

Investigating the engineering behavior of marl soils under the influence of thermal regimes and different pHs from a microstructural perspective

M. Amiri^{a*}, M. Dehghani^b, O. Jafari

^a Associate Professor, Faculty of civil Engineering, University of Hormozgan.

^b Assistant Professor, Faculty of civil Engineering, University of Hormozgan.

^c Master student of civil Engineering University of Hormozgan.

^{a*}Email: amirii@hormozgan.ac.ir,

Proximity of soil with pollution caused by landfills changes its pH. On the other hand, due to the heat generation potential of high-level waste, the used clay coating is exposed to different thermal regimes, which leads to changes in its physical, mechanical, and microstructural characteristics. Based on this, the aim of this article is to investigate the simultaneous effect of pH changes and thermal regimes in high-level waste disposal centers. In this study, the combined effect of pH and temperature on the behavior of marl soil was evaluated using unconfined compressive strength tests, weight loss and Atterberg limits, determination of carbonate amount by titration, X-ray diffraction (XRD) and scanning electron microscope (SEM) images. For this purpose, hydrochloric acid (HCl) and sodium hydroxide (NaOH) solutions have been used to change the pH. After the pH of the marl soil was fixed at 4, 6, 8.3, 11 and 13, the samples were dried in the oven, then exposed to the thermal levels of 25, 100, 300, 500, 700 and 900 degrees Celsius for 2 hours. One of the most important results of this research is the removal of carbonate in acidic conditions and prominent changes in the engineering characteristics of marl soil in the thermal range of 500 °C to 900 °C. Palygorskite mineral is destroyed in stable acidic and alkaline environment at 700 °C with the occurrence of dihydroxylation. On the other hand, the removal of carbonate in an acidic environment has led to an increase in plasticity properties and a change in the classification of marl soil. As the pH decreases and the temperature increases, the compressive strength increases.

KEY WORDS:

Marl soil, pH, Thermal stabilization, unconfined compressive strength, SEM & XRD microstructural studies.

* Corresponding Author: Email: amirii@hormozgan.ac.ir

1. Introduction

Marls, sedimentary deposits characterized by their composition of 35 to 65% clay and calcium carbonate, are widespread across the globe, with notable occurrences in regions such as Iran, Iraq, Italy, Spain, the United Kingdom, Germany, Greece, and Canada [1]. Despite their abundance, marls pose significant challenges in geotechnical projects due to their sensitivity to erosion and weathering [2]. Industrial pollution of water and soil stands as a significant environmental challenge in modern societies, drawing considerable attention from researchers [1, 2]. Industrial activities often generate wastewater containing acidic and alkaline pollutants, which can infiltrate water bodies and subsequently contaminate soil through leaching processes. The quality of soil pore water, influenced by this polluted water, undergoes rapid changes, thereby impacting soil properties [3].

In response to the escalating trend of soil and water pollution, numerous studies have investigated the effects of chemical pollutants on soil characteristics. Among the critical parameters in pollution assessment is soil pH, especially given its susceptibility to environmental fluctuations. Changes in soil pH can profoundly influence geotechnical and geoenvironmental properties [4]. Studies by [5] have demonstrated notable changes in soil classification associated with variations in pH. Particularly, an increase in pH levels, correlated with sulphate content, led to pronounced transformations in the classification of clayey soils according to the Unified Soil Classification System (USCS).

The use of clays as protective coatings in high-level waste is a common practice aimed at mitigating environmental risks associated with waste disposal. In such applications, clays are subjected to moderate to high thermal regimes and pH changes, which can significantly influence their behavior.

In this research, we aim to investigate the engineering behavior of marl soils under the combined influence of thermal regimes and pH changes from both micro-structural and mechanical perspectives. Understanding how marl soils respond to these dual environmental stressors is essential for assessing their suitability for landfill liner applications and ensuring long-term stability and effectiveness of landfill systems.

By examining key micro-structural and mechanical properties, we seek to elucidate the complex interactions between thermal effects, pH variations, and the engineering behavior of marl soils. Insights gained

from this study can inform better design and management practices for high-level landfills, contributing to enhanced environmental protection and sustainability

2. Materials and methods

The soil sample utilized in this study is sourced from a marl deposit located in southern Iran, situated on the northern shore of the Persian Gulf and west of Bandar Abbas. This region was chosen due to its proximity to various industrial activities, which increases the likelihood of pH fluctuations in the marl soil over time.

The experimental procedures in this study adhere to the ASTM standard and follow the guidelines of McGill University, Canada, particularly for geoenvironmental experiments.

According to the Unified Soil Classification System (USCS), the marl soil under investigation is classified as a type of clay of low plasticity (CL), with 98% by weight passing through sieve no. 200, corresponding to a 74 μm nominal Sieve Opening. Table (1) presents some key geotechnical properties of the marl soil, which are essential for understanding its behavior and characteristics in the study.

To adjust the pH of the marl soil samples, hydrochloric acid (HCl) solution with a concentration of 1 M was used to decrease the pH, while sodium hydroxide (NaOH) solution with a concentration of 1 M was added to increase the pH. The initial pH of the marl soil used in this research was 8.3, considered the normal pH for marl soil.

To stabilize the initial pH of the marl soil, 3 kg of dry soil passing through a 40 sieve was separated, and a suspension was prepared by mixing the soil with distilled water at a ratio of 1:5 (5 parts water to 1 part soil). The resulting suspension was stirred using a stirrer for 3 hours and then allowed to stand for 24 hours to ensure thorough hydration and stabilization.

Subsequently, to stabilize the pH of the marl samples at pH levels of 4, 6, 11, and 13, drops of 1 M NaOH and HCl solutions were added gradually to the soil-water mixture using a pipette. The volume of acid or alkaline solutions added was carefully controlled to achieve the desired pH levels, ensuring uniform mixing and distribution throughout the soil-water mixture.

The stabilized marl soil samples, adjusted to the desired pH, were initially passed through a 40 sieve to ensure uniformity. Subsequently, the samples were subjected to heat treatment at temperatures of 25 °C, 100 °C, 200 °C, 300 °C, 500 °C, 700 °C, and 900 °C. The oven

temperature was automatically increased at a rate of 5 degrees per minute. Upon reaching the desired temperature, the samples were maintained at that temperature for 2 hours before the oven was turned off.

Table 1: Geotechnical and Geo-Environmental Characteristics of the Southern Marl Soil Sample

Geotechnical properties of Southern Marl	Quantity measured	References for method of measurement
Clay (%)	37	ASTM, D422-63
pH (1:10; soil: water)	8.3	ASTM D4972
Carbonate content (%)	35.5	Hesse, 1971
Unconfined Compression Strength (UCS) (MPa)	0.24	ASTM D2166-06
Liquid limit (%)	40.43	ASTM, D4318
Plastic Limit (%)	21.7	ASTM, D4318
Plasticity Index (%)	18.73	ASTM, D4318
Maximum dry density (kN/m ³)	1.65	ASTM D698
Optimum water content (%)	15	ASTM D698
Classification	CL	ASTM D3282
Color	Green	
Mineral composition	Palygorskite, Sepiolite, Kaolinite, Calcite, Dolomite, Quartz	

3. Results and discussion

Figure 1 illustrates the unconfined compressive strength (UCS) of natural marl soil, which measures 0.24 MPa under normal conditions (pH = 8.3). In acidic environments (pH = 6 and pH = 4), the compressive strength increased to 0.26 MPa and 0.3 MPa, respectively. This increase can be attributed to the heightened attractive forces between soil particles due to the increased concentration of H⁺ ions in pore water, leading to the flocculation of soil particles and subsequent strengthening of the samples.

On the other hand, the addition of sodium hydroxide (NaOH) solution at pH = 11 resulted in a slight increase in compressive strength to 0.25 MPa, attributed to the ionic resistance of the pore fluid and the formation of a face-to-face (F-F) structure [1]. However, at pH = 13, the compressive strength remained at 0.24 MPa. Overall, acidic pore fluids exhibited a more pronounced effect on soil resistance parameters compared to alkaline fluids.

Figure 1 also depicts the compressive strength of marl samples at different temperatures. Upon heating to 100°C, the compressive strength increased significantly for all pH levels, reaching 2.45 MPa, 2.09 MPa, and 14 MPa for pH = 4, pH = 6, and pH = 8.3, respectively. This phenomenon underscores the substantial increase in compressive strength when free water exits the soil structure due to heating, compared to the wet state.

Further temperature increases to 300°C led to a gradual increase in compressive strength, with the pH = 8 sample reaching approximately 2.64 MPa. Dehydration

processes resulted in the reduction of interlayer water content and the strengthening of soil particles [50].

At 500°C, the compressive strength of samples at pH = 4, pH = 8.3, and pH = 13 reached approximately 4.92 MPa, 4.83 MPa, and 5.08 MPa, respectively. The presence of carbonate in marl acted as a levigating agent, contributing to greater resistance in samples with higher carbonate content.

The trend of increasing compressive strength continued, with samples reaching approximately 12 MPa, 10.9 MPa, and 10.1 MPa at 700°C for pH = 4, pH = 8.3, and pH = 13, respectively. This increase can be attributed to the beginning of the kaolinite dehydroxylation process, altering the structure and arrangement of clay mineral particles in marl soil.

However, at 900°C, the compressive strength of samples decreased, with pH = 4, pH = 8.3, and pH = 13 samples measuring 12.1 MPa, 5.6 MPa, and 5.5 MPa, respectively. This reduction can be attributed to the decomposition of calcium carbonate at temperatures above 830°C, leading to the formation of quicklime and subsequent porosity in the soil. Additionally, the interaction of amorphous silica and calcium oxide in soils containing carbonates led to the formation of a glass structure, contributing to a decrease in compressive strength [6].

In summary, the UCS of marl soil is significantly influenced by both pH and thermal regime, with acidic conditions and moderate temperatures resulting in the highest compressive strength values observed.

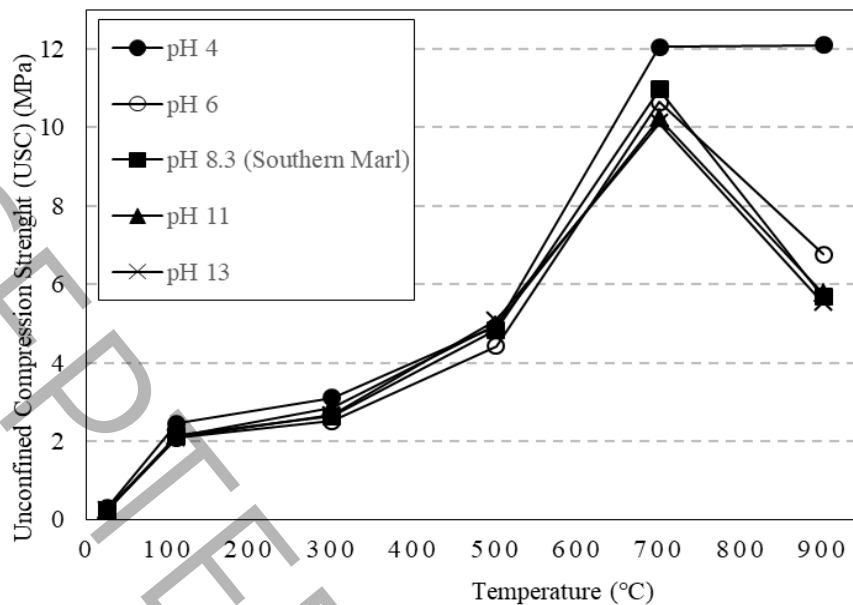


Figure 9: Temperature Effect Curve on Unconfined Compressive Strength (UCS) of Marl Soil at Different pH

4. Conclusion

Based on the microstructural analyses and geotechnical experiments conducted in this study, the following summarizes the key findings:

1. The engineering behavior of marl soil is significantly influenced by both soil pH and thermal regimes, with notable changes observed in the thermal range of 500°C to 900°C.
2. XRD analysis revealed that the addition of hydrochloric acid resulted in the formation of amorphous silica in the octahedral palygorskite structure, enhancing its stability in acidic environments ($\text{pH} \leq 4$). Palygorskite was also found to be stable in alkaline environments.
3. Investigation of the classification of marl soil exposed to heat showed that significant changes in classification and behavior occurred from 25°C to 300°C. At temperatures of 500°C and above, the clay structure was destroyed, leading to the soil becoming granular and non-plastic due to the onset of the dehydroxylation process.
4. Increasing temperature led to a corresponding increase in the compressive strength of marl soil. Samples with $\text{pH} \geq 6$ exhibited the highest compressive strength at 700°C. However, after complete dihydroxylation, the compressive strength decreased at 900°C due to the removal of carbonates. Samples with carbonate content demonstrated greater resistance compared to those with lower carbonate content.
5. Notably, increasing the temperature to 900°C and altering the atomic arrangement resulting from dihydroxylation led to the maximum compressive strength of marl soil with $\text{pH}=4$, reaching 12.1 MPa.

5. References

- [1] M. Amiri, B. Kalantari, M. Dehghani, F. Porhonar, M. Papi, R. Salehian, S. Taheri, Microstructural Investigation of Changes in Engineering Properties of Heated Lime-Stabilized Marl Soil, Proceedings of the Institution of Civil Engineers-Ground Improvement, (2021) 1-29.
- [2] D. Saidi, Importance and role of cation exchange capacity on the physicals properties of the Cheliff saline soils (Algeria), Procedia Engineering, 33 (2012) 435-449.
- [3] E.B. Khoshbakht, A.H. Vakili, M.S. Farhadi, M. Salimi, Reducing the negative impact of freezing and thawing cycles on marl by means of the electrokinetical injection of calcium chloride, Cold Regions Science and Technology, 157 (2019) 196-205.
- [4] M. Amiri, R. Salehian, Microstructural evaluation of the effect of initial pH on geotechnical and geoenvironmental characteristics of marl soils, Arabian Journal for Science and Engineering, 47(10) (2022) 12555-12568.
- [5] V. Ouhadi, R. Yong, Experimental and theoretical evaluation of impact of clay microstructure on the quantitative mineral evaluation by XRD analysis, Elsevier Appl. Clay Sci. J, 23(1-4) (2003) 141-148.
- [6] M. Amiri, M. Dehghani, M. Papi, Microstructure Evaluation of Thermal Stabilization Marls Case Study: Marl West Bandar Abbas, Ferdowsi civil engineering, 32(4) (2020) 67-86.