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Unconfined Compressive Strength of Stabilized Clay Using Rice Hull Ash – Derived Geopolymer

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Abstract — *Rice hull ash (RHA) is an industrial by-product that has pozzolanic properties and is rich in silica making it suitable as an aluminosilicate precursor for geopolymers. Geopolymers are the product of geopolymerization from the dissolution of aluminosilicate materials by an alkali activator. The effectiveness of geopolymers as admixture in concrete has been proven in several studies. This research determined the effects of RHA-based geopolymers on the unconfined compressive strength (UCS) and the corresponding stress-strain behavior of lean clay. Clay-only specimens were prepared as control. Samples with 5%, 10%, and 15% geopolymer content by weight were prepared and were cured for 7 and 28 days. In terms of UCS, the curing period did not have a significant effect regardless of the geopolymer content. The curing period also did not have significant effects on the stress-strain behavior of the geopolymerized samples. The addition of geopolymer in the soil sample increased the UCS of the soil. The higher the geopolymer content, the higher the UCS of the sample. There was a 547% increase in the UCS of the plain soil to the sample with 15% geopolymer content with a mean value of 418.5 kPa. Post-peak behavior of samples with higher geopolymer content exhibited pronounced strain softening.*

Keywords — *soil stabilization, geopolymerization, unconfined compressive strength*

I. INTRODUCTION

1.1 Background of the Study

Structures rely their overall stability on their foundation. With the archipelagic nature of the Philippines where land space is a luxury, it is common that these lot spaces contain clayey soils. Clays have a strong ability to retain water which softens it and in turn causes it to have poor strength. This characteristic constitutes to several construction difficulties. Hence, there is a need to stabilize the soil to improve its geotechnical properties making it suitable to support heavy structures such as landfills, dams, and reservoirs, among others.

There are several methods of soil stabilization. One of the emerging methods is the use of geopolymers. Geopolymers are amorphous gel that have hardened formed by the chemical process of geopolymerization. Geopolymerization is the dissolution of the aluminosilicate precursors and alkaline activators which are the two main components of geopolymers. Common alkaline activators are sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). Aluminosilicate precursors are raw materials that contain silica (SiO_2) and aluminum oxide (Al_2O_3). Source materials for aluminosilicate precursors should be rich in silicon (Si) and Aluminum (Al). Some of the naturally occurring materials that have been used as geopolymer precursors are fly ash, red mud, and rice hull ash.

Rice hull is the shell of the rice grain that constitutes about 20-22% of its weight. The Philippines produces about 19 million metric tons of rice every year which creates more than 3 million metric tons of rice hulls. The rice hull is indigestible to humans hence it is considered as an agricultural waste. They are used as garden soil additive for ornamental plants and as poultry farm beddings in some parts of the Philippines. However, rice hull is most used as burner fuel, utilizing its high heat value of 13-16 megajoules per kilogram. The heat generated from burning the hull can be used in industries involving boilers, cooking, drying and energy production. Rice hulls burned from these industries produce a by-product which is rice hull ash (RHA). With the need to reduce these waste materials, several studies have incorporated the use of rice hull ash especially in soil stabilization since it was found out that they contain high amount of silica and has pozzolanic properties. With this, it will be beneficial not just to the environment but also to the farmers if this industrial by-product turns into something useful.

1.2 Problem Statement

This study addresses the effectiveness of the geopolymerization of rice hull ash (RHA) specifically in the compressive strength of lean clay. The compressive strength is a significant parameter in construction of many earth structures and the improvement of these properties may widen the possible uses of clayey soils. Moreover, rice hull is a by-product from the agriculture industry, and it will be beneficial for the environment if there are more effective ways to use it.

1.3 Objectives

The general objective of the study is to determine the effects of RHA-based geopolymers on the unconfined compressive strength (UCS) of lean clay. Specifically, this study aims to: 1) determine the effects of curing period on the UCS and corresponding stress-strain behavior of geopolymer-treated lean clay; 2) identify the percentage of geopolymer content that will result to the highest UCS; and, 3) describe the stress-strain behaviors and failure patterns of geopolymerized samples.

1.4 Significance of the Study

The use of industrial by-product materials such as RHA in stabilization of soils for civil engineering applications poses significant effects in the environmental and economic aspects of geotechnical engineering. Moreover, the addition of geopolymer additives to soil is an emerging method of soil stabilization. Studying about it further widens the knowledge about its effectiveness.

1.5 Scope and Limitations

For the composition of the stabilized soil samples, several parameters are kept constant such as size of RHA and soil particles, NaOH-to-RHA ratio, RHA-to-clay ratio (for RHA-treated soil) and water content which are based on literature.

It is an assumption that the RHA samples are taken from one source only and are burned at equal temperatures. The effects of burning conditions of RHA will not be tackled in this study.

Tests, such as scanning electron microscopy, to verify the level of geopolymerization that occurred in the samples were not conducted.

1.6 Related Literature

Soil stabilization is the process of improving the physical and mechanical properties of soil to meet its purpose in various geotechnical applications. Since naturally there are some undesirable properties of soils such as high plasticity, low permeability, etc. which may or may not be good for its intended use, soil improvement techniques are essential. For instance, clay soils tend to lose their stiffness if they are saturated with water. Problematic clay soils such as soft clays pose threats in buildings and foundations due to its low compressive strength and excessive settlement. There are several ways to stabilize the soil. One of which is the use of admixtures that will be incorporated with the soil. Admixtures such as cement, fly ash and lime have pozzolanic properties that bind the soil particles more resulting to increased compressive strength, reduced swelling, enhanced California bearing ratio (CBR) and resistance against the effect of moisture and freeze. [1]

Geopolymerization is the synthesis of geopolymers through the dissolution of aluminosilicate materials by alkali activator solutions [2]. Various materials such as mine tailings, slags, glass, fly ash, and agricultural and industrial by-products are now used as aluminosilicate materials to synthesize geopolymers. Provis et al. [3] found out that geopolymers could be an alternative for cement at 80% lower carbon footprint. Geopolymerization comprises three major steps. First, leaching occurs to the aluminosilicate materials through dissolution by alkali activator and results into aluminate and silicate tetrahedral monomers. These monomers eventually form oligomers that cause further dissolution of aluminosilicate precursors thus, making the solution saturated of silicate, aluminate, and aluminosilicate components. Ultimately, the solution polymerizes into an amorphous gel. The amorphous gel condenses and hardens forming geopolymers. The effectiveness of geopolymers on improving the strength of concrete has been proven several times [4].

Alkali activator plays an important role as the catalyst for the reactivity in the geopolymerization process. It dissolves the pozzolanic material or the aluminosilicate material which results into the production of reactive aluminates and silicates. Alkali activators can be classified as alkalis or silicate additives [5]. Alkalis include alkali solutions such as sodium hydroxide (NaOH), potassium hydroxide (KOH), sodium carbonate (Na_2CO_3), and potassium carbonate (K_2CO_3) while silicate additives include sodium silicate (Na_2SiO_3) and potassium silicate (K_2SiO_3).

Fernandez-Jimenez [5] claimed that sodium geopolymers have higher mechanical strength compared to potassium geopolymers mainly because sodium geopolymers accelerates more the reactions involved in geopolymerization. This is supported by the findings of Zhang [5] which state that sodium hydroxide breaks down more aluminates and silicates compared to other alkali activators.

Rice hull is the protective hard coating of a rice grain and is 20% of the mass of a whole rice grain. Rice hull is composed of hemicelluloses, cellulose, lignin, ash, silica, and other elements. However, the composition of rice hull is dependent on the variety of rice, soil chemistry, fertilizer used, and the geographic location of its production. According to the Philippine Statistics Authority, the amount of rice that the Philippines produced in 2019 was 19.07 million metric tons. With this, around 3.8 million metric tons of rice hull was generated from the production of rice in 2019 alone.

Rice hull ash (RHA) is the by-product of the combustion of rice hull for energy source and similar purposes. One of the main applications of RHA is its use as a source of silica and its pozzolanic properties. Zhang et al. [7] observed significant increase in compressive and flexural strengths in the modified concrete compared to those of the regular concrete. Furthermore, research have been conducted regarding the potential of RHA as soil additive to improve the geotechnical properties of various soil types. With this, the potential of RHA in civil engineering applications has continuously been explored and it still pretenses possible research in the future in other fields.

Alhassan [8] studied the potential of RHA for soil stabilization by identifying the effects of RHA in terms of the compaction characteristics, California bearing ratio (CBR), and unconfined compressive strength (UCS). Alhassan observed that the UCS peaked between 6% and 8% RHA content for all the curing periods that Alhassan used. The decline in UCS after 8% could be the effects of excess RHA in the soil which formed weak bonds, instead.

Orale [9] investigated the impacts of RHA stabilization to the CBR value, Atterberg limits, and permeability of the treated soil with 2%, 4%, and 6% RHA content. With regards to permeability, Orale (2008) used compacted specimens in his tests. He observed that the permeability decreases as the RHA content of the treated soil increases. At 6% RHA content, the permeability was 0.000009 cm/s which was 97.24% lower than that of the untreated soil.

One of the few studies about the potential of geopolymers as soil stabilizer is made by Dungca and Codilla [10] which discussed the results of stabilizing silty sand using fly ash-based geopolymers as a material for embankments. The geopolymers were synthesized using 14M NaOH solution from NaOH pellets instead of the usual liquid alkali activators. They used 10%, 20%, and 30% geopolymer for their test cases to check strength properties such as CBR and UCS of the treated soil. Both properties exhibited an increasing trend as the geopolymer content of the samples was increased. The resulting UCS for the 30% geopolymer content was 1,349.74 KPa which was significantly higher than that of the 10% geopolymer content which was 78.29 KPa.

Kaur et al. [11] did a study on the compressive strength of rice hull ash based geopolymers using sodium hydroxide (NaOH) as alkali activator. They synthesized five geopolymer test cases with varying NaOH concentration and alkali activator to binder (AAB) ratio which in this case was rice hull ash. The samples were cured for 3 days, 7 days, 14 days, and 28 days before undergoing unconfined compression test. They found out that the maximum compressive strength was obtained by the optimum mix of 14 M NaOH and 0.7 AAB ratio at 39.95 MPa. With regards to varying AAB ratio, there was an increasing trend as the AAB ratio was increased. Similarly, as the molarity of NaOH was increased, the compressive strength increased as well.

II. MATERIALS AND METHODOLOGY
III.

2.1 Material Acquisition and Preparation

The soil used for the study was obtained from Barangay Batasan Hills, Quezon City through Geotechnics Philippines, Inc. (GPI). Routine geotechnical tests were performed on the soil to determine its soil index properties and its classification.

The rice hull ash (RHA), which is the aluminosilicate precursor of the geopolymer used, was obtained from the manufacturing company, Philbelt, located in Fairview, Quezon City. The rice hulls were used by the company for fuel to power their operations. The by-product of burning these rice hulls – the rice hull ash – was deemed waste, but was collected for the purposes of this research. The duration and temperature during calcination of the rice hulls were not available. No further physical preparation (i.e. milling and burning) was done to the acquired RHA. The chemical composition of the RHA was determined by the non-destructive X-ray Fluorescence analyzer.

2.2 Routine Tests

To be able to classify and determine its index properties, the following routine standard tests and methods were performed: Particle Size Analysis (ASTM D422), Atterberg Limits Test (ASTM D4318), Specific Gravity Test (ASTM D854), Standard Proctor Test (ASTM D698) and Soil Classification (ASTM D2487).

2.3 Soil Sample Preparation

To determine the effect of the geopolymer additive in the unconfined compressive strength of the soil, soil samples were designed to contain 0%, 5%, 10%, and 15% of geopolymer by weight. The samples containing geopolymer additives were cured in 7 and 28 days. The test cases are summarized in Table 1.

Table 1. Summary of Test Cases

Test Case	Geopolymer Content	Curing
0%	Clay Only	-
5% (7)	5% Geopolymer	7 days
5% (28)		28 days
10% (7)	10% Geopolymer	7 days
10% (28)		28 days
15% (7)	15% Geopolymer	7 days
15% (28)		28 days

All water content of the test cases was kept constant as the optimum moisture content of the soil. Five samples were prepared for each case.

To ensure equal distribution of particles, soil passing through Sieve No. 4 and RHA passing Sieve No. 40 were used. The composition of each test case was based on previous studies conducted, such that the optimum ratio of the sample composition established from previous experiments was utilized. The total liquid content (NaOH solution + water) for all test cases containing geopolymer additive was set as the optimum moisture content of the soil and all materials were hand mixed. These specifications are summarized in Table 2.

Table 2. Specification of Test Case Preparation

Test Case	Specifications
0%	Soil passing sieve no. 4
5%, 10%, 15%	NaOH Solution: RHA = 0.7 14 M NaOH Solution Soil passing sieve no. 4 Black RHA passing sieve #40

For the geopolymer synthesis, the NaOH solution-to-RHA ratio was set at 0.7 in which the NaOH solution had a concentration of 14 M. The solution was then mixed with RHA and ample amount of water was added to create a geopolymer paste. Soil was then mixed with the paste and hand-mixed thoroughly ensuring that all particles are properly mixed while continuously adding the remaining water needed. The mix design for the cases is shown in Table 3.

Table 3. Mix Design by Weight for Test Case Preparation

Test Case	Soil (g)	RHA (g)	NaOH (g)	Water (g)
0%	1000	105.7	0	320.7
5%	1000	40.9	28.6	292.0
10%	1000	86.3	60.4	260.2
15%	1000	137.1	96.0	224.7

2.4 Unconfined Compression Test

The samples were compacted into a cylindrical mold with a height of 4 inches and a diameter of 2 inches into 3 layers with 12 blows of the rammer each. After compaction, the samples were left to settle for 24 hours while still in the mold. Then, they were taken out and wrapped with moist cotton cloth and placed inside a Styrofoam box to facilitate moist curing.

Unconfined compressive test was performed following the standard method from ASTM D2166. Using the Instron Bluehill instrument, the unconfined compressive strength of each sample was obtained at a strain rate of 2 mm/min until cracking was observed. The moisture content of the samples after testing was determined by obtaining a portion of the specimen and weighing it before and after oven-drying as specified by the ASTM D2216.

III. RESULTS AND DISCUSSION

3.1 Soil Analysis

The soil index properties were determined in accordance with ASTM standards. Table 4 summarizes the results of these geotechnical routine tests.

Table 4. Soil Index Properties

Soil Property	Soil Sample
Passing #4 sieve	99.87%
Passing #10 sieve	99.18%
Passing #20 Sieve	95.26%
Passing #200 Sieve	50.72%
Liquid Limit	49
Plastic Limit	27
Plasticity Index	22
Specific Gravity	2.42
USCS	CL (Lean Clay)
Max. Dry Unit Weight	12.42 kN/m^3
Optimum Moisture Content	32.07%

3.2 Rice Hull Ash Composition

The XRF analyzer determined the composition of rice hull ash and the results are summarized in Figure 1. The most abundant elements in the sample are light elements (hydrogen to sodium) which is comprises 54% of the ash. Silicon, which is necessary for geopolymerization, comprises 43% of the ash composition.

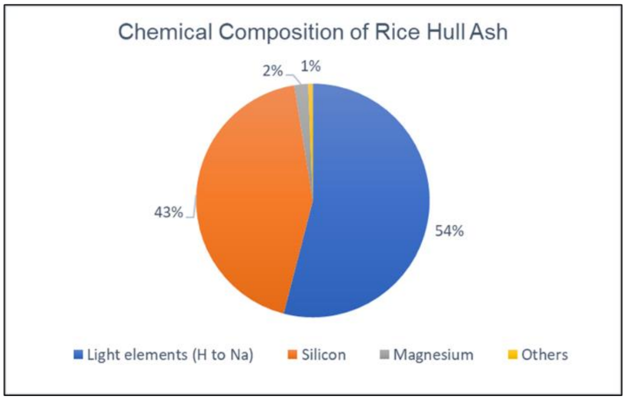

Figure 1. Chemical Composition of RHA

3.3 Effects of Curing Time

Figure 2 shows a scatter plot of unconfined compressive strength of the cured samples with different geopolymer contents. Figures 3, 4, and 5 shows the stress-strain curves of Case 5%, Case 10%, Case 15% for both curing periods, 7 days and 28 days.

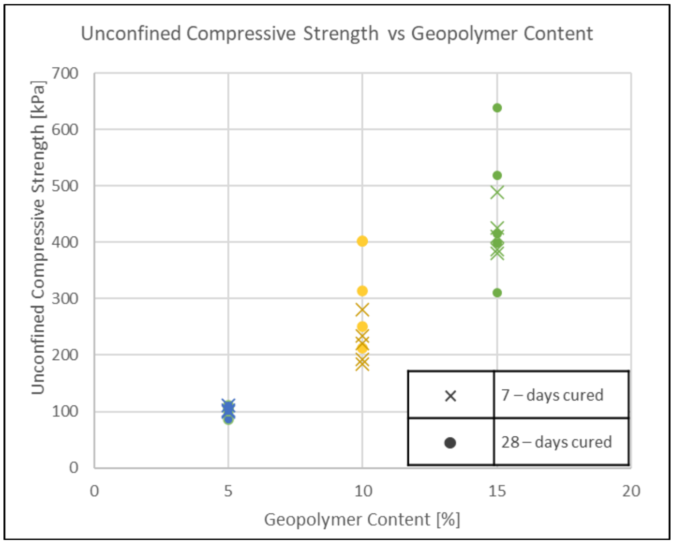

Figure 2. Scatter Plot of UCS vs Curing Period and Geopolymer Content

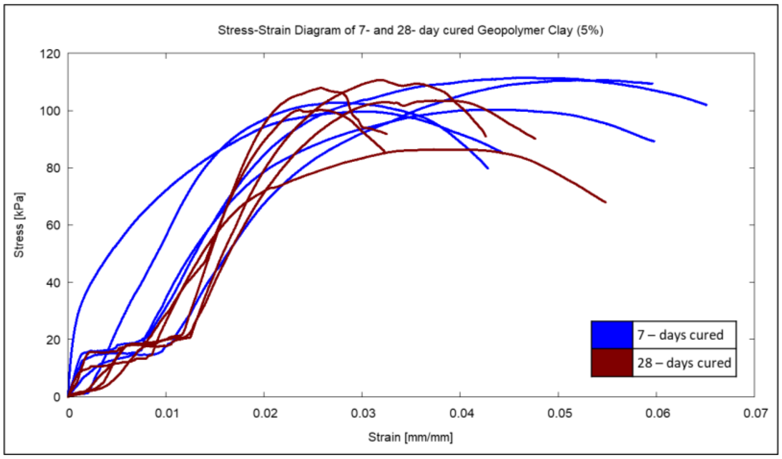

Figure 3. Stress-Strain Diagrams of 5% Geopolymer Clays

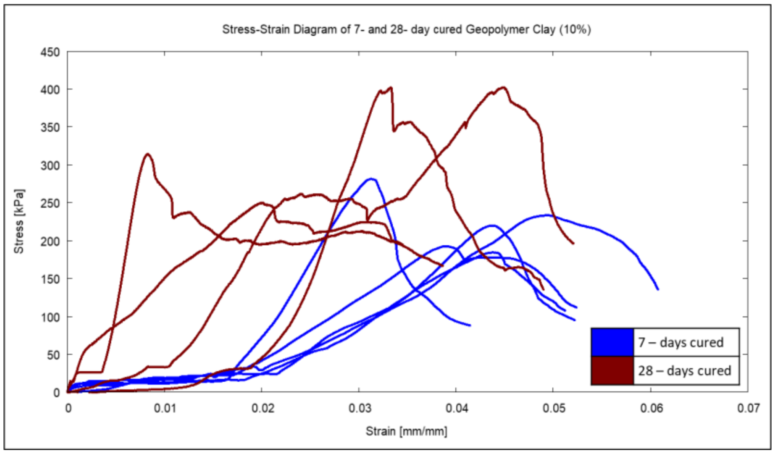

Figure 4. Stress-Strain Diagrams of 10% Geopolymer Clays

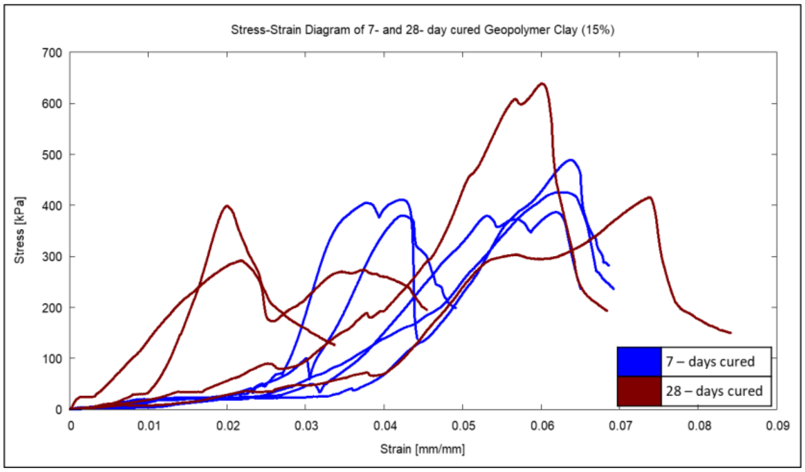

Figure 5. Stress-Strain Diagrams of 15% Geopolymer Clays

To determine the effects of curing period to the unconfined compressive strength (UCS), the UCS values of the geopolymer-stabilized samples are compared using a series of statistical tests. The tests showed that the curing period has no significant effect in the UCS of the geopolymer treated samples. This could be attributed to the immediate geopolymerization reaction between the alkali activator (NaOH) and aluminosilicate material (RHA) once they interact with each other during mixing.

As shown in Figure 3, the stress-strain diagrams of the samples with 5% geopolymer content, both with 7-day and 28-day curing have generally similar trends. The peak stresses fall in the same range of strains, at 2% to 4%.

In Figure 4, the stress-strain diagrams of the samples with 10% geopolymer content exhibit a difference due to the curing time. Although the peak stresses are not of significant difference, samples cured for 7 days develop their peak stresses at higher strains, 3% to 5%. Samples cured for 28 days have varying stress-strain behavior as shown.

Figure 5 shows the stress-strain diagrams of samples with 15% geopolymer content. The plots as shown have varying behaviors. Plots of 7-day and 28-day curing periods do not exhibit significant differences based on these samples.

3.4 Effects of Geopolymer Content

Figure 6 shows a scatter plot of the unconfined compressive strengths of the plain (0%) and stabilized samples (5%, 10%, and 15%). For this analysis, the stabilized samples considered are those cured for 7 days. The mean unconfined compressive strengths and water content at failure are summarized in Table 5. Statistical tests were conducted to these results to see if there are any significant difference in the strengths.

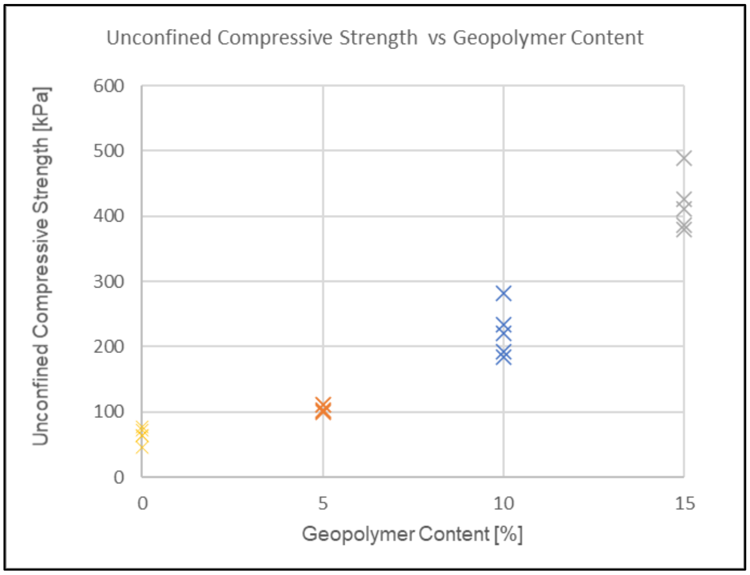

Figure 6. Scatter Plot of UCS vs Geopolymer Content

Table 5. Mean Values of Unconfined Compressive Strength for each Geopolymer Content

Geopolymer Content (%)	Mean Unconfined Compressive Strength (kPa)	Water Content (%)
0	64.6	17.11
5	105.0	20.66
10	222.4	25.17
15	418.5	23.04

Statistical tests showed that there is a significant difference among the UCS of soil samples with different geopolymer content. With this, the addition of geopolymer significantly increased the UCS of the samples. Moreover, there is an increase of 547% in the UCS of the plain sample to the treated sample with 15% geopolymer content. The increase in strength from plain sample to the sample with 5% geopolymer content is 62% while the strength gain from 0% to 10% geopolymer content is 244%.

The increase in UCS is attributed to the binding effect of geopolymers to the soil sample since the incorporation of geopolymers in the soil resulted to the formation of amorphous gels. As the geopolymer content increases, the amount of geopolymer gels increases which make the structure of particles more compact because they cannot be separated and are connected by geopolymer gels [9].

The stress-strain diagrams of the samples were plotted in juxtaposition in Figure 7. Significant differences can be observed in the plots. Samples with higher geopolymer contents have higher peak stresses. A general trend can be observed that with increase in geopolymer content, the peak stress tends to occur at a higher strain. Samples with 0% and 5% geopolymer content achieved peak stress at strains from 2% to 3%. Samples with 10% and 15% geopolymer content developed peak stresses at strains from 3% to 7%.

In the same scale, the curves generated by the 0% and 5% samples were flatter than those of the 10% and 15% samples. Samples with higher geopolymer content have higher modulus as manifested by the steeper curves in the elastic region.

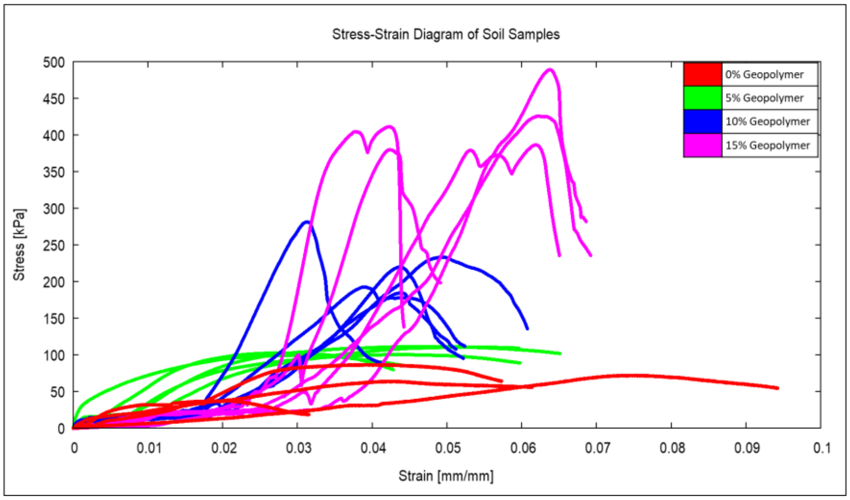

Figure 7. Stress-Strain Diagrams of Soil Samples at Different Geopolymer Concentrations

Post-peak behavior of the samples also has significant differences. The 0% and 5% samples generally follow an elastic-perfectly plastic behavior as manifested by flatter post-peak trend. The 10% and 15% samples have a more pronounced downward slope post-peak. In this case, these materials exhibit strain softening behavior. Strain softening is a common behavior of stiff clays and soft rocks. It is also worth noting that the typical UCS of very stiff clay and soft rock is 200 kPa to 400 kPa. [12]

3.5 Failure Patterns

Figure 8 presents the failure patterns of the soil samples at different geopolymer contents. The most prominent failure pattern is the occurrence of a well-defined shear plane. A few samples, regardless of the geopolymer content, failed due to multiple shear failure planes and bulging in the middle. It was observed that sample with higher geopolymer content tend to have small surface cracks. This may be a manifestation of the brittleness of geopolymer materials.

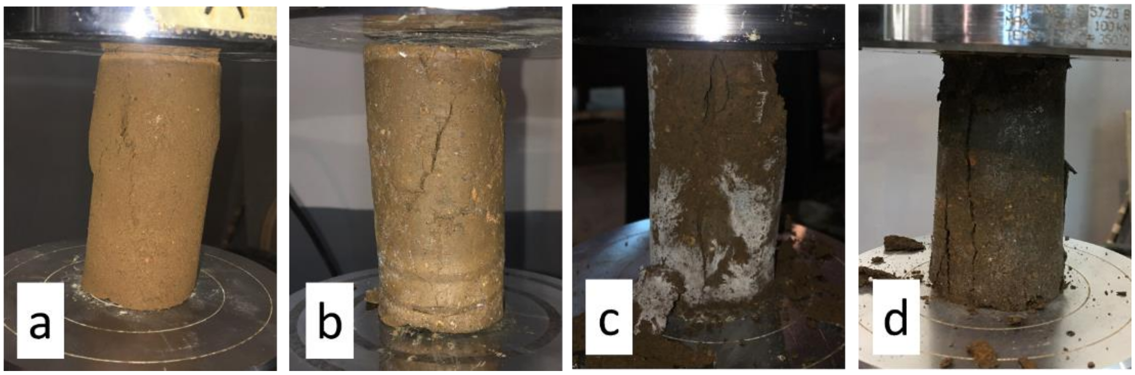

Figure 8. Typical Failure Patterns: a. 0%, b. 5%, c. 10%, d. 15%

IV. CONCLUSIONS AND RECOMMENDATIONS

This study analyzed the effects of rice hull ash-based geopolymers on the unconfined compressive strength and stress-strain behavior of clay. The clay sample used in the study is lean clay with a maximum dry unit weight of 12.42 kN/m^3 and an optimum moisture content of 32.07%. The geopolymers used are derived from black rice hull ash that is composed of 43% silicon.

The RHA-based geopolymer was found to modify the unconfined compressive strength and the stress-strain behavior of the soil. It was observed that the curing period did not have a significant effect on the unconfined compressive strength of stabilized clay regardless of the amount of geopolymers present in the soil. This could be explained by the fast occurrence of the geopolymerization processes the moment all its components start to interact with each other.

The samples with 15% geopolymer content exhibited the maximum mean unconfined compressive strength of 418.5 kPa. The addition of this amount of geopolymer increased the strength of the soil by 547%. Samples with higher geopolymer content have a higher unconfined compressive strength.

Samples with higher geopolymer content tend to develop peak stresses at higher stains. Samples with 0% and 5% geopolymer content achieved peak stress at strains from 2% to 3%. Samples with 10% and 15% geopolymer content developed peak stresses at strains from 3% to 7%. Samples with 10% and 15% geopolymer content exhibit more pronounced strain softening behaviors. In terms of UCS and post-peak behavior, samples with higher geopolymer content exhibit properties of stiff clays and soft rocks.

Well-defined shear plane failures were observed in all test cases with some having bulging failures. It was observed that highly geopolymerized samples tend to have cracked surfaces before failure which may be attributed to the brittle nature of geopolymer materials.

The study was limited to the effect to the unconfined compressive response of geopolymerized samples at 5%, 10%, and 15% geopolymer contents. The authors recommend determining the unconfined compressive strength of pure geopolymer samples to extend the understanding of the strength of the additive material. The authors also recommend determining the UCS of clays stabilized with the rice hull ash additive only which will exhibit pozzolanic reaction. This can be used to compare which method of stabilization would results in more improvements in the soil (i.e. increase in strength, ductility, etc.) Further, in-depth geochemical studies can be used to validate the findings of the study. Scanning Electron Microscopy (SEM) test can visualize the microstructures of the plain clay and stabilized clay. Comparison of these microstructures can confirm the geopolymeric reaction in the particle level and validate the increase in the unconfined compressive strength is attributed to the binding effect of the geopolymer.

VI. ACKNOWLEDGEMENTS

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