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Improving the Characteristics of a Soft Clay Soil Using Cement Activated Low-Calcium Fly Ash

Qutaiba G. Majeed[1,*], Abdalla M. Shihab[2], Jasim M. Abbas[2], Saad Sh. Sammen[2]

[1]Department of Road and Airport Engineering, College of Engineering, University of Diyala, 32001 Diyala, Iraq
[2]Department of Civil Engineering, College of Engineering, University of Diyala, 32001 Diyala, Iraq

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ABSTRACT

In this research, the potential improvement of some geotechnical characteristics of soft clay soil using the low Calcium fly ash was evaluated. (These characteristics include unit weight, shear strength, compaction characteristics and soil plasticity characteristics). In addition, the X-ray diffraction test was performed to measure the mineralogical changes in the soft clay soil when the low Calcium fly ash is added. The ordinary Portland cement was used to activate the fly ash. The total percent of flash and cement was10% to investigate the variation in the effectiveness of activation. The optimum moisture content that which computed by the compaction test was adopted in the rest of the experimental program. The test results revealed that the cement could be used to improve the activating of the fly ash efficiently. The maximum value of dry density was marginally affected due to activation from 1.747 to 1.738 g/cm3 along with a corresponding change in optimum water content from 17.45 to 15.5 %. The soil cohesion parameter increased from 188 to 206 kN/m2 whereas the angle of internal friction rose from about 56.7o to 59.1o. Finally, the results of the unconfined compression test reveal that the cement-activated fly ash could present better results than those obtained from a 28-days curing cement.

1. Introduction

Soil improvement is defined as any process that can enhance the engineering properties of the natural soil. This has been usually preformed using diverse mechanical, chemical and hydraulic mechanisms including stabilizing soil by using wide array of admixtures.

Over the few past decades, soil improvement and soil stabilization have gained great attention by the academic and industrial sectors alike. Researchers and practitioners have been investigating and analyze numerous methods, materials, and techniques in order to find the best environmentally-friendly, innovative and economical practices for soil stabilization. Special focus has been paid to investigate the effects of several locally available materials as potential stabilizers in achieving this purpose [1-6].

Fly ash is one of these materials that is widely used to improve the soil properties. Generally, fly ash, also called pulverized fuel ash, is a by-product material that is usually resulted from the combustion of coal in power plants operated by coal-fuel boilers. It is often appraised as a problem because of the contamination nature of its fine solid particles. As a result, it is normally considered as a waste material with negative environmental consequences. Based on the Calcium content, fly ash is categorized into two distinct classes; Class C which contains high calcium content and is obtained from low coal rank and Class F

* Corresponding author.
E-mail address: eng_qgm79@yahoo.com
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which contains lower Calcium content and is obtained from high coal rank. Regarding production sources, fly ash represents nearly 80% of the total coal ashes produced worldwide [7]. Furthermore, about 38% of the electric energy is produced from numerous power plants that yield such harmful by-product substances [8].

Calcium oxide (CaO) has been the governing factor in classifying fly ashes. According to literature, fly ash class C is found to contain large percentage of CaO, and as a result it has been utilized in various civil engineering applications. That is because of its inherent cementitious properties when blended with sufficient quantity of water [9]. Class F, in contrast, is less cementitious as a result of the low content of Calcium Oxide. Therefore, in order to activate this interesting characteristic, materials such as alkali liquids, Ordinary Portland cement (OPC) and hydrated lime are used and generally they have been found beneficial.

Generally, soft clay soils are defined as those soils with roughly (40-60) % water content [10], this range could even exceed their liquid limits. Such types of soils, as a result, could be with problematic characteristics including high compressibility level (Cc ranges between 0.19 and 0.44), low undrained shear strength (Cu usually less than 40 kPa) in addition to inherent problems in settlement and stability properties [11,12]. In the republic some countries such as Iraq, soft soils have been investigated by several geological and geotechnical researchers since it extends over large areas especially in the south regions [13]. The existence of such soil with risky properties also has motivated road agencies and highway engineers to investigate their behavior under traffic loading as it is possible to fail under heavy traffic loading and high-water contents occurred from underground water or due to rain.

As a response to these potential risks, great academic efforts are devoted to understand the possible improvement of a soft clay admixed with fly ash [14]. For instance, the potential contribution of lime-activated fly ash in enhancing an expansive soil was examined [15]. A similar study conducted by Jha et al. (2018) [16] was devoted to explore the stabilizing effects of using lime-activated coal fly ash in improving Gypseous soils on the micro level. Some studies were carried out with the aim of quantifying the enhancement in the properties of a kaolin clay soil admixed with polymer-activated fly ash [17]. A recent study [18] investigated to what extent can the calcium carbide residue aid in stimulating the cementation property of fly ash and hence can be utilized in stabilizing low strength soils.

Reviewing the relevant literature revealed that the potential role of the alkali solutions in activating coal ashes was considered by several recent studied to enhance and stabilize soils such as clay soil [19] and silty sand soil [20].

Therefore, the current study aims to enrich the knowledge about the possible role of the ordinary Portland cement in triggering the cementitious property of Class F (low calcium) fly ash. The study follows an experimental approach to quantify the expected improvements in selected engineering properties of a soft clay soil.

2. Materials and methods

2.1 Soil samples

The soil samples that used in this study were originally taken from a site located within the campus of the University of Diyala, Diyala city governorate, Iraq. Table 1 shows the key engineering properties for the soil sample.

Table 1: Geotechnical properties of soil samples

Property	Value	Specification
Specific gravity	2.71	ASTM D 854 – 14 [21]
Liquid limit	34	ASTM D 4318 – 17 [22]
Plastic limit	22.8	ASTM D 4318 – 17 [22]
Plasticity Index	11.2	/

Passing No.200	74%	/
Percent of sand	26%	ASTM D 422 [23]
Percent of clay	63%	ASTM D 422 [23]
Percent of silt	11%	ASTM D 422 [23]
USCS classification	CL	ASTM D-2487 [24]

2.2 Cement

The commercial ordinary Portland cement (OPC) of KARESTA brand has been used. Table 2 shows the standard chemical compositions of the cement used in the study.

Table 2: The chemical composition for OPC

Properties	Weight %
SiO_2	19.8
Al_2O_3	4.8
Fe_2O_3	3
CaO	61.9
MgO	3.8
Na_2O	0.61
SO_3	3

2.3 Fly Ash

The coal fly ash (class F) was obtained from the Deyana construction Projects Company. Its chemical composition is demonstrated in Table 3.

Table 3: The chemical composition for the Class F coal ash.

Properties	Weight %
SiO_2	55.3
Al_2O_3	25.7
Fe_2O_3	5.3
CaO	5.6
MgO	2.1
Na_2O	0.4
K_2O	0.6
SO_3	1.4
Loss on ignition	1.9

2.4 Testing procedures

According to Nicholson (2015), the typical amount of ordinary cement that should be considered to enhance a fine-grained soil could be range from 6 to 15 % (by weight). For the tests carried out in the present study, the entire weight percentage of soil stabilizer was choice to be 10%. In the first trial, the stabilizer is cement, in the second trial is fly ash whereas in the third it is half combination of each of them. The objective is to assess their ability as stabilizers in enhancing the soft clay soil.

.4.1 Compaction test

Generally, the compaction, is defined as the process that can lead to densify soil particles by reducing the air content within the voids. Soil dry density is the typical used in order to for measuring the degree of compaction [16]. The laboratory tests have been carried out in line with according to the specifications of ASTM D1557. The standard proctor test (heavy compaction) has been performed to observe the relationship between soil dry density and water content. Based on the analysis, the optimum moisture content (OMC) is that content that lead to maximum dry density (MDD). The computed OMC has then been used in the preparation of samples needed for the rest of the experimental program.

2.4.2 Direct shear test

Direct shear test is one of the widely tests that used to measure soil strength. Based on its results, the two key shear parameters, cohesion and angle of internal friction, can be quantified for both the natural and the treated soil samples. The same previously obtained OMC and compaction efforts have been used, and a curing chamber was used to cure the specimens of the stabilized soil at 25 ± 3 Co for a week. All the tests were carried out according to the standard procedure demonstrated in ASTM D 3080 [25] which considers the drained conditions of soil.

2.4.3 Liquid and plastic limit

The standard procedure illustrated in ASTM D 4318 [26] specification was followed to examine the moisture contents for the natural and treated soil samples to reach their liquid and plastic limits. The stabilized soil specimens, for all the three cases of treatment, were tested under loose condition, i.e., without compaction, and were cured for a week at 25 ± 3 Co.

2.4.4 Unconfined compression test

The unconfined compression test is the additional test that have been carried out to examine the variation in the shear strength for both treated and untreated soil samples. The samples were prepared with the same optimum water content and under the same compaction efforts resulted from the Proctor test. Ultimately, the specimens were also cured at 25 ± 3 C^o for seven days. The standard procedure demonstrated in ASTM D 2166 [27] was followed, and the dimensions of the molds were 10 cm height and 4.4 cm in diameter.

2.4.5 Mineralogical changes in term of XRD analyses

In order to evaluate the effect of different cases of stabilization on the variation of soil samples mineralogy, the mineralogical analysis was carried out using the XRD technique. In addition, this test could be used to identify the resulted Cementous materials. The test was implemented at the Central laboratory of Ibn Alhaytham College (University of Baghdad) for all the three stabilizing conditions. Match software was utilized for the purpose of Minerals matching.

3. Results and discussion

3.1 Compaction characteristics

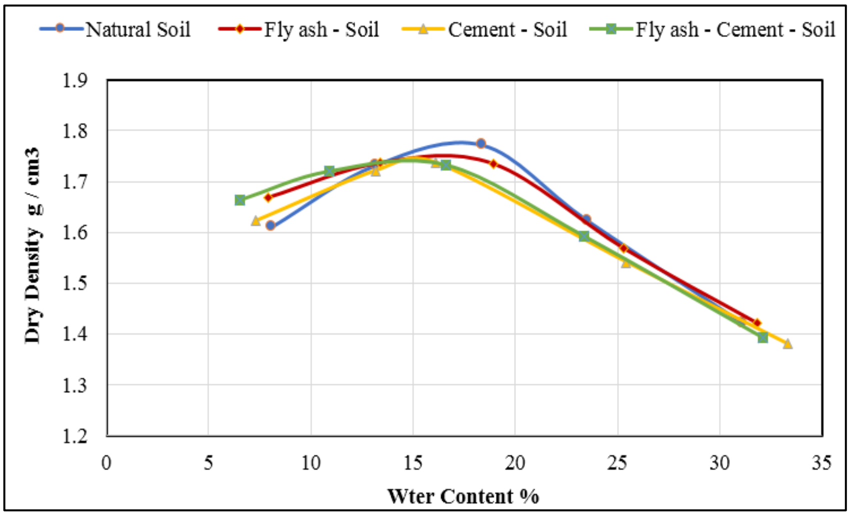


Figure 1. Compaction test results for the natural and stabilized soil samples

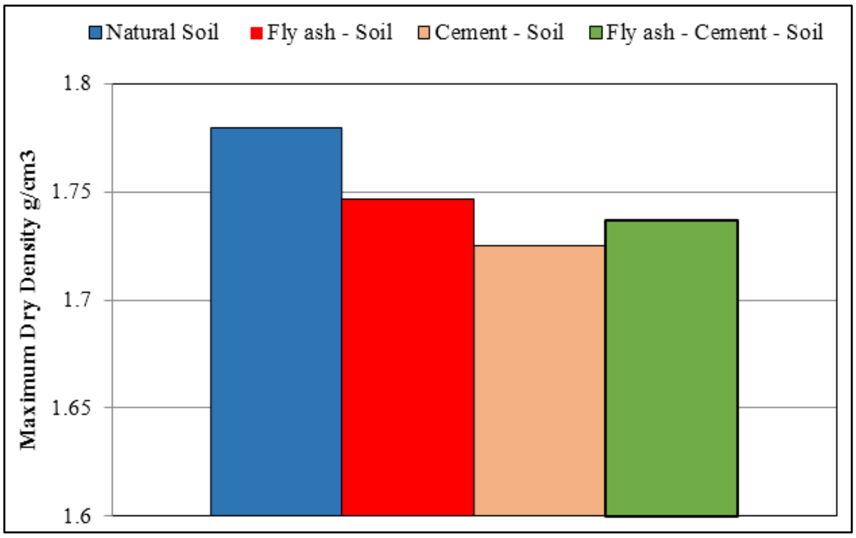


Figure 2. The variation in the maximum dry density for both the natural and the stabilized soil samples

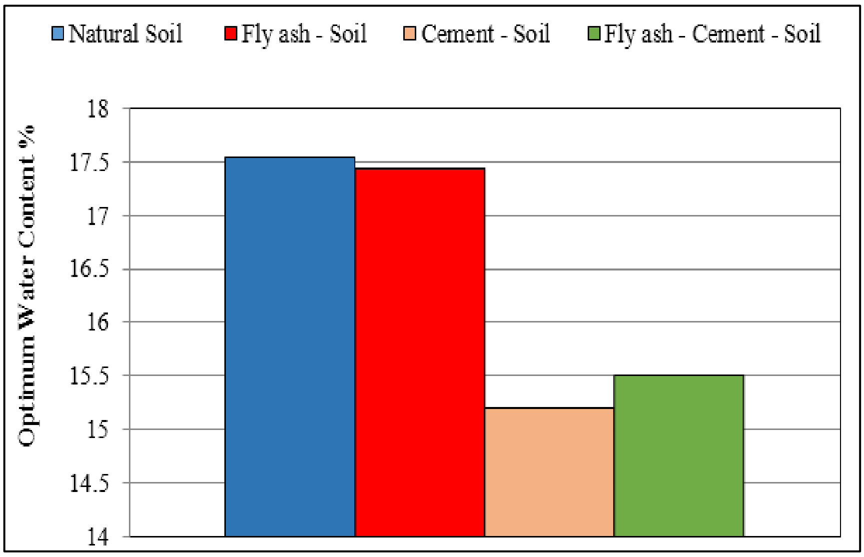


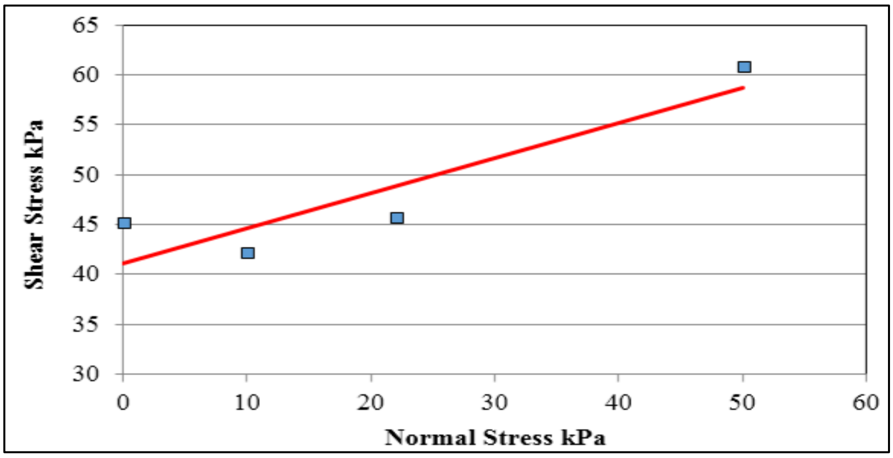
Figure 3. The variation in the optimum moisture content for both the natural and the stabilized soil samples

According to Figure 2, one of the most important points that should be underlined is that the natural (untreated) soil has the highest maximum dry density. All the other three combinations of stabilization, i.e., 100% fly ash, 100% cement and 50% fly ash-50% cement, resulted lower densities. This can be attributed to the values of specific gravity for both Class F fly ash and Portland cement which were 2.2 and 1.4 respectively.

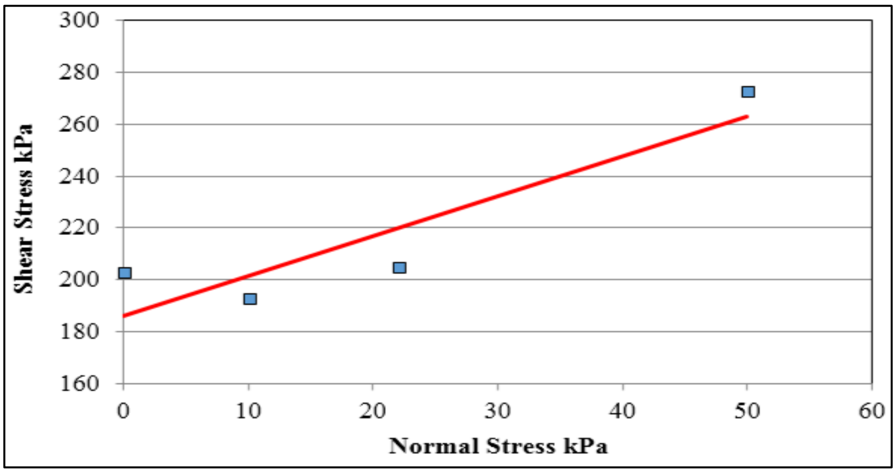
In contrast, regarding the optimum moisture content, Figure 3 shows that the optimum moisture content of the natural soil is higher than that found in the three stabilizing combinations. This is most likely because of the face-to-face flocculating and the resultant need for moisture for lubrication which is consistent with several types of additives used recently [28]. It is worth mentioning that the difference in moisture contents between a soil sample treated by fly ash and another treated by cement can confirm this interpretation. Especially when taken into account that the soil specimen treated by both class F fly ash and cement was with moisture content value lies in between; this is due to the effect of the cement in activating the fly ash.

3.2 Shear strength parameters

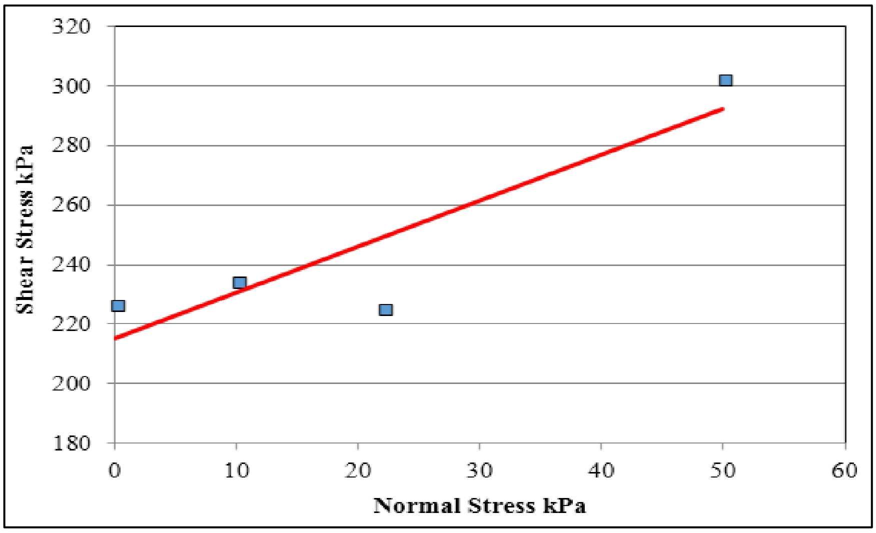
To evaluate the relative influence of the three adopted combinations of treatments, Figures 4, 5 and 6 have been constructed. Figure 4 depicts the results of the direct shear tests for the natural soil (4a) and the other three treated soils (4b, 4c and 4d). Figures 5 and 6 demonstrate the impacts of the used stabilizers on the values of cohesion parameter and angle of internal friction.



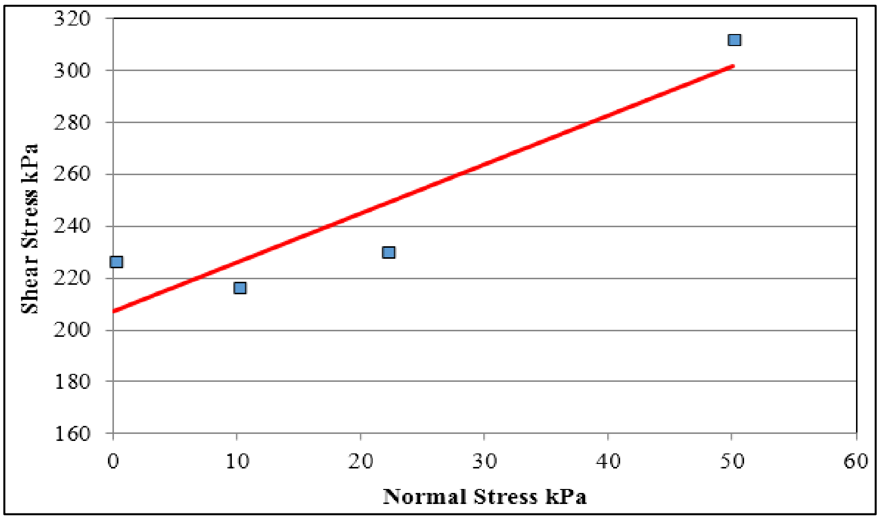
(a)



(b)



(c)



(d)

Figure 4. Results of direct shear tests, **a:** natural soil. **b:** soil-fly ash. **c:** soil-cement. **d:** soil-fly ash-cement

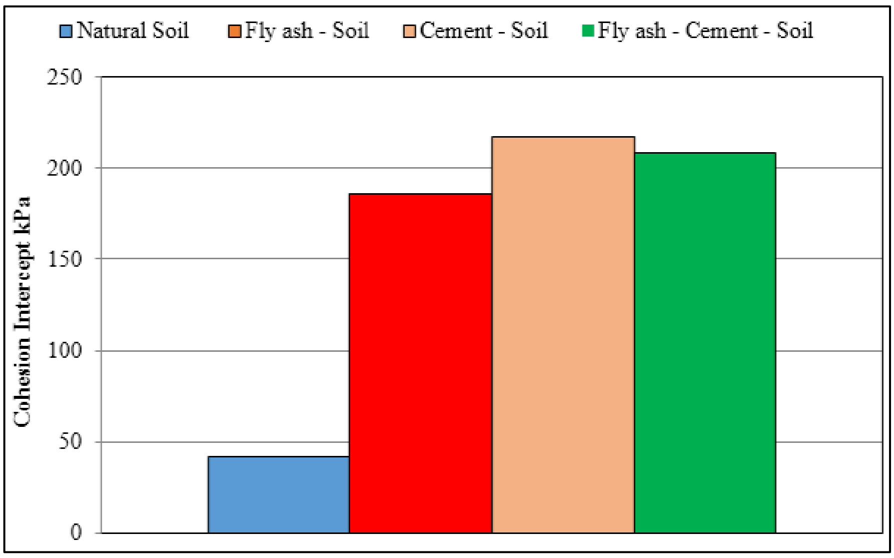


Figure 5. The variation in cohesion intercept for the natural and the three stabilized soil samples

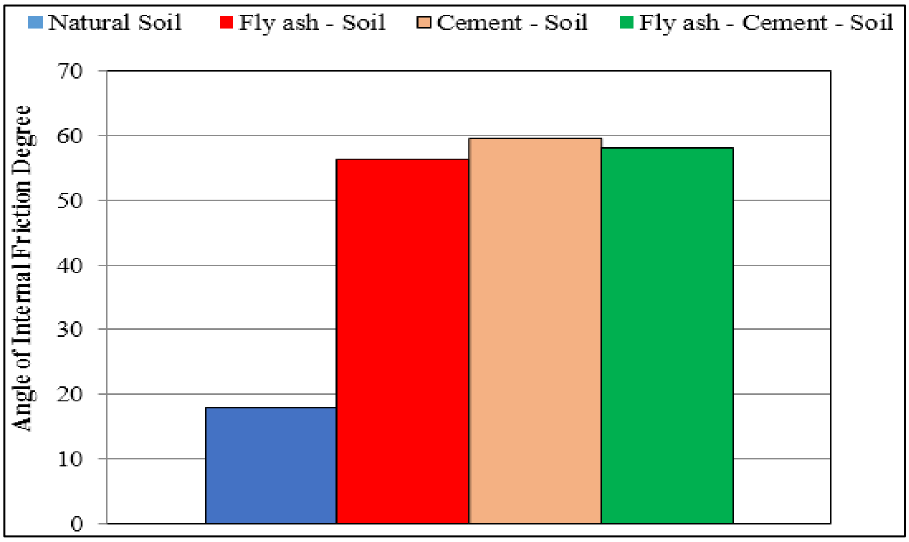
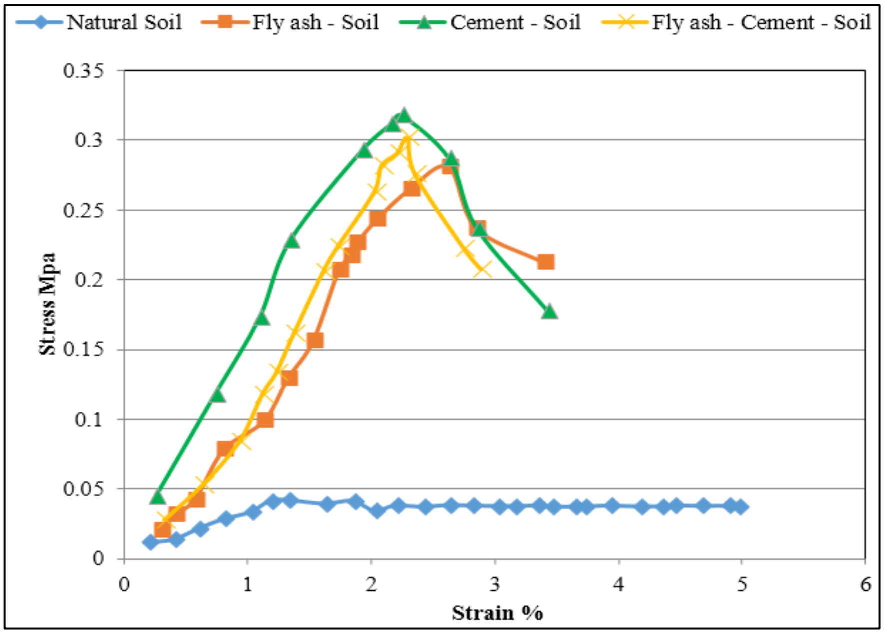


Figure 6. The variation in angle of internal friction values for the natural and the three stabilized soil samples

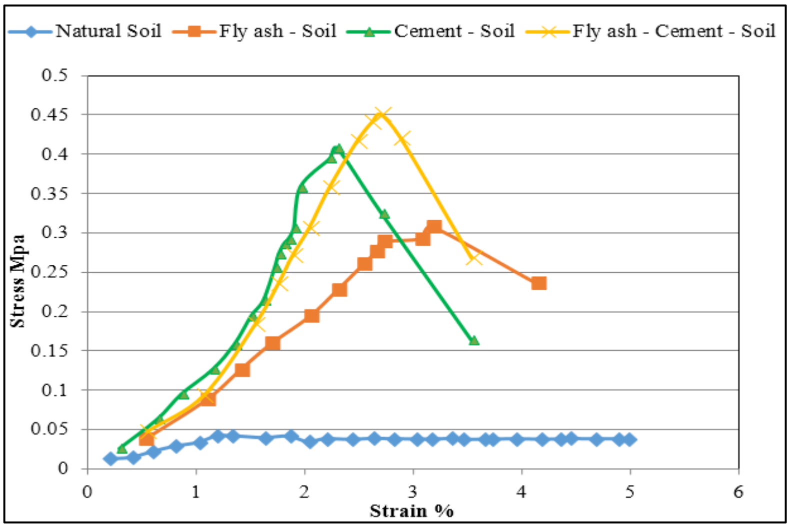
According to Figures 5 and 6, it is obvious that all the three combinations of admixtures have enhanced both the angle of internal friction and the cohesion intercept for the stabilized soil efficiently. In particular, soil samples that treated with cement have shown the highest increasing in the both shear strength parameters. This can be attributed for the typical ability of cement to develop the strength of the mixture during the first 7 days of curing [2]. Moreover, according to the figures, it can also be seen that the cement can play useful role regarding the consequent strength development; nevertheless, there is no significant differences between the amounts of increase in shear strength parameters between the three proposed combinations of admixtures.

3.3 Unconfined shear strength development

The results of the unconfined shear strength tests for the untreated soil sample and the three treated soil samples are demonstrated in Figures 7 and 8. Figure 7 shows the stress-strain curves whereas Figure 8 depicts the maximal compressive strength values.



(a)



(b)

Figure 7. Stress – strain curves for all the proposed treating combinations: (a) 7 days. (b) 28 days

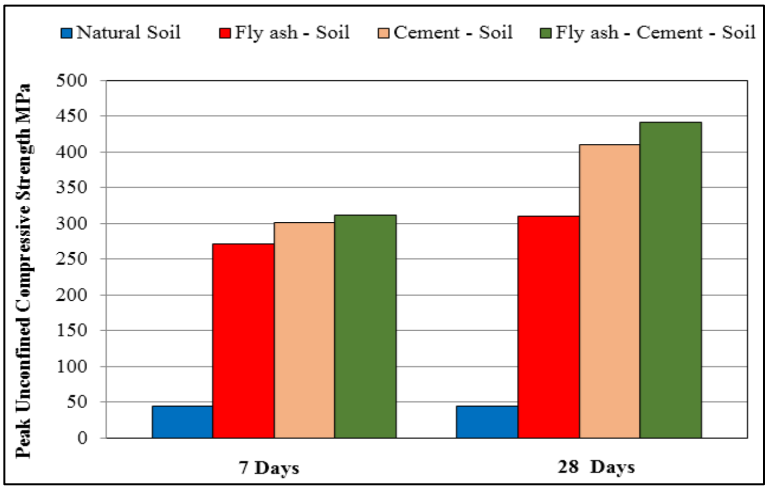


Figure 8. Results of peak unconfined compressive strength

recognized that admixing the soil with cement can noticeably aid in developing the soil strength in both ages - 7 days and 28 days. In particular, the cement with 7 days works to activate the fly ash to produce mechanical strength by nearly 10 % whereas this percent could go be up to nearly 33 % in the age of 28 days. This is most likely due to the typical time-dependent behavior of the soil-cement-fly ash mixture.

3.4 Liquid and plastic limit

The results for liquid limit, plastic limit and plasticity index for the untreated and the three treated soil specimens are shown in Figure 9. The figure illustrates evidently that all the three combinations of additives improved the liquid and plastic limits. The liquid limit was increased by about 27.7% and 32.4% with fly ash and cement respectively. Whereas treating the soil using both the cement and fly ash led to an increase in liquid limit of nearly 37.4 %. This is mainly due to the increasing in the soil particles effective size [29] that can lead to minimizing the resulting plasticity index.

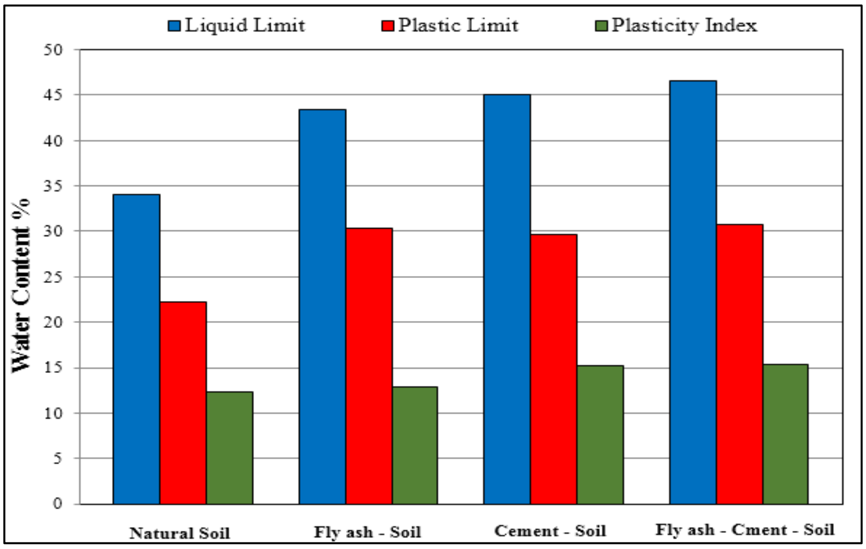
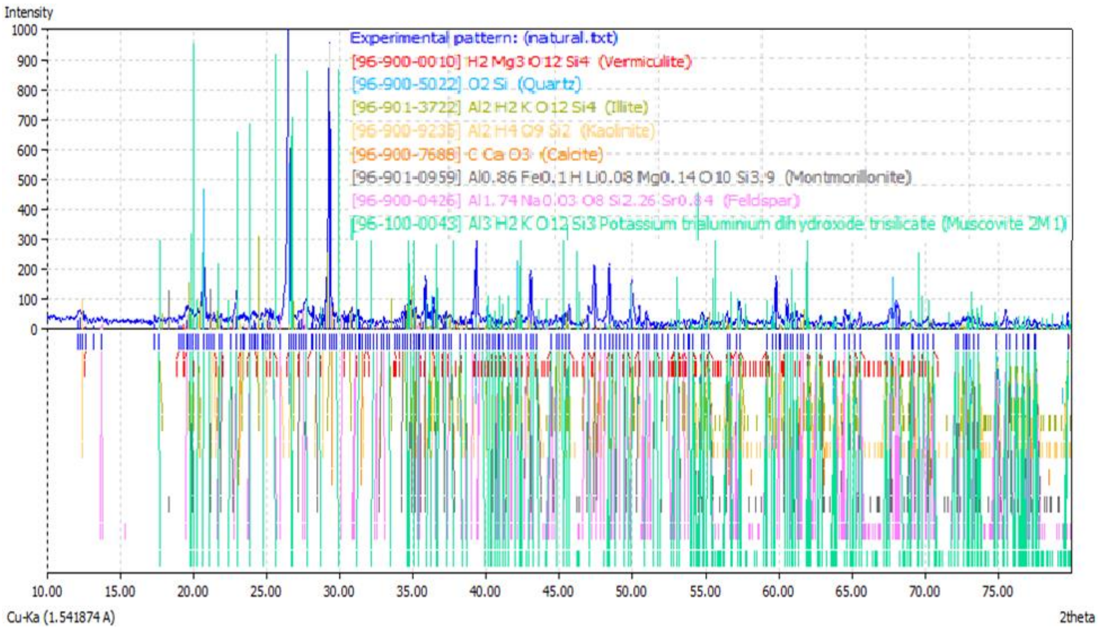


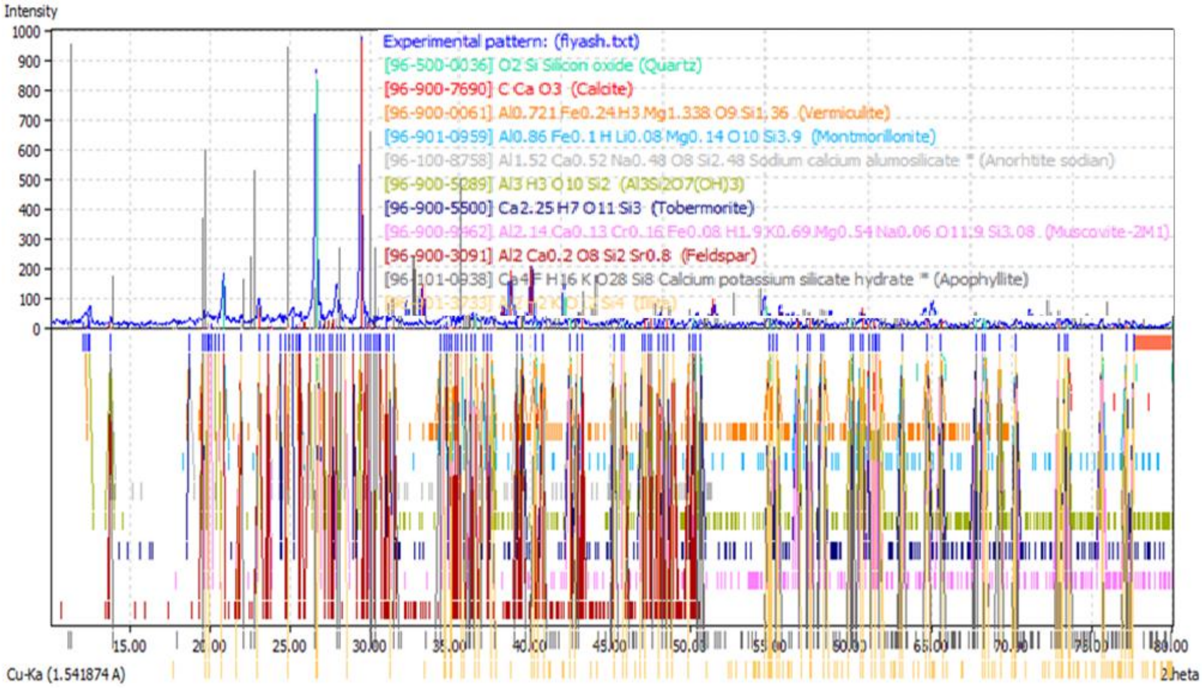
Figure 9. Liquid and plastic limit results for the soil samples

3.5 XRD analyses

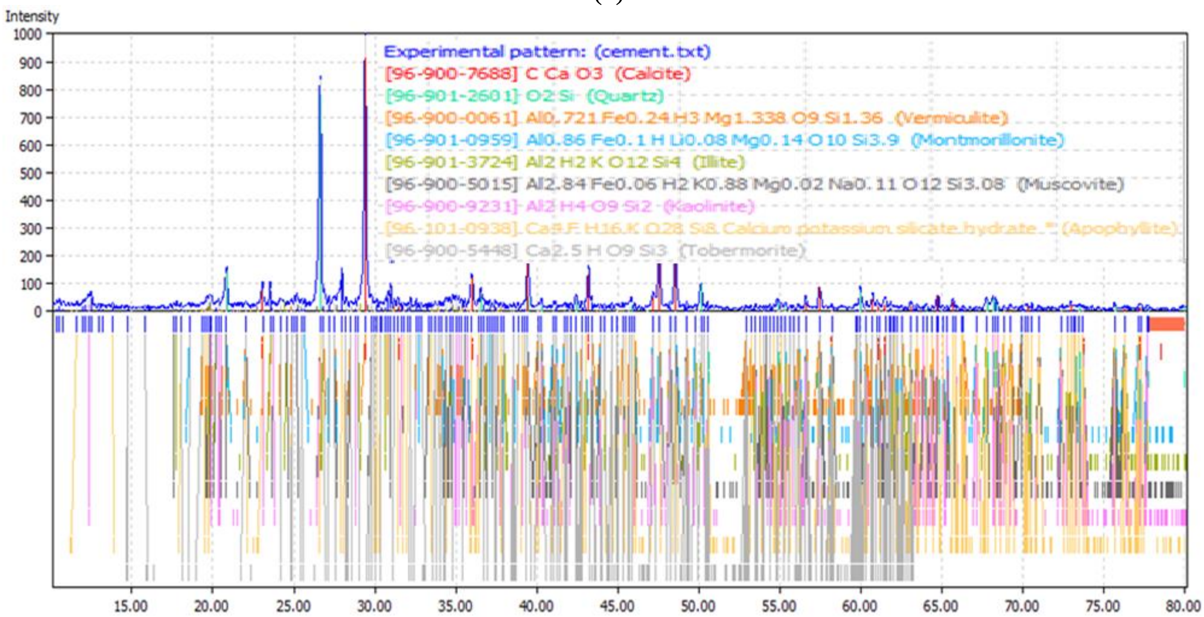
Regarding the mineralogical analysis, Figure 10 depicts the XRD test analysis results for the untreated soil and for the three treating combinations used. The detailed mineral composition for the natural soil sample and for soil-fly ash mixture is illustrated in Table 4, whereas the mineral composition for soil-cement and soil-cement-fly ash is illustrated in Table 5.



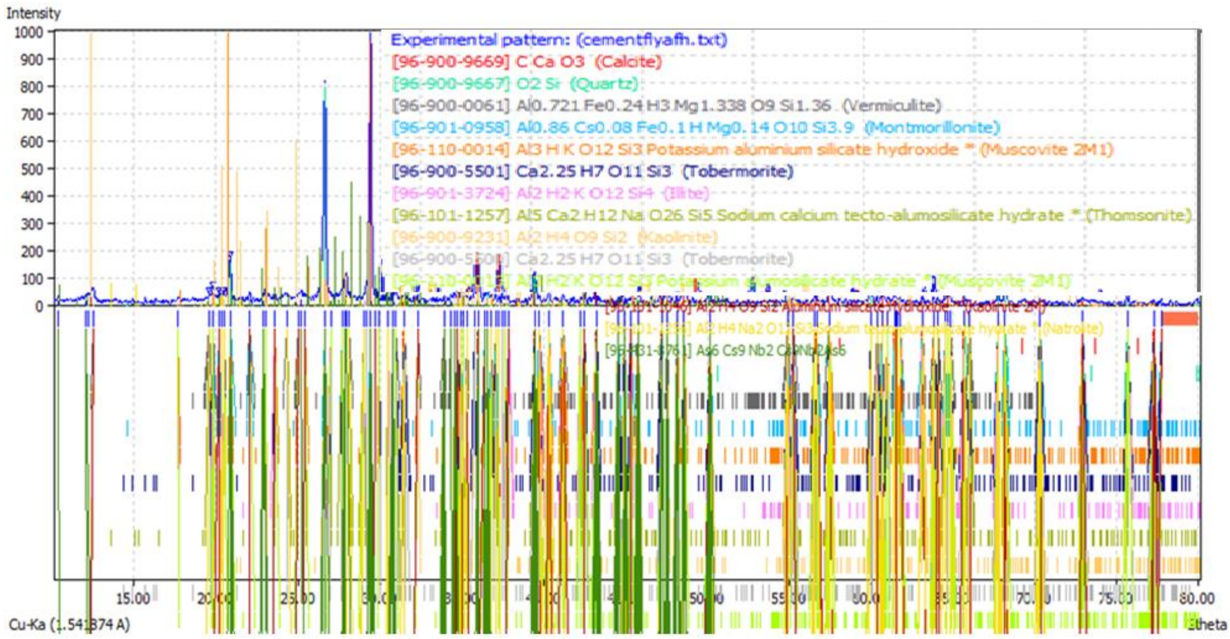
(a)


Intensity
Experimental pattern: (flyash.txt)
[96-500-0036] O2 Si Silicon oxide (Quartz)
[96-900-7690] C Ca O3 (Calcite)
[96-900-0061] Al0.721 Fe0.24 H3 Mg1.338 O9 Si1.36 (Vermiculite)
[96-901-0959] Al0.86 Fe0.1 H Li0.08 Mg0.14 O10 Si3.9 (Montmorillonite)
[96-100-8758] Al1.52 Ca0.52 Na0.48 O8 Si2.48 Sodium calcium alumosilicate * (Anorhtite sodian)
[96-900-5289] Al3 H3 O10 Si2 (Al3Si2O7(OH)3)
[96-900-5500] Ca2.25 H7 O11 Si3 (Tobermorite)
[96-900-9962] Al2.14 Ca0.13 Cr0.16 Fe0.08 H1.9 K0.69 Mg0.54 Na0.06 O11.9 Si3.08 (Muscovite-2M1)
[96-900-3091] Al2 Ca0.2 O8 Si2 Sr0.8 (Feldspar)
[96-101-0938] Ca4 F H16 K O28 Si8 Calcium potassium silicate hydrate * (Apophyllite)
Cu-Ka (1.541874 A)
2theta

(b)


Intensity
Experimental pattern: (cement.txt)
[96-900-7688] C Ca O3 (Calcite)
[96-901-2601] O2 Si (Quartz)
[96-900-0061] Al0.721 Fe0.24 H3 Mg1.338 O9 Si1.36 (Vermiculite)
[96-901-0959] Al0.86 Fe0.1 H Li0.08 Mg0.14 O10 Si3.9 (Montmorillonite)
[96-901-3724] Al2 H2 K O12 Si4 (Illite)
[96-900-5015] Al2.84 Fe0.06 H2 K0.88 Mg0.02 Na0.11 O12 Si3.08 (Muscovite)
[96-900-9231] Al2 H4 O9 Si2 (Kaolinite)
[96-101-0938] Ca4 F H16 K O28 Si8 Calcium potassium silicate hydrate * (Apophyllite)
[96-900-5448] Ca2.5 H O9 Si3 (Tobermorite)

(c)



(d)

Figure 10. The XRD mineralogical patterns: (a) Natural soil. (b) Soil-Fly ash. (c) Soil-Cement. (d) Soil-Cement-Fly Ash.

Table 4: The variation in mineral composition by XRD for both natural soil and soil-fly ash

Description	**Quantity %**	
Mineral name	Nature soil	Soil – Fly ash
Vermiculite	6.51	4.40
Quartz	22.88	25.33
Illite	47.1	
Kaolinite	12.94	
Calcite	2.96	38.99
Feldspar	8.15	6.70
Montmorillonite		0.28
Sodium calcium alumosilicate		9.12
$Al_3Si_2O_7(OH)_3$		1.94
Tobermorite (Calcium silicate hydrate(		
Muscovite		0.74
Calcium potassium silicate hydrate		

Table 5: Mineral composition by XRD for soil-cement and soil-cement-fly ash

Description	**Quantity %**	
Mineral name	Soil – Cement	Soil – Cement – fly ash
Vermiculite	8.02	6.47
Quartz	22.15	24.28
Illite		
Kaolinite	2.55	
Calcite	35.45	37.02
Feldspar		
Montmorillonite	1.68	4.50
Sodium calcium alumosilicate		13.97
$Al_3Si_2O_7(OH)_3$	11.06	
Tobermorite (Calcium silicate hydrate(		0.53
Muscovite	11.41	
Calcium potassium silicate hydrate	1.59	5.98

Figure 10 (b, c and d) shows obviously the lack of any new pecks which means there is no reaction has occurred between the natural soil and its source materials. Furthermore, Table 5 indicates clearly that the calcium silicate hydrate has very low percent in the soil-fly ash specimen; this is mainly because of the pozzolanic reaction nature. In addition, the opposite of this pattern of mineral composition has been noticed in the cement-treated soil specimen and it was at reasonable percent. On the other side, the activation effect can be recognized clearly in the soil samples stabilized by cement-fly ash combination by the presence of Sodium tecto-alumosilicate hydrate, Potassium alumosilicate hydrate and the low percent of Calcium silicate hydrates.

4. Conclusions

1. Adding a sufficient quantity of ordinary Portland cement to a soil stabilized by class-F fly ash can effectively aid in activating the ash and hence enhancing the soil geotechnical properties.
2. The experimental results confirm that several key properties can be improved when stabilizing the soft clay soil by cement-fly ash combination. The results are to large extent comparable to those obtained by only using the cement.

References

[1] Al-Madhhachi, A. S. T., Mutter, G. M., & Hasan, M. B. (2019). Predicting mechanistic detachment model due to lead-contaminated soil treated with Iraqi stabilizers. KSCE Journal of Civil Engineering, 23(7), 2898-2907.

[2] Baqir, H. H., AL-Soudany, K. Y., & Al-Gharbawi, A. S. (2020, February). Clay Columns Stabilized with Fly Ash in Soft Soils. In IOP Conference Series: Materials Science and Engineering (Vol. 737, No. 1, p. 012095). IOP Publishing.

[3] Al-Obaydi, M. A., Al-Kiki, I. M., & Al-Zubaydi, A. H. (2010). Strength and durability of gypseous soil treated with waste lime and cement. Journal Al-Rafidain Engineering, 18(1), 28-42.

[4] Mukhlif Aljobouri, M., & Suhail Idrees Khattab, D. (2012). Effect of combined stabilization by lime and cement on hydraulic properties of clayey soil

selected from mosul area. Al-Rafidain Engineering Journal (AREJ), 20(6), 139-153.

[5] Hasan, H. A. (2012). Effect of fly ash on geotechnical properties of expansive soil. Journal of Engineering and Sustainable Development, 16(2).

[6] Jassim, N. W. (2012). Influences of Fly-Ash and Eggshell Powder on Some of Engineering Properties of Al-Umara Soil. Journal of Engineering and Sustainable Development, 16(2).

[7] Abmaruzzaman M. “A review on the utilisation of fly ash”. Prog. Energy Combust. Sci.;36(3):327–363, 2010.

[8] Barnes D.I., Sear L.K.A. United Kingdom quality ash association; “Ash Utilization from coal-based power plants”, 2006.

[9] Parsa, J., Munson-McGee, S. H., and Steiner, R. “Stabilization/solidification of hazardous wastes using fly ash”, J. Environ. Eng.,122(10): 935–940,1996.

[10] Broms, B.B., “Stabilization of Soft Clay in Southeast Asia”. Proceeding 5th International Geotechnical Seminar 2-4 Dec, 1987.

[11] Abbawi, Z.W. “Proposed Techniques for Improving Soft Soilunderneath a Ballasted Track”. Ph.D. thesis, Building and Construction Engineering Department University of Technology, Baghdad, Iraq, 2010.

[12] Ranga, S. K. “Geotechnical Characterisation of Soft Clay Treated with a Bottom and Fly Ash Mixture”. Geo-China Journal GSP 258, 118 - 125, 118 – 125, (2016).

[13] Xiao, H., Shen, W., and Lee, F.H. (2017). Engineering Properties of Marine Clay Admixed with Portland Cement and Blended Cement with Siliceous Fly Ash. Journal of Materials in Civil Engineering, 29(10),

[14] AL-Adili, Aqeel & Baqir, Husam & sharef, Ali. (2018). Compressibility of soft Iraqi soil stabilized with traditional Iraqi stabilizers (cement and lime). MATEC Web of Conferences. 162.

[15] Premkumar, S., Piratheepan, J., Rajeev.,P. and Arulrajah, A., . (2016). Stabilizing Dispersive Soil Using Brown Coal Fly Ash and Hydrated Lime. Geo-Chicago 2016 GSP 271, 874-884.

[16] Hasan, H., Khabbaz, K., and Fatahi, B., (2016). Impact of Quicklime and Fly Ash on the Geotechnical Properties of Expansive Clay. Geo-China 2016 GSP 258, 94-100.

[17] Jha, A and Puvvadi, S, (2018). Potential of fly ash to suppress the susceptible behavior of lime-treated gypseous soil. Soils and Foundations. 58.

[18] Kang, X., Cao, K., and Bate, B. (2019). Large-Strain Strength of Polymer-Modified Kaolinite and Fly Ash–Kaolinite Mixtures. Journal of Geotechnical and Geoenvironmental Engineering, 145(2).

[19] Phummiphan, I., Horpibulsuk, S., Phoo-ngernkham, T., and Shen, S., (2017). Marginal Lateritic Soil Stabilized with Calcium Carbide Residue and Fly Ash Geopolymers as a Sustainable Pavement Base Material. Journal of Materials in Civil Engineering,

[20] Shihab, A. M., Abbas, J.M., and Ibrahim, A.M., (2018). Effects of Temperature in Different Initial Duration Time for Soft Clay Stabilized by Fly Ash Based Geopolymer. Civil Engineering Journal, 4(9), 2082 - 2096. doi:

[21] Rios, S., Cristelo, N., Viana da Fonseca, A., & Ferreira, C. (2017). Stiffness Behavior of Soil Stabilized with Alkali-Activated Fly Ash from Small to Large Strains. International Journal of Geomechanics, 17(3), 04016087.

[22] ASTM D 854 –14,” Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer”, American Society for Testing and Materials.

[23] ASTM D4318 – 17.” Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils”, American Society for Testing and Materials.

[24] ASTM D4222.” Standard Test Method for Particle-Size Analysis of Soils (Withdrawn 2016)”, American Society for Testing and Materials.

[25] ASTM D42487.” Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)”, American Society for Testing and Materials.

[26] ASTM D3080/D3080M-11,” Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions (Withdrawn 2020)” American Society for Testing and Materials.

[27] ASTM D4318 – 17.” Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils”, American Society for Testing and Materials.

[28] ASTM D2166.” Standard Test Method for Unconfined Compressive Strength of Cohesive Soil”, American Society for Testing and Materials.

[29] Amu O. O. and Salami B.A., “Effect of Common Salt on Some Engineering Properties of Eggshell Stabilized Lateritic Soil”. (ARPN) Journal of

Engineering and Applied Sciences, 5(9): 64-73, 2010.

[30] Phanikumar B. R. and MengXiaoguang. "Effect of lime and fly ash on swell, consolidation and shear strength characteristics of expansive clays a comparative study", Geomechanics and Geoengineering an International Journal. 4(2): 175-181, 2009.

[31] Das B.M, Sobhan K, "Principles of Geotechnical Engineering" Eighth Edition, SI, CENGAGE LEARNING, USA, 2014.

[32] Ali, N. A., & Karkush, M. O. (2021). Improvement of Unconfined Compressive Strength of Soft Clay using Microbial Calcite Precipitates. Journal of Engineering, 27(3), 67–75.

[33] Nicholson, P. G. (2015). Admixture Soil Improvement. Soil Improvement and Ground Modification Methods, 231–288.