Malaysian Journal
Of Civil
Engineering

CARBONATION PERFORMANCE OF KAOLIN TREATED WITH GROUND GRANULATED BLAST FURNACE SLAG

Azimah Ayub*, Nor Zurairahetty Mohd Yunus, Dayang Zulaika Abang Hasbollah, Brendon Feadrek, Nur Atiqah Mohd Zaini , Ahmad Safuan A Rashid

Department of Geotechnics and Transportation, Faculty of Civil engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bharu, Johor, Malaysia

Article history
Received
17 May 2023
Received in revised form
26 June 2023
Accepted
03 July 2023
Published online
30 July 2023

*Corresponding author
azimah28@graduate.utm.my
r

Graphical abstract

Abstract

This study is prompted by the fact that currently available information, regarding carbon dioxide (CO2) and ground improvement, is rather limited, as the emphasis in this area, is mainly directed at health and environmental issues. This includes efforts to counter climate change, by reducing the level of carbon dioxide levels in the atmosphere. Nonetheless, several geotechnical researchers have delved into CO2 sequestration, through magnesium-rich materials. Among such materials is ground granulated blast furnace slag (GGBS). This waste material, which contains between 5% to 9% magnesium, and roughly 35% calcium, appears to be a favourable option for CO2 sequestration. The purpose of this study, is to determine the appropriate optimal amount of GGBS (based on the strength value recommended by the Public Works Department), and its effect in terms of durability, for the treatment of kaolin clay, under ambient and carbonated conditions, with a 24-hour carbonation period, subjected to a CO2 pressure of 200 kPa. Compaction, unconfined compressive strength (UCS), and durability (wetting and drying) tests were performed, with various GGBS contents (5%, 15% and 25%), and curing periods (7, 14, 28 and 60 days). The test results indicate an increase in strength of almost 20 times, for kaolin clay treated with 25% GGBS, with a curing period of 60 days (ambient condition). An additional 22.86% increase in strength was registered, for carbonated conditions. The wetting and drying test, also demonstrated that GGBS-treated kaolin was improved in terms of durability, while retaining its strength under wet and dry conditions. Thus, it can be concluded that with an appropriate amount and curing period, GGBS has the potential to stabilize kaolin clay, and contribute towards the realisation of a more sustainable environment, by curbing the amount of CO2 released into the atmosphere.

Keywords: Carbon Dioxide, Kaolin Clay; Ground Granulated Blast-Furnace Slag (GGBS); Unconfined Compressive Strength (UCS); Durability (Wetting and Drying) test

1.0 INTRODUCTION

The construction sector is a major contributor towards Malaysia's progress, and suitable soil is a significant requirement for the development of buildings, highways and railways among others. In this regard, geotechnical engineers are at the forefront, when it comes to the conception of revolutionary soil-improvement technology, to counter the growing scarcity of stable soil, for the construction of retaining walls or buttresses, the thickening of roads or pavements, and the expansion of foundations among others. In the context of silt-clay soil, its strengthening, reduction in sensitivity to water, and improved resistance to stress, can be realized through the application of chemical stabilization methods (Yunus *et al.*, 2015; Cokca, Yazici and Ozaydin, 2009; Ehwailat, Mohamad Ismail and Ezreig, 2021) . Chemical stabilization methods also serve to alleviate total and differential settlement (Salimi and Ghorbani, 2020), reduce construction time and costs, as well as overcome problems affecting projects sited on soft ground. According to the results derived from previous studies, soil strength and stability can be enhanced, through the addition of waste materials. In an investigation conducted by Azhar *et al.*, (2017), the use of liquid polymer as an additive to kaolin, delivered a high UCS value. The compressive strength against the varying content of liquid polymer, correlated with the curing periods used to treat kaolin clay. Similarly, Kichou, (2015) used GGBS in increasing amounts, for the treatment of soft soil, to achieve high maximum UCS values of 6% and 10% respectively. Further addition of GGBS led to a gradual decline in strength. Greater awareness, regarding the threats posed by climate change and global warming, have led to the presentation of various approaches, aimed at curbing the release of carbon dioxide into the environment. It has been established that the strength of kaolin clay, can be enhanced, through its stabilization using GGBS, under a carbonated condition. The enhancement in strength of kaolin clay, treated with GGBS under a carbonated condition (Yi *et al.*, 2013a; Mazzotti *et al.*, 2005; M. A. Mohammed *et al.*, 2021), is attributable to the liquefaction of carbon dioxide in the water available, to form carbonic acid. Calcium carbonate and magnesium carbonate, produced from the breaking up of GGBS into calcium and magnesium hydroxide, liquefies to bond with the dissolved carbon dioxide. The resulting chemical then fills the vacant spaces in the soil, to enhance its strength. Therefore, this study aims to investigate the performance of carbonated kaolin treated with GGBS.

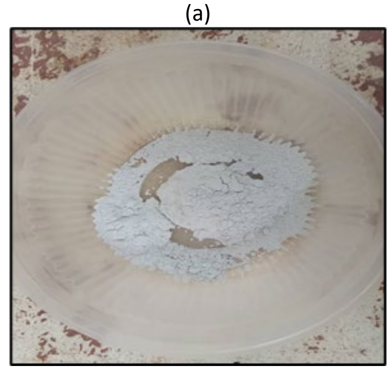
2.0 METHODOLOGY

2.1 Materials

Kaolin soil expands with the absorption of water, and contracts when it is released. This expansion and contraction behaviour of kaolin soil, poses an infrastructure hazard, as it translates into low strength and high compressibility. Consequently, the erection of flimsy or relatively heavy structures, on such soil, can prove to be rather problematic. The brown acidic kaolin used for this study, was sourced from Kaolin (Malaysia) Sdn. Bhd., located in Tapah, Perak, Malaysia as shown in Figure 1(a).

Ground granulated blast furnace slag (GGBS), was used as the by-product (waste material) additive, to ascertain its effectiveness, with regards to soil stabilization. Figure 1(b) shows the GGBS employed for this study, which was obtained from a local factory, located in Johor Bharu, Johor, Malaysia. GGBS is obtained by quenching molten iron slag, derived from blast furnaces, operating at over 1500°C, and supplied with a delicately balanced mixture of iron ore, coke, and limestone. While the iron ore is reduced to iron, the residual components rise to float on the surface as slag. The slag, which is regularly tapped out as a molten liquid, needs to be quickly cooled in considerable amounts of water, if it is to be employed in the production of GGBS. The quenching process improves the cementitious characteristics of the slag, while converting it into coarse sand-like granules. Subsequent to granulation, the slag is dried, and then reduced into a very fine powder.

(a)



(b)

Figure 1 a) Brown kaolin in inert size b) GGBS after granulation and reduction into a very fine powder

2.2 Preparation of Sample

2.2.1 Compaction Test

A compaction test was conducted on the soil treated with various rates of GGBS contents (0%, 5%, 15% and 25%) to determine the ideal moisture content and the maximum dry density for the mixtures, which were then taken into consideration, for the preparation of the UCS test samples. Varies amount of GGBS content limit to 25% as previous study conducted by A. M. A. Mohammed *et al.*, (2021) revealed that 25% of GGBS content provide significant amount of magnesium and calcium which benefits for carbonation testing later. The sample was prepared for each percentage of GGBS content. The standard compaction test (BS 1337: Part 4: 1990: 3.4) was performed at the geotechnical laboratory, school of civil engineering, Universiti Teknologi Malaysia, Johor, Johor Bahru, Malaysia, while the samples were prepared at the geotechnical teaching laboratory, Faculty of Civil Engineering, Universiti Teknologi Malaysia.

2.2.2 Unconfined Compressive Strength (UCS) Test

Unconfined compressive strength test for this study is separated into two sections; the first includes the testing to identify the optimum content of GGBS (5%, 15%, 25%) to treat kaolin clay. The optimum content of GGBS is determined based on the minimum requirement endorsed by Malaysia Pubic Work of Department. Table 1 beneath shows the complete number of tests for the stabilized kaolin with various content of

GGBS under various curing period. Following the determination of optimum GGBS content, another set of samples are prepared with optimum GGBS content at various curing periods of (7, 14, 28, 60) days to determine the optimum curing period for GGBS stabilized kaolin. After the determination of the optimum content of GGBS and curing period to treat kaolin clay, another sample with optimum GGBS content are prepared in order to apply carbon dioxide pressure of 200 kPa with carbonation period of 24 hrs under carbonated condition. The pressure maintained at 200kPa in order to ensure 99% of CO_2 gas applied to the sample during carbonation process (Wang, Zhu and He, 2019; Bargonza *et al.*, 1916; Huntzinger *et al.*, 2009; Yi *et al.*, 2016; Yi *et al.*, 2013a; Mo and Panesar, 2013; Yi *et al.*, 2013b; Fasihnikoutalab, 2015; M. A. Mohammed *et al.*, 2021). Meanwhile, Table 2 described total number of samples prepared to undergo carbonation condition.

Table 1 Total number of samples for treated kaolin under different curing periods

Percentage of GGBS (%) \ Curing Period (Days)	0	7	14	28	60
0	1	1	1	1	1
5	1	1	1	1	1
15	1	1	1	1	1
25	1	1	1	1	1
		Total = 20 samples.			

Table 2 Number of samples for treated kaolin with different curing periods at the same percentage of GGBS content.

Curing Period (Days)	0	7	14	28	60
Percentage of Optimum GGBS content (%)	1	1	1	1	1
			Total = 5 samples		

2.2.3 *Durability (Under Wetting And Drying Test)*

Durability performance (BS 4332-Part 4) assessment, Wetting and Drying test of treated kaolin with GGBS, conducted according to the optimum GGBS content and curing period obtained from UCS test. Based on the previously conducted UCS, selected samples with the optimum GGBS content, are examined, to determine their degree of durability, under both uncarbonated and carbonated conditions. The wetting and drying test generally ascertains the weight loss following each cycle. To ensure accurate readings, it is essential that every drying cycle is followed by a proper brushing and cleaning of the surface. The total number of samples for each condition is 15 samples. Hence, a total of 30 samples (uncarbonated and carbonated). In addition, the UCS test was also conducted prior and subsequent to the wetting and drying test, to ascertain the degree of improvement, in terms of durability. Tables 3 and 4 shows the complete number of samples in details.

Table 3 Number of samples at uncarbonated condition

GGBS Content (%)	Cycle														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Optimum GGBS Content (%)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Total number of samples															15

*1 Cycle: 5 hours wetting & 42 hours drying (Cured with optimum curing period obtained from early UCS test)

Table 4 Number of samples at carbonated condition

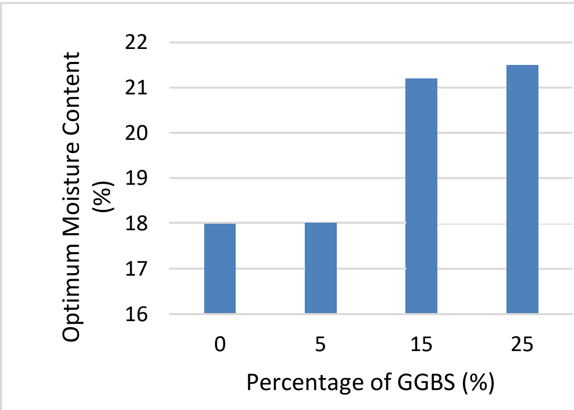
GGBS Content (%)	Cycle														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Optimum GGBS Content (%)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Total number of samples															15

3.0 RESULTS AND DISCUSSION

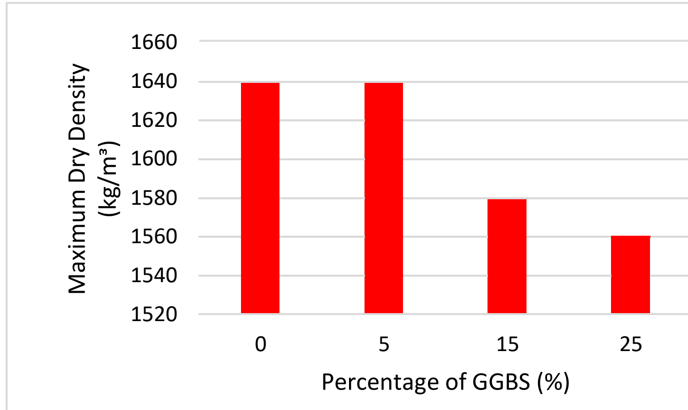
The strength and durability levels of GGBS-stabilized kaolin, as well as the effects of carbonation, are discussed herein.

3.1 Compaction Characteristics of Kaolin Treated GGBS

An increase in the percentage of GGBS, serves to raise the optimum water content. Up to a 5% GGBS content, no significant changes were observed. However, further GGBS additions of 5% and 15% led to an increase in OMC to 18% and 21% respectively. However, at a 15% and 25% content of GGBS, the effect is an insignificant 0.3% rise in OMC. The rise in OMC is attributed to the increase in surface area, brought about by the escalation in GGBS content, which raises the demand for water, to coat the treated kaolin particles (Nusly, 2017). However, as shown in Figure 2, the maximum dry intensity decreases, with the increase in the percentage of GGBS. MDD values fall from 1640 (kg/m3) for untreated kaolin, to 1564 (kg/m3) for kaolin treated with 25% GGBS. It is likely, that the increase infine particle content, attributable to the increase in GGBS content, contributes towards the attainment of a finer and less graded soil and less g soil mix, which enhances the void ratio, and reduces the maximum dry density of the mixture. The effect of different GGBS percentages (5%, 15% and 25%), on maximum dry density and optimum moisture content, can be observed as in Figures 2 (a) and (b).



(a)



(b)

Figure 2 (a) optimum moisture content at various GGBS content meanwhile **(b)** maximum dry density of treated samples at various GGBS content

3.2 Identification of Optimum GGB Content

The verification of optimum GGBS content is crucial, when it comes to determining the most favourable stabilizer (GGBS) amount required, to realize the optimal strength of stabilized kaolin clay. According to Malaysia's economic agenda which is to optimize the cost and fit for purposes for the low volume road especially in rural area, a design guideline was proposed by Jabatan Kerja Raya (JKR) for low volume roads in May 2012 where the minimum strength for the subgrade is 0.8MPa (JKR Specification for Low Volume Roads, 2012). Therefore, the unconfined compressive strength (UCS) test was performed on kaolin clay, with various amounts of GGBS content (0%, 5%, 15% and 25%). As can be gathered from Figure 3, the compressive strength of kaolin well raised, with the increase in GGBS (%) content. While the compressive strength of normal, untreated kaolin is 55.13 kPa, its strength was raised by 34%, 41% and 46% with the addition of 5%, 15% and 25% amounts of GGBS respectively. Although the GGBS content of 25% delivered the greatest strength increase of 25%, this is deemed insignificant as it is still below 100 kPa. This revelation is an indication that in the context of prompt strength improvement, GGBS may be lacking in effectiveness. This provides a signal to further examined the reaction at longer curing period. Therefore, the optimum content of GGBS that been selected for this study is 25% for further assessment at longer curing period in order to identify optimize strength utilization based on minimum the standard required for stabilization performance. 25% of GGBS been selected for further analysis as in terms of practical hands-on site, it is recommended to limit the excavation area as well as to replace the available soil at site. One more thing, the effect of GGBS on environmental aspects still new at this stage, hence moderate amount of GGBS used preferable at this stage.

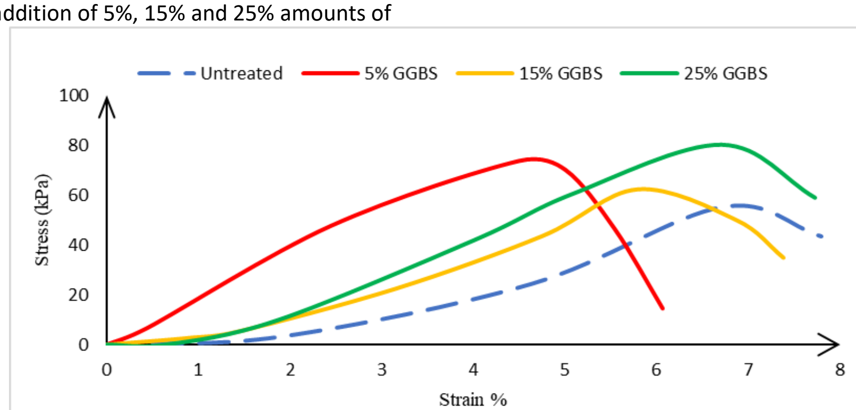


Figure 3 - Effect of UCS on GGBS contents for uncarbonated kaolin treated at 7 curing days

3.3 Optimum Curing Period At Optimum GGBS Content

The maximum GGBS content of 25%, which delivered the greatest kaolin strength, was used to determine the optimum curing time, by way of the UCS test. One sample, for each of the different curing periods (0, 7, 14, 28 and 60 days), was prepared and tested. The samples were cured under room temperature, with the sample size maintained at 76mm in height, and 38mm in diameter. Figure 4 shows the compressive strength obtained at optimum GGBS content (25%), with different curing periods. The influence of the curing period on soil stabilization was observed after 28 days, and by 60 days, the increase in soil strength was almost 20 times greater than the initial strength. The standard set by the Malaysian government (JKR, 2012), requires the UCS for stabilized subgrade to be at least 800 kPa (Al-obaid and Al-shamrani, 2015). Within the scope of study, the use of 25% GGBS can be considered effective, as the kaolin strength reached almost 800 kPa after a 28-day curing period. The use of a GGBS content less than 25% would be impractical, as this will extend the curing time required, to achieve the UCS of at least 800 kPa. Thus, the findings clearly support the use of 25% GGBS as the optimum stabilizer content, and a curing time of 28 days as the optimal curing period. In terms of early strength gain (<14 days), the effectiveness of a small GGBS content appears unremarkable. Recommendable, that further studies in this area, explore the use of a greater GGBS content (50%), which could significantly reduce the period required, to realize optimum soil strength. Following the determination of the optimum GGBS content, for treating kaolin clay in carbonated condition, another set of samples were prepared, with the optimum GGBS content (25%), and subjected to a 24-hour CO2 pressure of 200 kPa, for an accelerated carbonated condition. One sample was prepared for each curing period (7, 14, 28 and 60 days). The unconfined compressive test performed, to determine the outcome of kaolin treated in a carbonated condition, is in accordance with BS 1377: Part 7: 1990: 7. As demonstrated in Figure 6, carbonation, a natural process affecting cementitious materials (Bertos *et al.*, 2004), clearly enhances the strength of GGBS-stabilized kaolin. While only a slight increase in strength was observed for the samples under curing periods of 7, 14 and 28 days, the sample under 60 days of curing achieved a maximum value of 1352 kPa, an increase in strength 22.86% greater than the un-carbonated condition. The carbonation process to assess soil stability, typically involves the application of CO2 directly to samples, under a specific pressure and carbonation period. Calcium and magnesium, for example, can capture, sequester, and react with CO2, to form calcium carbonate or magnesium carbonate. Although the carbonation process did not lead to any significant increase in soil strength, the GGBS capacity for capturing CO2, serves to reduce the impact of greenhouse gases, and contribute towards a healthier environment. The test results verify that the optimal curing period for stabilized kaolin clay, at the optimal GGBS content (25%), for both uncarbonated and carbonated conditions, is 60 days.

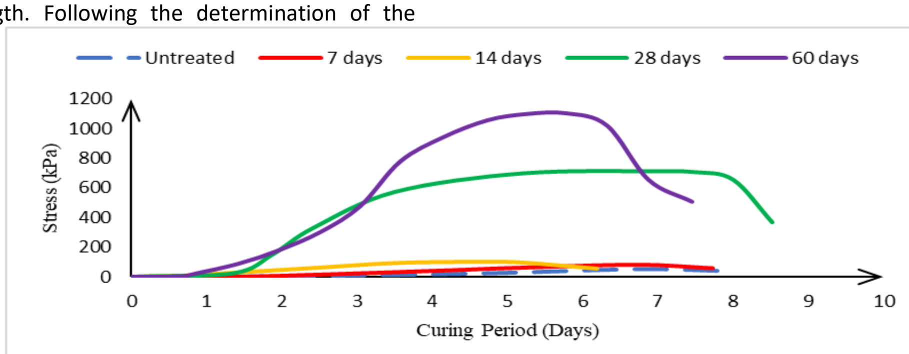


Figure 4 Effect of UCS on curing period of uncarbonated kaolin treated with 25% GGBS content

Figure 5 show the comparison of UCS values for two different conditions which were uncarbonated and carbonated treated kaolin with 25% GGBS at different curing periods. For the carbonated condition, the sample was placed under the pressure of 200 kPa of CO2 for 24 hours before the testing. The trends of UCS for the carbonated sample were same as the uncarbonated sample. The carbonated sample gives a slightly higher value of UCS compared to the uncarbonated sample. The most significant increment of strength can be observed at the 60 days where the UCS value for the uncarbonated and carbonated were 1100 kPa and 1352 kPa respectively. This is due to the CO2 liquefied in the water accessible inside the kaolin-GGBS mixture forming carbonic acid, increasing strength. The GGBS dissolved and transformed into calcium and magnesium hydroxide, which bonded with the dissolved CO2 to form MgCO3 (magnesium carbonate) and CaCO3 (calcium carbonate), respectively. These chemical compounds increase soil strength by filling the available voids in the mixture (Bertos et al., 2004). Despite showing insignificant strength increment after been carbonated, there is no significant increase in strength, it can be said that this study able to achieve two benefits at once as not only the strength increase but the possible climate change can be minimized to some extent.

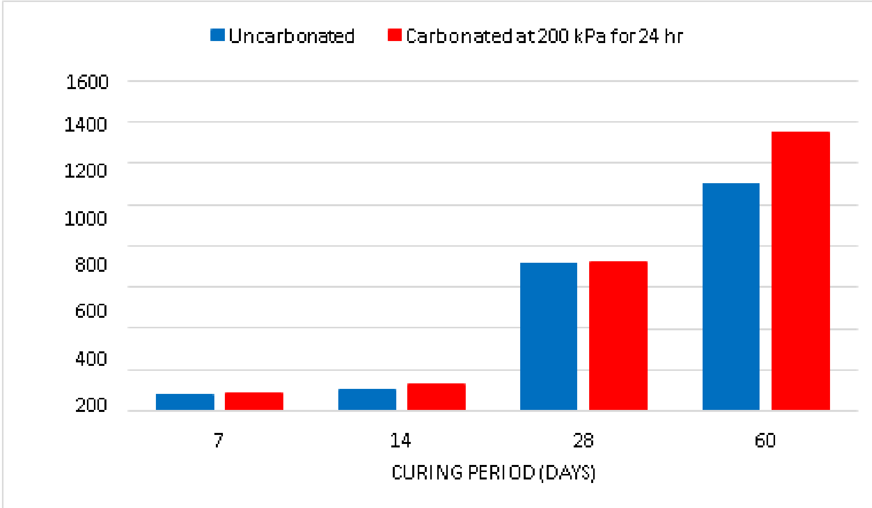


Figure 5 Comparison of UCS for kaolin samples treated 25% GGBS content with different curing periods under uncarbonated and carbonated condition.

3.4 Durability Performance of GGBS Stabilized Kaolin with Optimum GGBS Content and Curing Period, On Both Carbonated and Uncarbonated Conditions.

The similarly prepared samples for the durability test are cylindrical in shape, with a height of 76mm, and a diameter of 38mm. The testing process entailed the use of an optimum GGBS content of 25%, and an optimum curing period of 60 days. Subsequent to soaking in distilled water for 5 hours, the samples were subjected to drying in an oven set at 60 degrees, for a period of 42 hours. Following each drying cycle, the samples were brushed in downward strokes on all sides, to detect weight loss, if any. At the close of 15 drying and wetting cycles, the samples were subjected to a residual unconfined compressive strength test. The results derived through this test, are compared to the compressive strength of the soil samples, at uncarbonated state.

adsorption isotherm lacking a plateau, indicating a multi-layer adsorption (Daifullah et al., 2004). The Freundlich constants KF and intensity n could be calculated from the slope and intercept of the linear plot of ln qe versus ln Ce and the values are presented in Table 1. The correlation coefficient, R2 of Freundlich isotherm for oil palm shell-based adsorbent and activated carbon were 0.995 and 0.888, respectively, indicating that the equilibrium data were better fitted to Freundlich isotherm. Thus, the Freundlich isotherm model was used to estimate the adsorption capacity of the adsorbent for atrazine. The adsorption capacity, KF and intensity n for adsorption of atrazine on oil palm shell-based adsorbent were 0.007 (mg/g)(L/mg)1/n and 0.531, respectively. Furthermore, the value of n was less than one, indicating that the adsorption of atrazine on oil palm shell-based adsorbent was less favorable as compared to activated carbon.

Table 5 Durability test on Kaolin at optimum GGBS contents

Durability Wetting and Drying Test (BS 4332 – Part 4)					
60 Days (25% GGBS)					
Uncarbonated Condition			Carbonated Condition		
Initial Weight(gm)		136.60	Initial Weight (gm)		137.40
Cycle No	WeightLoss	% Loss	Cycle No	WeightLoss	% Loss
1	136.58	0.01	1	137.39	0.01
2	136.41	0.14	2	137.22	0.13
3	136.3	0.22	3	137.10	0.22
4	136.25	0.26	4	136.99	0.30
5	136.16	0.32	5	136.96	0.32
6	136.07	0.39	6	136.87	0.39
7	135.95	0.48	7	136.81	0.43
8	135.92	0.50	8	136.77	0.46
9	135.87	0.53	9	136.69	0.52
10	135.83	0.56	10	136.66	0.54
11	135.79	0.59	11	136.63	0.56
12	135.77	0.61	12	136.60	0.58

13	135.74	0.63	13	136.58	0.60
14	135.72	0.64	14	136.54	0.63
15	135.7	0.66	15	136.53	0.63
Average Percentageloss		0.44	Average Percentageloss		0.42

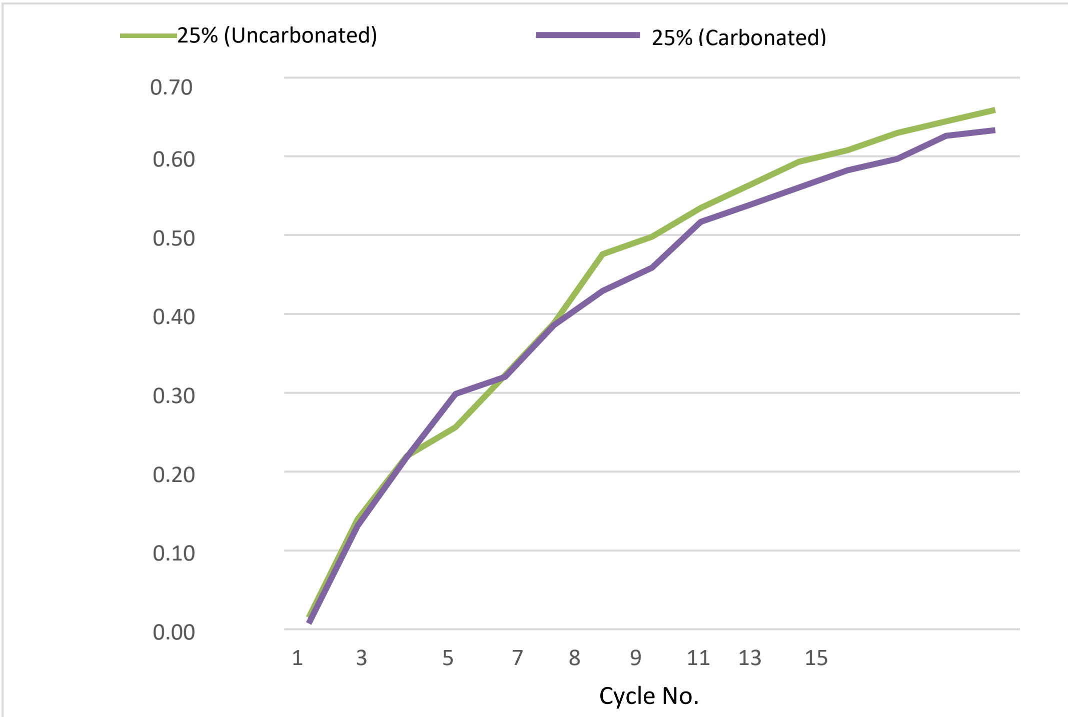


Figure 6 Number of weight loss after each drying and wetting cycles under

By referring to Table 5 and Figure 6, the average weight loss of the samples is very small and nearly identical in both uncarbonated and carbonated conditions, with 0.44% and 0.42% percent, respectively. However, there is a slight improvement in average weight loss percentage for carbonated condition with 0.02% less than uncarbonated condition. The weight of the uncarbonated sample was reduced from 136.60 gm to 135.57 gm, while the weight of the carbonated sample was reduced from 137.40 gm to 136.53 gm. The soil weight loss on durability test results shows a positive response to the use of GGBS for soil stabilization and the impact of carbonation. Both samples in (uncarbonated and carbonated) conditions, cured with an optimum curing period (60 days) and GGBS content (25%), have good resistance to wetting and drying, retaining their hape even after 15 cycles. The residual UCS result is then compared to the UCS results of the initial soil samples. The result can be seen in Figure 7. In the uncarbonated condition, there is a 2.85% loss of strength, and in the carbonated condition, there is a lesser (2.16%) loss of 3 strength. Even after 15 cycles of wetting and drying, only a mild reduction in strength can be seen and the sample could well maintain its shape against a continuous wet and dry conditions It's indeed clear that GGBS and the effect of carbonation play an important role in reducing the strength loss of kaolin, increasing its durability against wetting and drying. The noticeable presence of calcium and silica in GGBS as stabilizers aids in the pozzolanic reaction and carbonation process to occur which will enhance the engineering properties and increasing the strength of kaolin.

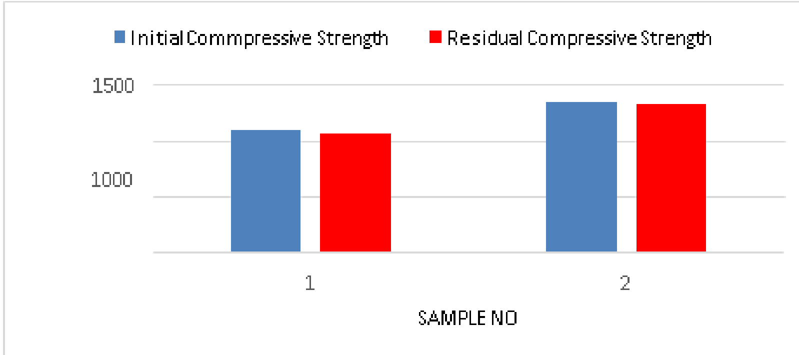


Figure 7 UCS comparison (before and after) durability test

4.0 CONCLUSIONS

In this study, identification of the optimum proportions of Ground Granulated Blast – Furnace slag (GGBS), the strength performance of carbonated and uncarbonated GGBS treated kaolin and to identify the durability performance of the stabilized soil are achieved and summarized as follows: -The UCS results show that the kaolin treated with 5%, 15%, and 25% GGBS improved in strength by 33.77 %, 41.03 %, and 45.35 %, respectively. The optimum GGBS content is the amount of GGBS that produces the highest compressive strength of the treated clay, which has been determined to be 25%, which, among other contents, increases the strength of the clay at the most by 45.35 %. Curing periods of 60 days have been observed to have a significant impact on the performance of kaolin. 60 days of curing with optimum GGBS content (25%), increases the soil strength by nearly 20 times from its initial strength, yielding a final strength of 1100.63 kPa.

Moving on to the effect of carbonation on GGBS stabilised kaolin, it can be seen that with optimum GGBS content (25 %) and curing period of 60 days, the strength significantly increases, reaching a final value of 1352.28 kPa, an increase in strength of 22.86 % over the uncarbonated condition. As a result, there was a positive response to the ability of GGBS to react and sequester with carbon dioxide (CO_2) during carbonation, leading to magnesite production, which may be capable of binding and enhancing kaolin properties.

The GGBS stabilized kaolin's durability test results are satisfactory, representing an actual effect of wet and dry weather in normal natural conditions. Without stabilizing agents, kaolin clay samples cannot withstand even one cycle and crumble to powder. GGBS is a waste and bi-product from steel manufacturing process could be very beneficial in soil strengthening work with appropriate amount and curing period, GGBS can be seen as a potential substance not only for kaolin clay stabilization, but as well react with carbon dioxide CO2, reducing the harmful gases quantity in the surrounding while at the same time strengthening the clay, give rise to a healthier and more sustainable to environment.

Acknowledgements

The authors acknowledge the research grants provided by the support from Collaborative Research Grant National with Universiti Sains Malaysia (R.J130000.7351.4B496) and the Ministry of Higher Education under Fundamental Research Grant Scheme, Proposal No: FRGS/1/2019/TK10/UTM/02/21. The authors would like to thank both parties for kind collaboration.

References

[1] Azhar, A.T.S., Fazlina, M.I.S., Nizam, Z.M., Fairus, Y.M., Hakimi, M.N.A., Riduan, Y. and Faizal, P. (2017). Shear Strength of Stabilized Kaolin Soil Using Liquid Polymer. In International Research and Innovation Summit. 226–232

[2] Bargonza, S., Peete, J., Freer-Hewish, R. and Newill, D. 1916. Carbonation Of Stabilised Soil-Cement And Soil-Lime Mixtures. In *Proc of Seminar H, MTC Transport and Planning, Summer Annual Meeting, University of Bath,*. London: P-TRC Education and Research Services, 29–48.

[3] Bertos, M.F., Simons, S.J.R., Hills, C.D. and Carey, P.J. 2004. A Review of Accelerated Carbonation Technology in the Treatment of Cement-based Materials and sequestration of CO2. *Journal of Hazardous Materials*. 112(3): 193–205.

[4] Cokca, E., Yazici, V. and Ozaydin, V. 2009. Stabilization of expansive clays using granulated blast furnace slag (GBFS) and GBFS-Cement. *Geotechnical and Geological Engineering*. 27(4): 489–499.

[5] Celik, E. and Nalbantoglu, Z. 2013. Effects of Ground Granulated Blastfurnaces slag (GGBS) on the Swelling properties of lime-stabilized sulfate-bearing soils. *Engineering Geology*. 163: 20–25.

[6] Chemeda, Y.C., Deneele, D., Razafitianamaharavo, A., Villiéras, F. and Ouvrard, G. 2021. Assessment of surface heterogeneity of lime treated kaolinites: Probed by low-pressure argon and nitrogen gas adsorption. *Applied Clay Science*. 206(November 2020): 0169–1317.

[7] Ehwailat, K.I.A., Mohamad Ismail, M.A. and Ezreig, A.M.A. 2021. Novel approach to the treatment of gypseous soil-induced ettringite using blends of non-calcium-based stabilizer, ground granulated blast-furnace slag, and metakaolin. *Materials*. 14(18): 10–12.

[8] Fasihnikoutalab, M.H. 2015. Olivine for Soil Stabilization. *The Pertanika Journal of Scholarly Research Reviews*. 1(1): 18–26.

[9] Huntzinger, D.N., Gierke, J.S., Kawatra, S.K., Eisele, T.C. and Sutter, L.L. 2009. Carbon dioxide sequestration in cement kiln dust through mineral carbonation. *Environmental Science and Technology*. 43(6): 1986–1992.

[10] Islam, A., Alengaram, U.J., Jumaat, M.Z. and Bashar, I.I. 2014. The development of compressive strength of ground granulated blast furnace slag-palm oil fuel ash-fly ash based geopolymer mortar. Materials and Design. 56: 833–841.

[11] Kichou, Z. 2015. *A study on the effects of lime on the mechanical properties and behaviour of London clay*. London South Bank University.

[12] Mazzotti, M., Carlos, J., Allam, R., Lackner, K.S., Meunier, F., Rubin, E.M., Sanchez, J.C., Yogo, K. and Zevenhoven, R. 2005. Mineral carbonation and industrial uses of carbon dioxide. *IPCC Special Report on Carbon dioxide Capture and Storage*. (October), 319–

338. Available at: http://www.ipcc.ch/pdf/special-reports/srccs/srccs_chapter7.pdf

[13] Mo, L. and Panesar, D.K. 2013. Accelerated carbonation - A potential approach to sequester CO_2 in cement paste containing slag and reactive MgO. *Cement and Concrete Composites*. 43: 69–77.

[14] Mohammed, A.M.A., Yunus, N.Z.M., Hezmi, M.A. and Rashid, A.S.A. 2021. Sequestration of carbon dioxide using ground granulated blast furnaces slag and kaolin mixtures. *Global Nest Journal*. 23(1): 105–111.

[15] Mohammed, M.A., Zurairahetty, N., Yunus, M., Azril Hezmi, M., Zulaika, D., Hasbollah, A., Safuan, A. and Rashid, A. 2021. Ground improvement and its role in carbon dioxide reduction: a review. *Environmental Science and Pollution Research. 28: 8968–8988.* DOI: https://doi.org/10.1007/s11356-021-12392-0.

[16] Salimi, M. and Ghorbani, A. 2020. Mechanical and compressibility characteristics of a soft clay stabilized by slag-based mixtures and geopolymers. *Applied Clay Science*. 184(July 2019): 0169–1317.

[17] Wang, D., Zhu, J. and He, F. 2019. CO2 carbonation-induced improvement in strength and microstructure of reactive MgO-CaO-fly ash-solidified soils. *Construction and Building Materials*. 229.

[18] Yi, Y., Lu, K., Liu, S. and Al-Tabbaa, A. 2016. Property changes of reactive magnesia–Stabilized soil subjected to forced carbonation. *Canadian Geotechnical Journal*. 53(2): 314–325.

[19] Yi, Y.L., Liska, M., Unluer, C. and Al-Tabbaa, A. 2013(a). Initial investigation into the carbonation of MgO for soil stabilisation. *18th International Conference on Soil Mechanics and Geotechnical Engineering: Challenges and Innovations in Geotechnics, ICSMGE 2013*. 3(September): 2641–2644.

[20] Yi, Y.L., Liska, M., Unluer, C. and Al-Tabbaa, A. 2013(b). Initial investigation into the carbonation of MgO for soil stabilisation. *18th International Conference on Soil Mechanics and Geotechnical Engineering: Challenges and Innovations in Geotechnics, ICSMGE 2013*. 3: 2641–2644.

[21] Yunus, N.Z.M., Marto, A., Pakir, F., Kasran, K., Jamal, M.A.A., Jusoh, S.N. and Abdullah, N. 2015. Performance of lime-treated marine clay on strength and compressibility chracteristics. *International Journal of GEOMATE*. 8(2): 1232–1238.

[22] Zainuddin, N.E.B., Yunus, N.Z.M., Marto, A., Al-bared, M.A.M., Mashros, N. and Abdullah, R.A. 2016. A review: Reutilization of waste material to stabilize marine clay. In The 11th International Civil Engineering Post Graduate Conference - The 1st International Symposium on Expertise of Engineering Design SEPKA-ISEED'16..1–12.

[23] Zhang, Y., Ong, Y.J. and Yi, Y. 2021. Comparison between CaO- and MgO-activated ground granulated blast-furnace slag (GGBS) for stabilization/solidification of Zn-contaminated clay slurry. Chemosphere. 286.