INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 16 No. 4 (2024) 39-46
https://publisher.uthm.edu.my/ojs/index.php/ijie

# Durability of Slag Based Geopolymer Stabilized Clay with High Moisture Condition

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DOI: https://doi.org/10.30880/ijie.2024.16.04.006

**Article Info**

Received: 1 January 2024
Accepted: 12 June 2024
Available online: 12 August 2024

**Keywords**

Geopolymer, soil stabilization, clay, ground granulated blast furnace slag (GGBS)

**Abstract**

Clay soils, characterized by their cohesiveness and water retention capacity, exhibit low aeration and tend to swell when water is absorbed, leading to subsequent contraction. The moisture content significantly affects the properties of marine clay, resulting in low strength and high compressibility. Traditional stabilizers such as lime and cement have been extensively studied for their ability to enhance the compressive strength, reduce swelling potential, and improve the overall durability of the soil. These stabilizers offer numerous benefits in terms of soil properties and have been extensively researched. However, due to environmental concerned, geopolymer has been explored as an alternative replacement to the traditional stabilizer. In this research, stabilized clay soil using ground granulated blast furnace slag (GGBS) based geopolymer were prepared and tested for the compressive strength and durability characteristic. Different percentages of GGBS (10%, 20% and 30%) were used to stabilize the clay soil with different activator/binder ratio (0.5, 0.75 and 1.0) and initial moisture content ($0.75w_L$, $1.0w_L$, and $1.25w_L$). Cement stabilized specimen were also prepared for comparison. Unconfined compression test and wet-dry cycle were performed to evaluate the compressive strength and durability of treated soil. It was found that the strength of treated sample decreased with increment of initial moisture content. Increasing the binder dose was necessary to achieve the strength requirements for high water content soils. Thus, it shows that the use of a GGBS based geopolymer binder for the purpose of stabilizing soft soil is an alternative that is both effective and environmentally friendly.

## 1. Introduction

Clay soils are typically rigid when dry, but become significantly less rigid when they are completely saturated with water. In an area with high water table, the strength of clay soil is very low make it unsuitable for construction. Marine clay is a type of alluvial sediment that comes from the ocean floor and forms in shallow, salty coastal water [1]. It was also reported that marine clay was contaminated with biological and chemical contaminants [2]. Marine clay is usually black, grey, or green and can be found in the ocean and on the seabed. The moisture content has a significant impact on the marine clay's properties, particularly its low strength and high compressibility. When dried, the marine clay will become more compact, but it will expand when more moisture is added to it. The high level of displacement can cause issues for foundation structures that have been built on it [3]. Marine clay is characterized by its fine particle size, typically classified as silt or clay. The particle size distribution is dominated by particles smaller than 0.063 mm in diameter. Due to its high plasticity, marine clay can be easily moulded and retains its shape when moist. It has a high water-holding capacity and exhibits a soft and easily deformable nature. The high-water content contributes to its cohesive behaviour and makes it prone to settlement and consolidation issues [4]. Soil stabilization is an unavoidable process today because of the low quality of soil properties. Soil stabilization is a technique for improving soil performance for building and engineering uses by modifying soil parameters [5]. Soil stabilization helps in achieving the needed soil properties for the type of construction job [6]. For loose and soft soils, chemical stabilization can often be accomplished through either deep mixing or grouting [7].

Cementitious binders are combined with contaminated or waste soil in this method to immobilize heavy metals in the soil matrix and raise the physical strength of the soil [8]. Ordinary Portland cement (OPC) is the stabilizer that is used the most frequently, and when it is applied, it leads to the creation of hydration products, which play a significant part in the stability of the soil. Although the stabilizer is typically utilized in dosages that are on the lower end, between 1% and 7% of the total mass of the improved soil, it is still considered to be a significant quantity [9]. In the meantime, the production of OPC is generally acknowledged to be the primary source of greenhouse gases that are released into the atmosphere. According to data from the International Energy Agency (IEA), this constitutes between 6% and 7% of the total $CO_2$ emissions. It is anticipated that there would be a nearly 200 percent rise in demand for OPC around the globe by the year 2050. The development of new types of sustainable, environmentally friendly, and intelligent self-healing materials is necessary for the reduction of $CO_2$ emissions caused by activities associated with OPC [10].

One variety of environmentally friendly cementitious material is known as geopolymer binder that hardens quickly, shrinks rapidly, and has low acid and alkali corrosion resistance [11]. In recent years, a newly discovered category of binder materials called geopolymers has been heralded as a more sustainable and environmentally friendly alternative to lime and cement [12]. GGBS based geopolymer has been used for soil stabilization work. Recent study found that when the amount of GGBS is increased while the water content is kept low, the stability efficiency of clay soil can be increase. It has been observed that the ratio GGBS to the alkaline activator solution has significant impact to the unconfined compressive strength (UCS) of stabilized soil [13].

Furthermore, the reduced water content and alkaline activator content with GGBS produced higher UCS values due to compact packing between the soil particles. Higher water content of the alkaline mixture resulting in poor bonding between soil particles and decreasing of alkaline solution concentration that cause lower UCS value of stabilized soil. At the same content ratio, the GGBS treated soil shows better results compared to the fly ash based geopolymer treated soil [13]. Analysis of the soft clay soil behaviour including mechanical, physical and hydraulic behaviour is crucial before application of GGBS for any type of treatment. Because of its higher cementitious nature, GGBS is far more effective than lime stabilization. Treatment of sulfate-rich soils using GGBS for pavement construction was used to lower the rate of swelling and make the soil more resistant. The presence of water in GGBS at a very low rate will instantly begin the hydration process [13].

Recent studies have proven the potential of utilizing GGBS as geopolymer for soil stabilization. However, the performance of GGBS geopolymer to stabilize Perlis marine clay remains unknown especially when subjected to high moisture condition. The durability aspect of stabilized soil requires further investigation. Therefore, in this study, the mechanical performance of clay soil treated with different GGBS content and alkali activator to binder ratio together with the water stability and resistance to wet-dry cycles were tested. This was done to investigate the UCS of GGBS based geopolymer stabilized soils [14].

## 2. Methodology

### 2.1 Materials

The clay used in this study was obtained from the seashore area of Kuala Perlis, Perlis. The disturbed soil sample was obtained manually at a depth of 0.5 m below ground level and bagged to be transported to laboratory for further process. The obtained sample were tested for the specific gravity, Atterberg limits and compaction test. The summary of the physical properties is shown in Table 1.

The GGBS based geopolymer used for this research consisted of GGBS and alkali activator. The GGBS used in this study were supplied by a local supplier. The utilization of GGBS contributes to a reduction in the quantity of waste that, in the alternative, would be delivered to a landfill. Table 2 summarizes the chemical composition of GGBS using X-ray fluorescence (XRF). Sodium hydroxide (NaOH) and sodium silicate ($Na_2SiO_3$) are the most often utilized alkaline activator (A) liquids and selected for this study. This mixture activates the utilized precursor, resulting in an efficient geopolymer with good workability. Because of its lower cost and greater ability to dissolve silica and alumina from the source material, the NaOH solution is utilized to generate monomers [15]. For comparison purposes, cement was also used to stabilized clay soil. The ordinary Portland cement (OPC) were used with tap water for stabilization of soil. The term binder (B) in this study refer to either dry GGBS or cement.

**Table 1** *Physical properties of Kuala Perlis clay soil*

| Physical properties | Value |
|---|---|
| Specific gravity | 2.30 |
| Liquid limit (%) | 62 |
| Plastic limit (%) | 33 |
| Plasticity index (%) | 29 |
| Maximum dry density (Mg/m$^3$) | 1.31 |
| Optimum moisture content (%) | 28.2 |

**Table 2** *Chemical composition of GGBS using XRF*

| Element | Percentage (%) |
|---|---|
| $SiO_2$ | 28.8 |
| $Al_2O_3$ | 12.7 |
| $Fe_2O_3$ | 0.49 |
| CaO | 46.9 |
| MgO | 6.03 |
| $K_2O$ | 0.75 |
| $TiO_2$ | 0.65 |
| $Na_2O$ | 0.17 |
| Others | 3.51 |

## 2.2 Sample Preparation

The sample preparation started with air drying the soil sample for one week continued with 24 hours of oven dried. The sample were pulverized into smaller particles. Sieved soil passing 2 mm sieve size were stored in plastic container and ready to be used for preparation of unconfined compression test and wet-dry cycles.

The alkali activator was prepared by mixing $Na_2SiO_3$ and NaOH (8 M) 24 hours prior to mixing with soil. Initial water content based on the soil's liquid limit were added to the dry soil prior to the mixture with GGBS. The amount of initial water content added is varied from 0.75, 1.0 and 0.75 of liquid limit ($w_L$). Dry GGBS were added to the moist soil at required amount as shown in Table 3. The amount of GGBS were varied from 10% to 30% of dry weight of soil. The GGBS-soil mixture was manually mixed for 3 minutes. The alkali activator was added to the GGBS-soil mixture and mixed for another 5 minutes to achieve homogeneity. The amount of alkali activator used is based on the alkali activator/binder (A/B) ratio. The prepared mixed was transferred to the cylindrical mould (42 mm dia. x 84 mm) and compacted.

The sample was cured in oven at a temperature of 40°C. Once the desired level of hardening was achieved, the samples were carefully removed from the mould in their desired shape. In order to minimize the moisture lost from the soil, samples were wrapped with plastic wrap as shown in Fig. 1. Those steps were repeated with other mixture composition. All sample were tested for UCS at 28 days of curing.

## 2.3 Testing

The unconfined compression test was used in this study to determine the UCS of the stabilized soil sample. The test was performed at the rate of 0.5 mm/min. Motorized unconfined compression was used to perform the unconfined compression test for all stabilized sample.

To conduct the wet-dry tests, standardized methods for preparing UCS mixtures were followed to prepare the samples. After the selected samples had undergone a curing period of 28 days, they were subjected to a series of wetting and drying cycles. The process involved immersing the samples in potable water at room temperature for 5 hours, allowing them to absorb moisture for the wetting phase. After that, the process continued with the drying phase and the sample is oven dried for 42 hours at 71 °C. Afterward, the samples were left exposed to the ambient air for 1 hour. This entire process of wetting and drying constitutes one wet-dry cycle, which spans a duration of 48 hours.

At the end of each wet-dry cycle, the samples were carefully weighed to measure the amount of weight they had lost. This weight loss serves as an indicator of the material's performance and its ability to withstand the stresses imposed by wetting and drying conditions. By tracking the changes in weight throughout multiple wet-dry cycles, a comprehensive understanding of the material's durability and resistance to weather-induced deterioration can be obtained. These wet-dry cycle tests provide valuable data for assessing the long-term performance of pavement materials and aid in the development of more robust and resilient infrastructure.

**Table 3** *Details of laboratory testing program*

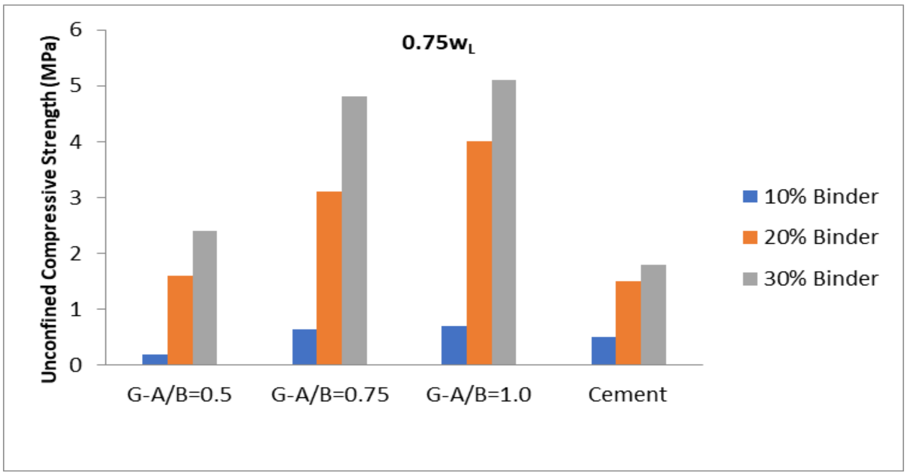
| Parameters | GGBS geopolymer | OPC |
|---|---|---|
| Materials | GGBS, Soil | OPC, Soil |
| Binder content (%) | 10, 20, 30 | 10, 20, 30 |
| Alkali activator | $Na_2SiO_3$, NaOH | - |
| Activator/Binder (A/B) | 0.5, 0.75, 1.0 | - |
| Initial moisture content of liquid limit ($w_L$) | $0.75w_L$, $1.0w_L$, $1.25w_L$ | $0.75w_L$, $1.0w_L$, $1.25w_L$ |
| Tests | UCS, wet-dry cycle | UCS, wet-dry cycle |

**Fig. 1** *Stabilized soil sample wrapped with plastic film for curing process*

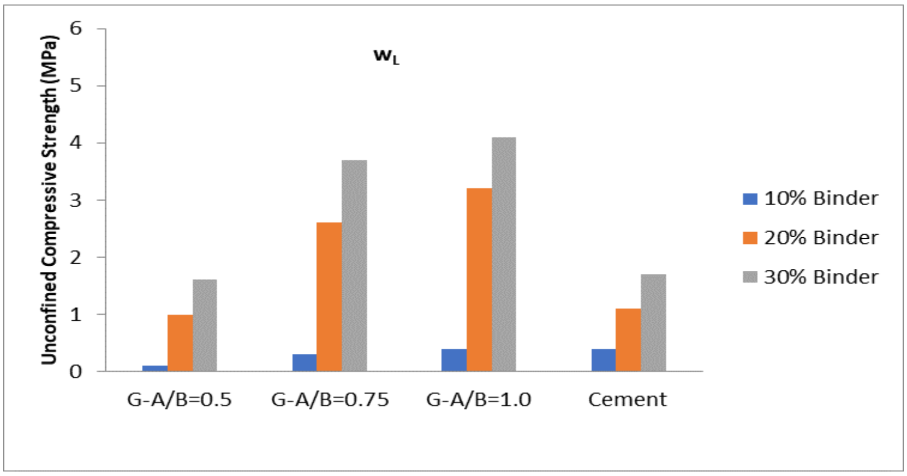
## 3. Results

### 3.1 Unconfined Compressive Strength (UCS)

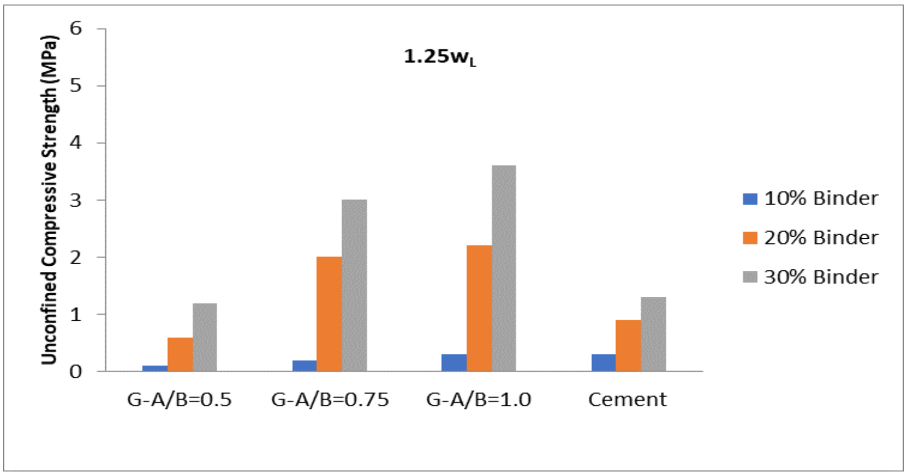
Fig. 2 shows the UCS of the treated soil sample with varied content of GGBS, A/B ratio under different initial moisture content. It can be clearly observed that the specimen treated with GGBS based geopolymer binder provide higher UCS value compared to the cement treated specimens at the same binder content, except for the sample with A/B ratio of 0.5 and a water content ratio of $1.25w_L$. This notable difference in strength are the results from both high pozzolanic and geopolymer reactions within the GGBS-treated mixes, as depicted in Fig. 2. Unlike the cement-treated specimens, which undergo solely pozzolanic reactions, the inclusion of GGBS in the geopolymer mix results in enhanced reactivity and additional geopolymeric reactions. This synergistic effect contributes to the superior strength development observed in the geopolymer-treated specimens.




**(a)**




**(b)**




**(c)**

**Fig. 2** *UCS of stabilized soil with different binder content and A/B ratio with varying initial moisture content*

The higher UCS values achieved by the GGBS geopolymer specimens demonstrate the favourable pozzolanic and geopolymeric reactions, indicating the enhanced binding and structural performance of these mixes. The presence of GGBS allows for a more extensive chemical reaction, resulting in the formation of a stronger and more durable matrix. This finding emphasizes the potential of GGBS geopolymer as a viable alternative to cement-based materials, offering improved mechanical properties and a more sustainable approach to construction.

Addition of binder content from 10% to 20% have significantly increase the compressive strength (UCS) value, regardless of the type of binder, water content, and A/B ratio. However, when the binder content was further increased to 30%, the strength gain was reduced. This phenomenon was observed in both cement and slag-geopolymer treated specimens. The decrease in strength at higher binder contents can be attributed to the localized flocculated crystal that formed within the geopolymer gels. These crystals will continue to expand lead to non-uniformity together with small bond breakages due to internal stresses.

Fig. 2 provides insights into the effect of initial water content and A/B ratio on the UCS of the treated specimens. It can be observed that as the initial water content increased, the UCS decreased for all binder contents. This decrease may be attributed to a reduction in the activator concentration required for geopolymerization, resulting in a less favourable reaction and lower strength development. Comparing the A/B ratio of 0.5 to higher ratios (0.75 and 1.0), there is significant improvement of UCS, indicating that a higher A/B ratio promotes better strength development. Interestingly, the geopolymer paste with an A/B ratio of 0.5 exhibited low viscosity, making it challenging to achieve a homogeneous mixture during treatment. On the other hand, A/B ratios of 0.75 and 1.0 resulted in a geopolymer paste with a more favourable viscosity, simplifying the mixing process and leading to a uniformly treated matrix. Higher A/B ratio at the same binder content means more alkali activator provided to the mixture. This condition will allow for more alkali activator to react with GGBS for geopolymerization process. Higher geopolymer gel produced will increase the strength of the GGBS stabilized soil sample compared to the lower amount of alkali activator from lower A/B ratio. The peak strength at A/B = 1.0 can be observed for all specimens under different initial moisture condition.

Based on the UCS test results, it is evident the minimum requirement of 0.8 MPa as required in the Design Guideline for Alternative Pavement Structures (Low Volume Roads) of Malaysia Public Work Department (PWD), were failed to achieve by the stabilized soil using 10% binder content with A/B of 0.5. This was observed even with at low water content of $0.75w_L$. Therefore, specimens treated with 10% binder content with A/B ratio of 0.5 were excluded from further testing due to their inability to meet the desired strength criteria.

## 3.2 Durability

Fig. 3 presents the volumetric variations observed in the cement and geopolymer binder stabilized specimens subjected to a total of 12 wetting and drying (w-d) cycles. It can be seen that all geopolymer treated soil sample has successfully endured the whole w-d cycles. without significant volumetric changes. However, the 20% and 30% cement treated specimens exhibited significant volumetric changes and could only withstand a maximum of 6 and 7 w-d cycles, respectively. Examining Fig. 3, the least volumetric change with comparison to other specimen shows by the geopolymer sample with 20% and 30% binder content with A/B value of 0.75.

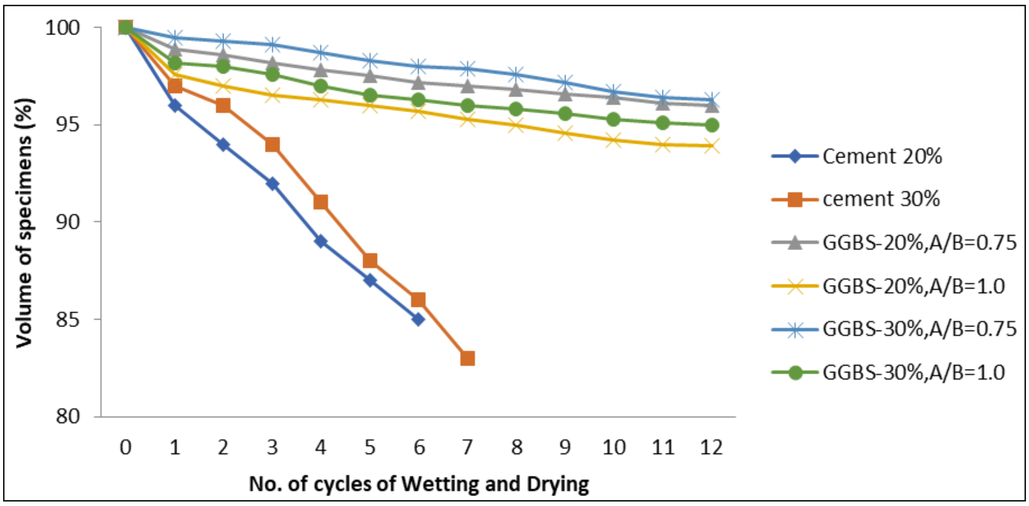



**Fig. 3** *Volume changes of stabilize soil under wet-dry cycles*

The durability results in form of mass loss (%) for the treated sample subjected to w-d cycles are presented in Fig. 4. The figure illustrates the changes in mass over time for the treated mixes. As depicted in Fig. 4, the geopolymer treated mixes initially exhibited a substantial amount of mass loss during the first cycle. However, as the cycles progressed, there was a modest increment in mass loss up to the third cycle. Subsequently, up to the 12 w-d cycles the mass loss were relatively constant. This indicates that the geopolymer treated mixes experienced a significant and steady level of mass loss over the duration of the w-d cycles.

On the other hand, the cement-treated mixes displayed a different pattern in terms of mass loss. For these mixes, there was a considerable and linear increase in mass loss up to three cycles. However, after reaching this point, the mass loss remained relatively constant until the sixth and seventh cycles for the mixes with 20% and

30% binder content, respectively. This suggests that the cement-treated mixes experienced a significant and consistent level of mass loss during the initial cycles, which then stabilized to a certain extent.

Comparing the amount of mass lost over time, it can be observed that the geopolymer treated mixes demonstrated better durability performance compared to the stabilized soil using cement. The soil sample treated with geopolymer exhibited a more sustained level of mass loss throughout the w-d cycles, indicating their ability to withstand the cyclic wetting and drying conditions. This suggests that the geopolymer treatment provided improved resistance to the detrimental effects of moisture and contributed to the enhanced durability of the specimens.

In summary, the analysis of mass loss in Fig. 4 reveals distinct trends for the geopolymer and cement treated mixes. The geopolymer treated mixes showed a consistent and significant level of mass loss throughout the cycles, while the cement-treated mixes experienced an initial period of linear mass loss followed by a relatively stable level. Furthermore, the geopolymer treated mixes exhibited greater durability, as evidenced by their sustained mass loss over time when compared to the cement-treated mixes.

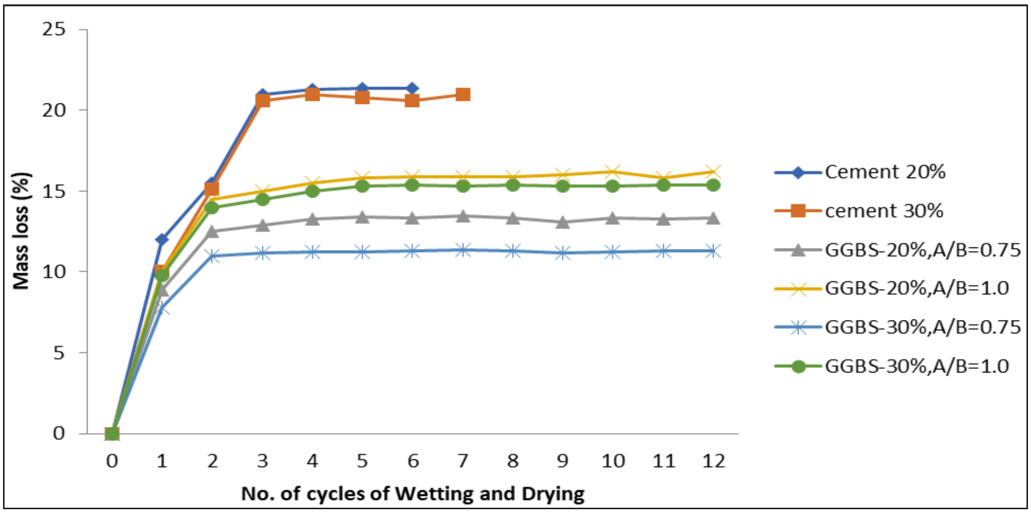



**Fig. 4** *Mass loss of stabilized soil under wet-dry cycles*

## 4. Conclusion

The unconfined compression test was conducted to evaluate the strength characteristics of specimens treated with geopolymer and cement. The results indicated that the GGBS based geopolymer treated specimens exhibited higher unconfined compressive strength (UCS) values compared to the specimens treated with cement, despite being treated with the same dose. This observation can be attributed to the unique properties of geopolymer, which undergoes both pozzolanic and geopolymeric reactions.

The relationship between the initial moisture content of the soil and the unconfined compressive strength of the treated specimens were tested using an unconfined compression test. The results revealed that as the moisture content of the soil increased, the strength of the treated specimens decreased. As the moisture content of the soil increases, the alkaline activator concentration may become diluted, leading to a decrease in its effectiveness in dissolving ions and promoting geopolymerization.

GGBS stabilized clay soil has been shown to possess good durability when subjected to wetting and drying cycles. The stabilized soil demonstrated minimal volume change and loss in mass throughout the 12 cycles, indicating its ability to withstand moisture variations and maintain its structural integrity.


## Acknowledgement

The author would like to acknowledge the support from the Fundamental Research Grant Scheme (FRGS) under a grant number of FRGS/1/2020/TK0/UNIMAP/03/1 from the Ministry of Education Malaysia.


## Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

## Author Contribution

*The authors confirm contribution to the paper as follows:* ***study conception and design:*** *T. H. H. Hong, M. M. Ahmad, M. F. M. Zaki;* ***data collection:*** *T. H. H. Hong, M. F. M. Zaki;* ***analysis and interpretation of results:*** *T. H. H. Hong, Z. M. Ghazaly, M. M. Ahmad;* ***draft manuscript preparation:*** *N. F. Bawadi, M. M. Nujid, K. Muhamad. All authors reviewed the results and approved the final version of the manuscript.*

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