The Stabilization of a Soft Soil Subgrade Layer Using a New Sustainable Binder Produced from Free-Cement Blending of Waste Materials Fly Ashes

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ABSTRACT: Recently, the production of blended cement and/or the development of new cementitious materials as binder alternatives in different civil engineering projects has noticeably increased. Using such materials could be considered as one of the sustainable solutions to reduce cement production and its effect on global warming. This study represents an evaluation of the geotechnical properties of soft soil stabilized with new sustainable binders produced from the blending of different types of waste materials. Initially, the experiments were conducted to optimize a calcium-based waste material (CBW) along with two different fly ashes (FA1 and FA2) used as pozzolanic activators. The outcome of this investigation indicated a significant reduction in plasticity index (PI) where it was decreased from 21 for the virgin soil to 13.17 for the soil treated with 12% of CBW. Additionally, the Unconfined compressive strength (UCS) was developed by factors of 4.6 and 5.1 with binary and ternary treatment respectively.

1 INTRODUCTION

Global urbanization and industrial development have increased the demand to enlarge and develop the networks of roads and highways. The construction of highway and road projects is a major component of civil infrastructure. Such projects are essential to the economy and contribute to large quantities of natural resources consumption in addition to the amounts of financial resources (Coleri and Harvey, 2013). The roads and highways construction projects are usually allocated in sites with in non-suitable subgrade layers such as soft soil subgrades which have low bearing capacity, high compressibility and exhibit a significant volume change when their water content changes (Laguros, 1962, Zheng and Qin, 2003, Consoli et al., 2015). The accepted usual method to mitigate the properties of such soil to meet the requirement of an engineering project is the replacement with stronger materials. Due to the high cost of the later technique, researchers have been motivated to look for alternative methods, and one of these methods is the process of soil stabilization (Cristelo et al., 2013, Sol-Sánchez et al., 2016).

Chemical stabilization is the most suitable technique for soft soil stabilization which is usually applied by adding binder materials to the soil. These binders bind soil particles to each other and produce strong products and consequently increase the soil strength and bearing capacity (Makusa, 2012, Hashad and El-Mashad, 2014). Stabilization of subgrade soil has traditionally relied on treatment with either lime and/or cement which react chemically to bind the soil particles to each other resulting in stronger soil structure, or special additives such as Pozzolanic materials. Pozzolanic materials such as fly ash (FA), micro silica (SF), rice husk ash (RHA) ground granulated blast furnace (GGBS), etc. are regarded as waste materials which can be used for soil improvement as indicated in recent research (Yoder and Witczak, 1975, Wild et al., 1998, Abd El-Aziz et al., 2006, Rios et al., 2016, Jafer et al., 2016b). Cement (normally Ordinary Portland Cement or OPC) is the most utilized construction material worldwide. It is used as a binder, in different construction activities. However, the manufacturing of OPC accounts for around 5% of global carbon dioxide emission in addition to the other negative environmental impact and financial issues (Schumacher and Juniper, 2013, García-Gusano et al., 2015, Mikulčić et al., 2016). Therefore, it has become essential to look for alternatives, such as waste and by-products materials, to be used as cement replacement in construction industry. Using such materials in construction field might be a valuable attempt as a sustainable solution towards the reduction of cement production and greenhouse gases (GHGs), and achieving an eco-friendly industry.

Recently, waste and by-product materials have been increasingly used as supplementary cementitious materials (SCMs) in the manufacture of blended cement and in the development of free-cement blended binders. SCMs are usually rich in alumina and/or silica in which react with hydrated lime (or any calcium-based material) to produce stronger mortars and concrete. The latter is attributed to the increase in the production of cementitious compounds such as calcium-silicate hydrated (C-S-H) and calcium-aluminate-hydrated (C-A-H) (Pontikes and Snellings, 2014, Puppala et al., 2015, Jafer et al., 2015, Pustovgar et al., 2016). The aforementioned encouraged researchers to carry out extensive experimental works attempting to produce new sustainable cementitious materials since the mid-1990s (Antiohos et al., 2007). Consequently, many researchers have utilized different procedures of mix design to produce new cementitious materials. Binary, ternary and even quaternary blending systems have been investigated. Additionally, researchers have adopted different activation methods, such as chemical and mechanical activation, to activate the base cementitious material. Alkali activation, which is performed by adding alkaline and/or pozzolanic materials, is the most common chemical method, whereas, a grinding process using mill ball or mortars is considered as a mechanical activation method (Antiohos et al., 2007, O'Rourke et al., 2009, Sadique et al., 2013, Dave et al., 2016, Soriano et al., 2016, Jafer et al., 2016a).

In this research project, an intermediate soft soil with medium organic matter content was stabilized using a new sustainable binder produced from binary and ternary free-cement blending using different types of waste materials fly ashes. Initially, the calcium-based material (CBW) was optimized dependent on the results of unconfined compressive strength (UCS) tests conducted on specimens of soil treated with different percentages of CBW (3, 6, 9, 12, and 15% by the dry weight of soil) and cured for 7, 14, and 28 days. After that, CBW was chemical activated using two different types of fly ashes (FA1 and FA2), which were high alkaline and silica rich materials respectively, by adopting binary and ternary mix design for a fixed binder content (same of optimum content of CBW obtained from the first stage of this research project). The effect of the produced blends on the geotechnical properties of the treated soil were evaluated by conducting Atterberg limits, compaction and UCS tests.

2 MATERIALS AND METHODS

2.1 *Soil Sample*

The treated soil in this study was collected from the riverbank of the estuary of the River Alt which is located in Hightown to the north of Liverpool, UK. Soil samples were extracted from a depth ranged between 0.3 and 0.5m below ground level, then placed in sealed plastic bags before the transferring to the laboratory. Once the soil arrived at the laboratory, representative specimens of soil were taken to determine the natural moisture content (NMC), and the remaining soil was oven dried at 100^{o}C to be ready for other experiments. The required experimental works for soil identification and classification were carried out, such as particles size distribution (sieve analysis and hydrometer tests), consistency limits test (to determine liquid limit (LL), plastic limit (PL) and plasticity index (PI), compaction parameters testing (maximum dry density (MDD) and optimum moisture content (OMC)), etc. Table 1 illustrates the main physical and geotechnical characteristics of the soft soil used in this study.

Table 1. Main physical and geotechnical properties of the soft soil used in this study.

Property	Value
Natural Moisture Content (NMC) %	52.14
Liquid Limit LL %	44
Plasticity Index IP	20.22
Sand %	13.08
Silt %	43.92
Clay %	43.00
Specific Gravity (GS)	2.57
γd max (MDD) g/cm3	1.57
Optimum moisture content OMC %	23
pH	7.78
Organic Matter Content %	7.95
UCS qu (kPa)	202

g/cm^3= gram/cubic centimeter, kPa = kilopascal

2.2 *Waste Materials*

The waste materials used in this study were collected from different industrial locations. They were in a powder state and resulted from the incineration processes in different energy generation plants as well as at different temperatures of combustion. The first material has a high calcium content which is marked as CBW in this study. While the other two fly ashes (FA1 and FA2) have high alkalinity and silica content respectively as it was observed from the results of X-ray fluorescence analysis (XRF) and other chemical properties shown in Table 2. From Table 2, it can be seen that CBW has calcium dioxide (CaO) content of approximately 70% which is very high. Thus, this material was considered as the principle cementitious material in this study. Moreover, the pH value of FA1 was found to be equal to 13.04 which can increase the alkalinity of reaction environment as well as increase the pozzolanic reactivity. The high silica content of FA2 (90.203) makes this material very promising to provide the required silica for pozzolanic reaction to increase the production of cementitious compounds. It should be noted here, that FA1 was ground (using low grinding energy for 10mins.), and then sieved on a mesh size of 150μm before it was used in this study in order to remove the incomplete combusted particles as well as increase its fineness.

Table 2. Chemical properties of waste materials used in this study

Item	CBW	FA1	FA2
pH	12.86	13.04	8.98
LOI %	N/A	2.779	2.047
CaO %	66.761	10.472	0.493
SiO_2 %	25.123	61.361	90.203
Al_2O_3 %	2.385	7.509	4.029
Fe_2O_3 %	0.027	1.538	0.183
MgO %	2.575	5.640	0.609
Na_2O %	1.716	1.732	0.897
K_2O %	0.310	7.525	1.36
SO_2 %	0.263	2.930	--

2.3 *Laboratory tests*

There were two stages of experimental works in this study. The first stage was carried out for the optimization of CBW content, while the effect of ternary blending on the geotechnical properties of the treated soil was investigated during the second stage. The experiments conducted and their corresponding standards in this study are as follows:

- Compaction parameters test: standard Proctor compaction tests were conducted in accordance to BS 1377-4:1990 (British Standard, 1990b) using approximately 2000g of dry soil or soil-binder passed through a sieve size of 3.36mm then molded inside the standard mold in three layers after mixing with a required amount of water. Each layer was subjected to 25 blows using 2.5kg hammer.
- Atterberg limits tests - (Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI)). These limits were determined in accordance to BS 1377-2:1990 (British Standard, 1990a). The cone penetration method was utilized to determine the LL using a Cone Penetrometer device.
- Unconfined Compressive Strength testing was performed according to BS 1377-7:1990 (British Standard, 1990c). At least three specimens were prepared for each corresponding percentage of CBW and ternary mixtures and were tested for different periods of curing (7, 14, and 28 days) in addition to the untreated soil specimens.

2.4 *Samples preparation and conditioning*

After achieving the dry soil, the soil lumps were pulverized and passed through a sieve size of 3.36mm to be ready for the compaction parameters test. This was performed for the virgin soil and the soil treated with different percentages of CBW. The purpose of this test is to determine the MDD and OMC for each corresponding percentage of CBW which are required to prepare the specimens for UCS testing later on in the optimization for BCW content. Moreover, soil samples for the Atterberg limits test were prepared after passing the soil through a sieve size of 475μm, then the binder material was added. All dry soil-binder mixtures were prepared by manual mixing which was continued until achieving a homogenous color, then distilled water was added to prepare the pastes.

With respect to the specimens for the UCS tests, a fixed volume mold with specific dimensions was used to produce specimens with 38mm diameter and 76mm in height. Specimens of untreated soil, soil treated with different percentages of CBW (3, 6, 9, 12, and 15%), and soil treated with ternary mixtures, produced from CBW, FA1, and FA2 with different proportions, were prepared. This was achieved by mixing dry soil with corresponding percentages of binders then the water was added to the mixture to prepare soil-binder paste. The later was inserted in the fixed volume mold and pressed using a hydraulic jack. After that, specimens were ejected from the mold, wrapped, labeled, placed in well-sealed plastic bags and then stored for the required periods of curing. The curing conditions in this study were maintained at temperature of 20±2°C and 100% relative humidity using humidity cabinet. Figure 1 shows the sequences of UCS specimen preparation.

With respect to the second stage of this study, the optimum content of CBW was fixed as the binder content, then a mix design process was carried out using binary and ternary blending systems for the waste materials used in this study to prepare mixtures with different proportions as illustrated in Table 3.

Table 3. Ternary mixing program adopted in the study.

Mixture ID	CBW%	FA1%	FA2%
VS	0	0	0
U	100	0	0
B1	75	25	0
B2	75	0	25
B3	50	50	0
B4	50	0	50
T1	75	12.5	12.5
T2	50	25	25

VS= the compacted untreated virgin soil; U= the unary mixture which is represented by the optimum content of CBW; and B and T= the binary and ternary mixtures respectively.

Figure 1. Preparation sequences of UCS test specimens.

3 RESULTS AND DISCUSSION

3.1 *Optimization for CBW content*

The first stage of this study was represented by conducting the experiments to determine the optimum content of CBW material. The optimization was dependent on the results obtained from UCS tests; therefore, it was essential to determine the compaction parameters to evaluate the MDD and OMC for each corresponding percentage of CBW as they are required to prepare the specimens for UCS testing. Figure 2 shows the density-moisture content results for the untreated soil and soil treated with different percentages of CBW (3, 6, 9, 12, and 15% by the dry weight of soil). As shown in this figure, the MDD decreased dramatically while the OMC increased with the continuous increment in CBW content. This indicates that CBW has high water absorption property which may be useful in the stabilization of sites associated with high moisture. However, this property sometimes is considered as undesirable because it decreases the workability at site. Similar behavior was observed for soils treated with lime and/or cement in previous research in which the common factor was that all of these materials have a high content of CaO (Okyay and Dias, 2010, Ashango and Patra, 2014, Jafer et al., 2016b).

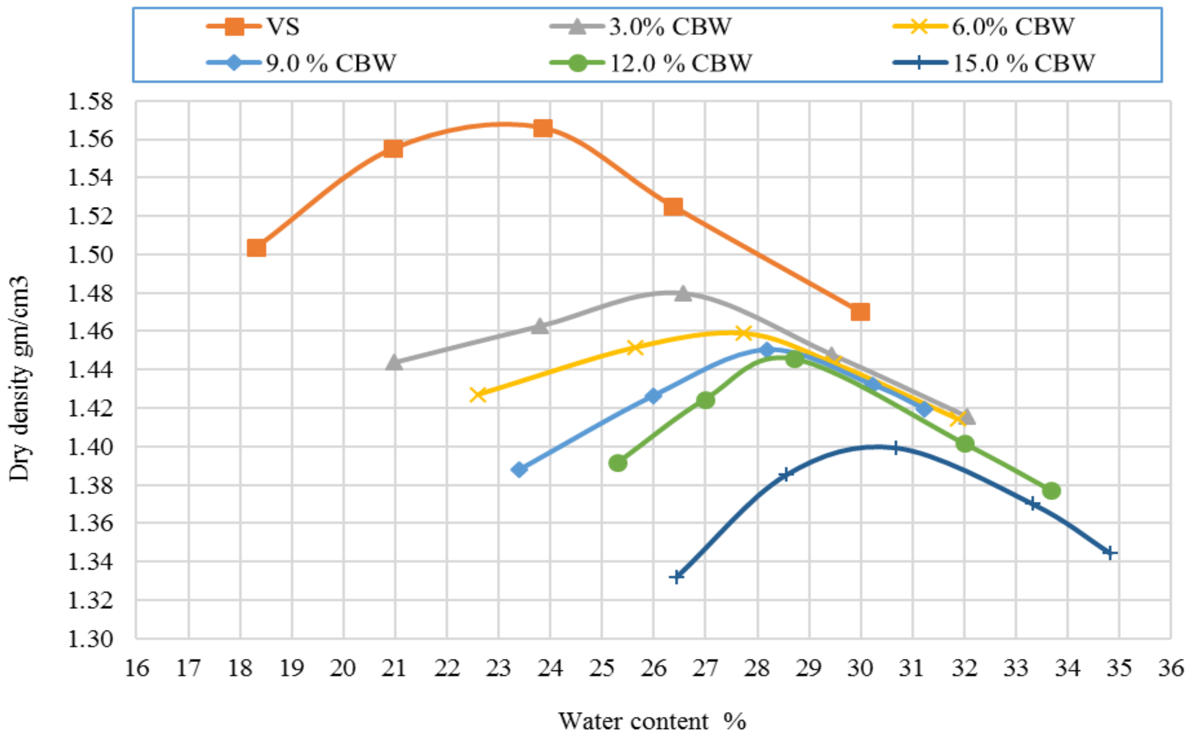

Figure 2 Dry density-water content diagrams for soil treated with different percentages of CBW.

The UCS test was conducted on specimens of soil treated with different percentages of CBW (0, 3, 6, 9, 12, and 15%), and cured at different curing periods (7, 14, and 28 days) to investigate strength development through the time of curing). Figure 3 shows the relationship between the maximum soil compressive strength achieved from the UCS tests and CBW content for at different curing periods. The UCS was found to be increased with the increase of CBW content up to 12% and then decreased beyond that and the same behavior was observed for all curing periods. The results indicated that 12% of CBW was the optimum percentage which exhibited the higher values of UCS. Moreover, significant developments in soil strength were achieved by treatment with CBW after a short period of curing (7 days) and for curing longer than 7 days, the soil strength developed gradually. The improvement in the UCS may be attributed to the hydration reaction of the calcium oxide provided by CBW with the silicates provided from the minerals of stabilized soil which resulted in the formation of cementitious products. The later contributed to bind soil particles to each other resulting in a stronger structure.

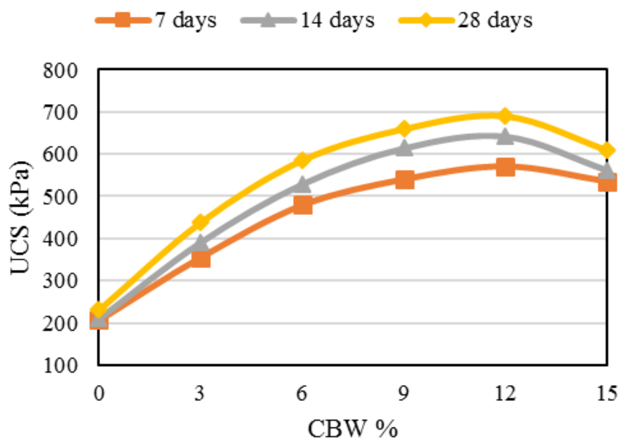

Figure 3 Relationship between UCS and CBW content

3.2 *Results of blending treatment*

3.2.1 *Consistency limits*

The effect of different mixtures, produced from binary and ternary blending of the waste materials used in this study with different proportions, on the consistency limits (LL, PL, and PI) of the treated soil along with effect of the optimum unary mixture (12% CBW) was evaluated by conducting liquid limits testing. This was achieved using a cone penetrometer, and plastic limits testing using the rolling method. The values of LL, PL, and PI of the soil treated with different types of mixtures are illustrated in Table 4. It can be seen that there was a significant improvement in soil plasticity index after the treatment with the unary mixture where the PI was decreased from 20.22 for the virgin soil to 13.45.

Table 4. Consistency limits of the soil after different treatments.

Mixture ID	LL %	PL %	PI
VS	44	23.78	20.22
U	51.3	37.85	13.45
B1	49.3	36.52	12.78
B2	54.5	38.93	15.57
B3	48	36.27	11.73
B4	53	38.68	14.32
T1	52.4	39.14	13.26
T2	52	36.75	15.25

Additionally, the blending treatment also indicated reductions in PIs for approximately the same level, while B3 indicated the lowest value of PI. These reductions would improve the soil strength against volume changes and stress due to the changes in water content of the soil. The reduction that occurred in the PI was attributed to the increase in the LL and PL, due to the increment in water holding capacity after the treatment of the mixtures containing CBW (Eskisar, 2015), but since the increment in LLs were higher than those for PLs, therefore, PIs decreased.

3.2.2 *Compaction parameters*

The results of compaction test of the soft soil treated with different types of mixtures are shown in Figure 4. In general, the results of compaction testing indicated that there was a reverse proportion between the MDD and OMC, in which when the MDD increases, the OMC decreases and the vice versa. From Figure 4, it can be recognized that there was a sharp reduction in MDD of the soil treated with 12% of CBW alone (mixture U) accompanied with a significant increase in OMC. The later may be attributed to the increment that occurred in the specific surface area due to the treatment with CBW in addition to the cation exchange that took place between the clay minerals of the treated soil and the positive cations of CaO of CBW (Jauberthie et al., 2010).

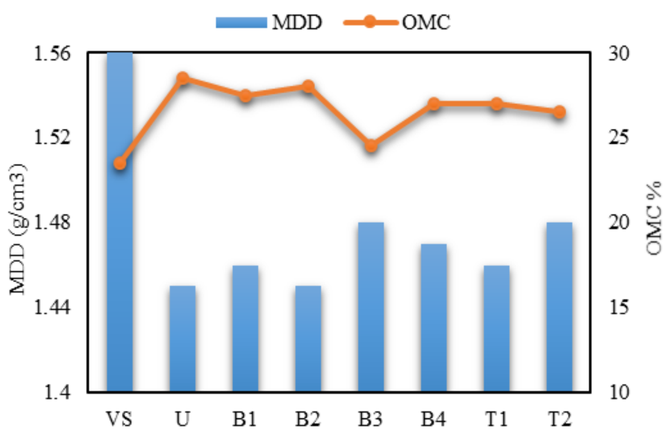

Figure 4 Effect of unary and ternary treatment on MDDs and OMCs of the soft soil used in this study.

The cation exchange increased the water holding capacity of the treated soil and resulted in the increment in OMC and a reduction in MDD. Furthermore, the results of the compaction test showed different rates of increments in MDDs and reductions in OMCs after blended mixtures treatment; significant increments of MDD were observed for the treatment with B3 and T2, while the reduction in OMC of B3 treatment was greater than that for T2 treatment. In reference to Table 4, it can be seen that the lowest PI was achieved by B3 and with reduction of OMC, the workability of soil-B3 mixture would be enhanced significantly. However, this behavior of compaction parameters might be attributed to the reduction of CaO after binary and ternary blending with FA1 and FA2 which have very little content of CaO, thus the water demand of the soil-binder mixture decreased. The later led to decrease in the OMC and increase in MDD, the same behavior was observed by previous researchers (Harichane et al., 2011, Sivrikaya et al., 2014).

3.2.3 *Unconfined compressive strength (UCS)*

UCS testing was carried out on specimens of soil treated with different types of mixtures and at different curing periods (7, 14, and 28 days). The maximum strength measured from these tests are shown in Figure 5. The results indicated an acceptable improvement in UCS after blending treatment in comparison to the unary treatment. Additionally, UCS values, for all types of mixtures, exhibited a significant development after the first week of curing, and graduate increments were observed for curing periods of longer than 7 days. More specifically, the specimens treated by binary mixtures contained CBW and FA1 where specific proportions exhibited UCSs higher than those for specimens contained CBW and FA2 with similar proportions. For instance, the UCS values obtained from the soil treated with B1 (75% CBW + 25% FA1) were higher than those obtained from the soil treated with B2 (75% CBW + 25 FA2) for all ages of curing. However, the best UCS was obtained from the soil specimens treated with ternary mixture (T1) which was produced from mixing proportions 75%:12.5%:12.5% of CBW, FA1, and FA2 respectively. The results of UCS tests also indicated that the mixtures containing 75% CBW of the binder content, exhibited highest values of UCS rather than those for mixtures contained 50% CBW of binder content.

The development in the compressive strength of the treated soil after blending treatment is attributed to the pozzolanic reaction that took place between the hydrated lime ($Ca(OH)_2$) produced by the hydration of CaO, provided from CBW, and the silicates and aluminates provided from the other fly ashes (Sadique et al., 2013, Puppala et al., 2015). The later reaction led to increase in the production of cementitious compounds which have the responsibility of strength development as explained in equations 1 and 2.

$$Ca(OH)_2 + SiO_2 = CaO\text{-}SiO_2\text{-}H_2O \quad (1)$$

$$Ca(OH)_2 + Al_2O_3 = CaO\text{-} Al_2O_3\text{-}H_2O \quad (2)$$

The cementitious compounds produced, as described ins equations (1) and (2), are called calcium-silicate-hydrated (C-S-H) and calcium-aluminum-hydrated (C-A-H). It was reported that, the high alkaline environment of the chemical reaction of binder materials is more preferable to boost the hydration and pozzolanic reaction because such environment accelerates the solution of glassy phases of silicates and in turn provides an extra amount of silica that has the susceptibility to react with the hydrated lime to produce more cementitious compounds (Puppala et al., 2015).

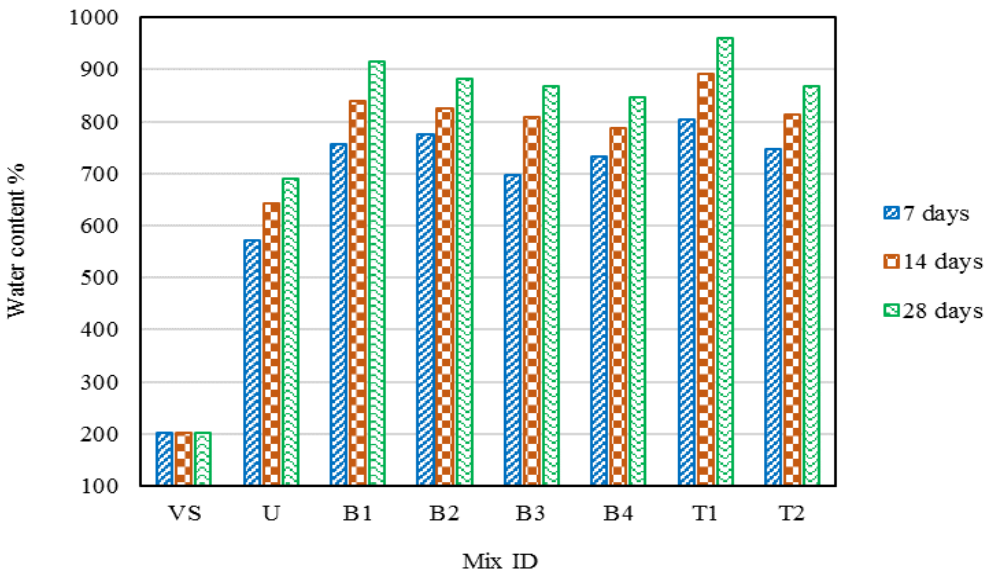

Figure 5 UCS results of soil treated with unary and different ternary mixtures.

The aforementioned along with the high pH value of FA1 may elucidate the higher UCS achieved using binary mixtures produced from FA1 with the combination of CBW such as B1 and B3 when compared to B2 and B4. Finally, the availability of sufficient amounts of CaO in CBW with a sustainable alkaline medium for chemical reaction maintained by FA1, and extra amorphous amounts of silica provided by FA2 could be the reason that resulted in T1 being the best mixture to achieve the improvement in UCS for stabilized soil.

4 CONCLUSIONS

The effect of several mixtures, produced from ternary blending of three types of waste materials fly ashes with different proportions, on the geotechnical properties of a soft soil for the use as subgrade layer was investigated in this study. According to the results achieved in this study, the following conclusions can be drawn:

4.1 *CBW optimization*

- The compaction parameters of the treated soil were highly affected with the treatment of CBW due to the later high water demand. The results of compaction testing indicated significant reductions of MDD along with gradual increments of OMC with the continuous increase in CBW content. MDD was reduced from 1.58 to 1.4 g/cm^3 with treatment of 15% CBW by the dry weight of the soil.
- The results of UCS tests showed that 12% was the optimum percentage of CBW which produced the highest UCS for the treated soil. Using this percentage, the UCS was increased from 202kPa for compacted untreated soil to almost 700kPa after 28 days of curing.
- The optimum percentage of CBW was found very effective to improve the consistency limits of the treated soil where it decreased the PI from 22.22 for untreated soil to 13.45.

4.2 *Blended mixtures treatment*

- The results of consistency limits testing indicated further development in plasticity index especially for mixture B3 (1:1 of CBW to FA1which indicated the lowest value of PI (11.73). However, some mixtures increased the PI slightly in comparison to that for soil treated with CBW.
- MDD was increased at different rates with blending treatment. On the other hand, the results of compaction testing indicated reductions in OMC. This behavior was attributed to the reduction in CBW portion after binary and ternary blending, as its water demand is very high.
- The best UCS value was achieved by using T1 which was produced from the blending of 75, 12.5, and 12.5% of CBW, FA1, and FA2 respectively. Moreover, the results of UCS tests showed that the percentage of CBW in binder should not be less than 75% to achieve higher compressive strength. Nevertheless, the mixture that contained 50% of CBW and 50% of FA1 and/or FA2 exhibited higher UCS than that for soil treated with unary mixture. Furthermore, the treating with binary mixtures produced from CBW and FA1 blending indicated better UCS than those produced from CBW and FA2 because of the high alkalinity of FA1 in comparison to the alkalinity of FA2.

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