were conducted using a Cone Penetrometer device.
- Standard Proctor compaction tests were conducted in accordance to BS 1377-4:1990 [25] using 2000g of dry soil or soil-binder passed through sieve size 3.35mm mixed with five different water contents. For each value of water content, the soil paste was compacted in a standard mould using a 2.5kg hammer. The compacted soil paste was formed inside the mould in three layers; each layer was subjected to 25 blows.
- Unconfined compressive strength testing was carried out according to BS 1377-7:1990 [24] on four groups for each corresponding percentage of CWM and FWM which were tested for three different periods of curing (7, 14, and 28 days) in addition to the uncured specimens.

IV. Results and Discussion

A. Atterberg Limits

Liquid limit and plastic limit tests were conducted on soil samples treated with both CWM and FWM using 0, 3, 6, 9, 12, and 15% to find the effect of the fineness of the waste material used in this study on the Atterberg limits of the stabilised soil. Fig. 8 shows the comparative Atterberg limits for the soil treated with CWM and FWM. It can be seen that both grades of fineness of WM have a positive effect to improve the plasticity index for the soft soil when IP was decreased significantly from 20 to less than 14 by adding 12% of CWM and to 13.1 by adding 15% of FWM. The reduction occurred in the soil plasticity due to the exchange of cations between the clayey minerals in the soft soil and the WM [26]. However, the results of Atterberg limits test revealed that FWM indicated better results in comparison to CWM.

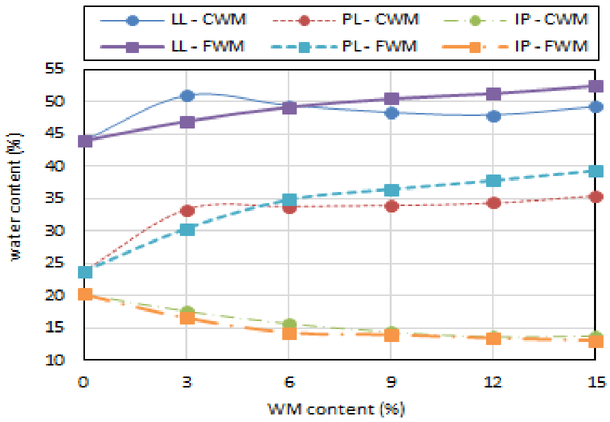


Fig. 8 Atterberg Limits for Soil Treated With CWM and FWM

B. Compaction Test

The compaction test is one of the essential tests that should be conducted to find maximum dry density and optimum moisture content for soils which are known as compaction parameters. These parameters vary dependant on soil types, stabiliser type, and the percentage of the added stabiliser. The preparation of the specimens for the experiments to find the other geotechnical properties such as UCS, consolidation, Triaxial, California bearing ratio tests, etc., are dependant mainly on the values of MDD and OMC obtained from compaction test.

In this study, standard Proctor compaction tests were carried out on the soft soil untreated and treated with different percentages of CWM 3, 6, 9, 12, and 15% by the dry weight. The results of the compaction tests for the soil treated with CWM are shown in Fig. 9. It can be seen that MDD decreased and OMC increased significantly with the continuous increase of CWM percentage. The results indicated that MDD was decreased from 1.56g/cm^3 for untreated soil to 1.42g/cm^3 for the soil treated with 15% CWM, while OMC was increased from 23 up to 29% by using 15% CWM. However, this behaviour gives an indication that this waste material has a high water absorption property which can help to accelerate drying of very wet sites. Furthermore, the compaction testing was conducted on the soil treated by 9, 12, and 15% of FWM to investigate the effect of the fineness on compaction parameters. The results indicated that the MDD of the soil treated with FWM was lower than that for the soil treated with CWM, and the vice versa with respect to the values of OMC as shown in Figs. 10 (a), and (b). This phenomenon is due to the increase in the surface area provided for FWM, which increases the water demand of soil-additive mixture, and this leads to increased OMC. From Fig. 10 (a), it can be recognised easily that there was a sharp decrease in MDD when FWM increased from 12 to 15%. However, MDD decreased from 1.44g/cm^3, for soil treated with 12% FWM, to 1.4g/cm^3 for soil treated with 15% FWM. On the other hand, and as shown in Fig. 10 (b), OMC was increased significantly from 28 up to 30.5% for soil treated with 9 and 15% of FWM respectively.

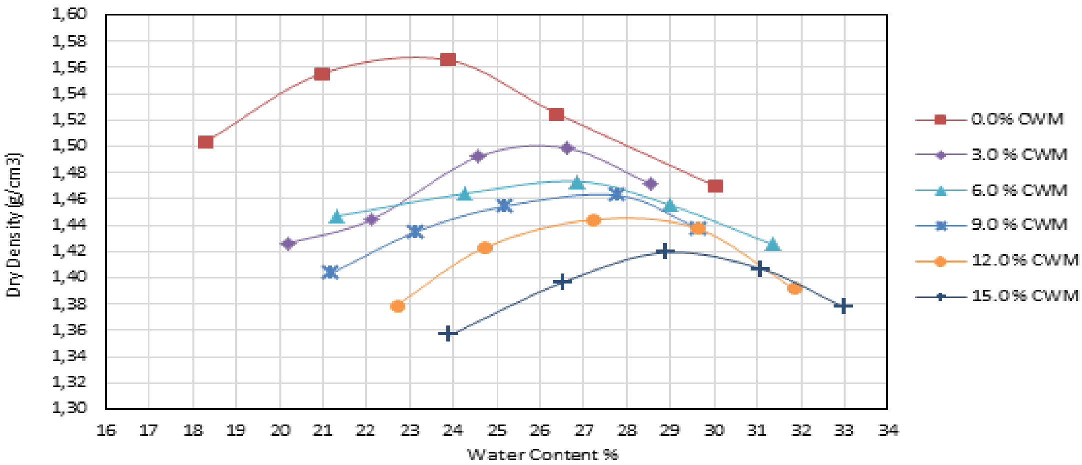
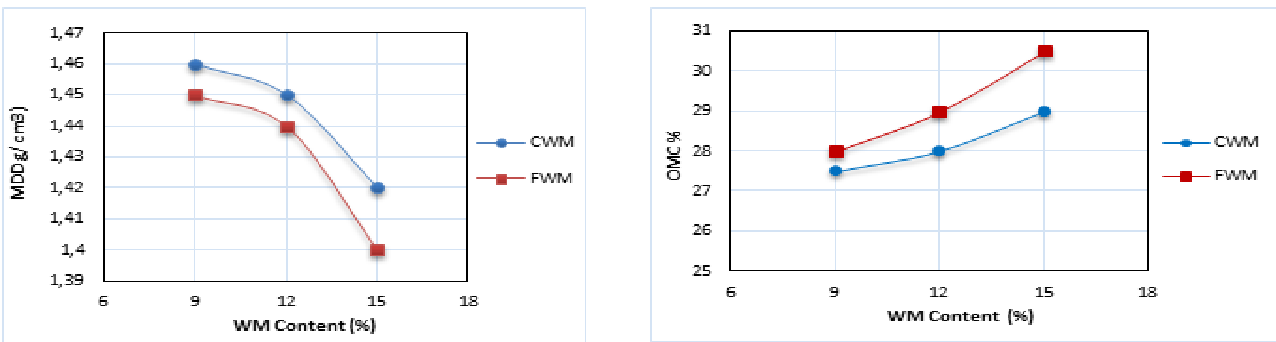


Fig. 9 Compaction Parameters for the Soft Soil Treated with CWM



(a) (b)

Fig. 10 Effect of Fineness of WM on the Compaction Parameters: (a) MDD, and (b) OMC

C. Unconfined Compressive Strength Test (UCS)

UCS test was conducted first on specimens of soil treated with different percentages of CWM (0, 3, 6, 9, 12, and 15%) to find the optimum value of CWM that gives higher UCS. The specimens were tested with different curing ages (zero, 7, 14, and 28 days) as shown in Fig. 11. From this figure, it can be seen that the compressive strength increased with increase of the added percentage of CWM up to 12% then later decreased slightly. At the same time, the value of UCS increased with the increase of curing period. The results of UCS tests for soil treated with CWM revealed that the optimum percentage of CWM is 12% of the dry weight of the stabilised soil.

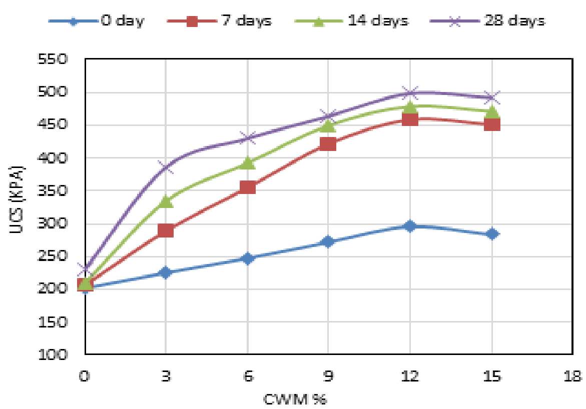


Fig. 11 Relationship between UCS and Percentages of CWM in Different Periods of Curing

To investigate the effect of fineness of the waste material used in this study on the UCS, 12% and values either side were added to the soft soil, and the specimens were tested with different curing periods (0, 7, 14, and 28 days). The measured values of UCS for the soil treated with different percentages of FWM and different periods of curing are shown in Fig. 12. It can be seen that similar to CWM, 12% FWM implemented the highest values of UCS for all ages, and the decrease in UCS by using 15% is very clear which indicated UCS even less than that for soil treated with 9% FWM.

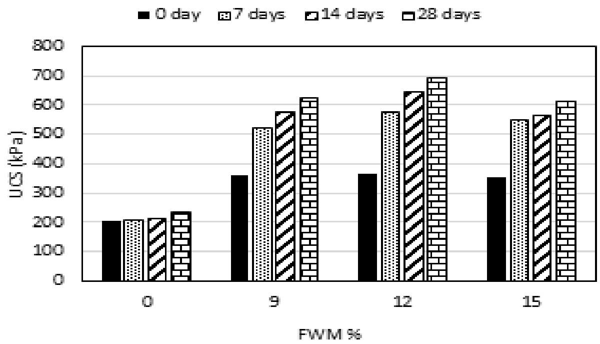


Fig. 12 UCS Test Results for Soil Treated with FWM

Fig. 13 shows the comparative UCS for 28 days cured specimens of soil treated by 9, 12, and 15% for both types of fineness. It can be found that the maximum value of UCS was recorded for specimen of soil treated with 12% FWM. Nevertheless, the other percentages of FWM improved the UCS significantly in comparison to those for soil treated with CWM. However, the UCS for 12% was increased by approximately 200kPa after 28 days curing by using FWM.

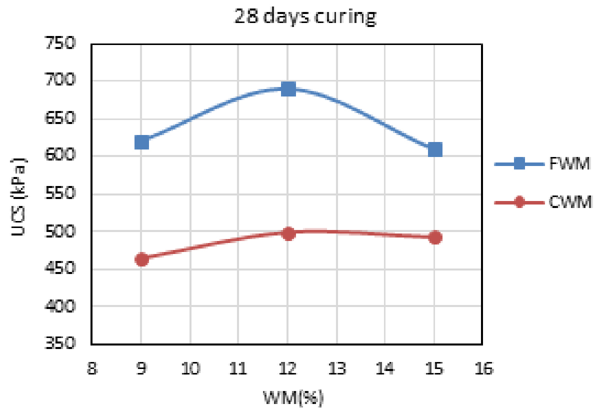


Fig. 13 Comparative UCS for soil treated with CWM and FWM

The comparative development of UCS values with time of curing for untreated and soil treated with 12% CWM and FWM is presented in Fig. 14. It can be recognised that even for uncured samples, the soil treated with FWM indicated a significant high value of UCS in comparison to the case of untreated and soil treated with CWM. Furthermore, and unlike the CWM, the UCS of soil treated with FWM kept increasing gradually even after 7 days curing. This is due to the continuity of the hydration processes because more fineness provided more surface area to boost the hydration reaction. [21].

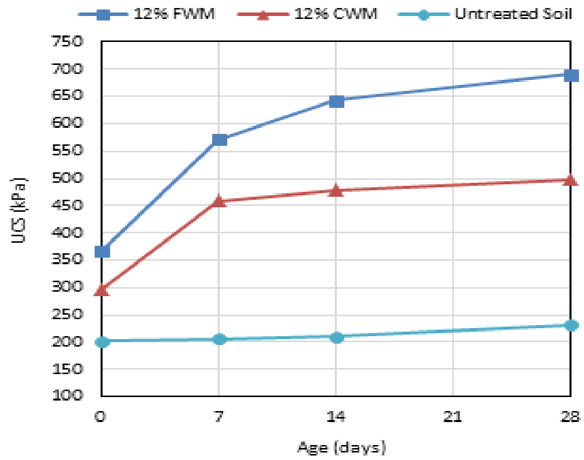


Fig. 14 UCS Development with Time of Curing

V. Conclusion

The aim of this study was to investigate the potential of the suitability of a waste material to be used as SCM and to find the effect of the fineness of this waste material on its performance in soil stabilisation. The following conclusions from this study can be summarised as follows:

- In case of CWM, the results indicated that the waste material used in this study is a promising material to represent a base substance for new cementitious materials.
- Regardless the fineness of the waste material used as a soil stabiliser, both the CWM and the FWM improved the physical properties of the soft soil significantly with decreased IP to a value of approximately 13.0. This means that for the clay particles flocculation occurs due to the exchange of cations and the process does not depend on the fineness of the added material.
- The fineness of the WM used in this study has a significant effect on the compressive strength of the stabilised soil, especially for early age of stabilisation. The results showed that the use of FWM imparted an improvement in UCS equal 1.4 times of the UCS achieved for soil stabilised with CWM.
- In comparison to the particle size distribution of OPC, the FWM remains slightly coarse and it is expected to provide better results if it were to be exposed to low grinding energy.

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