Carbon Sequestration Potential of Iron Slag in Unsaturated Conditions to Stabilize Soft Clays

Ammavajjala Sesha Sai Raghuram*,1, and Anasua GuhaRay[1]

[1]*Department of Civil Engineering, Birla Institute of Technology and Science (BITS) Pilani Hyderabad Campus, Hyderabad, Telangana, India*

**email:* raghuram.ammavajjala@hyderabad.bits-pilani.ac.in

Abstract: The research aims to evaluate the effects of the addition of iron slag on the soil water characteristic curve (SWCC) fitting parameters, carbon sequestration potential, and Unconfined Compressive Strength (UCS) of stabilized soft clays. Laboratory experiments were conducted by mixing varying proportions of iron slag with soft clay. Results indicated that the incorporation of iron slag into soft clay yields notable improvements in the UCS values. Additionally, carbonation experiments were conducted in a fabricated carbonation chamber to estimate the carbon sequestration capacities of soft clay stabilized with iron slag in unsaturated conditions. The outcomes revealed that the carbon sequestration capacity of the stabilized soil increased with an increase in the iron slag content. Moreover, filter paper tests were conducted to estimate the SWCC fitting parameters on carbonated and uncarbonated samples. Furthermore, the study explored the SWCC changes within the stabilized soil due to the interaction between the iron slag particles and the clay matrix. The results indicated that the water retention capacity increased significantly after the carbonation of the treated soft clays. Overall, this research highlights the potential of iron slag as an effective and sustainable stabilizing agent for soft clays in unsaturated conditions.

Introduction

Soft clays are characterized by their low strength, high compressibility, and poor bearing capacity due to which they pose significant challenges in geotechnical applications. Stabilization of these soils is often essential to improve their mechanical properties and ensure the stability and durability of structures built on them [1]. Conventional soil stabilization techniques typically involve the use of cement and lime; however, these materials are associated with high energy consumption and carbon emissions, prompting the need for sustainable alternatives [2]. Industrial by-products such as iron slag have garnered attention as potential soil stabilizers due to their abundance, cost-effectiveness, and pozzolanic properties.

On the other hand, the concept of carbon sequestration in stabilized soils has emerged as an innovative approach to mitigate climate change [3]. By incorporating industrial by-products that promote carbonation reactions, soils can act as carbon sinks, thereby reducing atmospheric CO2 levels [4]. Carbonation reactions involving metallic oxides, such as calcium and magnesium, are highly exothermic in nature; the reactions are presented in eqs. (1) and (2):

$$CaO(s)+CO_2(g) \rightarrow CaCO_3(s) \quad (1)$$

$$MgO(s)+CO_2(g) \rightarrow MgCO_3(s) \quad (2)$$

Mineral carbonation is a process in which alkaline metal oxides react with CO_2 in a single step, either by a gas-solid (dry) or aqueous (wet) route. The gas-solid carbonation method is the most cost effective of the two process routes [1]. Additionally, most of the soils are in unsaturated state [5]. Soil water content and soil suction plays a major role in understanding the unsaturated behaviour of soil [6-8]. Hence understanding the soil water characteristic curve (SWCC) (relation between soil suction and soil water content) is essential for assessing the hydromechanical behavior of unsaturated soils. Iron slag contributes to improved suction behavior and water retention due to its finer particles and reactive components that modify the clay fabric. The pozzolanic reaction between iron slag and clay minerals leads to cementitious compounds (e.g., C-S-H, C-A-H), improving unconfined compressive strength. Simultaneously, the alkaline environment promotes carbonation, sequestering CO_2 in stable forms such as calcium and iron carbonates, thus contributing to carbon sequestration. However, the effect of incorporating iron slag on the SWCC fitting parameters, carbon sequestration potential, and unconfined compressive strength (UCS) of soft clays remains underexplored. Iron slag was selected due to its high calcium and iron content, fineness, and availability, with limited prior studies exploring its carbon sequestration potential in unsaturated conditions. Therefore, the present study evaluates the influence of soft clay stabilized with carbonated iron slag on the UCS and SWCC.

Literature

A considerable amount of research has been dedicated to exploring the carbon sequestration potential of binders in concrete, yet limited attention has been given to their application in soft clay stabilization. For instance, Ukwattage et al. [9] investigated the carbon capture capabilities of coal fly ash through accelerated carbonation. They reported that one metric ton of Hazelwood fly ash could absorb 7.66 kg of CO_2, with the absorption rate being influenced by the CO_2 pressure in the reaction vessel. Yi et al. [10,11] studied reactive magnesia (MgO) for stabilization purposes, demonstrating that carbonated MgO-treated soils could achieve strength levels comparable to portland cement-stabilized soils in a matter of hours. Dananjayan et al. [3] conducted experiments on the direct carbonation of coal fly ash using pure CO_2 gas at room temperature and pressures below 10 bars (1,000 kPa). They concluded that conventional direct carbonation methods are suitable for using coal fly ash for carbon capture.

Cai and Liu [12] examined the compaction, mechanical, and microstructural characteristics of silt stabilized with carbonated reactive MgO at varying MgO-soil ratios, finding that six hours of carbonation significantly improved the unconfined compressive strength. Fasihnikoutalab et al. [13] explored soil stabilization using olivine with advanced techniques like alkaline activation and carbonation, noting that soil strength increased by up to 60% after seven days of carbonation compared to untreated samples. Tiwari et al. [14] investigated the carbon sequestration capacity of construction and demolition waste, observing a 25% carbonation rate when CO_2 was applied at a flow rate of 1 L/min. Yu et al. [15] stabilized synthetic soils with carbonated steel slag, reporting a significant enhancement in compressive strength compared to uncarbonated samples. Liu et al. [16] tested the feasibility of the MgO mass carbonation technique for improving soft soil subgrades in field conditions, attributing the enhanced engineering properties to cementation reactions and pore-filling by hydrated carbonates. Similarly, Mohammed et al. [17] evaluated carbonated GGBS as a stabilizer for kaolin, finding that its use improved the material's strength. Recently Dejenie et al. [1] evaluated the carbon sequestration capacity of stabilized soft clays with Finnish recycled binders.

While previous studies underscore the potential of carbonated binders in enhancing the strength of soft clays, research has predominantly focused on materials like cement, lime, fly ash, GGBS, and construction and demolition waste. The reuse of industrial by-products (like iron slag) offers significant environmental, economic, and technical advantages for geotechnical applications, but investigations into their carbon sequestration capacity in unsaturated state remain scarce. This study seeks to evaluate the carbon sequestration potential of iron slag for stabilizing soft clays in unsaturated conditions. To the best of the authors' knowledge, this is the first study to address this topic comprehensively, providing novel insights into the carbonation processes of stabilized clays.

Materials and Methods

Materials

The soft clay used in this study was sourced from Kakinada (port area) in Andhra Pradesh. The basic and engineering properties of the soft clay are summarized in **Table 1**. The iron slag was obtained as an industrial by-product from Visakhapatnam steel plant in Andhra Pradesh, India. The slag used was air-cooled and ground to pass through a 425 μm sieve. The chemical composition analyzed using X-Ray Fluorescence (XRF) spectroscopy are presented in **Table 2**. **Table 2** confirms the presence of cementitious compounds such as calcium oxides and magnesium oxides.

Sample Preparation

In all experiments, the soft clay and iron slag were compacted to achieve a target density of 15 kN/m^3 with a natural water content of 15%. The soft clay was blended with the binder at room temperature and compacted to the same specified density. Each test consisted of 12 specimens: three subjected to carbonation, three serving as reference samples, three used for filter paper tests without carbonation, and three used for filter paper tests after carbonation. The test specimens measured 38 mm in diameter and 76 mm in height, with compaction carried out in five layers. The weight of stabilized clay required for each layer was calculated based on the volume of the specimen to achieve the desired unit weight of 15 kN/m^3, and the corresponding moisture content was determined. Iron slag was incorporated into the soft clay at binder contents of 5%, 10%, and 15% by weight-to-volume ratio.

Table 1. Basic and engineering properties of soft clay.

Property	Soft clay
Liquid limit, w_l (%)	79
Plastic limit, w_p (%)	39.4
Plasticity Index, PI (%)	39.6
Sand (%)	6
Silt (%)	28
Clay (%)	67
Specific gravity, *G*	2.61
Optimum moisture content, OMC (%)	21.4
Maximum dry density, MDD (kN/m^3)	14.77
USCS classification	CH
Unconfined compressive strength, UCS (kPa)	38

Table 2. Major chemical constituents of iron slag based on XRF results.

Chemical composition	Value in (%)
Fe_2O_3	31.7
SiO_2	25.1
CaO	23.3
Al_2O_3	7.0
MgO	6.8
MnO	4.0
Misc.	2.1

Experimental Procedures

Each carbonation specimen was carefully extruded and placed in a triaxial chamber for carbonation. In contrast, the reference specimens were stored in a designated storage area. To prevent moisture loss, all reference samples were sealed in plastic bags during storage.

Unconfined Compressive Strength (UCS) Tests

Unconfined compressive strength (UCS) tests were conducted on both carbonated and reference specimens to evaluate the impact of CO_2 sequestration on the strength of the stabilized soft clay. UCS tests were carried out after 7 days of curing for both carbonated and uncarbonated samples. The compressive strength values reported in the present study represent the average of three parallel specimens for each condition.

Carbonation Experiments

The samples were stored in a CO_2-rich laboratory atmosphere to facilitate carbonation. CO_2 sequestration of the stabilized soft clay was conducted in a triaxial chamber, following the procedure outlined by Yi et al. [10,11]. Based on the results from trial tests, the samples remained in the triaxial chamber for 4 hours to achieve complete carbonation of the soil specimens. The carbon sequestration capacity was quantified by measuring the weight gain and analyzing the formation of carbonates using thermogravimetric analysis (TGA).

SWCC Determination

Filter paper tests suggested by Han and Vanapalli [18] and Raghuram et al. [19] were performed to estimate the SWCC fitting parameters for both carbonated and uncarbonated samples. The results were fitted using the Fredlund and Xing [20] SWCC model.

Results and Discussions

Carbon Sequestration Potential

The carbonation experiments revealed that the carbon sequestration capacity increased with higher iron slag content, with maximum sequestration observed at 15% slag. The weight gain and TGA results confirmed the formation of calcium carbonates, indicating effective CO_2 capture. Figs. 1(a) and 1(b) illustrate the DTG and TG curves, respectively, for carbonation conducted on soft clay stabilized with iron slag at three different percentages. Fig. 1(a) shows three distinct endothermic peaks occurring at 150–200 °C, 500–550 °C, and 700–750 °C. The third peak, at 750 ± 20 °C, represents the decarbonization of newly formed calcium carbonates to calcium oxide. These findings align with previous research observations [24]. Figure 1(b) highlights weight loss between 150 °C and 750 °C, corresponding to the endothermic peaks in Figure 1(a).

The decomposition extent can be quantified by analyzing the weight loss in the TG plot, particularly within the carbonate decomposition range of 475 °C to 800 °C. A significant observation from Figures 1(a) and 1(b) is the higher weight loss in soft clay stabilized with 15% iron slag compared to 5%. This increase can be attributed to the higher binder content, which elevates calcium and magnesium levels in the soft clay, leading to greater CO_2 sequestration. Consequently, soft clay stabilized with a higher iron slag content captures more CO_2. For instance, the carbon sequestration potential was found to be 9.4 kg, 10 kg, and 11 kg of CO_2 per metric ton of stabilized mix for 5%, 10%, and 15% iron slag contents, respectively, after 7 days of curing.

SWCC Fitting Parameters

Figure 2 shows the influence of carbonation and binder content on the SWCC's of treated soft clay. The SWCC results showed that the air-entry value increased with increasing slag content, indicating improved water retention characteristics. This improvement can be attributed to the development of a finer pore structure in the soil matrix, facilitated by the partial filling of larger pores and the formation of additional cementitious gels (e.g., C–S–H, C–A–S–H phases) due to slag hydration. The refinement of pore size distribution shifts the SWCC curve, allowing the soil to retain water at higher matric suctions. As a result, water is held more tightly within the soil, improving its retention characteristics across a broader suction range. Moreover, carbonated samples displayed higher residual water content compared to uncarbonated ones, reflecting the effects of densification and reduced pore sizes resulting from carbonation-induced reactions. These findings underscore the positive influence of slag and carbonation on the hydromechanical behavior of stabilized soils.

Strength Improvements

The UCS results indicated a significant increase in strength with the addition of iron slag, with the maximum improvement observed at 15% slag content. The enhanced strength is attributed to the pozzolanic reactions and the formation of cementitious compounds like calcium carbonates and magnesium carbonates. Figure 3 presents the influence of binder content on the UCS values of the carbonated and uncarbonated soft clays treated with iron slag. The data provided in figure 3 revealed that carbonated samples exhibited higher UCS values than their uncarbonated specimens across all binder contents. For instance, at 5%, 10%, and 15% binder content, the UCS values for carbonated samples were 51.3 kPa, 66.12 kPa, and 75.24 kPa, respectively, compared to 44.84 kPa, 53.2 kPa, and 60.04 kPa for uncarbonated samples. This trend highlights the significant role of carbonation in enhancing the strength of stabilized soft clay.

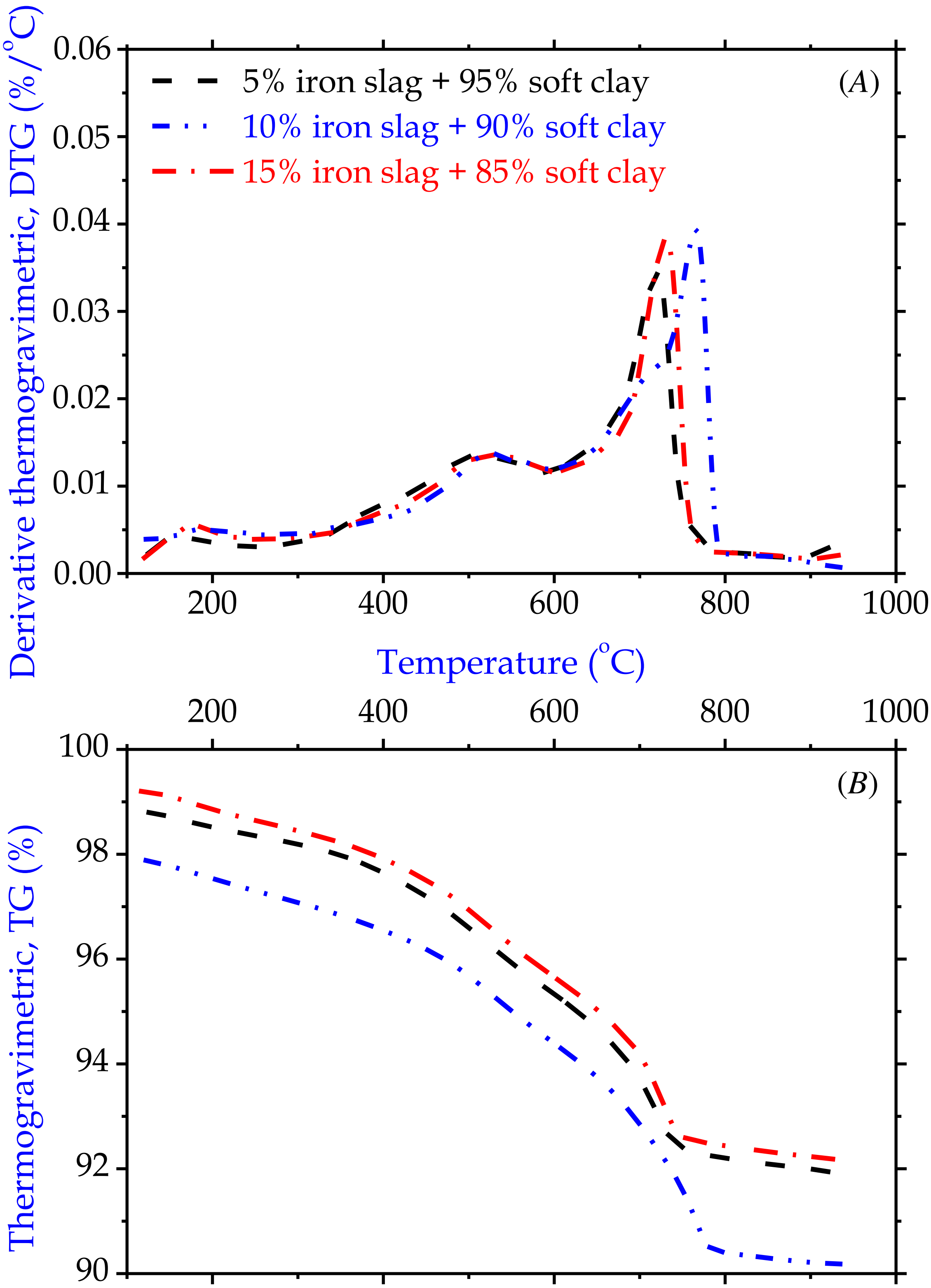

Figure 1: Carbonated soft clay stabilized with various percentages of iron slag: (A) DTG curves and (B) TG curves.

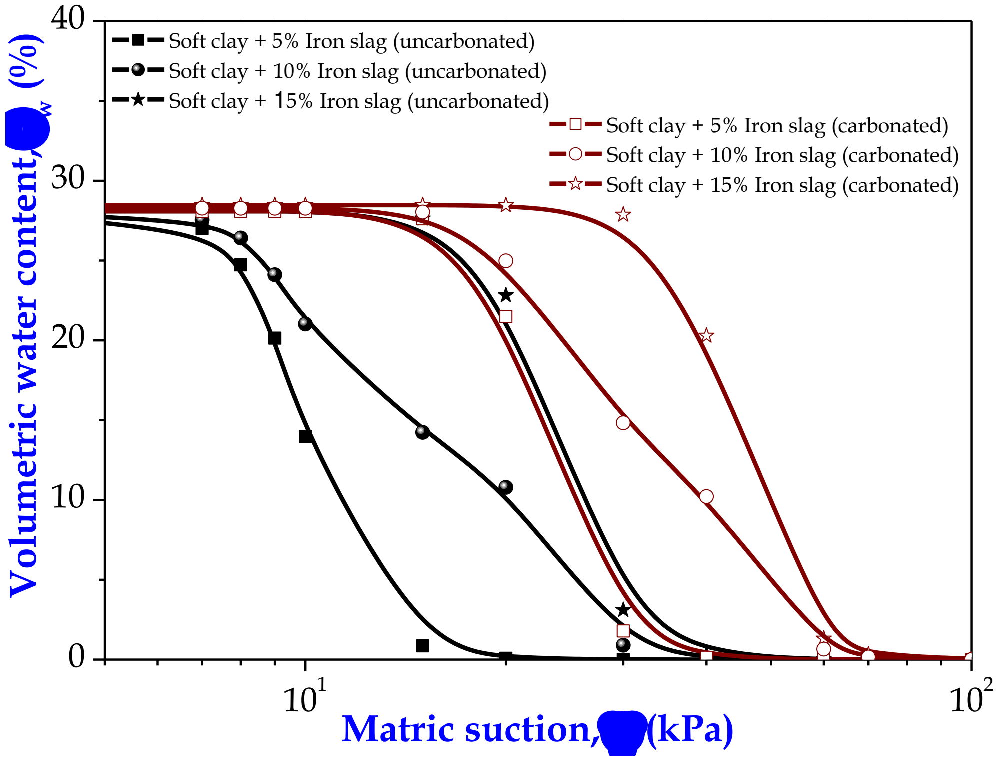

Figure 2: Effect of carbonation and binder content on the SWCC.

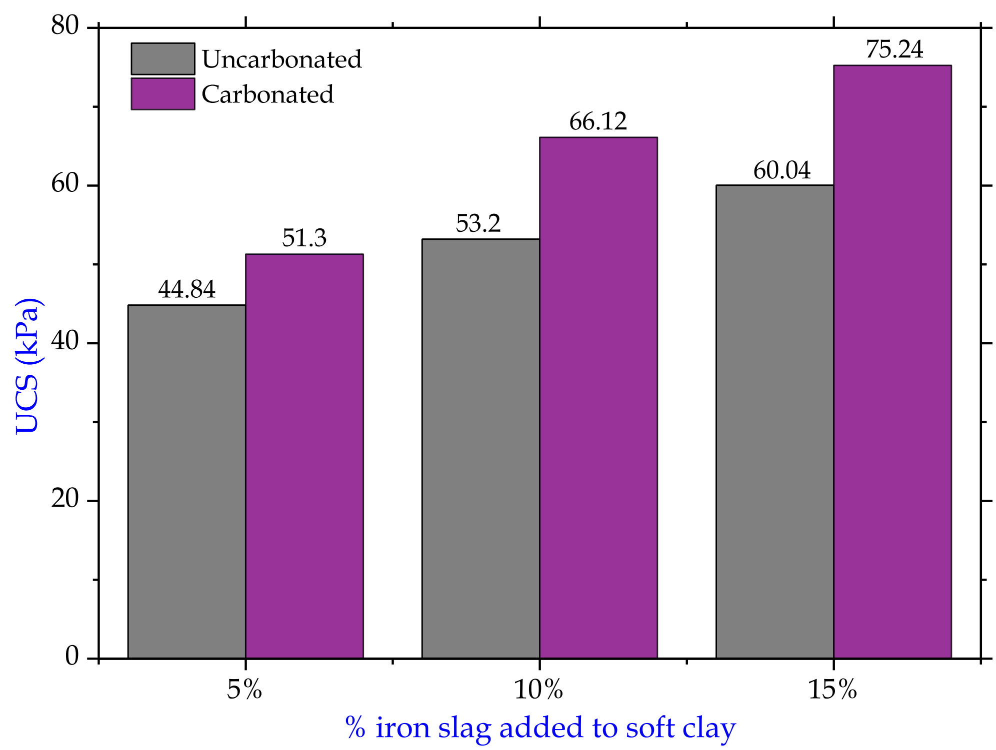

Figure 3. Effect of binder content on UCS values of carbonated and uncarbonated stabilized soft clay.

Conclusions

The following are the key findings from the present study:

- The addition of iron slag significantly increased the unconfined compressive strength (UCS) of stabilized soft clays. The maximum UCS improvement was observed at 15% slag content.
- Carbonated samples consistently exhibited higher UCS values than uncarbonated samples, highlighting the role of carbonation in forming cementitious compounds like calcium and magnesium carbonates.
- The carbon sequestration capacity of stabilized soft clay increased with higher iron slag content, with the maximum observed at 15%.
- Thermogravimetric Analysis (TGA) and Differential Thermogravimetric (DTG) results confirmed the formation of calcium carbonates, demonstrating effective CO_2 capture.
- Higher binder content enhanced CO_2 sequestration, with 15% slag sequestering 11 kg of CO_2 per metric ton of stabilized mix after seven days.
- The Soil-Water Characteristic Curve (SWCC) results showed an increase in air-entry value with higher slag content, indicating improved water retention capacity.
- Carbonated samples displayed higher residual water content due to densification and reduced pore sizes from carbonation reactions.

Overall, this study highlights iron slag as an effective stabilizing agent for soft clays, improving strength, water retention, and carbon sequestration capacities. These findings underline the potential of iron slag for sustainable geotechnical applications, particularly in unsaturated soil conditions.

References

[1] BB Dejenie, ASS Raghuram, L Korkiala-Tanttu, J Forsman, H Gustavsson. Carbon Sequestration Capacity of Stabilized Soft Clays with Recycled Binders. *Geotechnical Testing Journal*, 47(1): 5-21, 2024.

[2] BC McLellan, RP Williams, J Lay, A van Riessen, and GD Corder. Costs and carbon emissions for geopolymer pastes in comparison to ordinary Portland cement. *Journal of Cleaner Production*, 19(9-10): 1080–1090, 2011.

[3] RRT Dananjayan, P Kandasamy, and R Andimuthu. Direct mineral carbonation of coal fly ash for CO_2 sequestration. *Journal of cleaner production*, 112(5): 4173-4182, 2016.

[4] P Lahtinen, H Jyrävä, and K Kuusipuro. Development of Binders for Organic Soils. In Dry Mix Methods for Deep Soil Stabilization, 1st ed., edited by H. Bredenberg, G. Holm, and B. B. Broms, 109–114. Rotterdam, the Netherlands: A. A. Balkema, 1999.

[5] DG Fredlund, and H Rahardjo. *Soil mechanics for unsaturated soils*, John Wiley & Sons, 1993.

[6] SK Vanapalli, DG Fredlund, and DE Pufahl. The influence of soil structure and stress history on the soil-water characteristics of a compacted till. *Geotechnique*, 49(2): 143–159, 1999.

[7] ASS Raghuram, PS Negi, BM Basha, and AAB Moghal. Effect of Sample Size, Dry Unit Weight, and Hysteresis of Expansive Soil on SWCC and Finite Slope Stability. *International Journal*

of Geosynthetics and Ground Engineering, 10(2): 18, 2024.

[8] ASS Raghuram, N Mounika, BM Basha, and AAB Moghal. Soil water characteristic curves of soils exhibiting different plasticity. *International Journal of Geosynthetics and Ground Engineering*, 9(3): 25, 2023.

[9] NL Ukwattage, PG Ranjith, and SH Wang. Investigation of the potential of coal combustion fly ash for mineral sequestration of CO_2 by accelerated carbonation. *Energy*, 52(1): 230-236, 2013.

[10] Y Yi, M Liska, A Akinyugha, C Unluer, and A Al-Tabbaa. Preliminary Laboratory-Scale Model Auger Installation and Testing of Carbonated Soil-MgO Columns. *Geotechnical Testing Journal*, 36(3): 1–10, 2013.

[11] Y Yi, M Liska, C Unluer, and A Al-Tabbaa. Carbonating magnesia for soil stabilization. *Canadian Geotechnical Journal*, 50(8): 899-905, 2013.

[12] G Cai, and S Liu. Compaction and mechanical characteristics and stabilization mechanism of carbonated reactive MgO-stabilized silt. *KSCE Journal of Civil Engineering*, 21(7): 2641-2654, 2017.

[13] MH Fasihnikoutalab, A Asadi, C Unluer, BK Huat, RJ Ball, and S Pourakbar. Utilization of alkali-activated olivine in soil stabilization and the effect of carbonation on unconfined compressive strength and microstructure. *Journal of Materials in Civil Engineering*, 29(6): 06017002, 2017.

[14] SK Tiwari, BS Giri, V Thivaharan, AK Srivastava, S Kumar, RP Singh, R Kumar, and RS Singh. Sequestration of simulated carbon dioxide (CO_2) using churning cementations waste and fly-ash in a thermo-stable batch reactor (TSBR). *Environmental Science and Pollution Research*, 27(22): 27470-27479, 2020.

[15] C Yu, C Cui, Y Wang, J Zhao, and Y Wu. Strength performance and microstructural evolution of carbonated steel slag stabilized soils in the laboratory scale. *Engineering Geology*, 295: 106410, 2021.

[16] SY Liu, GH Cai, GY Du, L Wang, JS Li, and XC Qian. Field investigation of shallow soft-soil highway subgrade treated by mass carbonation technology. *Canadian Geotechnical Journal*, 58(1): 97-113, 2021.

[17] AMA Mohammed, NZ Mohd Yunus, MA Hezmi, ASA Rashid, and S Horpibulsuk. Carbonated Ground Granulated Blast Furnace Slag Stabilising Brown Kaolin. *Environmental Science and Pollution Research*, 28 (40): 57308–57320, 2021.

[18] Z Han, and SK Vanapalli. Relationship between resilient modulus and suction for compacted subgrade soils. *Engineering Geology*, 211: 85–97, 2016.

[19] ASS Raghuram, BM Basha and AAB Moghal Effect of fines content on the hysteretic behavior of water-retention characteristic curves of reconstituted soils. *Journal of materials in civil engineering*, *32*(4): 04020057, 2020.

[20] DG Fredlund, and A Xing. Equations for the soil-water characteristic curve. *Canadian Geotechnical Journal*, 31(4): 521–532, 1994.