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Experimental Study on Bearing Capacity of Alkaline Activated Granular Asphalt Concrete Columns on Soft Soils

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Abstract

In civil engineering, alternative materials showed rapid progress. Asphalt derived from Buton Island in Indonesia, also known as Asbuton, was located in the limestone bedrock. A large deposit of Asbuton could guarantee the supply of alternative construction materials. In that regard, Asbuton performance as an alternative material to several subjects needs to be analyzed. Therefore, this study was conducted to analyze Asbuton's behavior as a filler in a floating column model as a soft soil improvement concept. Asbuton added to sand and gravel mixture as filler and waterglass as a binder. CBR samples were tested to acquire the optimum composition with varied curing days namely 0, 3, and 7 days, following ASTM D-1883, followed by a compressive column model test which was based on ASTM D-2166. Finally, the column applied to the soft soil layer to be tested in a loading test, and the results are then compared for each composition. The results showed that the granular material's composition including Asbuton, the waterglass content, and the curing period significantly affect the engineering properties of the artificial column. The results revealed that the granular column with the addition of waterglass could increase soil's load capacity and reduce the settlement of soft soils.

Keywords: California Bearing Ratio (CBR); Soft Soils; Asbuton; Stone Column; Alkaline Activated.

1. Introduction

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The soil conditions influence the stability of a structure. To increase the mechanical value of the soil, soil stabilization must be carried out, whether mechanically or chemically. Stone columns (or granular columns) are one type of mechanical soil improvement, which is now increasingly used for soil improvement. Soil improvement mechanisms depend mostly on soil type. Several methods are available for improving granular soils such as layered compaction [1]. But for soft soil, improvement methods could vary depending on a certain condition, such as material availability [2]. Considering the abundant amount of material and necessity to increase the stiffness of a stone column, this study was conducted to analyze the performance of Asbuton and waterglass-stabilized stone column with geogrid encasement in reducing settlement of soft soil layer due to static loading. The final result will be delivered systemically according to the general process which presented in several sections; Introduction to give the readers a brief review of the paper, Literature Study to provide supporting theories from previous study and findings, Methodology to state the process of the research, Result, and Discussion to represent the data gathered along with the research, and Conclusion to state our final finding and analysis result.

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2. Literature Review

2.1. Soil Settlement

The settlement of soils in response to loading can be broadly divided into two types: elastic and time-dependent settlement. Elastic settlements are the simplest to deal with; they are instantaneous, recoverable, and can be calculated from linear elastic theory. Time-dependent settlements occur in both granular and cohesive soils, although the response time for granular soils is usually short [3].

Settlement analysis is very important and should be calculated before construction begins [4]. The settlement pattern of an embankment may not always be the typical one in which the maximum settlement occurs at the center. Other types of patterns may be developed with changes in embankment width or surcharge arrangements, which will require special settlement calculation methods and engineering measures. Four possible settlement patterns are one-dimensional, sagged, typical, and transitional [5].

The primary application of various geotechnical construction techniques is for ground improvement. Many soil improvement methods have been developed due to the ongoing increase in urban and industrial growth and the need for greater access to lands. Stone columns are one of the best available techniques for soft clay soil improvement. In this method, subsurface soils that are weak and unstable are replaced with compacted dense aggregate columns that often entirely penetrate the weak layers [6].

2.2. Buton Asphalt/Asbuton

Asbuton is a natural rock asphalt that was founded on the island of Buton in Southeast Sulawesi province, has large deposits but not yet well utilized [7]. Asbuton deposits are mainly boulders with varying thicknesses between 1-40 meters. The potential for Asbuton deposits included in 2 categories, namely: measured reserves and inferred reserves. The amount of potential Asbuton in the measured reserves with a volume of 6.1 million cubic meters (m³) is 17.0 million tons. The potential of inferred Asbuton reserves with a volume of 22.2 million cubic meters (m³) is 62.1 million tons "Suryanto". Limestone as a source rock from Asbuton deposit is another mineral that needs to be studied further for its quantity and quality during asphalt mining activities. Limestone handling efforts need to be planned properly to optimize the utilization of all potential existing deposits.

Table 1. Buton asphalt deposit

No	Block	Distribution Area (m ²)	Thickness (m)	Deposit (ton)
1	Rongi	57.755.000	78	226.165.670
2	Kabungka	181.004.200	78	312.718.460
3	Lawele	130.906.500	78	99.786.080
4	Epe	1.720.000	78	2.011.157
5	Rota	4.530.000	78	19.596.780
6	Madullah	620.000	78	2.682.120
Total		376.537.850		662.960.267

The estimated of Asbuton deposit in Kabungka and Lawele is about 670 million tons [8]. Asbuton has a bitumen content of about 30% and minerals about 70% which are originally in the form of limestone and sandstone [9]. Recently, Asbuton started to apply as additive material, for example in making a paving block [7].

2.3. Sodium Silicate/Waterglass

Chemical stabilization is an effective method to improve the soil properties by mixing additives to soils. For many years, the term chemical grout was synonymous with sodium silicate grouts but in the last three decades a lot of chemical compounds produced as chemical grouts which provide a wide selection [10].

Waterglass or sodium silicate is a water-soluble salt with a composition of sodium metasilicate (Na₂SiO₃ or NaSiO₃.9 H₂O). In solid form, it looks like a crystal, dissolves in warm water, and melts at 1018 °C. The waterglass with its liquid form, the pores of the soil-filled by binding it to become stronger. Although at room temperature, the form is a [9], with the addition of an appropriate amount of water, the movement to penetrate pores becomes easier [11]. The construction industry has made only limited use of sodium silicate solutions, confining the applications to unusual foundation and construction problems and road construction operations of a very minor extent [12].

2.4 Stone Columns

Stone columns, one of the most commonly used soil improvement techniques, have been utilized worldwide to increase bearing capacity and reduce total and differential settlements of structures constructed on soft clay. Stone columns also act as vertical drains, thus speeding up the process of consolidation. However, the settlement of stabilized bed is not reduced in many situations for want of adequate lateral restraint. Encasing the stone column with a geogrid enhances the bearing capacity and reduces the settlement drastically without compromising its effect as a drain, unlike a pile [13].

By using stone columns, the ground improvement achieved by partially replacing, or displacing, weak soils with highly compacted columns of aggregate tightly interlocked with the surrounding soil. The process is similar to Vibro-compaction except that gravel or slag used as the backfill material. The vibrator used to compact and force the stone into the surrounding soft soil [14].

With the inclusion of stone aggregates to the in-situ soil, its stiffness and load-carrying capacity increases. It also helps to reduce the static as well as the differential settlement of the soils. Bulging action of the stone columns imparts lateral confinement to the surrounding soils and it also acts as a drainage path accelerating the consolidation of cohesive soils. These stone columns generally used for soils that are much more compressible but not weak enough to necessitate a pile foundation [15].

Stone column reinforced ground can be analyzed by the homogenization technique to have equivalent material properties. However, the current homogenization techniques found in the literature require modification in the finite element constitutive model which is difficult to apply by practical engineers [16]. One of the possible ways of predicting settlement performance for ground improved by a stone column by offering a laboratory-scaled model.

In the stone column method, compacted stone or gravel columns are installed on soft soil with a diameter of 0.6 to 1.0 meters with a certain distance. The installation of stone columns can be done by Vibro-floatation or pneumatic compaction. The stone column functions to increase soil shear strength and reduce settlement. Apart from stone columns, it is also common to implement sand columns that are installed utilizing a Vibro-Compactor [17].

3. Materials and Methods

To provide a consistent classification of the materials used in the experimental study, a laboratory investigation program was carried out to evaluate the basic and mechanical properties of the untreated and stabilized soils, in this case, a mixture of gravel, sand, Asbuton, and waterglass. The laboratory testing was executed in Soil Mechanics and Geo-Environmental Laboratory of Hasanuddin University, South Sulawesi, Indonesia.

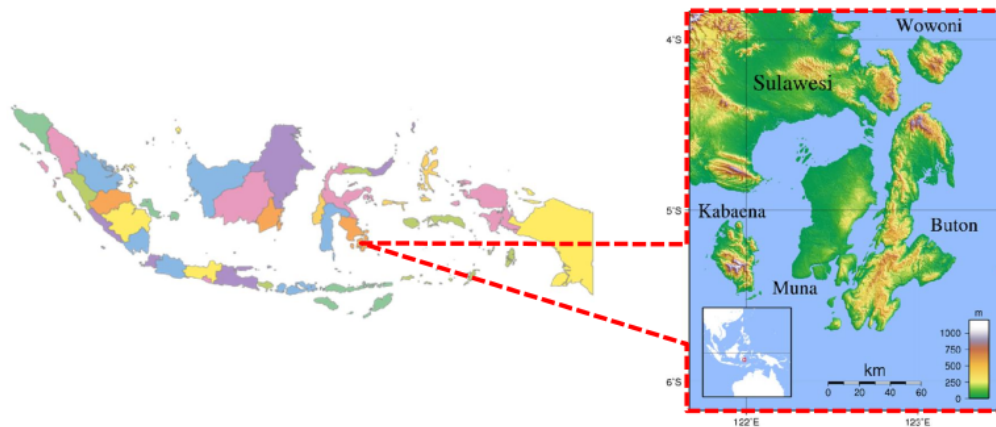


Figure 1. Buton Island in Southeast Sulawesi

Asbuton material is brought directly from Buton Island, while waterglass and aggregate are sourced from nearby locations. The Asbuton and the aggregates are then tested to analyze its properties. California Bearing Ratio and Unconfined Compressive Test is carried out as a parameter to evaluate the engineering properties following ASTM D-1883 testing standards for CBR and ASTM D-2166 testing standards for UCT. Before the engineering properties are analyzed and tested, the standard proctor method was conducted by following ASTM D-698 to determine the maximum density.

The CBR test is intended to determine the composition of the mixed aggregate grain that has the highest density value, assuming that the highest density value is correlated with the highest CBR value. While the compressive strength test is intended to determine the load capacity of the artificial stone column, so that the optimum composition of aggregate, Asbuton, and waterglass can be determined.

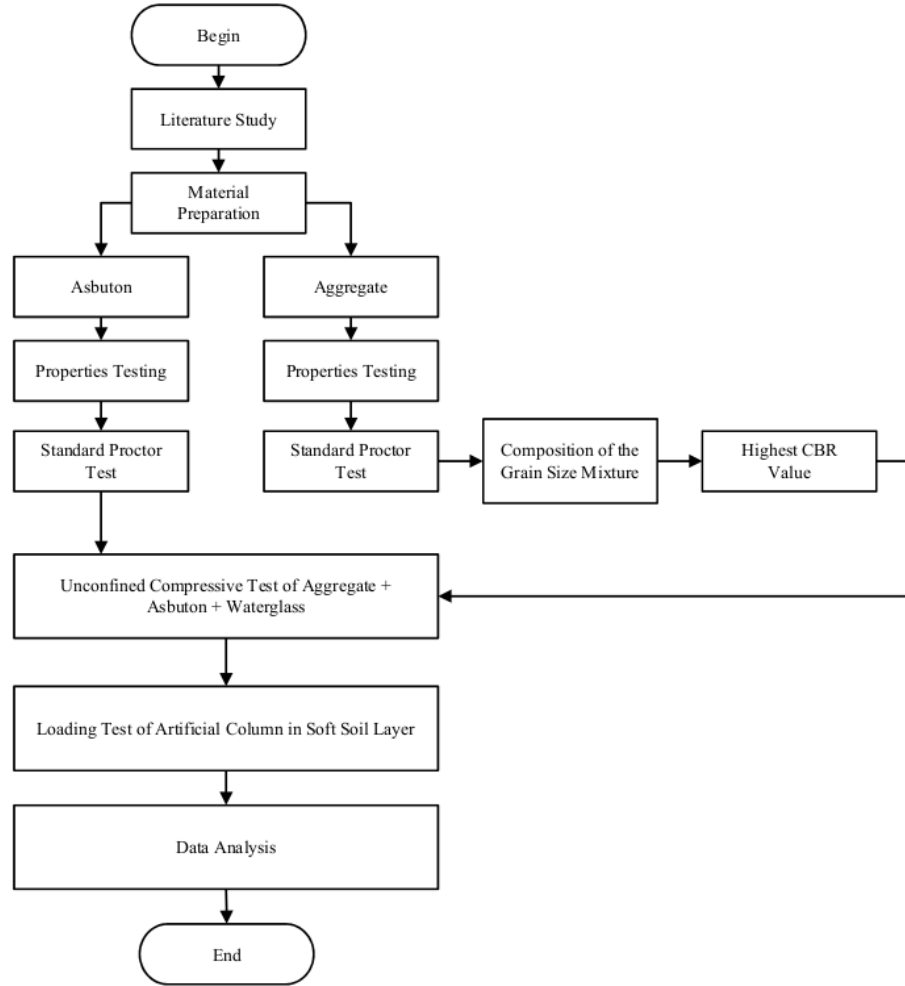


Figure 2. General research stage flowchart

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4. Results and Discussion

The results of the basic properties and mechanical properties are shown in the following table.

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Table 2. Basic properties and mechanical properties of aggregate

Test	Test Results	
	Result Value	Unit
<i>Basic Properties of Overboulder:</i>		
Specific Gravity (Gs)	2.68	-
Sieve Analysis and Hydrometer :		
(a) Gravel	0.00	%
(b) Sand	85.00	%
(c) Silt and Clay	15.00	%
Standard Proctor :		

(a) Maximum Dry Density, (γ_d)	1.28	gr/cm ³
(b) Optimum Moisture Content (OMC)	25.67	%
Classification According to USCS: SP		
<i>Mechanical Properties of Overboulder:</i>		
California Bearing Ratio	1.79	%

Based on the result of the tests, the aggregate was dominated by a gravel fraction of 82.48%. By referring to the Unified Soil Classification System, the gravel used in this study was classified as GW or Well Graded Gravelly Sand, due to 5.16 in CU value and 1.29 in CC value, with little/no fine-grained soil [18]. While the mechanical properties that could be determined were CBR considering the nature of the material was non-cohesive, granular, and loose.

Table 3. Basic properties of Asbuton

Test	Test Results	
	Result Value	Unit
<i>Basic Properties of Overboulder:</i>		
Specific Gravity (Gs)	2.68	-
Sieve Analysis and Hydrometer :		
(a) Gravel	0.00	%
(b) Sand	85.00	%
(c) Silt and Clay	15.00	%
Standard Proctor :		
(a) Maximum Dry Density, (γ_d)	1.28	gr/cm ³
(b) Optimum Moisture Content (OMC)	25.67	%
Classification According to USCS: SP		
<i>Mechanical Properties of Overboulder:</i>		
California Bearing Ratio	1.79	%

The physical and mechanical characteristics of Asbuton showed that Asbuton was classified as SP/Poorly Graded Sand [18]. It has no gravel fraction, resembling coarse sand. The CBR value shows a lower value compared to the aggregate. This is due to the difference of density value, which is affected by the material's basic composite then the end determines its specific gravity. Because the increase in density value is directly proportional to the CBR value of the soil, the higher the density value of soil, the higher the soil CBR value [19].

The chemical composition of Asbuton is dominated by SO₃ or sulfur compounds. Apart from sulfur, Asbuton also contains a lot of CaO or lime compounds. In addition to these two compounds which have a percentage of more than 50% of the total components, 2 compounds have a smaller percentage, namely SiO₂ or Silica at 19.61% and Al₂O₃ or Aluminum at 12.47%. The least compounds found in Asbuton are sodium and magnesium.

Based on the results of the sieve analysis, the ratio between gravel and sand is 80:20. So, in this study, several mixes of varied grain sizes will be used by changing the ratio between gravel and sand to obtain a grain size mix with the highest interlocking capability using CBR value as comparable measurement. Furthermore, after obtaining the best mixture, the sand fraction will be substituted using Asbuton as filler. The grain size mixture composition showed in the following table.

Table 4. Grain Size Mixing Plan

Mix	Sand (%)	Gravel (%)
1	20	80
S2	15	85
S3	10	90

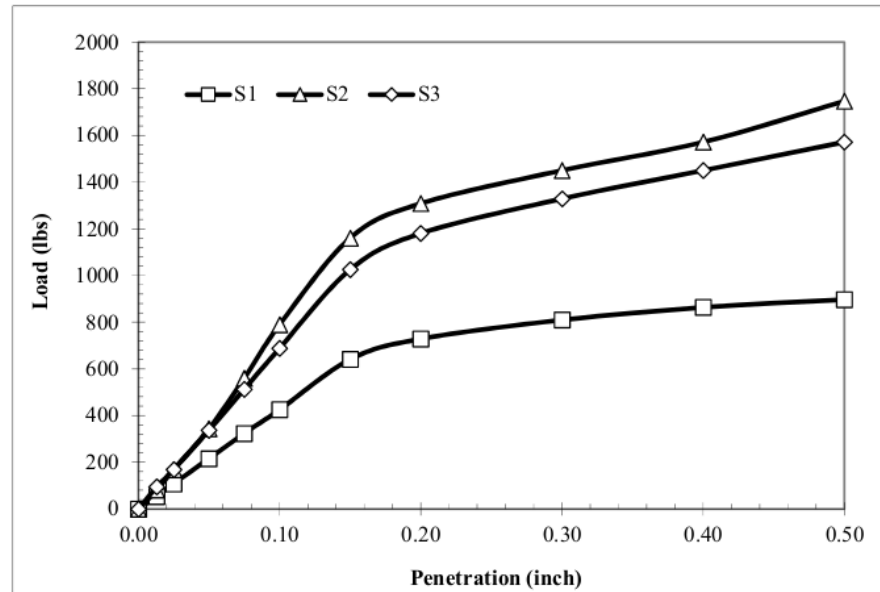


Figure 3. Penetration-Load behavior of CBR specimens with varied grain size

Composition 3 with 90% gravel and 10% sand shows a CBR value of 26%. Composition 2 with 85% gravel and 15% sand shows a CBR value of 29%. Meanwhile, composition 1 with 80% gravel and 20% sand shows a CBR value of 16%. From these results, it can be concluded that the best composition is 85% gravel and 15% sand with the highest CBR value of 29% compared to the other two compositions. It is assumed that the interlocking that occurs between grains is better than the other two compositions.

With the CBR results achieved, the composition of the gravel for column specimens has been determined with a ratio of 85:15. Furthermore, sand will be substituted with 10% Asbuton. So, the final ratio of gravel: Asbuton: sand is 85:10:5. Then to get better interlocking, liquid sodium silica (Waterglass) was added to replace water with a percentage of 2%, 4%, and 6%. The percentage waterglass added to the mixture was referring to an experimental study conducted by Marthen M Tangkeallo with the journal entitled Experimental Study on Bearing Capacity of Laterite Soil Stabilization Using Zeolite Activated by Waterglass and Geogrid Reinforcement as Base Layer. To analyze the effect of additive Asbuton and waterglass to the mix, the CBR test was again carried out to determine the changes in the CBR value that occurred. CBR testing is carried out with a curing period of 0, 3, and 7 days to let the sodium silica dries and crystallizes to create better cohesion and interlocking power.

Table 5. Mix plan of Asbuton, gravelly sand, and waterglass

Mix	Asbuton (%)	Sand (%)	Gravel (%)	Waterglass (%)	Total (%)	γ_{dry} (gram/cm ³)	γ_{wet} (gram/cm ³)
W1	6.2	4.1	87.7	2.0	100	1.85	1.89
W2	6.1	4.0	86.0	3.8	100	1.85	1.93
W3	6.0	4.0	84.4	5.7	100	1.85	1.96

Table 6. CBR test results in the varied composition

MIX Asbuton	CBR (%)		
	25 0 Days (Curing)	3 Days (Curing)	7 Days (Curing)
W1	29,23	29,53	29,97
W2	29,67	30,12	32,97
W3	30,72	32,37	34,92

Table 6 shows that increasing waterglass content added to the mixture, the higher the CBR value obtained, as well as the increasing curing period. The highest CBR value obtained was 34.92%, with 6% Waterglass content and 7 days

of curing time. Referring to these results, unconfined compressive strength specimens were tested with a curing period of 7 days.

In some cases, the most influencing factor in increasing the mechanical value of CBR was the alkaline content of the mixture, which acts as a binder and increase or add the cohesive force of the grain [20-23]. Unconfined compressive strength samples of aggregate, Asbuton, and waterglass are remolded into cylindrical form with 6 inches diameter and 12 inches height or approximately 15 cm diameter and 30 cm height. The specimen was dynamically compacted with the same compaction energy as the CBR specimen with 56 blows. This column test is an unconfined compression test that refers to ASTM D-2166 but with a bigger dimension. While the density value is based on the CBR with 56 blows following ASTM D-1883, which then converted to required compaction energy based on the D-698 proctor standard. To maintain the shape and size, the gravel column is encased using 2 layers of Bi-Axial Geogrid. Furthermore, the specimens of the column elements are statically loaded until it collapses.



Figure 4. Artificial column compressive strength test

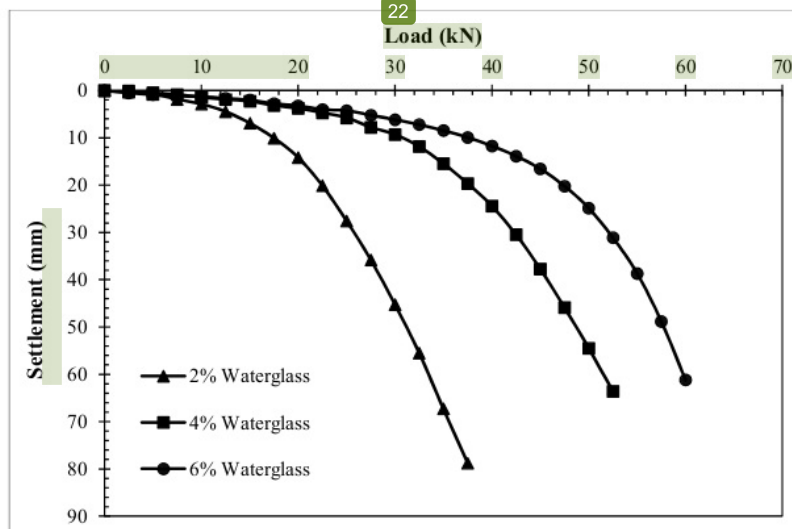


Figure 5. Load-deformation behavior of compressive test with varied waterglass content

Figure 5 shows the stiffness of the sample increased along with increasing waterglass content added. Besides the stiffness, the peak load it can withstand has increased as well. In this case, the vertical deformation of the specimen decreased by 17.6 mm and the peak load increased by 22.5 kN with 2% waterglass. Whereas for 4% waterglass the vertical deformation decreased by 2.45 mm and the peak load increased by 7.5 kN. Geogrid encasing provides a significant function. The strength of a compressive specimen fundamentally depends only on the cohesion strength of the material. However, with the Geogrid as a wrapper, the shape of the mixture of gravel, sand, and gravel is more preserved, as well as providing restraint against the bulging that occurs, resulting in a much higher maximum stress [2].

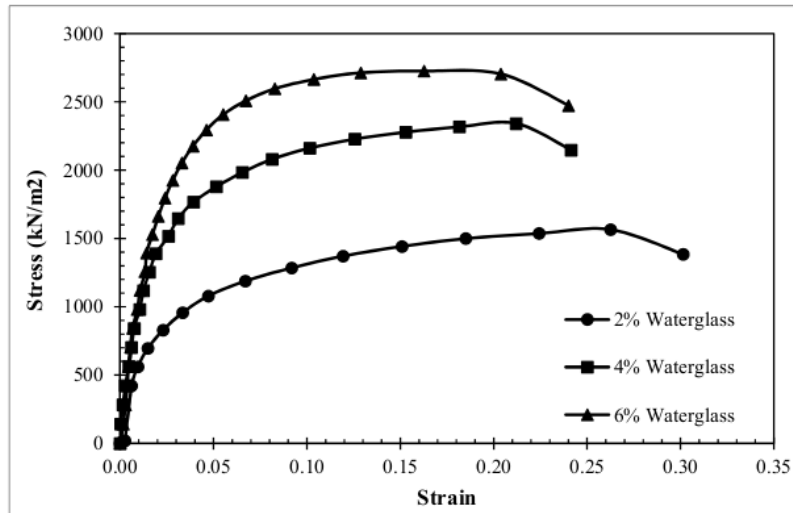


Figure 6. Strain-stress behavior of column element with varied waterglass content

Figure 6 shows that the ultimate stress occurs with the addition of 6% waterglass. The ultimate stress that occurs is 2725.93 kN/m². The ultimate load that occurs is obtained from the strength of the mixture itself, and the restraint of the Geogrid. The load capacity and stiffness of the artificial columns can be significantly increased due to the comprehensive encasement using geogrids. With geogrid restraint, lateral bulging can be greatly minimized. From this point, waterglass and Asbuton are assured to increase the interlocking capability.

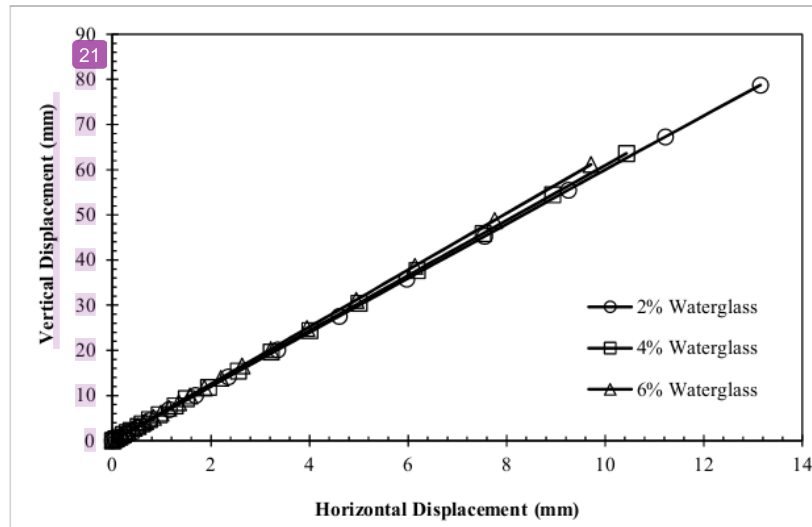


Figure 7. Comparison of vertical and horizontal displacement

Based on Figure 7, the vertical and horizontal deformation patterns show a uniform pattern. By comparing the transverse (ϵ_t) and axial (ϵ_a) strains, a Poisson Ratio can be obtained. The transversal strain is obtained by comparing the change in the transverse dimension to the initial dimension ($\Delta D/D$) while an axial strain is obtained by comparing the change in the axial dimension to the initial dimension ($\Delta H/H$). In the specimen of column elements with 2% waterglass, the largest vertical deformation was 78.75 mm with a horizontal deformation of 13.15 mm. With an initial height of 300 mm and a diameter of 150 mm, the transverse strain value obtained was 0.088 and the axial strain obtained was 0.263. Thus, the Poisson Ratio obtained was 0.334. Whereas in the specimen of column elements with 6% waterglass, the largest vertical deformation obtained was 61.15 mm with a horizontal deformation of 9.7 mm. With an initial height of 300 mm and a diameter of 150 mm, the transverse strain value obtained was 0.065 and the axial strain was 0.204. Thus, the Poisson Ratio obtained was 0.318. The elastic modulus of the geosynthetic used plays

an important role in causing the load capacity and column stiffness. The bridge stress that occurs will be higher for a more rigid encasement. Generally, for soil, the Poisson Ratio ranged between 0.2 to 0.4 depending on type of the soil. For gravel and rock in general, the Poisson ratio is about 0.3.

After the compressible column samples are tested without soil confinement (unconfined), the next step is to test the performance of the specimens in reducing soft soil's settlement. The compacted artificial stone column is immersed in soft soil's top layer. The soil used in the model was soft soil with compressive strength of 24 kN/m². The load is applied directly above the column.



Figure 8. Stone column model test in laboratory scale

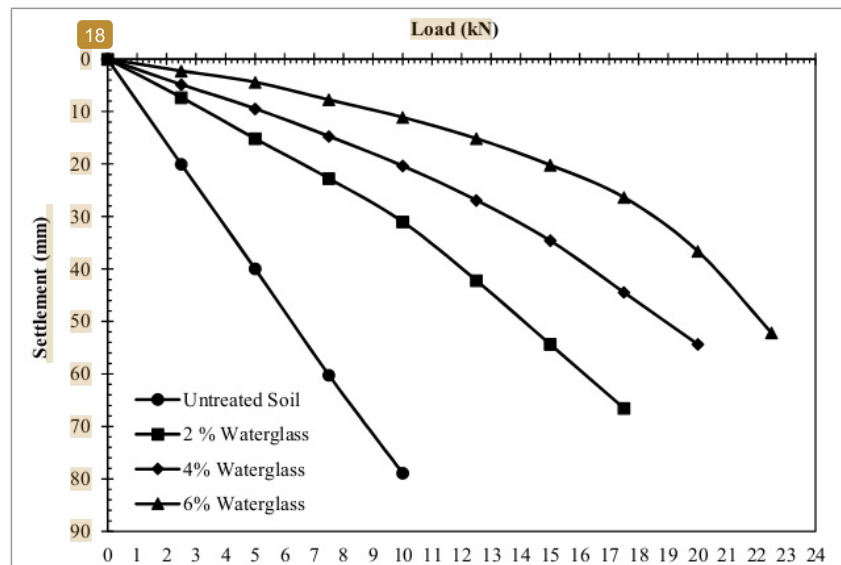


Figure 9. Deformation due to static loading of column-stabilized soil with varied waterglass content

In Figure 9, the comparison between soft soil without column reinforcement and soft soil reinforced by gravel Asbuton column with waterglass content is clear. With the presence of columns, the decrease that occurs due to static loads can be reduced significantly. Also, the load that occurs has increased. With these results, it can be concluded that as more waterglass is added to the column composition, the performance of the soft soil layers is better. The restraint at the top of the column, where the bulging occurs is greatest, is required to increase column capability. And the optimum depth for an encasement column is 2 times the diameter. This is intended to prevent excessive bulging which will weaken the bridge stress because, at a larger diameter, the stress that occurs will be greater so that the encasement performance is less than optimal.

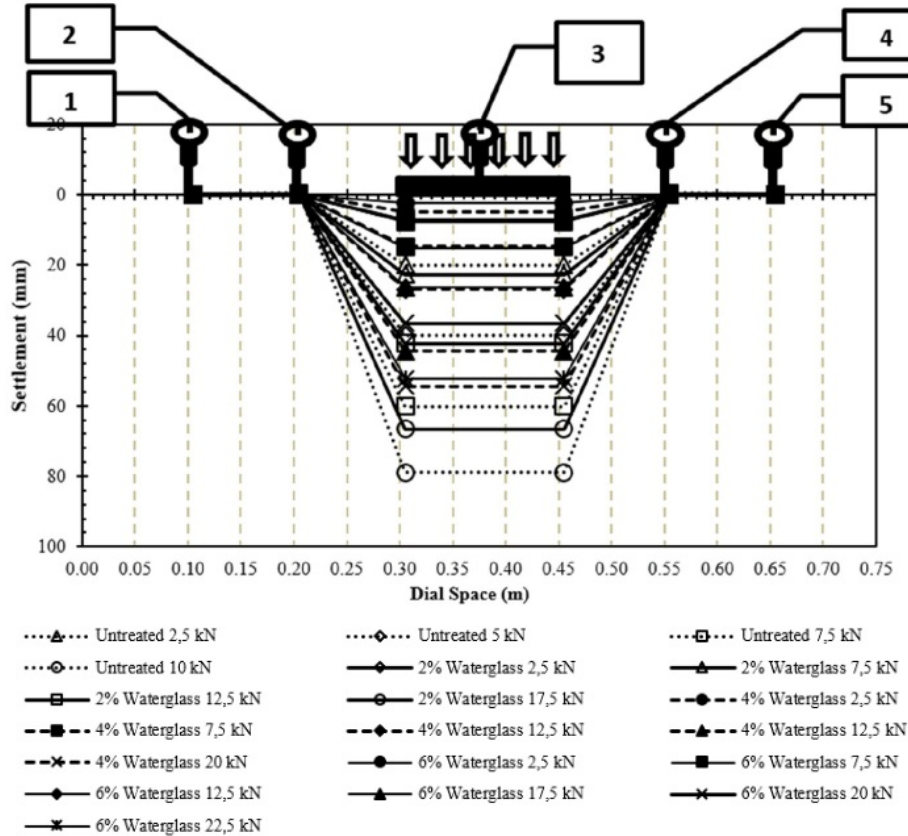


Figure 10. Deformation pattern of soft soil stabilized by Asbuton column per load stage



Figure 11. Stone column model test after static loading

Soft soil shows the deepest settlement that occurs without any soil improvement. Meanwhile, by strengthening the column, the settlement that occurs in each stage of loading can be reduced. Meanwhile, the peak load that occurs has increased with the increase in the waterglass content. The results of the column test and model test show the same behavior. The increase in the load capacity of the geogrid-encased column is not as sensitive as the increase in shear resistance to the pressure caused by the soft soil around the column, especially for the rigid column. The amount of load distributed to the column can be increased by using a more rigid encasement. So, it can be concluded that based on the synchronization of the results of the elements and models, the gravel column with Asbuton filler and waterglass binder can be a mechanical and chemical soil stabilization solution.

5. Conclusion

The stone column is one of the most applicable solutions to the soft soil problem. Choosing the right grain size mix could guarantee the interlocking capability of the column and increase its compressive strength. However, the compressive strength could still be increased by adding filler and binder to strengthen the interlocking force. In this study, it is proved that adding Asbuton as a substitutive filler instead of sand and waterglass as a binder agent could increase the load capacity of the artificial column by a factor of 1.7 or increased by 70%. With the presence of waterglass and Asbuton, the interlocking between aggregate grains becomes stronger, as shown by the column element test results. When applied in a soft soil layer, the artificial column could reduce the settlement by around 50% with load capacity increased by 225%. The results conclude that Asbuton as local content could be used as a stabilization alternative. This also could be used as a comparative solution in using asphalt not only for wear coarse in road pavement or waterproof layer but also can be used as a filler agent to increase stiffness and compressive strength of a stone column. A further study is needed to validate these results when a full-scale stone column is applied in the field. This kind of stone column is very applicable to areas where the soft soil deposit is too large to be piled, compacted, or stabilized by other options. Improvement offered by this result is considered as a floating foundation concept.

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7. Conflicts of Interest

The authors declare no conflict of interest.

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