Geotechnical Properties of Soil-Lightweight Aggregate Mixtures

Wurood Jassim Aljboori
Department of Civil Engineering, College of Engineering, Mustansiriyah University, Baghdad, Iraq
Wrood.aljboori@uomustansiriyah.edu.iq (corresponding author)

Madhat Shakir Al-Soud
Department of Civil Engineering, College of Engineering, Mustansiriyah University, Baghdad, Iraq
ms_madhat@uomustansiriyah.edu.iq

Asma Mahdi Ali
Department of Civil Engineering, College of Engineering, Mustansiriyah University, Baghdad, Iraq
asmaaali_civil@uomustansiriyah.edu.iq

Received: 26 October 2024 | Revised: 22 November 2024 | Accepted: 8 December 2024

ABSTRACT

This study investigates the stabilization and strengthening of clayey soils using several Lightweight Aggregates (LWAs), including Lightweight Expanded Clay Aggregate (LECA), Ponza (Pumice), and Thermostone. LWAs were incorporated into the soil to evaluate their impact on critical geotechnical parameters, such as compaction, consolidation, Unconfined Compressive Strength (UCS), and shear strength. The results revealed that incorporating LWAs effectively reduces the soil density, increases the void ratios, and enhances certain soil properties. LECA demonstrated the most substantial impact in decreasing soil density and increasing porosity, achieving a maximum density reduction of 60% and a void ratio increase of 75% at a 60% addition. While LWAs enhanced the internal friction angle by up to 90% - with Thermostone showing the highest increase at a 60% addition- cohesion diminished across all concentrations. The UCS peaked with a 94% increase at a 10% LECA addition but decreased with higher LWA percentages due to the porous nature of the additives disrupting the soil matrix. Optimal performance was observed with LWA concentrations between 10% and 30%, balancing improved strength and soil integrity. These findings suggest that LWAs can effectively stabilize and strengthen clayey soils, particularly in applications requiring reduced weight and enhanced shear strength, provided that the mixing ratios are carefully calibrated to align with project-specific requirements.

Keywords-LECA; Ponza (Pumice); thermostone; soil stabilazation; sustainable materials in civil engineering

I. INTRODUCTION

Clayey soils exhibit significant challenges in geotechnical engineering due to high compressibility, low shear strength, and susceptibility to volume changes under varying moisture conditions. These characteristics can compromise the stability of structures built in such soils. Stabilization and reinforcement techniques, such as driven piles, drilled shafts, stone columns, chemical stabilization, Controlled Low-Strength Materials (CLSM), geosynthetic reinforcement, and the use of low-density materials, are commonly employed to mitigate consolidation settlements [1]. For clay deposits, approaches like sand drains, Preloading with Sand (PWD), and chemical treatments are well- established for expediting consolidation, while loose sand deposits are often densified using compaction sand piles or stone columns. Conventional soil improvement methods typically involve replacing weak soil with high-quality materials. However, a complete soil replacement is often infeasible due to the high costs and environmental concerns associated with the mining and reclamation activities. A practical alternative is the selective replacement within critical zones, substituting poor-quality soils, for instance, medium to heavy clay, with granular materials, such as sand or gravel [2]. Recent advancements have explored innovative reinforcement methods, such as incorporating waste plastic strips into clay-sand mixtures. This reinforcement enhances soil properties, with studies showing increased shear strength and ductility under higher stresses when using corrugated plastic strips [3]. The utilization of LWAs in construction is gaining traction due to practical and economic benefits, particularly in residential projects. The inherent voids in these aggregates improve the thermal and acoustic insulation properties, reduce material weight, and lower the overall building costs [4, 5]. LWAs vary significantly in composition, density, surface roughness, porosity, and water absorption [6]. While some LWAs occur naturally, others are derived from industrial byproducts or processed from natural sources. Natural LWAs are limited by their availability [7]. Several studies have demonstrated the potential of LWAs in structural engineering applications. Specifically, authors in [8] investigated the crushed Ponza aggregate in lightweight cement mortars for thermal insulation, achieving acceptable strength and thermal properties with a reduced bulk density. In [9], the LWAC was examined using LECA combined with steel fibers, highlighting an improved mechanical performance. Authors in [10] emphasized the benefits of LWAC in reducing dead loads in tall structures, enhancing construction efficiency, and promoting sustainability. In road infrastructure, embankment settlement is a critical concern, often leading to considerable damage to pavement layers. All soil types experience settlement due to compressive forces, resulting in volume reduction [11]. Conventional stabilization techniques focus on strength enhancement but often neglect the benefits of reducing the soil weight to minimize the structural loads. This study explores the integration of LWAs, such as LECA, Pumice (Ponza), and Thermostone in stabilizing clayey soils. Although LWAs are recognized for their lightweight properties and thermal insulation benefits, their geotechnical potential remains under-researched, particularly concerning the optimal mixing ratios. The current study aims to evaluate the effects of LWAs on clayey soils by evaluating parameters, such as compaction, consolidation, UCS, and shear strength.

II. EXPERIMENTAL WORK

A. Materials

1) Clayey Soil

The soil samples were collected from a depth of 2-2.5 m below the surface at the AL-Budoor Baghdad Complex, located in the Abu-Ghuraib district. The soil used in this study was classified as low-plasticity clay according to ASTM D4318 [12]. These natural soil samples were prepared and subjected to laboratory tests to determine their physical/mechanical properties. The results of these tests are summarized in Table I.

TABLE I. PHYSICAL/MECHANICAL SOIL PROPERTIES

Property	Magnitude	Specification
The Specific Gravity (*Gs*)	2.71	ASTM D854-23 [13]
Liquid Limit %	29.8	BS 1377-2 [14]
Plastic Limit %	18.57	ASTM D4318 [12]
Plasticity Index%	11.23	
Optimum Moisture Content *OMC* (%)	12	ASTM D698-12 [15]
Maximum Dry Density *MDD* (kN/m)	18	

2) Lightweight Expanded Clay Aggregate

LECA is a sustainable material widely used in various civil engineering applications. It is produced in rotary kilns using raw materials containing clay minerals. The raw material is processed, shaped, and then subjected to firing at temperatures from 1100 °C to 1200 °C, resulting in a significant volumetric increase due to the material's expansion properties [16]. The specific gravity test for LECA was conducted in accordance to [17], while the absorption (%) was measured according to ASTM C127-15 [18]. The dry unit weight was determined following ASTM C29/C29M-23 [19]. The physical properties of LECA are presented in Table II.

TABLE II. PHYSICAL PROPERTIES OF LECA

Properties	Results
Specific Gravity	0.6
Absorption (%)	52.1
Dry Unit Weight (kg/m^3)	408

3) Ponza or Pumice Aggregate

Naturally occurring lightweight white fine aggregate was derived from Ponza stones, which are indigenous to the northern region of Iraq. Ponza is an amorphous foam formed by volcanic eruptions. The specific gravity test for Ponza was performed in accordance with [17], while the absorption (%) was measured following ASTM C127-15 [18]. The dry unit weight was determined according to ASTM C29/C29M-23 [19]. The physical properties of Ponza are illustrated in Table III.

TABLE III. PHYSICAL PROPERTIES OF PONZA

Properties	Results
Specific Gravity	0.8
Absorption (%)	48.2
Dry Unit Weight (kg/m^3)	65.2

4) Thermostone

The Thermostone used in this study is a waste material derived from Thermostone blocks. Similarly to Ponza and LECA, the physical properties of Thermostone are portrayed in Table IV.

TABLE IV. PHYSICAL PROPERTIES OF THERMOSTONE

Properties	Results
Specific Gravity	1.12
Absorption (%)	31.4
Dry Unit Weight (kg/m^3)	133.4

B. Specimen Preparation

Three types of LWAs were utilized in the experimental program: LECA, Ponza, and Thermostone. LECA is an artificial aggregate, Ponza is a natural aggregate, and Thermostone consists of waste aggregates. To examine the effect of LWAs on soil behavior, each type was mixed with the soil in five proportions: 10%, 30%, 40%, 50%, and 60% by the dry weight of the soil. The LWAs were initially crushed using a crushing machine (powder machine) and then prepared for sieve analysis. Crushed LWAs having been passed through sieve No. 4 (4.75 mm) and retained on sieve No. 8 (2.36 mm) were selected for mixing with the soil. Figure 1 depicts the three types of LWAs.

Fig. 1. The three types of LWAs after crushing and sieving: (a) LECA, (b) Ponza, and (c) Thermostone

III. RESULTS AND DISCUSSION

A. Compaction Test

A standard Proctor Test was conducted according to ASTM D698 [15] to assess the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) for each soil type, including the incorporation of various percentages of LWAs with the soil. The compaction tests revealed that increasing the proportion of the three LWAs resulted in a decrease in soil density. This indicates that the inclusion of LWAs positively affects the total weight of the soil, which can be advantageous in scenarios where minimizing the load on foundations or other structures is critical. The MDD of natural soil was found to be 18.3 kN/m³, with an OMC of 12%. The lowest MDD was observed with a 60% addition of LWAs. Figures 2-4 demonstrate the results of the Proctor Test.

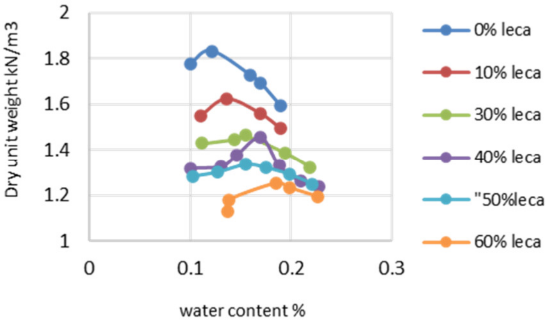

Fig. 2. LECA and soil standard Proctor Test.

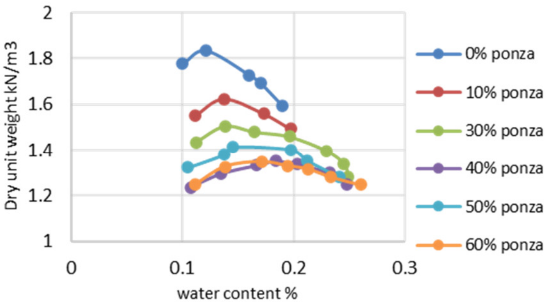

Fig. 3. Ponza and soil standard Proctor Test.

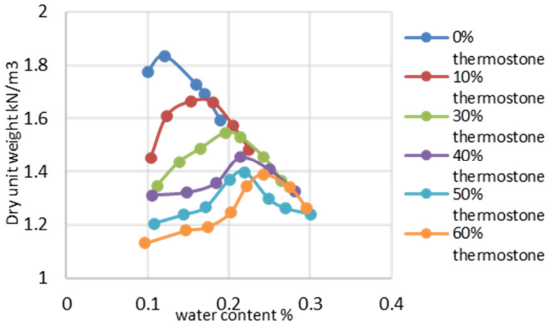

Fig. 4. Thermostone and soil Proctor Test.

The incorporation of LWAs, such as LECA Ponza, and Thermostone, into the soil leads to a reduction in the soil's total density for several reasons:

- **Intrinsic Lightness of Materials:** LWAs, like LECA, which is made of expanded clay, and materials, such as Ponza and Thermostone, are inherently lighter than natural soil particles, including sand, silt, or clay. LECA has a porous structure filled with air, making it significantly lighter. Ponza and Thermostone also have low specific gravity and porous structures, which make them lighter than the conventional soil particles. When incorporated into soil, they displace denser particles, thus reducing the bulk density.
- **Increased Porosity:** These lightweight materials often increase the soil's porosity by creating air gaps between the particles. Since air is much lighter than solid particles, this further reduces the bulk density.
- **Resistance to Compaction:** Due to their porous nature, lightweight materials tend to resist compaction. They absorb pressure without substantial collapse, meaning the soil mixture retains a lower density even under compression.

B. Consolidation Test

The consolidation test was conducted in accordance with ASTM D2435 [20]. The samples were prepared using the MDD and OMC derived from the compaction test for each soil type, along with treated soil incorporating lightweight materials at five different percentages, namely10%, 30%, 40%, 50%, and 60%. The results are presented in Figures 5-7.

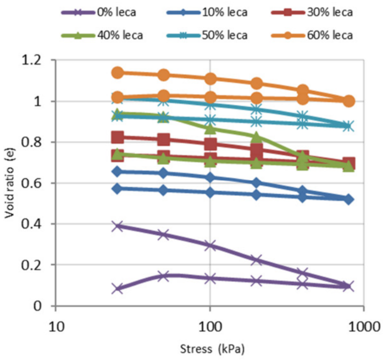

Fig. 5. Relationship between void ratio and applied stress for soil mixed with varying percentages of LECA.

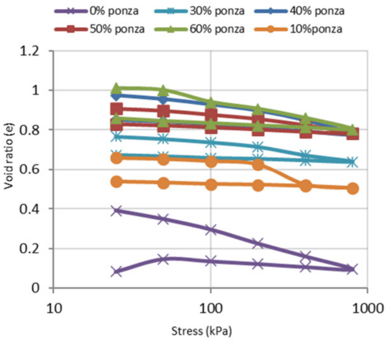

Fig. 6. Relationship between void ratio and applied stress for soil mixed with varying percentages of Ponza.

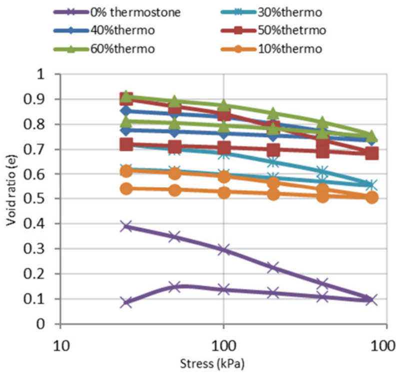

Fig. 7. Relationship between void ratio and applied stress for soil mixed with varying percentages of Thermostone.

Incorporating lightweight materials, such as LECA, Ponza, and Thermostone, into soil enhances the void ratio, especially at elevated proportions of these substances. LECA has the most pronounced impact, sustaining a superior void ratio under escalating loads in comparison to Ponza and Thermostone. These materials mitigate soil compaction under load, rendering them advantageous for applications where preserving a lighter and less dense soil structure is essential. In untreated soil, the void ratio decreased rapidly with an increasing load. At 25 kPa, the void ratio was 0.39, and at 800 kPa, it was reduced to 0.096. However, when soil was mixed with LECA, the void ratio remained elevated at every load compared to the natural soil. For example, with 60% LECA, the void ratio at 25 kPa was 1.14, compared to the 0.39 in the untreated soil. The decrease in void ratio was less pronounced with the LECA mixture, as the load increased. A similar pattern was observed for Ponza and Thermostone. At 25 kPa, the void ratios for soil mixed with 60% Ponza and 60% Thermostone were 1.01 and 0.91, respectively.

C. Unconfined Compressive Strength

The examination was conducted in accordance with ASTM D2166-6 [21]. The specimens were prepared based on the OMC and MDD determined by a compaction test. The samples were then placed in a mold with a cell diameter of 40 mm and a height of 8.5 mm. After their removal from the mold, the specimens were positioned in the testing apparatus. Sixteen samples were tested, including natural soil and different proportions of LECA, Ponza, and Thermostone. The compressive strength of the soil, both without any additives and with all the LWAs added, is presented in Table V and the results are depicted in Figures 8-11.

TABLE V. RESULTS OF THE UCS

Percent	LECA		Ponza		Thermostone	
	Stress (kPa)	q_u (kPa)	Stress (kPa)	q_u (kPa)	Stress (kPa)	q_u (kPa)
0%	306.67	153.34	306.67	153.34	306.67	153.34
10%	596.14	298.07	555.98	277.99	394.19	197.09
30%	498.04	249.02	486.64	243.32	308.84	154.42
40%	373.85	186.92	320.94	160.47	238.06	119.03
50%	316.18	158.09	221.06	110.53	159.67	79.83
60%	245.89	122.94	168.66	84.33	144.60	72.30

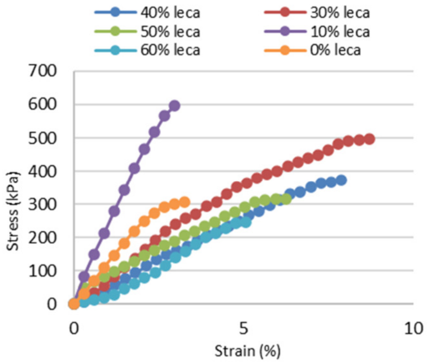

Fig. 8. Stress-strain behavior of soil with varying percentages of LECA.

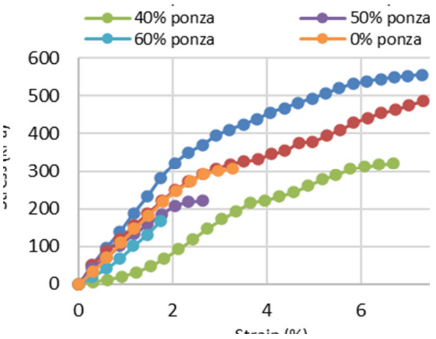

Fig. 9. Stress-strain behavior of soil with varying percentages of Ponza.

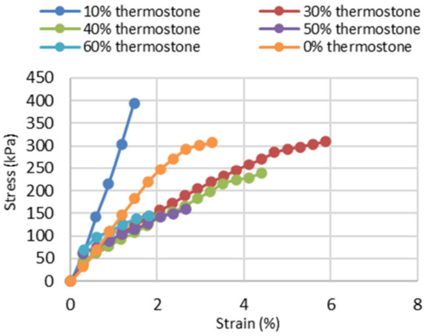

Fig. 10. Stress-strain behavior of soil with varying percentages of Thermostone.

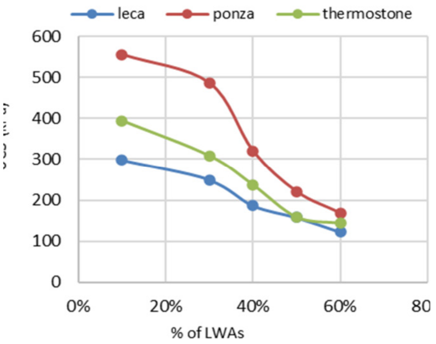

Fig. 11. Varation of UCS with different percentages of LWA additives.

The highest compressive strength was observed with a 10% addition of LWAs for all types, with the UCS of the soil-LWA mixtures reaching 596.14 kPa for LECA, 555.98 kPa for Ponza, and 394.19 kPa for Thermostone.

LECA, Ponza, and Thermostone are lightweight materials characterized by porous structures and lower density compared to natural soil. When incorporated in small quantities, these materials initially enhance soil strength due to their ability to fill the voids in the soil matrix without disrupting its structural integrity. However, as the percentage of LWAs increases, the overall density of the soil-additive mixture decreases, resulting in reduced compressive strength. At lower concentrations (10%-30%), the additives effectively occupy gaps in the soil matrix, enhancing the load-bearing capacity without compromising cohesion. In contrast, at higher concentrations (40%-60%), the porous nature of the LWAs introduces additional voids into the soil structure, weakening the integrity. Furthermore, the increase in lightweight particles reduces the inherent cohesive characteristics of the soil. Cohesion, especially in fine-grained soils, is crucial for maintaining strength. The incorporation of larger, porous particles diminishes the cohesive bonds between the soil particles, leading to a decline in compressive strength at higher additive levels.

D. Direct Shear Test

Direct shear tests were conducted to evaluate the strength characteristics of the LWAs. The test utilized a square box measuring 6 × 6 × 3.23 cm, performed in accordance with ASTM D3080 [22]. Specimens were prepared according to the OMC and MDD obtained from the compaction test. These specimens were then compacted within the direct shear cell. The results of the tests are portrayed in Table VI and Figures 12, 13.

The results demonstrate the variation in both cohesion (*c*) and internal friction angle (*phi*) with different percentages of LWAs. Cohesion (*c*) constantly diminished as the LWA% escalated, indicating that the material becomes less cohesive and more susceptible to sliding or separation under shear stresses. The internal friction angle (*phi*) rose with the addition of LWAs, signifying enhancements in shear strength in resisting sliding, particularly at elevated percentages of LWAs. LECA exhibited greater cohesion at lower percentages, and the internal friction increased with higher percentages. Ponza demonstrated a more pronounced increase in the internal friction angle alongside a decrease in cohesion relative to LECA. Thermostone displayed the lowest cohesion and a moderate internal friction angle, indicating it possesses the least shear strength among the three materials.

TABLE VI. DIRECT SHEAR TEST REUSLTS

Percent	LECA		Ponza		Thermostone	
	c (kPa)	Ø (degree)	*c* (kPa)	Ø (degree)	*c* (kPa)	Ø (degree)
0%	182	15.42	182	15.42	182	15.42
10%	234.59	18.72	258.05	16.33	204.2	19.4
30%	197.26	22.39	221.42	19.63	158	22
40%	161	23.73	171.9	23.15	126.71	25.81
50%	101.47	27.20	105.28	29.10	89.35	31.82
60%	80.81	29.31	71.55	34.40	63.21	33.1

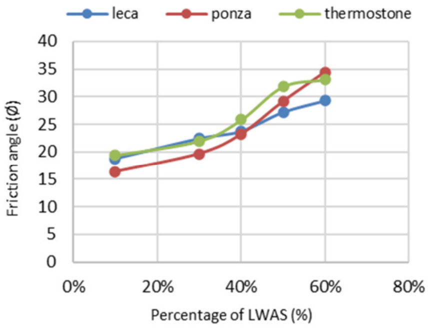

Fig. 12. Variation of friction angle with different percentages of LWA additives.

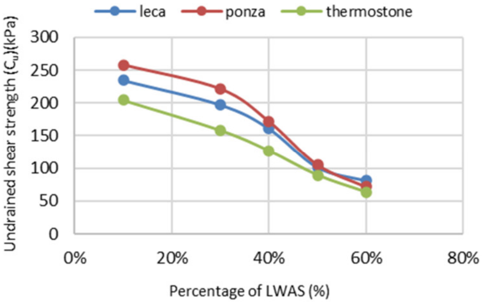

Fig. 13. Variation of undrained shear strength (Cu) with different percentages of LWA additives.

E. Triaxial Test

Standard triaxial tests were conducted on cylindrical specimens measuring 35 mm in diameter and 70 mm in height. Seven specimens were tested, including natural soil and mixtures containing 40% and 50% of LECA, Ponza, and Thermostone. The specimens were prepared at MDD and OPC. The tests were performed under three confining pressures of 100 kPa, 200 kPa, and 300 kPa, following the ASTM D2850-23 guidelines [23]. The results of the triaxial tests are presented in Table VII and Figures 14–20.

TABLE I. RESULTS OF TRIAXIAL TESTS

Percentage	LECA		Ponza		Thermostone	
	c (kPa)	Ø (degree)	*c* (kPa)	Ø (degree)	*c* (kPa)	Ø (degree)
0% (Natural soil)	150	17.362	150	17.362	150	17.362
40%	154	23.85	168.64	22.71	120.37	27.7
50%	107.5	26.10	100.38	29.11	85.22	32.93

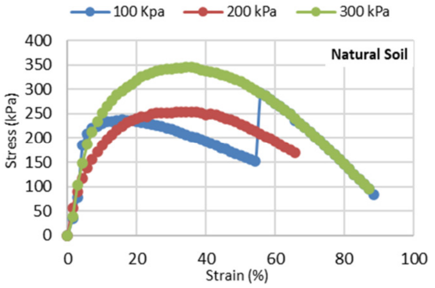

Fig. 14. Stress-strain relationship of natural soil.

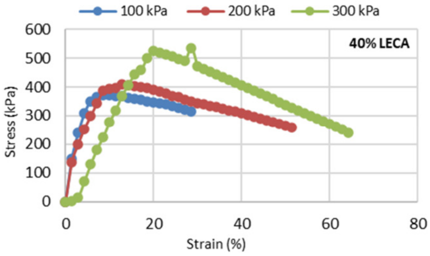

Fig. 15. Stress-strain relationship of 40% LECA.

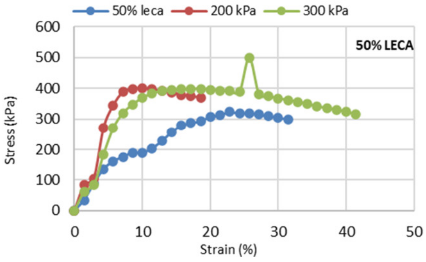

Fig. 16. Stress-strain relationship of 50% LECA.

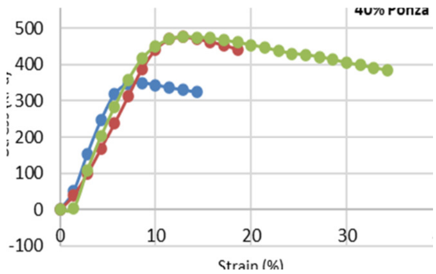

Fig. 17. Stress-strain relationship of 40% Ponza.

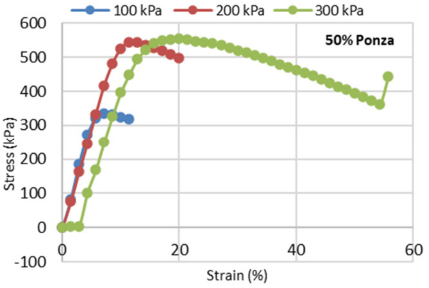

Fig. 18. Stress-strain relationship of 50% Ponza.

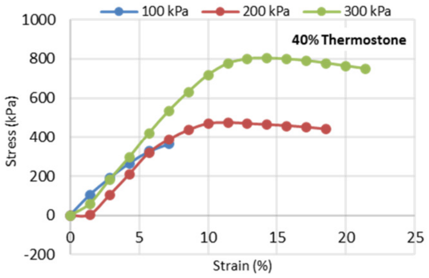

Fig. 19. Stress-strain relationship of 40% Thermostone.

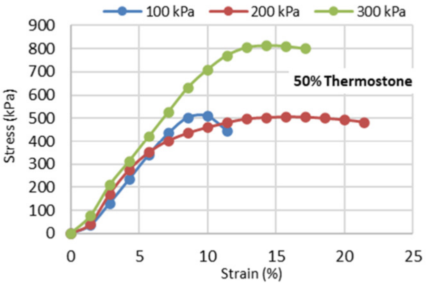

Fig. 20. Stress-strain relationship of 50% Thermostone.

The incorporation of LWAs, namely LECA, Ponza, and Thermostone, significantly impacts the shear strength of native soil by enhancing the friction angle (ϕ) while reducing cohesion (c) at higher percentages. Native soil has modest cohesion (150 kPa) and a low friction angle (17.362°), but the addition of LWAs markedly increases the friction angle (ϕ), with Thermostone at 50% achieving the highest value (32.935°), signifying a superior shear strength. LECA and Ponza improve both parameters at 40%, with Ponza showing the highest cohesion (168.64 kPa). At 50%, all LWAs display reduced cohesion due to their porous nature but achieve significant friction angle gains, critical for the shear resistance. Thermostone at 50% demonstrates the best friction angle improvement, making it particularly advantageous for slope stability applications, where enhanced shear strength is paramount.

Figure 21 illustrates the relationship between cohesion and the percentage of LWAs additives, while Figure 22 depicts the relationship between the friction angle and the percentage of LWAs additives.

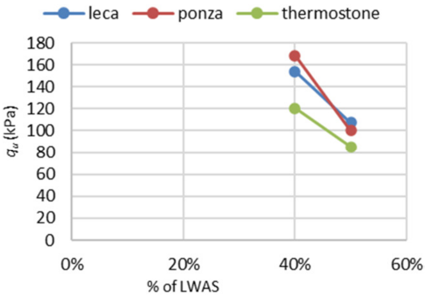

Fig. 21. Undrained shear strength (q_u) variation with different % of LWAs.

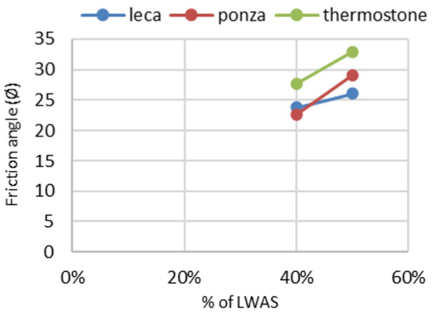

Fig. 22. Friction angle (Ø) variation with different % of LWAs.

The observed behavior can be attributed to the interplay between the soil matrix and the physical properties of lightweight additives, LECA, Ponza, and Thermostone. At a 40% concentration, the additives optimize the particle interlock and bonding, leading to an enhancement in both the cohesion and friction angle, thereby improving the soil's shear strength. However, at a 50% concentration, the excessive presence of additives disrupts the soil matrix, creating additional voids and reducing the cohesive forces among the particles. The increase in friction angle (ϕ) can be credited to the granular and rough texture of the additives, which promotes the interparticle friction. This granular interaction elevates the soil's shear resistance, particularly under higher additive concentrations. However, the reduced cohesion (c) with a 50% addition is a direct consequence of the porous structure and lower density of these materials, which compromise the integrity of the soil matrix. The augmentation of additives, like LECA, Ponza, and Thermostone, indeed enhances the shear strength primarily through an increased friction. Still, a 40% concentration emerges as the optimal balance, offering significant improvements in strength without overly compromising cohesion. At a 50% concentration, although the friction angle remains high, the diminished cohesion may limit the overall soil performance, especially in applications requiring cohesive strength.

IV. CONCLUSION

This study investigated the influence of three Lightweight Aggregates (LWAs) - Lightweight Expanded Clay Aggregate (LECA), Ponza, and Thermostone- on the geotechnical properties of clayey soils. Each material demonstrated unique advantages in soil stabilization, summarized as follows:

- **Density Reduction:** LECA exhibited the highest void ratio, increasing porosity and making it suitable for lightweight structures while maintaining reduced soil mass.
- **Void Ratio:** LECA also resulted in the highest void ratio among the three materials, enhancing porosity and making it ideal for reducing soil weight while maintaining a lighter structure.
- **Friction Angle (ϕ):** Thermostone provided the highest friction angle at a 50% concentration, highlighting its suitability for applications prioritizing shear resistance, such as slope stability and embankments.
- **Cohesion (c):** Ponza achieved the highest cohesion at a 40% concentration, offering an optimal balance between the cohesive strength and frictional resistance. However, Thermostone exhibited lower cohesion relative to the other materials.
- **Compressive Strength:** Maximum compressive strength was observed with a 10% additive concentration for all materials, with LECA achieving the highest values. Beyond 10%, the compressive strength diminished due to the porous nature of the LWAs disrupting the soil matrix.
- **Optimal Proportions for Applications:** At lower concentrations (10–30%), all LWAs enhanced the soil strength and stability by filling voids without compromising the structural integrity. At higher concentrations (40–60%), the increased void formation reduced the cohesion and compressive strength, necessitating a careful proportioning for practical use.
- **Overall Performance:** LECA demonstrated the best overall performance for reducing the soil density and increasing the void ratio, making it ideal for lightweight and load-reducing applications. Thermostone excelled in enhancing the friction angle, which is critical for slope stability applications. Ponza provided a balanced improvement in cohesion and shear strength, making it suitable for scenarios requiring a moderate strength enhancement.

REFERENCES

[1] A. Pedarla, S. Chittoori, A. J. Puppala, L. R. Hoyos, and S. Saride, "Influence of Lime Dosage on Stabilization Effectiveness of Montmorillonite Dominant Clays," pp. 767–776, Apr. 2012, https://doi.org/10.1061/41095(365)75.

[2] I. D. A. Zukri, "Bearing Capacity of Footing on Soft Clay Strengthened by Lightweight Expanded Clay Aggregate Raft," *CONSTRUCTION*, vol. 3, no. 1, pp. 6–14, Apr. 2023, https://doi.org/10.15282/construction.v3i1.8915.

[3] S. H. Fadhil, M. S. Al-Soud, and R. M. Kudadad, "Enhancing the Strength of Clay-Sand Mixture by Discrete Waste Plastic Strips," *Journal of Applied Science and Engineering*, vol. 24, no. 3, pp. 381–391, 2021, https://doi.org/10.6180/jase.202106_24(3).0013.

[4] R. de Gennaro, P. Cappelletti, G. Cerri, M. de'Gennaro, M. Dondi, and A. Langella, "Neapolitan Yellow Tuff as raw material for lightweight aggregates in lightweight structural concrete production," *Applied Clay Science*, vol. 28, no. 1, pp. 309–319, Jan. 2005, https://doi.org/10.1016/j.clay.2004.01.014.

[5] J. Alduaij, K. Alshaleh, M. Naseer Haque, and K. Ellaithy, "Lightweight concrete in hot coastal areas," *Cement and Concrete Composites*, vol. 21, no. 5, pp. 453–458, Dec. 1999, https://doi.org/10.1016/S0958-9465(99)00035-9.

[6] A. Mladenovič, J. S. Šuput, V. Ducman, and A. S. Škapin, "Alkali–silica reactivity of some frequently used lightweight aggregates," *Cement and Concrete Research*, vol. 34, no. 10, pp. 1809–1816, Oct. 2004, https://doi.org/10.1016/j.cemconres.2004.01.017.

[7] A. M. Neville, *Properties of concrete*, 5th.ed. London, United Kindom: Pearson, 1995.

[8] R. A. Fattah, B. S. Al-Shathr, and S. K. Abed, "Some properties of thermal insulating cement mortar using Ponza aggregate," *Open Engineering*, vol. 13, no. 1, Jan. 2023, https://doi.org/10.1515/eng-2022-0478.

[9] A. H. Shaalan and A. Z. Hamoodi, "Mechanical Properties of Structural Lightweight Aggregate Concrete Using Light Expanded Clay (LECA) with Steel Fiber," *International Journal of Mechanical Engineering*, vol. 7, no. 2, pp. 3713–3724, Feb. 2022.

[10] S. M. Selman and Z. K. Abbas, "The Use of Lightweight Aggregate in Concrete: A Review," *Journal of Engineering*, vol. 28, no. 11, pp. 1–13, Nov. 2022, https://doi.org/10.31026/j.eng.2022.11.01.

[11] A. Marradi, U. Pinori, and G. Betti, "The Use of Lightweight Materials in Road Embankment Construction," *Procedia - Social and Behavioral Sciences*, vol. 53, pp. 1000–1009, Oct. 2012, https://doi.org/10.1016/j.sbspro.2012.09.949.

[12] *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*, ASTM D4318-17e1, Apr. 2018.

[13] *Standard Test Methods for Specific Gravity of Soil Solids by the Water Displacement Method*, ASTM D854-23, Nov. 2023.

[14] *Method of test for soils for civil engineering purposes – Classification tests and determination of geotechnical properties,* BS 1377-2:2022, Mar. 2022.

[15] *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort*, ASTM D698-12, Jul. 2021.

[16] A. H. Abdullah and S. D. Mohammed, "The Fire Effect on the Performance of Reinforced Concrete Beams with Partial Replacement of Coarse Aggregates by Expanded Clay Aggregates," *Engineering, Technology & Applied Science Research*, vol. 13, no. 6, pp. 12220–12225, Dec. 2023, https://doi.org/10.48084/etasr.6412.

[17] Estefan G., Sommer R., and Ryan J., *Methods of Soil, Plant, and Water Analysis: A manual for the West Asia and North Africa region,* 3rd ed. Beirut, Lebanon: International Center for Agricultural Researchin the Dry Areas (ICARDA), 2013.

[18] *Standard Specification for Lightweight Aggregates for Insulating Concrete*, ASTM C332-17, Jul. 2023.

[19] *Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate,* ASTM C29/C29M-23, Oct. 2023.

[20] *Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading,* ASTM D2435/D2435M-11, Apr. 2020.

[21] *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil,* ASTM D2166-06, Dec. 2010.

[22] *Standard Test Methods for Direct Shear Test of Soils Under Consolidated Drained Conditions*, ASTM D3080-04, 2012.

[23] *Standard Test Method for Unconsolidates-Undrained Triaxial Compression Test on Cohesive Soils*, ASTM D2850-23, 2024.