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EFFECT OF FLY ASH GEOPOLYMER CONTENT AND ALKALI RATIO ON SILTY SUBBASE SOIL COMPACTION AND STRENGTH

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ABSTRACT: This study evaluates the compaction and strength properties of silty subbase soil treated with fly ash-based geopolymer (FAG) and determines the synergistic effects of FAG content and alkali ratio (AR) on the soil's Maximum Dry Density (MDD), Optimum Moisture Content (OMC), and California Bearing Ratio (CBR) under soaked condition. The silty subbase soil samples were treated with FAG content at 10%, 20%, and 30% by dry weight of the soil. 10 molars (M) of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), with AR (NaOH to Na_2SiO_3) of 0.33, 1.00, and 3.00, were used to activate the FAG. Testing, such as Compaction and California Bearing Ratio (CBR), was carried out on the prepared soil samples using the guidelines indicated in AASHTO T 180 (Method D) and AASHTO T 193, respectively. Relative to untreated soil, the results showed a slight increase in MDD of about 0.65%, a decrease of about 17.34% in OMC, and a significant improvement in the CBR of about 775%. Moreover, a higher proportion of NaOH in the AR is observed to have developed a significant improvement in MDD, OMC, and CBR compared with a higher proportion of Na_2SiO_3. The extent of these improvements is influenced by the FAG content and AR, which indicates that the behavior is not governed by a single parameter but by their combined effects. Furthermore, the findings of this study present that geopolymer with fly ash is a viable, effective, and sustainable alternative to cement-based stabilization.

Keywords: Fly Ash Geopolymer, Alkali Ratio, Compaction, California Bearing Ratio, Silt Soil

1. INTRODUCTION

Road structural integrity and longevity are primarily determined by the engineering properties of their underlying soil layers. Among these layers, the subbase soil plays a crucial role, as it acts as a load distributor, transferring traffic loadings to a wider area, thereby preventing the subgrade layer from experiencing extreme stress. Positioned between the base course and the subgrade, the subbase layer provides additional structural support and contributes significantly to the overall stability and durability of the pavement system [1]. To ensure the quality of subbase soil materials, appropriate material selection, quality testing, and proper construction implementation are essential. Accordingly, a properly designed and implemented subbase soil enhances load distribution, improves pavement durability, and minimizes premature deterioration, thus reducing maintenance costs and promoting long-term road sustainability [2]. According to the 2025 National Road Classification by the Department of Public Works and Highways (DPWH) [3], about 19.09% of the Philippines' total road network, equivalent to 6,807.65 kilometers, is in poor or bad condition, a condition partly caused by the unsuitable quality of the underlying subbase soil layer [4].

Several existing methods are used to improve the subbase soil that supports the pavement. Among these methods, soil stabilization by compaction using smooth or heavy rollers remains the most widely adopted technique in practice. Soil compaction is a process of rearranging soil particles against resistance under force, which decreases the void space in the soil and increases the density [5]. Despite its effectiveness, the main constraint of this method is that it is limited only to shallow depths and is not sufficient for improving deeper weak soil layers [6]. Another commonly used method is called soil replacement, which involves the removal of the unsuitable soil layer and replacing it with more suitable materials [7]. However, this method introduces significant economic and construction efficiency trade-offs, as it requires extensive excavation, material hauling, and material disposal [8]. On the other hand, soil stabilization using chemical additives has become increasingly popular due to its ability to improve the physical and mechanical properties of in-situ soils without the need for extensive excavation [9]. Soil stabilization by chemical method refers to the modification of soil properties through the application of additives to produce a more improved soil material with certain engineering characteristics [10]. The additives that were commonly studied in civil engineering research are categorized as traditional and non-traditional additives. The traditional additives consist of lime, cement, bituminous, waste/recycled materials (e.g., shredded tire, plastic bottle strips, crushed glass, etc.), fly ash, slag, rice husk ash, etc. On the other hand, the non-traditional additives consist of various combinations such as nano additives, acids, ions, liquid polymers, fibers, enzymes, resins, petroleum emulsions, silicates, and lignin derivatives. Amongst the additives used in chemical soil stabilization, the widely used additive/stabilizer is cement due to its ready availability and cost efficiency [11]. However, cement production has a significant environmental impact, accounting for about 8-15% of global carbon dioxide (CO_2) emissions, which is highly detrimental to the environment as it intensifies global warming and accelerates climate change [12-13]. With increased environmental awareness among practitioners today, there is an ongoing search for more environmentally sustainable alternatives to traditional cement [14].

In recent years, geopolymers have proven to be an environmentally sustainable binder system and a feasible alternative to cement in various construction applications, including roads, buildings, bridges, and structures exposed to aggressive environments such as saltwater [15]. Generally, geopolymers are synthesized through dissolution of aluminosilicate materials in a highly alkali solution, which releases reactive silica and alumina, and undergo polycondensation, forming a solid and durable matrix [5, 12, 16-21]. The commonly used aluminosilicate materials in geopolymer are waste from industry (e.g., fly ash, ground granulated blast furnace slag, silica fumes, etc.) and agriculture (rice husk ash, sugarcane bagasse ash, etc.). Additionally, natural minerals such as metakaolin are also used in geopolymer. Amongst the aluminosilicate materials, fly ash (FA) is the most widely used due to its availability and reactivity in highly alkali solutions [22]. In the Philippines, FA has accumulated in significant quantities, estimated at approximately 2.78 million tonnes (MT), and is projected to increase to nearly 13.02 MT by 2035. However, around 75% of the bulk of FA is disposed of in landfills, while only about 25% being used for other applications [23]. FA is produced from the combustion of coal into fuel for power generation. Depending on the type of coal burned, it contains pozzolans that can initiate chemical reactions. [24-25]. There are three types of FA: Class F, Class C, and Class N. However, due to their pozzolanic characteristics, Class F and Class C are commonly used as replacements for Cement. The primary difference between Class F and Class C is the Calcium (Ca) content, where Class F has Ca content less than 10%, while Class C has Ca content higher than 10% [26]. On the other hand, alkali solutions/activators such as sodium (or potassium) hydroxide and sodium (or potassium) silicate are customarily used [27]. The role of alkali activators in geopolymer is to act as catalysts that facilitate the chemical process and influence both the rate of setting and the strength of the geopolymer [18-19].

Based on prior research, the use of fly ash-based geopolymer (FAG) for soil stabilization yields variable results depending on several factors, including the soil type and mineral composition, the content, type of precursor and alkali activator (AA), the molarity (M) and alkali ratio (AR), curing time, and treatment conditions [5]. Accordingly, several researchers have investigated the viability of FAG in chemical soil stabilization, considering these influencing factors to improve certain engineering properties of soil. In a study conducted by Muntaha [28], FAG was applied at 3%, 7%, and 10% by dry weight of soft clay soil, using a mixture composed of 70% FA (Class C) by weight of the geopolymer and 8 M solution of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) at an AR ($NaOH/Na_2SiO_3$) of 1.0. The study resulted in significant improvements in engineering properties. These improvements were evident in the decrease in optimum moisture content (OMC), and increase in maximum dry density (MDD), and California Bearing Ratio (CBR). On the other hand, Hartono [5] conducted an experiment to investigate the effect of AR and NaOH molarity on the compaction properties of silt soil. A varying concentration of NaOH at 12 M, 14 M, and 16 M with an AR of 1, 1.5, 2, and 2.5, while the FA (Class F) content of 20% were applied in the experiment. The results of their study showed that at an AR of 1.0, an increase in the concentration of NaOH from 12 M to 16 M leads to an increase in the MDD and a decrease in OMC. Although several studies have investigated the effect of FA, molarity of AA, and AR, limited attention has been directed toward evaluating the combined effects of varying FAG content and AR on the strength and compaction performance of soil [29]. Moreover, the determination of the optimum mix composition (precise ratio of FAG content and AR) of soil treated with FAG is crucial to achieve maximum improvement in strength and compaction properties [30].

To maximize the potential of FAG, the present study examines the effect of varying FAG content and AR on the compaction (MDD and OMC) and strength (CBR under soaked condition) properties of the silty subbase soil. The MDD and OMC are adopted as primary parameters in this study due to their influence on the strength and performance of subbase soil [31]. Accordingly, CBR under soaked condition was also included as a primary parameter, since in the Philippines, soaked CBR is used as the acceptance criterion for the strength of subbase materials in road infrastructure design and construction [7]. The samples were prepared and tested in accordance with the AASHTO standard. Moreover, the subbase soil is treated using FA and synthesized with 10 M of NaOH and Na_2SiO_3, applied at AR (NaOH/Na_2SiO_3) of 0.33, 1.00, and 3.00. The AR was established based on previous studies indicating that a balanced ratio of 1.0 yields optimal strength and compaction results. Additionally, AR values of 0.33 and 3.00 were included in this study to assess the effects of lower and higher proportions of NaOH and Na_2SiO_3 on the resulting material properties. To ensure homogeneity, the weight of the FA content is maintained at a constant ratio of 1:1 with respect to the combined weight of AA [32]. On the other hand, the FA content used in the study is fixed at 50% by weight of geopolymer. Likewise, FAG content is composed of the combined weight of FA and AA and applied to the soil at 10%, 20%, and 30% by dry weight of the silty subbase soil [29]. Furthermore, the results of the FAG-treated soil are compared with the untreated soil to evaluate the extent of improvement in compaction and strength properties.

2. RESEARCH SIGNIFICANCE

The result of this study provides a valuable understanding of the optimization of mixture compositions for improving the engineering properties of subbase soil in the pavement system. The identification of the optimum mix composition of subbase soil treated with FAG contributes to more durable, eco-friendly, and cost-efficient road design and construction. Furthermore, the current study promotes sustainability by using FA as a primary aluminosilicate material in geopolymer as an alternative soil stabilizer, reducing dependence on cement, and supporting the reuse of industrial waste by-products for sustainable and environmentally responsible infrastructure development.

3. MATERIALS AND METHODOLOGY

3.1 Material Source

The current study used a medium-plastic silt soil and classified as A-4 material in accordance with the AASHTO Soil Classification System. Silts are sedimentary geomaterials characterized by weak interparticle bonding, low dry strength, and poor engineering performance under pavement and traffic loading [33]. Moreover, the subbase soil was collected in Brgy. Anupul, Bamban, Tarlac City, Philippines. Table 1 presents the geotechnical properties of the obtained subbase soil.

Table 1. Geotechnical properties of subbase soil

Parameters	Values
Liquid Limit, %	26.67
Plasticity Index, %	9.00
Moisture Content, %	10.25
Maximum Dry Density, g/cm^3	1.993
Optimum Moisture Content, %	11.260
CBR (under soaked condition), %	7.84
AASHTO Classification System	A-4

On the other hand, the geopolymer used in the study is composed of FA and sodium-based alkali activators. The FA used in the study was classified as Class F and obtained from Pozzolanic Philippines, Inc. (PPI) coal-fired power plant in Calaca, Batangas, Philippines. Table 2 presents the properties of fly ash.

Table 2. Properties of Fly Ash

Parameters	Values
Silicon Dioxide (SiO_2), %	61.5
Aluminum Trioxide (Al_2O_3), %	21.7
Ferric Oxide (Fe_2O_3), %	5.09
Calcium Oxide (CaO), %	3.5
Magnesium Oxide (Mgo), %	2.4
Specific Gravity (G_s)	2.14

Likewise, the alkali activators used in the study are procured from a local commercial supplier in Quezon City, Philippines. The sodium-based alkali activators consist of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). NaOH is in pellet form, while Na_2SiO_3 is in viscous liquid gel. Tables 3 and 4 present the properties of NaOH and Na_2SiO_3.

Table 3. Properties of NaOH

Parameter	Values
Total Sodium Hydroxide (T-NaOH), %	98.21
Sodium Carbonate (Na_2CO_3), %	0.17
Sodium Chloride (NaCl), %	0.0194
Iron (Fe), %	0.00024
Sodium Sulfate (Na_2SiO_4), %	0.0012

Table 4. Properties of Na_2SiO_3

Parameter	Values
Baumé (degree)	56
Specific Gravity	1.63
Sodium Oxide (Na_2O)	15.548
Silicon Dioxide (SiO_2)	34.912
Weight Ratio (SiO_2/Na_2O)	2.25

3.2 Sample Preparation

The collected subbase samples were prepared in accordance with the AASHTO Standards. On the other hand, the NaOH pellets and Na_2SiO_3 viscous liquid gel are prepared to form a 10 M concentration of solution. Table 5 presents the composition of NaOH and Na_2SiO_3 solutions used in this study.

Table 5. Composition of NaOH and Na_2SiO_3 solutions

FAG Content	AR	AA (50%)	
		NaOH soln.	Na_2SiO_3 soln.
%	-	kg	kg
untrd.	-	-	-
10	0.33	0.775	2.925
10	1.00	1.550	1.550
10	3.00	2.925	0.775
20	0.33	1.550	4.650
20	1.00	3.100	3.100
20	3.00	4.650	1.550
30	0.33	2.325	6.975
30	1.00	4.650	4.650
30	3.00	6.975	2.325

When the 10 M of NaOH and Na_2SiO_3 solutions are prepared, both the solutions are mixed to form the AA at varying AR of 0.33, 1.00, and 3.00. The mixed AA were then gradually introduced to the FA and thoroughly mixed to produce the FAG. Before incorporating the FAG into the silty subbase soil, the soil is oven-dried at 110 °C until the water on the soil is removed. Moreover, the weight of the dry soil (DS) used in this study is 620 kilograms, which consists of 44 kg for compaction test (11 kg per trial) and 18 kg for CBR test (6 kg per compaction effort). Further, the FAG was introduced into the dry soil at varying FAG content of 10%, 20%, and 30% by weight of dry soil. The mixture is thoroughly mixed until a uniform and homogeneous consistency is achieved. Table 6 presents the composition of untreated and FAG-treated subbase soil used in the study. Likewise, the sample preparation procedure is presented in Fig. 1.

Table 6. Composition of untreated and treated soil

FAG Content	AR	DS	FA (50%)
%	-	kg	kg
untreated	-	62	-
10	0.33	62	3.1
10	1.00	62	3.1
10	3.00	62	3.1
20	0.33	62	6.2
20	1.00	62	6.2
20	3.00	62	6.2
30	0.33	62	9.3
30	1.00	62	9.3
30	3.00	62	9.3

3.3 Testing Methodology

The prepared untreated and FAG-treated samples were tested to determine the CBR under soaked condition, MDD, and OMC. The testing procedure is presented in Fig. 2 and 3.

3.3.1 Compaction test

Compaction is one of the most important processes in geotechnical engineering, as it plays a significant role in the stability, bearing capacity, and long-term performance of embankment, subgrade, subbase, and other earth structures. Proper compaction increases soil density by reducing the volume of air voids, thereby improving strength and deformation under traffic loads [34]. In this study, the test on compaction was performed in accordance with AASHTO T 180 (Method D) to determine the relationship between soil moisture content and density after compaction [35]. In this test, the prepared samples were placed into a 152.4 mm (6 inches) diameter mold in five equal layers, with each layer compacted by 56 uniformly distributed blows from the 4.54 kg (10 lb.) rammer falling from 457 mm (18 inches). After the compaction, the corresponding wet density of soil is determined using the ratio of the mass of soil and the known volume of the mold (0.002124 m^3). On the other hand, a representative portion of about 1 kg is taken from each compacted subbase soil sample to determine the moisture content by oven-drying at a temperature of 110°C. The calculated moisture content is used to determine the dry density. Furthermore, the resulting dry densities and moisture contents are plotted in a graph, with the dry densities along the y-axis, while the moisture contents are along the x-axis. The peak of the compaction curve represents the MDD, while the moisture content corresponding to this peak is identified as the OMC.

3.3.2 California Bearing Ratio (CBR) test

California Bearing Ratio (CBR) is a geotechnical parameter in pavement design that is used to determine bearing capacity. Moreover, CBR under soaked condition is used to simulate the worst-case moisture condition, which represents its most critical performance state [1]. The consideration of the CBR under soaked conditions ensures safe, conservative, and reliable design and construction of pavement. In this study, the test on CBR under soaked condition was performed in accordance with AASHTO T 193 [36]. In this test, the prepared sample is placed into a CBR mold of 152.4 mm (6 inches) diameter and compacted at different compaction efforts of 10, 30, and 65 blows. The compacted samples are soaked for four days to saturate the soil and simulate the worst-case moisture condition. After soaking, the samples are tested to determine the CBR values at different compaction efforts using a CBR machine. Dry densities are also determined in accordance with AASHTO T 180 (Method D) for each compaction effort. The resulting dry densities were recorded and plotted together with the CBR at different compaction efforts, with MDD along the y-axis, while CBR is along the x-axis. The CBR of the untreated and FAG-treated subbase soil is determined using the corresponding MDD.

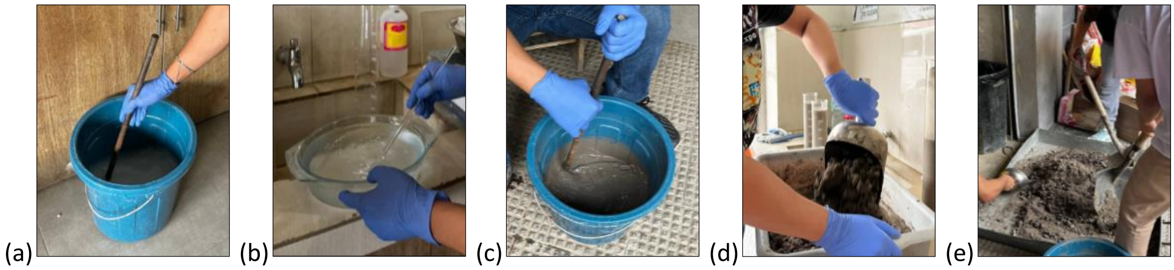

Fig. 1 Sample Preparation Procedure: (a) preparation of NaOH, (b) preparation of Na_2SiO_3, (c) mixing of alkali activator solutions and fly ash to produce FAG, (d) preparation of the soil, and (e) mixing of subbase soil and FAG

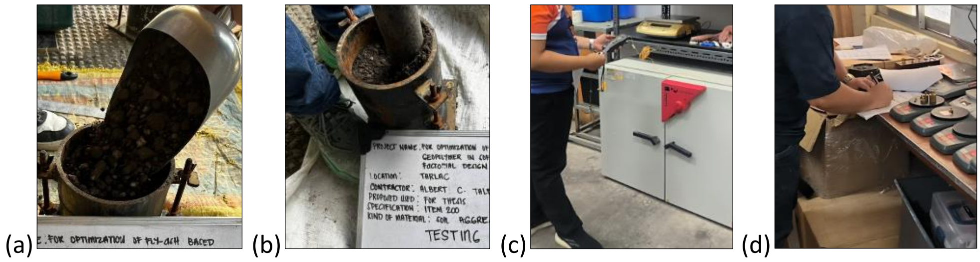

Fig. 2 Compaction Testing Procedure: (a) placing the sample on the compaction mold, (b) compaction of the sample at 56 blows, (c) oven-drying of representative soil sample, and (d) determining the MDD and OMC

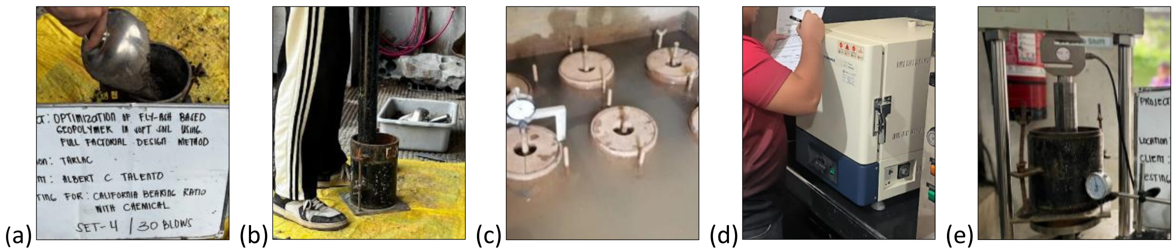

Fig. 3 CBR Testing Procedure: (a) placing the sample on the CBR mold, (b) compaction of the sample at different compaction effort levels, (c) soaking of the sample for four days, (d) determining the dry densities and MDD of the samples, and (e) determination of the CBR values at different compaction efforts using a CBR machine.

4. RESULT AND DISCUSSION

4.1 Compaction test results

The results of the compaction test are presented in Figures 4 and 5, respectively.

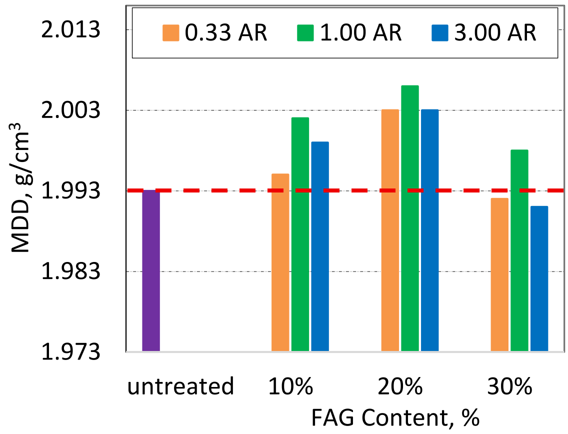

Fig. 4 MDD of untreated and FAG-treated soil at varying FAG content and AR

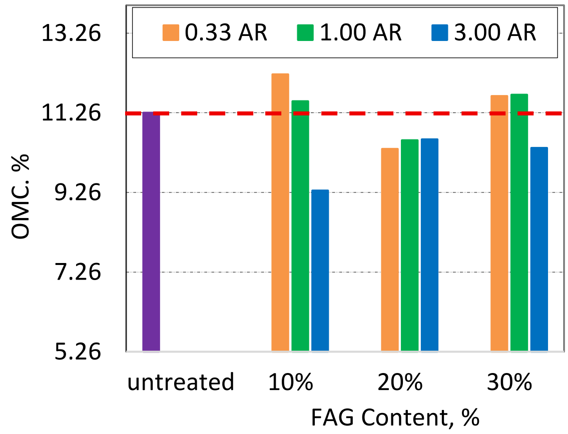

Fig. 5 OMC of untreated and FAG-treated soil at varying FAG content and AR

The MDD of the untreated subbase soil is observed to be 1.993 g/cm^3, and the corresponding OMC is 11.260%. The resulting values are adopted as the baseline references (red dash line) for comparison in this study. On the other hand, the addition of varying FAG and AR on the silty subbase soil resulted in both an increase and a decrease in MDD and OMC. These variations indicate that the compaction properties are influenced by the interaction between FAG content and AR, demonstrating that the behavior is not governed by a single parameter but by their combined and interdependent effects.

Generally, an increase in MDD is considered an indicator of soil improvement. This behavior is observed at FAG contents of 10% and 20% across all AR, where a slight increase in MDD is noted. However, when the FAG content increased to 30%, and the AR are 0.33 and 1.00, the resulting MDD becomes lower than that of the untreated soil. This unusual behavior can be ascribed to the specific gravity of both soil and FA. The specific gravity of FA used in the study is 2.14, which is lower than that of silt soil, which has a typical specific gravity ranging from 2.66 to 2.70 [37]. As the amounts of FA in the soil increase, the specific gravity of the resulting mix of soil and FA decreases, which leads to lower MDD. This observation is consistent with the findings of Teing and Thiha [38-39].

On the other hand, a slight increase in OMC is observed at FAG content of 10% and 30% with ARs of 0.33 and 1.00. This behavior can be attributed to the alkali molarity, which potentially slows down the geopolymerization process and affects the moisture requirement during compaction. This observation is similar with the findings of Muntaha [28] and Turan [42]. Further, a notable reduction in OMC is observed at FAG content of 20% across all AR, as well as at FAG content of 10% and 30% with both AR of 3.00. The observed behavior can be ascribed to the role of AA in the geopolymer mixture, which acts as a lubricating medium that diminishes repulsive forces and augments the interparticle sliding of the silt particles. The introduction of the AA can result in lubrication, which leads to a decrease in the amount of free water needed to achieve optimal compaction, hence reducing the OMC. In addition, due to the insertion of FA during the process of geopolymerization, silt is partially replaced with FA. Thus, the inclusion of the FA in the geopolymer resulted in a reduction in the total surface area of the FA particles possessing silty characteristics, thereby decreasing the need for water. These observations are similar with the findings of Hartono [5], Ahmad [41], and Turan [42].

Overall, soil stabilization with FAG increases the MDD by 0.65%, with the highest MDD of 2.006 g/m^3 observed at FAG content of 20% with AR of 1.0 (balance AA). On the other hand, the addition of FAG into the soil decreases the OMC by 17.34%, with the lowest OMC of 9.307% is observed at FAG content of 10% with AR of 3.00 (higher proportion of NaOH). The increase in MDD and decrease in OMC are ascribed to the ability of FA to fill the void spaces in the soil, and the polymerization reaction causes the soil containing FAG to lose moisture, increasing the MDD and decreasing the OMC [40].

4.2 CBR test results

The result of the CBR test to determine the CBR under the soaked condition is presented in Figure 6.

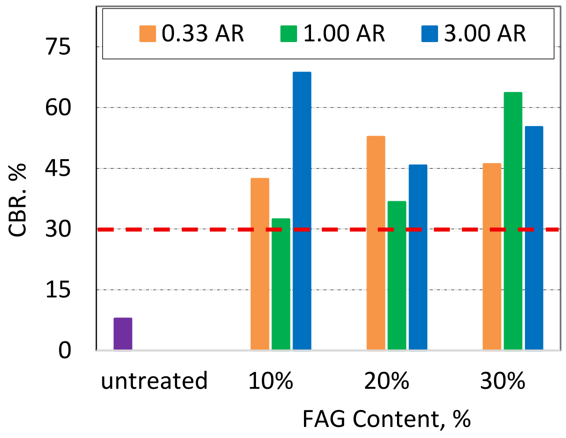

Fig. 6 CBR of untreated and FAG-treated soil at varying FAG content and AR

The CBR of the untreated subbase soil is observed to be 7.84%, which is lower than the prescribed minimum requirement of 30% (red dash line) established by DPWH [7]. However, with the addition of FAG on the soil, the CBR significantly increases and exceeds the prescribed minimum requirement. Despite these significant improvements in the CBR, abrupt decreases are also observed at certain combinations of FAG content and AR. For instance, at an AR of 0.33, the CBR consistently increases with increasing FAG content up to 20%; however, further increases beyond this level result in a slight reduction in CBR. These observations are similar with the findings of Ahmad [41], which observed that a higher proportion of Na_2SiO_3 in the AA contributes to a consistent increase in strength; however, increasing the FA content beyond the optimum level, where maximum strength is achieved, leads to a significant reduction in strength.

Meanwhile, at an AR of 1.00, the CBR exhibits a continuously increasing trend with increasing FAG content. On the other hand, at AR of 3.00, early strength development is observed at FAG of 10%; however, further increase beyond this level results in an abrupt reduction in CBR.

Moreover, the addition of FAG into the silty subbase soil resulted in a significant increase in CBR of up to 775%, with the highest recorded CBR of 68.6% with FAG content of 10% and AR of 3.00 (higher proportion of NaOH). This observation aligns with the study of Santhikala [29] that an increase in NaOH in AA increases the strength of FAG treated soil. Furthermore, increasing the NaOH proportion in the AR can enhance strength development; however, caution must be exercised, as excessive NaOH content may lead to a reduction in strength.

5. CONCLUSION

The results of the study show that the addition of FAG into silty subbase soil leads to improved compaction (high MDD and low OMC) and enhanced strength (high CBR under soaked condition) properties. However, the extent of these improvements varies, depending on the FAG content and AR. In this study, the highest MDD is obtained at FAG content of 20% and AR of 1.0, with a corresponding value of 2.006 g/m^3. This represents a slight increase of about 0.65% from the untreated soil. Moreover, the lowest OMC is 9.307%, which is observed at FAG content of 10% and AR of 3.00. The decrease is about 17.34% relative to the untreated soil. On the other hand, the CBR results across all soil-treated with FAG exceeded the prescribed DPWH minimum requirement of 30%, indicating that the FAG can be considered as a viable additive/stabilizer in silty subbase soil application. Likewise, a significant increase in CBR of up to 775% with respect to the untreated soil is observed at FAG content of 10% and AR of 3.00, with the corresponding CBR of 68.6%. Accordingly, the results of the higher proportion of NaOH in the AR (3.00) are observed to have developed a significant improvement in MDD, OMC, and CBR compared with the higher proportion of Na_2SiO_3 in the AR (0.33). However, caution must be exercised, as excessive NaOH content may result in further reduction in strength.

Overall, the study determined that the varying FAG content and AA in FAG influence the compaction and strength properties of silty subbase soil; however, it should also be acknowledged that the present study is limited to only three evaluation metrics. As such, the scope does not include long-term durability performance, microstructural analysis, or field-scale validation, which may be necessary to fully establish the broader applicability and sustainability of the observed improvements.

6. ACKNOWLEDGMENTS

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