Arch. Min. Sci. **66** (2021), 4, 511-522

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI: https://doi.org/10.24425/ams.2021.139594

OMAR ASAD AHMAD[1*]

THE STRENGTH BEHAVIOUR OF TRANSITIONAL GROUP A-2-7 SOIL STABILISED WITH FLY ASH AND LIME POWDER

Recent works aimed to investigate geotechnical properties of Transitional Group A-2-7 (TGA-2-7) soil affected by the use of hydrated lime and fly ash class F, by-products from quarries and a cement factory in Jordan, to compensate for the gap in the granular distribution. Host soil was exposed to various proportions of fly ash and lime powder. The blended specimens were subjected to different tests related to index properties, including Atterberg limits, compaction properties and California bearing ratio. The results demonstrate that 2% fly ash led to a reduction in the plasticity index from 19% to 10%, while lime powder reduced it from 19% to 13%. A sufficient improvement of maximum dry density was observed at 20% lime addition and increased from 15.11 kN/m^3 to 16.29 kN/m^3. California bearing ratio that measures the strength soil linearly increased up to 10% induced by 20% lime addition.

Keywords: Soil stabilisation, lime powder, fly ash, TGA-2-7 soil, engineering index

1. Introduction

Natural and synthetic soil reinforcement, dewatering, natural and synthetic drains, and chemical stabilisation are the strategies developed to enhance soil geotechnical properties. The most suitable selected strategy must be according to soil type, project characteristics, expenditure, existing expertise, and other factors. A popular ground improvement method is the addition of different admixtures and additives to alter soil properties. For instance, soil can be made stronger via chemical strategies involving the addition of cementitious admixtures (e.g. lime, cement); on the downside, such strategies cause irreversible changes in the soil environment [1,2].

---

[1] AMMAN ARAB UNIVERSITY, CIVIL ENGINEERING DEPARTMENT, FACULTY OF ENGINEERING, P.O BOX. 2234, AMMAN 11953, JORDAN

* Corresponding author: oahmad@aau.edu.jo

In general, fine materials such as clay or silt are present in natural soils in varying amounts [3-5]. The source of the fine particles may be rock breakdown or aggregation under the effect of flows or gravity. Factors like weathering and internal erosion can cause alterations in their proportion [6-8]. From previous studies, there are differences in behaviour between clayey-silty sands and pure coarse sands, with the basic state variable of void ratio regulating the properties of soil mixtures, including shear strength [9-11], compressibility [12-15], and permeability [6].

Clayey-silty sands behaviour depends on the composition of fines present in its fabric. The behaviour is regulated primarily by the coarse material when the fraction of fines is low. The transitional fine content represents the fine fraction limit that separates the relative prevalence of coarse and fine materials, being in the range of 20-50%, with discrepancies between values depending on the measurement method employed [17,18]. The method used by Dash, 2010 [17] proposed definitions of equivalent void ratio, which accounts for the fines content, whereas [18] implies that the values of transitional fines content, determined from experimental data are a better indicator of changes in the soil behaviour, which may be critical to the engineer. The agreement between theoretical and experimental values is better when the discrepancy between the sizes of the sand particles and the fines is high.

Ample empirical research has been dedicated to the compression behaviour of clayey-silty sands [13,19,15,20], yielding a range of frameworks. It was suggested that if the fine fraction exceeds the transitional fine content, the fine particles can serve as a matrix, while the coarse grains can serve as inclusions [21,22]. The mixture theory can be applied for modelling mechanical behaviour [15,23,24]. It must be noted, that such a strategy underpinned by the mixture theory is incompatible with gap-graded mixtures with a fine fraction that does not exceed the transitional fine content.

Sand aggregates and fines represent the composition of clayey-silty sands and respectively constitute the structure between aggregates and fill the space between them. Coarse sands become stiffer when fines are present, which in turn engenders a few advantageous engineering properties, such as decreased settlement after construction and the arching effect of foundations and dams. Fine sands, silts, and clay aggregates are the major constituents of fines in clayey sands. The clay aggregate is defined by a cluster of clay particles, with insignificant alteration in volume within a standard range of stress [25].

The treated soil unit weight is among the parameters of quality control and may be of significance for projects where the ground needs to be improved to make the slope more stable and provide uplift resistance [26-27]. However, knowledge is limited about how this parameter was affected by the cement treatment and mix ratio. According to Topolnicki (2013) [26], the type of soil, chemical admixture, and mixing technique determine whether the treated soil unit weight increases or decreases in the majority of cases. In Broms (2003) [28] and FHWAHRT-13-046 (2013) [27], high in-situ water and dry soil mixing resulted in an increased unit weight of organic soils. By contrast, other studies indicated that wet soil mixing and jet grouting either altered (increased) the soil unit weight insignificantly or decreased it [29,30]. The original high unit weight of the clay and extra water content from the cement slurry was identified as the reasons for the decrease in unit weight. It has been argued that if the unit weight of untreated soil exceeds that of cement slurry, then the unit weight of treated soil may be less than the unit weight of untreated soil [27]. Such an argument may not be correct, as the hydration reaction involves water absorption by cement and the mineralogical composition of numerous clay soils suffers changes because of the pozzolanic reaction between such soils and cement. Meanwhile, Kawasaki (1978) [31] and Uddin (1997) [32], have discovered a linear increase in the unit weight of cement-treated clays (soft Bangkok clay) with the cement content and curing duration.

Substantial advances were made over the past ten years in terms of the use of FA-based geopolymer in the context of soft soil engineering. Soil improvement with FA-based binder was confirmed to be practical in a large number of studies, which have demonstrated that such a binder made treated soils stiffer and more durable [33-37].

Alkaline activation can make soil stiffer, according to the soil starting materials, alkaline solution concentration, and curing regime. It also increases the brittleness of soil significantly. This issue is comparable to soils subjected to treatment with cement and lime, which increase strength since aluminium-silicate hydrate (ASH) is the cementitious agent in cement, and calcium-silicate hydrate (CSH) is the cementitious agent in lime [38-41].

Fly ash (FA) is a viable soil additive because of its pozzolanic character. As a solid waste generated by industrial activity, FA has been shown to make soil stronger yet less plastic and compressible [42].

Lime powder (LP) and fly ash (FA) are known to have a negative impact on the environment, so their production occurs as a by-product from quarries in the case of LP and direct combustion from cement factories in the case of FA. The laboratory-based work conducted in the present study sought to assess how LP and FA performed as soil stabilisers and measure their effect on soil indices and strength behaviour when added to TGA-2-7 soil in various proportions. The choice of TGA-2-7 soil to use in the investigation was justified by the scarcity of a particular size range and the effects of lime powder (LP) and fly ash (FA) on geotechnical properties. The main properties of such soil can be properly evaluated, including fine fraction, Atterberg limits, densities and CBRs.

2. Experimental investigation

The experimental investigation employed TGA-2-7 soil extracted from a 1 m depth in the Jordanian city of Amman. Its natural water content was 8%, its classification as clayey-sand (SC) and A-2-7 based on the Unified Soil Classification System (USCS) and American Association of State Highway and Transportation Officials (ASHTOO) classification framework, respectively, was informed by its grain size distribution, 43% liquid limit (LL), and 19% plasticity index (PI). The Proctor compaction test indicated that the soil maximum dry density ($\gamma_{d\,\mathrm{max}}$) was 15.11 kN/m^3, and its optimum moisture content (OMC) was 20.87%. The sieve analysis and grain size distribution are associated with the TGA-2-7 soil presented in Figure 1. The ASTM C136 was applied when conducting sieve analysis. The index properties and compaction features of the natural soil are outlined in Table 1.

The empirical work used LP and FA procured from quarries and a cement factory in Jordan, respectively. These two types of waste were in powder form and air-dried. Table 2 indicates how they were chemically constituted. Measurement of the LL, PI, and (PL) of soil was conducted for a range of concentrations of LP and FA in compliance with the ASTM D4318. Measurement of the Proctor compaction features of OMC and $\gamma_{d\,\mathrm{max}}$ was performed for different LP and FA concentrations as well. The Proctor compaction tests employed air-dried soil sieved through a 4.75 mm mesh and complied with the ASTM D698a.

The outcomes of the Proctor compaction tests indicated that the dry densities of the FA mix design did not increase as much as was anticipated, with the highest increase being achieved at an FA concentration of 6%. This FA concentration was similar to the dry densities of the selected soil. The addition of LP in a different concentration determined a dry density increase of 8%, thus improving the strength of the TGA-2-7 specimen. The LP with concentrations of 5-20% was subjected to a different set of tests to measure the compaction features and CBR. Measurement of the LL, PL, and PI was conducted as well.

The mix designs were measured for their California bearing ratio (CBR). Just like with the UCS tests, the CBR tests involved compaction of the specimens at their corresponding OMC and $\gamma_{d\,\max}$. Furthermore, the preparation of the TGA-2-7 soil and blended samples for CBR tests was undertaken in line with the ASTM D1883-05. The diameter and height of the CBR samples were 150 mm and 175 mm, respectively.

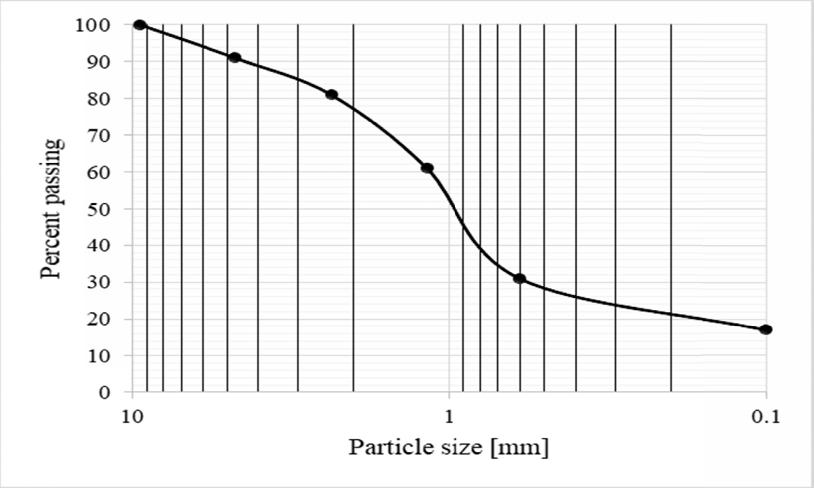

Fig. 1. The curve of grain size distribution associated with natural soil

TABLE 1

The index properties and compaction features displayed by TGA-2-7 soil

Soil property	TGA-2-7
Liquid Limit, LL (%)	43
Plastic Limit, PL (%)	24
Plasticity Index, PI (%)	19
Maximum Dry Unit Weight $\gamma_{d\,\max}$ (kN/m^3)	15.11
Optimum Moisture Content OMC (%)	20.87
Soil Classification ASHTOO	A-2-7
Unified Soil Classification System (USCS)	SC

TABLE 2

Flay ash (FA) and lime powder (LP) chemical composition

Material	FA	LP
SiO_2	58.11	0.25
Al_2O_3	22.56	0.1
Fe_2O_3	6.48	0.24
CaO	3.30	54.72
MgO	1.45	2.95
K_2O	1.70	0.1
SO_3	0.24	0.45

3. Results and Discussions

An overview of the impact of lime powder and fly ash on the Atterberg limits (LL, PL, and PI) of TGA-2-7 soil is provided in Table 3. The impact of FA addition in various concentrations on the three index properties of soil blends is illustrated in Figures 2 and 3. When FA was added to the blended soils in a proportion of 2-8%, the LL increased while the PI decreased, which could be attributed to the substitution of highly plastic clay content with the FA lacking plasticity.

PI decreased from 19 to 12% at 0-8% addition due to the flocculation promoted by FA due to its pozzolanic nature. By contrast, an increase in LL from 43 to 47% occurred as a result of the addition of 2-6% FA to TGA-2-7 soil blends.

The impact of the LP addition on the index properties of TGA-2-7 soil is illustrated in Figures 4 and 5. The increase in LP concentration caused the LL and PL to increase and decline,

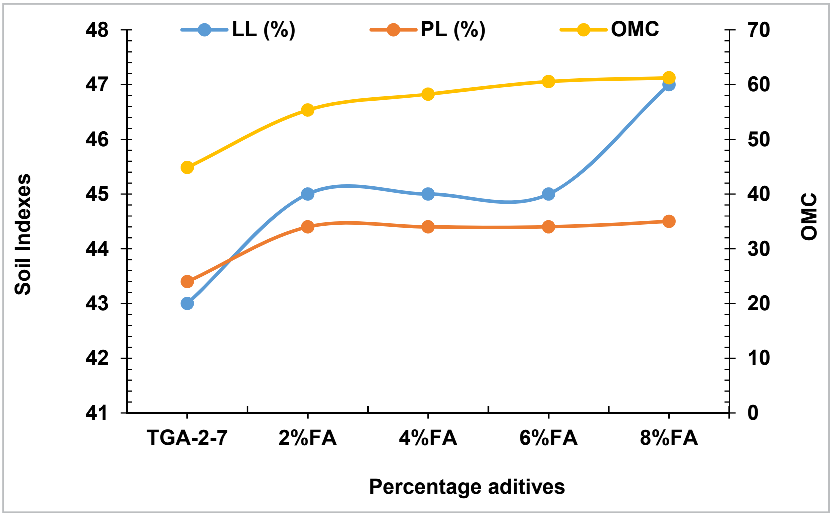

Fig. 2. The impact of FA concentration on the soil PI, PL, and LL

TABLE 3

The index properties associated with natural and blended soils

Soil property	Liquid Limit, LL (%)	Plastic Limit, PL (%)	Plasticity Index, PI (%)
TGA-2-7	43	24	19
2% FA	45	35	10
4% FA	45	34	11
6% FA	45	34	11
8% FA	47	35	12
5% LP	39	26	13
10% LP	43	24	19
20% LP	42	21	21

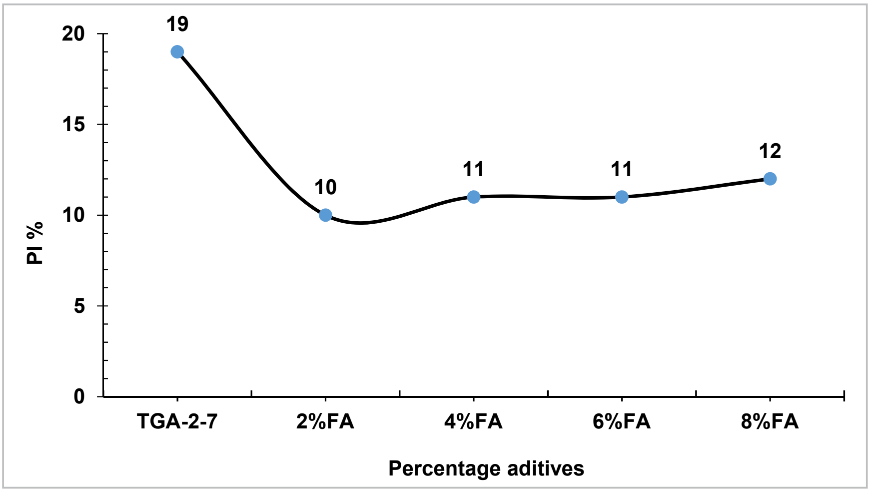

Fig. 3. The impact of FA concentration on PI

respectively. Therefore, the concentration of 5% LP was the only one associated with a reduction in PI and LL. Meanwhile, an LP concentration of 10-20% determined an increase in both LL and PI. The reduction in LL and PI and the increase in PL were due to the substitution of clay particles of high plasticity with the non-plastic LP particles. The formation of flocs in the blend was due to the outcome of clay particle flocculation determined by LP due to its pozzolanic nature. An increase in LP concentration from 0 to 5% resulted in an LL reduction from 43 to 39% and a PI reduction from 19 to 13%.

The premise frequently applied during the design phase is that treated soil has a $\gamma_{d\max}$ identical to or exceeding TGA-2-7 soil. However, the $\gamma_{d\max}$ may be below the conjectured value (Table 4). The impact of LP and FA on the soil compaction properties is illustrated in Figures 6 and 7. Compared to 0% LP concentration or TGA-2-7 soil, 5 and 10% LP concentrations were associated with lower $\gamma_{d\max}$, as indicated by the compaction data. On the other hand, there was a substantial increase in $\gamma_{d\max}$ at 20% LP concentration. Such results can be attributed to the fact

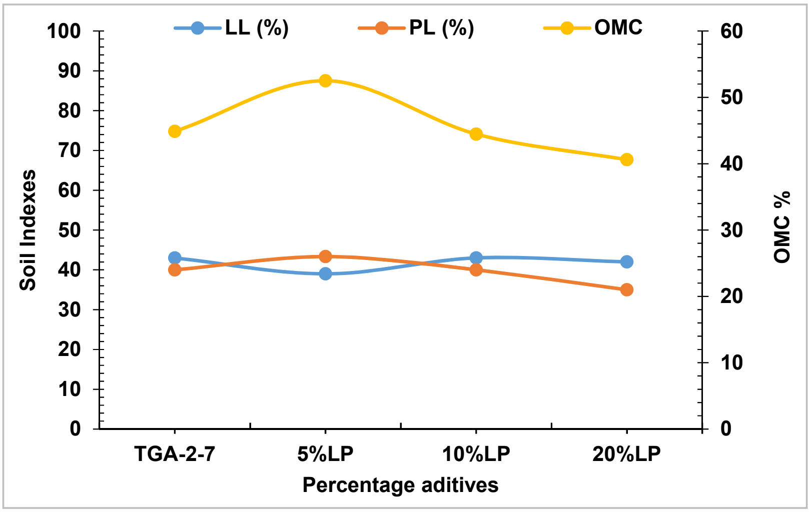

Fig. 4. The impact of LP concentration on soil index properties

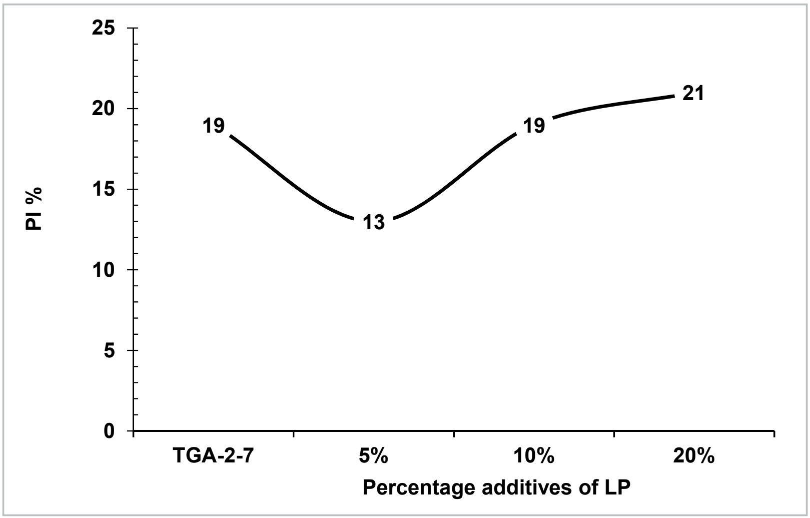

Fig. 5. The impact of LP concentration on PI

that the poor reaction of LP in a small concentration in flocculation failed to promote an increase in the $\gamma_{d\max}$, which only occurred when the LP concentration was elevated. By contrast, to the $\gamma_{d\max}$, the OMC declined at higher LP concentration, with 5% being the only LP concentration associated with a rise in OMC. One explanation for this is the fact that LP absorbs water. Table 5 and Figure 7 provide further details on the $\gamma_{d\max}$ and OMC.

A reduction in the $\gamma_{d\max}$ at lower FA concentration was observed upon addition of FA to TGA-2-7 soil blends in different concentrations (2, 4, 6, and 8%). The compaction data associated with FA blends at various concentrations is presented in Figure 6. At 6% FA, the $\gamma_{d\max}$ increased, while an ongoing increase displayed by the OMC up to 6% FA, followed by a minor reduction at 8% FA. It can be implied that more additives of fly ash reduces the $\gamma_{d\max}$ because of more adsorbed water to soil fabric, and this is consistent with the results of the optimum moisture content increase.

TABLE 4

The compaction features displayed by treated soils

Treated soils	**Optimum moisture content OMC (%)**	**Maximum dry unit weight $\gamma_{d\max}$ (kN/m^3)**
TGA-2-7	20.87	15.11
2% FA	21.35	14.32
4% FA	24.24	14.72
6% FA	26.55	15.00
8% FA	26.23	14.91
5% LP	26.51	14.70
10% LP	20.46	14.70
20% LP	19.61	16.29

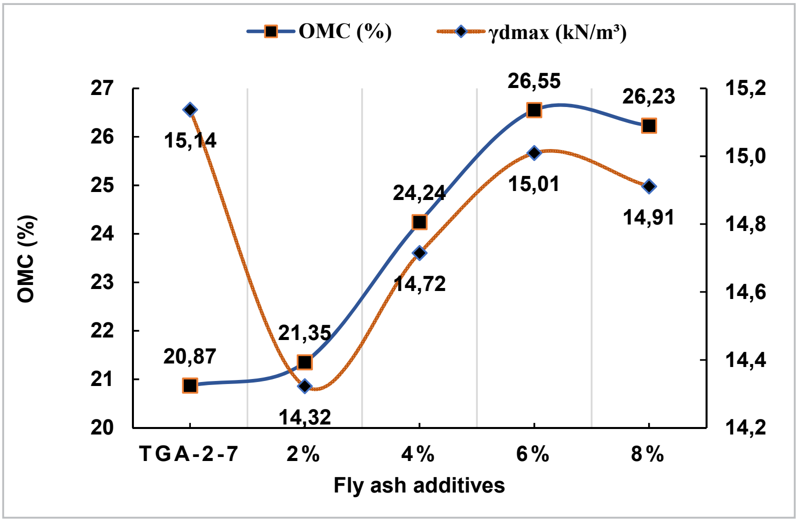

Fig. 6. The impact of FA concentrations on the $\gamma_{d\max}$ and OMC of treated TGA-2-7 soil

The CBR varied with the concentration of LP and FA added to blended soils (Figure 8). Every blended soil displayed a rise in the CBR in line with the LP concentration, which was most prominent at 20% LP. The increase in the $\gamma_{d\max}$ at 20% LP may explain the rise in the CBR. Compared to TGA-2-7 soil, the CBR improved considerably, from 79 at 5% LP to 84 at 20% LP. Furthermore, the CBR was enhanced by a low FA concentration of 2% from 77 to 82. On the other hand, the CBR declined as the FA concentration was increased from 4 to 8%, although it remained higher than TGA-2-7 soil. Table 6 details the CBR data at various additive concentrations.

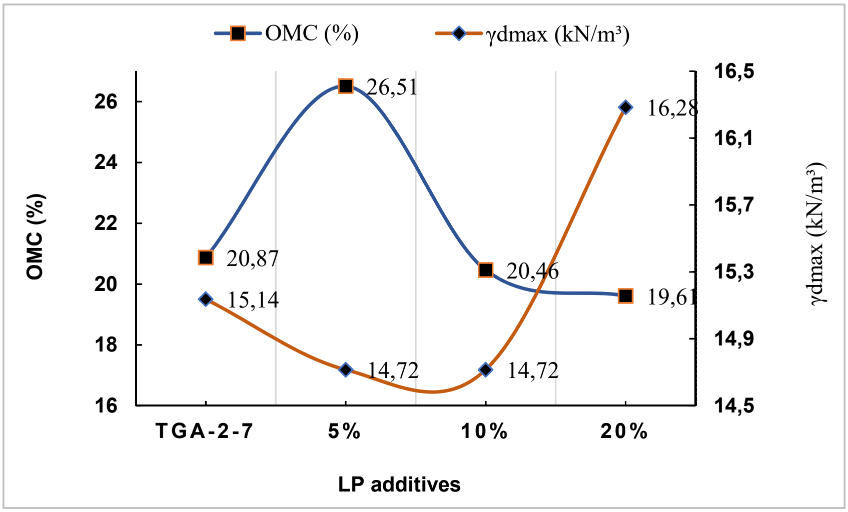

Fig. 7. The impact of LP concentrations on the $\gamma_{d\max}$ and OMC of treated TGA-2-7 soil

TABLE 5

CBR data for TGA-2-7 and blended soils

Soil property	% C.B.R
TGA-2-7	77
2% FA	82
4% FA	80
6% FA	79
8% FA	79
5% LP	79
10% LP	83
20% LP	84

There is widespread recognition that soil-lime and soil-cement reactions are complex [43]. Clay stabilisation is achieved by lime sludge via hydration, cation exchange, and pozzolanic reactions that take place when water is present. The process of hydration involves a reaction between the CaO from the stabiliser and water that yields $Ca(OH)_2$. Since this process uses water, it causes the drying of the stabilised soil, which automatically makes it stronger. Meanwhile, cation exchange involves the substitution of monovalent cations like sodium (Na^+) and hydrogen (H^+) in the soil with calcium (Ca^{2+}) present in $Ca(OH)_2$. Because of this substitution, the double diffuse layer (DDL) becomes thinner, and consequently, the attraction between soil particles intensifies [44-45]. Pozzolanic reactions involve the formation of calcium-silicate hydrate (C-S-H) and calcium-aluminate-hydrate (C-A-H) gels over time, and cementitious properties are presented by both these gels.

The main mechanism involves the transportation of calcium hydroxide via water within the soil to combine with the aluminate and/or silicate clay minerals. The high surface area aluminate and silicate minerals are pozzolan phases, which in the presence of water and an alkali (e.g., calcium) produce cementitious materials, comprising calcium silicates and aluminate hydrates. Any dissolved Ca^{2+} ions within the soil then react with any dissolved SiO_2 and Al_2O_3 located on clay particles to produce hydrated gels of C-S-H and C-A-H, which cement soil particles together.

4. Conclusions

Waste materials from different industrial activities, lime powder and fly ash were used in this study in various concentrations to create TGA-2-7 soil blends. The properties of plasticity, compaction, and C.B.R. of those blends were subsequently analysed. The addition of LP to the blends had a notable impact on the compacted density at both 2% FA and 20% LP concentration. Therefore, several conclusions could be derived, as outlined below.

Firstly, a low LP concentration determined a reduction in the LL and PI of the TGA-2-7 soil. However, this reduction was especially prominent with the addition of increasing concentrations of FA. Secondly, compared to 0% FA concentration, 2-8% FA concentration was associated with a lower $\gamma_{d\max}$ of the TGA-2-7 blends. On the other hand, at 20% LP concentration, there was a slight increase in the $\gamma_{d\max}$, but the OMC decreased. By contrast, increased concentrations of FA determined an increase in the OMC, as the FA absorbed water. Thirdly, as the LP concentration increased, CBR of TGA-2-7 soil also increased; for instance, at 20% LP concentration, the CBR increased by 9%. Similarly, 2% FA concentration increased the CBR by 6.5%. Overall, the findings obtained support the use of LP and FA for stabilising TGA-2-7 soils.

This work brings new concepts to soil stabilisation, providing a comparatively new approach for efficacious improvement of TGA-2-7 soil, which in turn might lead to decreased settlement after construction and the arching effect of foundations.

Acknowledgements

This research undertaken at the College of Engineering would not have been possible without the support of the Deanship of Scientific Research at Amman Arab University.

References

[1] J.I. Chang, G.C. Cho, Geotechnical Engineering Behaviors of Gellan Gum Biopolymer Treated Sand. Canadian Geotechnical Journal **53** (10), 1-38 (2016a). DOI: https://doi.org/10.1139/cgj-2015-0475

[2] J.I. Chang, G.C. Cho, Introduction of Microbial Biopolymers in Soil Treatment for Future Environmentally-Friendly and Sustainable Geotechnical Engineering. Sustainability **8**, 251-273 (2016b). DOI: https://doi.org/10.3390/su8030251

[3] C. Guo, Y. Cui, Pore Structure Characteristics of Debris Flow Source Material in the Wenchuan Earthquake Area. Engineering Geology **267**, 105499 (2020). DOI: https://doi.org/10.1016/j.enggeo.2020.105499

[4] J. Park, J.C. Santamarina, Revised Soil Classification System for Coarse-Fine Mixtures. J. Geotech. Geoenviron. Eng. **143** (8), 04017039 (2017). DOI: https://doi.org/10.1061/(ASCE)GT.1943-5606.0001705

[5] D. Peng, Q. Xu, F. Liu, Y. He, S. Zhang, X. Qi, K. Zhao, X. Zhang, Distribution and Failure Modes of the Landslides in Heitai Terrace, China. Eng. Geol. **236**, 97-110 (2018). DOI: https://doi.org/10.1016/j.enggeo.2017.09.016

[6] Y. F.Cui, X.J. Zhou, C.X. Guo, Experimental Study on the Moving Characteristics of Fine Grains in Wide Grading Unconsolidated Soil Under Heavy Rainfall. J. Mt. Sci. **14** (3), 417-431 (2017). DOI: https://doi.org/10.1007/s11629-016-4303-x

[7] W.B. Chen, K. Liu, W.Q. Feng, L. Borana, J.H. Yin, Influence of Matric Suction on Nonlinear Time-Dependent Compression Behavior of a Granular Fill Material. Acta Geotechnica **15** (3), 615-633 (2020). DOI: https://doi.org/10.1007/s11440-018-00761-y

[8] Z. Zhou, H. Yang, X. Wang, B. Liu, Model Development and Experimental Verification for Permeability Coefficient of Soil-Rock Mixture. Int. J. Geomech. **17** (4), 04016106 (2017). DOI: https://doi.org/10.1061/(ASCE)GM.1943-5622.0000768

[9] R. Salgado, P. Bandini, A. Karim, Shear Strength and Stiffness of Silty Sand. J. Geotech. Geoenviron. Eng. **126** (5), 451-462 (2000). DOI: https://doi.org/10.1061/(ASCE)1090-0241(2000)126:5(451)

[10] T. Ueda, T. Matsushima, Y. Yamada, Effect of Particle Size Ratio and Volume Fraction on Shear Strength of Binary Granular Mixture. Granular Matter **13** (6), 731-742 (2011). DOI: https://doi.org/10.1007/s10035-011-0292-1

[11] P. Ruggeri, D. Segato, V.M.E. Fruzzetti, G. Scarpelli, Evaluating the Shear Strength of a Natural Heterogeneous Soil Using Reconstituted Mixtures. Géotechnique **66** (11), 941-946 (2016). DOI: https://doi.org/10.1680/jgeot.15.P.022

[12] M.M. Monkul, G. Ozden, Compressional Behaviour of Clayey Sand and Transition Fines Content. Engineering Geology **89** (3), 195-205 (2007). DOI: https://doi.org/10.1016/j.enggeo.2006.10.001

[13] T.G. Ham, Y. Nakata, R.P. Orense, M. Hyodo. Influence of Gravel on the Compression Characteristics of Decomposed Granite Soil." J. Geotech. Geoenviron. Eng. **136** (11), 1574-1577 (2010). DOI: https://doi.org/10.1061/(ASCE)GT.1943-5606.0000370

[14] N.J. Jiang, K. Soga, M. Kuo, Microbially Induced Carbonate Precipitation for Seepage-Induced Internal Erosion Control in Sand-Clay Mixtures. Journal of Geotechnical and Geoenvironmental Engineering **143** (3), 04016100 (2016). DOI: https://doi.org/10.1061/(ASCE)GT.1943-5606.0001559

[15] X.S. Shi, J. Yin, Experimental and Theoretical Investigation on the Compression Behavior of Sand-Marine Clay Mixtures Within Homogenization Framework. Comput. Geotech **90** (Oct), 14-26 (2017). DOI: https://doi.org/10.1016/j.compgeo.2017.05.015

[16] X.S. Shi, I. Herle, D. Muir Wood, A Consolidation Model for Lumpy Composite Soils in Open-Pit Mining. Géotechnique **68** (3), 189-204 (2018). DOI: https://doi.org/10.1680/jgeot.16.P.054

[17] H.K. Dash, T.G. Sitharam, B.A. Baudet, Influence of Nonplastic Fines on the Response of a Silty Sand to Cyclic Loading. Soils and Foundations **50** (5), 695-704 (2010). DOI: https://doi.org/10.3208/sandf.50.695

[18] L. Zuo, B.A. Baudet, Determination of the Transitional Fines Content of Sand-non-Plastic Fines Mixtures. Soils Found. **55** (1), 213-219 (2015). DOI: https://doi.org/10.1016/j.sandf.2014.12.017

[19] C. Chu, Z. Wu, Y. Deng, Y. Chen, Q. Wang, Intrinsic Compression Behavior of Remolded Sand-Clay Mixture. Canadian Geotechnical Journal **54** (7), 926-932 (2017). DOI: https://doi.org/10.1139/cgj-2016-0453

[20] Z. Wu, Y. Deng, Y. Cui, Y. Chen, Q. Wang, Q. Feng, Investigations on Secondary Compression Behaviours of Artificial Soft Sand-Clay Mixtures. Soils Found. **59** (2), 326-336 (2019). DOI: https://doi.org/10.1016/j.sandf.2018.11.008

[21] W. Zhou, K. Xu, G. Ma, L. Yang, X. Chang, Effects of Particle Size Ratio on the Macro- and Microscopic Behaviors of Binary Mixtures at the Maximum Packing Efficiency State. Granular Matter **18** (4), 81 (2016). DOI: https://doi.org/10.1007/s10035-016-0678-1

[22] X.S. Shi, J. Yin, Estimation of Hydraulic Conductivity of Saturated Sand-Marine Clay Mixtures with a Homogenization Approach. Int. J. Geomech. **18** (7), 04018082 (2018). DOI: https://doi.org/10.1061/(ASCE)GM.1943-5622.0001190

[23] X.S. Shi, J. Yin, J. Zhao, Elastic Visco-Plastic Model for Binary Sand-Clay Mixtures with Applications to One-Dimensional Finite Strain Consolidation Analysis. J. Eng. Mech. **145** (8), 04019059 (2019a). DOI: https://doi.org/10.1061/(ASCE)EM.1943-7889.0001623

[24] X.S. Shi, J. Zhao, J. Yin, Z. Yu, An Elastoplastic Model for Gap-Graded Soils Based on Homogenization Theory. Int. J. Solids Struct. 163 (May), 1-14 (2019b). DOI: https://doi.org/10.1016/j.ijsolstr.2018.12.017

[25] T.S. Nagaraj, F.J. Griffiths, R.C. Joshi, A. Vatsala, B.R.S. Murthy, Change in Pore-Size Distribution due to Consolidation of Clays Discussion. Géotechnique **40** (2), 303-309 (1990). DOI: http://eprints.iisc.ac.in/id/eprint/35250

[26] M. Topolnicki (3-ed edition), In Situ Soil Mixing, In: K. Kirsch, A. Bell (Eds.), Ground Improvement, CRC Press, London (2013).

[27] FHWA-HRT-13-046, Federal Highway Administration Design Manual: Deep Mixing for Embankment and Foundation Support, U.S. Department of Transportation, Federal Highway Administration (2013).

[28] B.B. Broms, Deep Soil Stabilization: Design and Construction of Lime and Lime/Cement Columns. Royal Institute of Technology, Stockholm, Sweden (2003).

[29] Cement Deep Mixing (CDM), Design and Construction Manual for CDM Institute. Partial English Translation, Cement Deep Mixing Association of Japan, Tokyo, Japan, (1985).

[30] A.J. McGinn, T.D. O'Rourke, Performance of Deep Mixing Methods at Fort Point Channel. Federal Highway Administration, Washington, DC (2003).

[31] T. Kawasaki, A. Niina, S. Saitoh, R. Babasaki, Studies on Engineering Characteristics of Cement-Base Stabilized Soil. Takenaka Technical Research Report **19**, 144-165 (1978).

[32] K. Uddin, A.S. Balasubramaniam, D.T. Bergado, Engineering Behavior of Cement-Treated Bangkok Soft Clay. Geotech. Eng. **28** (1), 89-119 (1997). DOI: http://worldcat.org/issn/00465828

[33] N. Cristelo, S. Glendinning, L. Fernandes, A.T. Pinto, Effects of Alkaline- Activated Fly Ash and Portland Cement on Soft Soil Stabilization. Acta Geotechnica **8** (4), 395-405 (2013). DOI: https://doi.org/10.1007/s11440-012-0200-9

[34] M. Zhang, H. Guo, T. El-Korchi, G. Zhang, M. Tao, Experimental Feasibility Study of Geopolymer as the Next-Generation Soil Stabilizer. Constr. Build. Mater. **47**, 1468-1478 (2013).
DOI: https://doi.org/10.1016/j.conbuildmat.2013.06.017

[35] S. Rios, N. Cristelo, T. Miranda, N. Arau, J. Oliveira, E. Lucas, Increasing the Reaction kinetics of Alkali-Activated Fly Ash Binders for Stabilization of a Silty Sand Pavement Sub-Base. Road Mater. Pavement Desing. **19** (1), 201-222 (2016). DOI: https://doi.org/10.1080/14680629.2016.1251959

[36] H.H. Abdullah, M.A. Shahin, P. Sarker, Stabilisation of Clay with Fly-Ash Geopolymer Incorporating GGBFS. In: Proceedings of the second Proceedings of the Second World Congress on Civil, Structural and Environmental Engineering (CSEE'17), 1-8 (2017).

[37] A.B. Moghal, State of the Art Review on the Role of Fly Ashes in Geotechnical and Geo Environmental Applications. J. Mater. Civ. Eng. **29** (8), 04017072 (2017). DOI: https://doi.org/10.1061/(ASCE)MT.1943-5533.0001897

[38] S. Pourakbar, A. Asadi, B.B. Huat, N. Cristelo, M.H. Fasihnikoutalab, Application of Alkali-Activated Agro-Waste Reinforced with Wollastonite Fibers in Soil Stabilization. J. Mater. Civ. Eng. **29** (2), 04016206 (2016).
DOI: https://doi.org/10.1061/(ASCE)MT.1943-5533.0001735

[39] Elkhebu, A. Zainorabidin, I. Bakar, B.K. Huat, L. Abdeldjouad, W. Dheyab, Alkaline Activation of Clayey Soil Using Potassium Hydroxide and Fly Ash. International Journal of Integrated Engineering **10** (9), 99-104 (2019).
DOI: https://doi.org/ 10.30880/ijie.2018.10.09.016

[40] L. Abdeldjouad, A. Asadi, R.J. Ball, H. Nahazanan, B.K. Huat, W. Dheyab, A. Elkhebu, Effect of Clay Content on Soil Stabilization with Alkaline Activation. International Journal of Geosynthetics and Ground Engineering **5**, (2019b). DOI: https://doi.org/10.1007/s40891-019-0157-y

[41] L. Abdeldjouad, A. Asadi, R.J. Ball, H. Nahazanan, B.K. Huat, Application of Alkali-Activated Palm Oil Fuel Ash Reinforced with Glass Fibers in Soil Stabilization. Soils and Foundations **59** (5), 1552-1561 (2019c).
DOI: https://doi.org/10.1016/j.sandf.2019.07.008

[42] B.R. Phanikumar, E. Ramanjaneya, Compaction and Strength Characteristics of An Expansive Clay Stabilized with Lime Sludge and Cement. Soils and Foundations **60**, 129-138 (2020).
DOI: https://doi.org/10.1016/j.sandf.2020.01.007

[43] D.N. Little, E.H. Males, J.R. Prusinski, B. Stewart Cementitious Stabilization, A Research Report, A2J01, Committee on Cementitious stabilization. Louisiana State University (2016).

[44] Z.D. Zhu, S.Y. Liu, Utilisation of a New Soil Stabilizer for Silt Subgrade. Eng. Geol. **97** (3-4), 192-198 (2008).
DOI: https://doi.org/10.1016/j.enggeo.2008.01.003

[45] X.B. Yu, B. Zhang, D. Cartweight, Beneficial Utilization of Lime Sludge for Subgrade Stabilization: A pilot investigation. Ohio Department of Transportation, Office of Research and Development (2010).