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Research Paper

Experimental Study on Clay Stabilization with Waste Limestone from Marble Industry

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ABSTRACT

In this research, chemical stabilization on clay soils was performed using waste limestone powder from marble industry and acrylic acid. The research was aimed to analyze the characteristics of waste marble, to analyze clay strength before and after stabilized with waste marble powder, to analyze the effect of acrylic acid as activator in clay stabilization using waste marble, and finally to study the microstructure of soil stabilized by marble powder and acrylic acid solution. Laboratory tests were performed by mixing marble powder in the amount of 5%-30% of clay and with addition of acrylic acid solution as much as 5%-15% of water mixed. For soil microstructure study, SEM and XRD tests were conducted. Clay mixture with 20%-30% of marble powder increased CBR value to more than 6%. Addition of acrylic acid solution with optimum content of marble powder with 3- and 7-day curing increased the value of UCS to medium consistency. Marble powder contains dominantly of CaO compound of 97.15% which is an effective material for clay soil stabilization. These results show that the mixture of clay with marble powder and acrylic acid as stabilization agents could increase soil bearing capacity for road subgrade layer.

1. Introduction

Opening access road sometimes encounter soil types that do not meet requirement for subgrade layer. Soil stabilization is one of the options for addressing the soil condition. It is intended to improve the properties of local soil by adding a certain material that results in the changing in the properties of original soil. Soil stabilization is also performed to improve low bearing capacity, high plasticity index, high swelling, and poor gradation, to become a better material for foundation especially for roads (Millard, 1993; Rios et al., 2016).

Soil stabilization are generally divided into three categories: mechanical, chemical, and physical methods. Mechanical means are based on mechanical efforts, such as compaction and consolidation. The mechanical method is the most used technique in order to increase density, to reduce compressibility which increases bearing capacity. In chemical method, binder additive such as cement, lime, fly ash, mineral is mixed with soil which then change the property and strength of the soil (Al-Amoudi, 2002; Harianto et al. 2019). While on the physical means,

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material such as geotextile is inserted or arranged on the soil layer to strengthen the soil.

The research revealed that the waste marble in Pangkep District consist of 52.69% of CaO, 41.92% of CaCO3, 0.84% of MgO, 1.76% of MgCO3, 1.62% of SiO2, and 0.37% of Al2O3 and Fe2O3. The results show that the main component of marble waste is lime. Currently in South Sulawesi, the marble industry is developing, however, the waste marble powder from the marble cutting plant has not been economically exploited.

Lime has been widely studied for soil stabilization material, and the results show that lime can increase the strength of soil. However, some current research found some limitation of lime as a soil stabilization material. Therefore, it is necessary to add other materials that can strengthen the soil (Tang et al., 2007; Harianto et al., 2008). Based on the usage of acrylics acid as adhesive and its resistance to water, it is selected as an additive to study soil consistency and bearing capacity as a subgrade (Mengue et al., 2017; Joel and Agbede, 2011) .

The research was performed by combining the chemical and mechanical techniques to develop clay soil stabilization that use easily acquire local soil and the utilization of waste marble powder. The research investigated the effects of marble powder for clay stabilization and its optimum percentage in the mixture. The research also compared the stabilization with only marble powder, and stabilization with marble powder and acrylic acid solution by using unconfined compressive strength values.

1.1. Clay for subgrade

Pressure on road pavement due to wheel load is higher on the road surface and is smaller further down because of the load spreading. Due to this load spreading from the surface, layers of better material are located higher above subgrade. The Subgrade is the topmost soil layer below the pavement. If the local soil meets the requirement, it can be compacted to function as subgrade layer. For the road that is built on clay soil which has low bearing capacity, the pavement must be thick so that the pressure on the soil remains small. Given the behavior of clay soil which is strongly influenced by changes in moisture content, the soil should be mixed with other materials so that it could have higher bearing capacity.

2. Characteristics of Clay Soil

2.1. Characteristic of Clay Soils

The clay consists mostly of microscopic and submicroscopic particles that are flat plates. Clay is defined as a soil particle group measuring less than 0.002 mm (ASTM D-653). Clay has low permeability, high capillary water rise, cohesive, high shrinkage rate, and slow consolidation process. The nature and behavior of clay is shown in the mineral composition, chemical elements, and influences of surrounding environment. Clay is stiff in dry condition, while in wet condition is plastic, soft, cohesive, swell, so that it has a large volume change.

2.2. Expansive Clay Characteristics

Expansive clay soil has a large swelling and shrinking nature that directly related to water content. High water content causes soil expands and bearing capacity decrease, on other hand low water content causes soil shrink and bearing capacity increase.

Montmorillonite, Illite, and Kaolinite form the hydro-crystalline aluminum silicate, however, the three minerals have different properties and structures. Montmorillonite has very high swelling properties, so that clay containing this mineral will have a very high swelling potential. Illite has a medium to high swelling nature, so that the clay material containing this mineral has a medium swelling property. Kaolinite has a larger particle size and smaller swelling properties. The particle size of the clay mineral and the cation exchange capacity is depicted in **Table 1**.

Table 1. Range of clay mineral characteristics

	Kaolinite	*Illite*	*Montmorilonite*
Particle thickness	0,5-2 *microns*	0,003-1 *microns*	< 9,5 A°
Particle diameter (*microns*)	0,5 - 4	0,5 - 10	0,05 – 10
Spesific area (m^2/gr)	10 - 20	65 - 180	50 - 840
Cation exchange capacity (meq/100g)	3 - 15	10 - 40	70 - 80

2.3. Identification of expansive soil

Identification of expansive soil can be done in direct way and indirect way. The direct way is to measure the shrinkage soil sample, while the indirect way is to conduct analysis of the soil parameters, such as the Atterberg limits and the values of activity.

Some of the ways to identify an expansive indirect way are as follows:

2.3.1. Holz and Gibbs method

Holz and Gibbs present the criteria to estimate the swelling potential of soil by the total volume change from air dry to saturated under surcharge loading of 6.9 kPa. ***Table 2*** *shows the relationship between swelling and soil parameters, i.e., Plasticity Index, Shrinkage Limit, Colloid Content, and possible volume changes.*

Table 2. Correlation between index test with degree of swelling (Achmad Zultan, 2011)

Index test data			*Volume increase (%)*	*Degree of swelling*
Colloid Content (%)	*Plasticity Index (%)*	*Shrinkage Limit (%)*		
> 28	*> 35*	*< 11*	*> 30*	*Very high*
20 - 31	*25 - 41*	*7 - 12*	*20 - 30*	*High*
13 - 23	*15 - 28*	*10 - 16*	*10 - 20*	*Medium*
< 15	*< 18*	*> 15*	*< 10*	*Low*

2.3.2. Chen Method

Chen propose method of using Plasticity Index (PI). ***Table 3*** *shows the relationship between the plasticity index (PI) with the swelling potential which is divided into four categories, namely: Low, medium, high and very high swelling potential. The expansive soil is in high (PI of 20-55%) to very high categories (PI > 55%).*

Table 3. Correlation between Plasticity Index and Swelling Potential (Achmad Zultan, 2011)

Plasticity Index (PI) %	Swelling Potential
0 – 15	Low
10 – 35	Medium
20 – 55	High
> 55	Very high

2.3.3. Skempton Method

Skempton identified expansive soil with activity value, which is a ratio between the Plasticity Index (PI) and percentage of the clay fraction (CF), with **Eq. 1**:

$$Ac = PI/CF \quad [1]$$

Where:
Ac = Activity
PI = Plasticity Index
CF = percentage of clay fraction (< 0.002 mm)

Table 4 shows correlation between the swelling potential and activity value. The soil is expansive when the activity value (Ac) > 1.25%.

Table 4. Activity values and swelling potential (Achmad Zultan, 2011)

Actifity (Ac)	Activity level	Swelling potential
< 0,75	Non active	Low
0,75 < Ac < 1,25	Normal	Medium
> 1,25	Active	High

Seed et al. (1962) introduced modified Skempton activity values, **Eq. 2.** ***Figure 1*** *shows relationship between the percentage of the clay passing sieve No. 200, activity value, and swelling potential.*

$$Ac = PI/(CF – 10) \quad [2]$$

Number 10 is reduction factor.

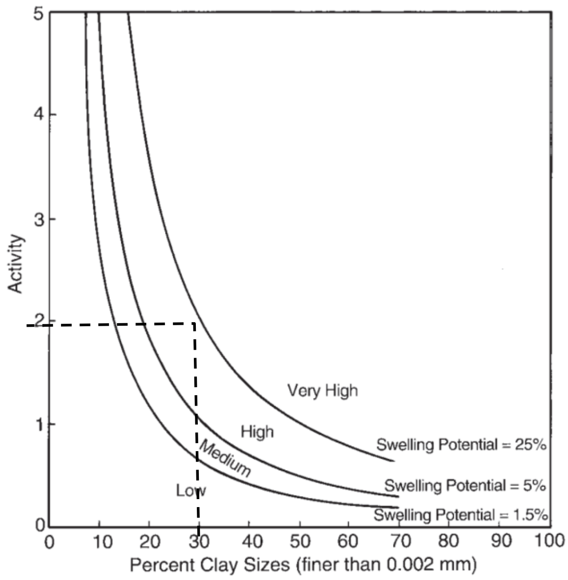


Figure 1. Relationship between clay content and activity (Seed et al., 1962)

3. Additives

Marble or limestone is a rock that results from metamorphoses from limestone which change its composition and color of mineral content. Marble is widely used for buildings such as tiles, walls, decorations, ornaments and household furnishings. In the production process marble stone is cut into various sizes by using saw. Sawmills produces marble powders that are considered waste. It is necessary to study the usefulness of marble powder in clay soil stabilization. Previous studies have used marble powder as a stabilization material for clay soil. The chemical elements contained in marble powder can be seen in **Table 5**.

Table 5. Chemical content in waste marble from Pangkep District

Oxide	Content (%)
CaO	52,69
$CaCO_3$	41,92
MgO	0,84
$MgCO_3$	1,76
SiO_2	1,62
$Al_2O_3 + Fe_2O_3$	0,37

Acrylic acid ($C_3H_4O_2$) is fluid that is used as a reinforcing material and adds adhesive to the tile gap filler with additional synthetic latex. Other uses are in diaper industry, water treatment industry, and textile industry.

4. Soil stabilization

There are two ways of soil stabilization namely by mechanical and by chemical means (Sukmak et al., 2015). Mechanical stabilization is aimed at obtaining well-graded soil to meet the desired specifications. By modifying gradation soil could have higher density. This is done by mixing soil with other soil type, the resulted mixture will have a better gradation.

Stabilization of expansive soil can be done with the following actions:

4.1. Expansive soil stabilization by removal and replacement

This method is done by mixing expansive soils with non-expansive soils. It is expected the mixture can improve the nature of the expansive soil. Non-expansive soil with greater density and carrying capacity, could improve the expansive soil with low density. The cost of this method is more economical than other methods, because this method does not require expensive construction equipment. The disadvantage of this method is the thickness of the mixture could be thicker that could not conform to the designed thickness.

4.2. Stabilization of expansive soil by remolding and compaction

Swelling potential of expansive soil can be reduced by changing the density of the soil. This method of remolding and compaction indicates that compaction at low density and at water content below optimum content in standard Proctor Test can lead to a less swelling potential than compaction in high density and lower moisture content.

4.3. Stabilization of expansive soil using chemical admixture

4.3.1. Stabilizing soil with lime

Stabilizing soil with lime has been widely used on road projects in many countries. For optimum results, lime used is usually between 3% to 10%. The largest values of dry density, CBR unsoaked and soaked were achieved by mixing with a 10% lime.

4.3.2. Stabilizing of soil with cement

Hydraulic cement is the most widely used binding material that has a strong hydraulic bonding. The material becomes hard so that it produces new, stable, and durable materials. By adding cement to the soil, it will increase the shrinkage limit and shear strength.

4.3.3. Stabilizing of soil with fly ash

Fly ash can also be used as stabilizing agents since if it is mixed with soil, there will occur pozzolanic reaction. Soft lime soil that is mixed with fly ash, with a ratio of one to two, has shown improvement in soil bearing capacity.

5. Scanning Electron Microscope (SEM)

SEM uses a high energy-focused electron beam to produce various signals on the surface of the solid specimen. Signals derived from electron-sample interactions reveal information about the samples including external morphology (texture), chemical composition, and crystal structure and orientation of the material forming the sample. SEM is also able to perform location analysis of the selected point in the sample, this approach is very useful in qualitative or semi-quantitative determinations of chemical composition, crystal structure, and crystal orientation. SEM is routinely used to produce high resolution images of object shapes and to show special variations in chemical composition. SEM is also widely used to identify phases based on qualitative chemical analyses and/or crystal structures.

6. X-Ray Diffraction Test (XRD)

XRD Characterization aims to determine the crystal system. The X-ray diffraction method can explain the lattice parameters, types of structures, different atomic arrays of crystals, the presence of imperfections in crystals, orientation, grain and grain size. The main components of XRD consist of a cathode tube (X-ray forming), a sample holder, a detector, computers and CPU. Each pattern that appears in the XRD represents a single crystal field that has a specific orientation.

7. Past Research

The research on stabilization by adding additives to both marble and other materials has been done. Some reseराchers reported study of the behavior of soil with swelling and shrinking properties by stabilization with marble powder and stabilia. Both materials were tested with clay from Pejaten, in order to know the changes in the plasticity, strength, swelling, the thickness of the soil affected by water as function of time, and the effect of initial water content to swelling and compression strength. The samples were mixed with 3% to 12% of marble powder and stabilia from 0.3% to 3.0% of soil weight. It was found that both materials led to a decrease in soil swelling and increased soil strength.

Onur Baser (2009), study the use of lime dust (density of 2.68 gr/cm^2) and marble waste (density of 2.8 gr/cm^2), both byproduct of the marble industry, for stabilization of expansive soils. Expansive soil is prepared in the laboratory as a mixture of kaolinite and bentonite. The limestone powder and the dolomitic marble waste were added to the expansive soil as stabilization material with variations from 0% to 30%. The test results showed that the use of 30% waste marble can reduce PI by 45%-50%, decrease swelling value by 30%-50%. Curing affects the percentage of swelling by ± 8%-9%.

Vinay Agrawal and Mohit Gupta, (2011) investigated the potential of marble powders as additives to stabilize expansive soil. This evaluation involves determining the swelling potential of an expansive soil in the natural state and when mixed with varying proportions of marble powders (0%-30%). The mixture with marble powders lowers liquid limit, plasticity indices and increased shrinkage limits. The experiment results also showed that the swelling decreased with the increasing percentage of marble powder. Addition of marble powders reduces the contents of clay and thereby increases the percentage of coarse particles, reduces LL, and raises SL. The higher percentage of marble powder, the less swelling percentage. Sample with marble powder could reduce its swelling by 50%. Expansive soil could be stabilized to reduce swelling by 25%-30%.

Chayan Gupta and Dr. Ravi Kumar Sharma, (2014) study the influence of waste materials such as marble dust and fly ash on characteristics of clay for subgrade. From tests conducted in the laboratory on fly ash, sand, expansive soil which further mixed with marble powder 0-20%, it was concluded that 15%marble dust is sufficient to increase soaked CBR up to 200%.

8. Methods

The research is to review the physical characteristics, mechanical and chemical of clay after stabilization with marble powders and acrylic acid. Research was conducted in the Soil Mechanics Laboratory of Civil Engineering, Faculty of Engineering Gowa campus, Hasanuddin University. The X-ray diffraction test was conducted at Microstructure Laboratory of the Makassar State University.

8.1. Soil materials and tools

The soil sample is clay in disturbed conditions from the border between Sidrap and Wajo districts, South Sulawesi Province. Marble powder used is the waste of a marble cutting plant in Enrekang district.

8.2. Mixture Combination

The combination of mixture prepared for stabilization is as follows:

95% Original soil + 5% Marble powder
90% Original soil + 10% Marble powder
85% Original soil + 15% Marble powder
80% Original soil + 20% Marble powder
75% Original soil + 25% Marble powder
70% Original soil + 30% Marble powder

8.3. Mixture of clay soil, marble powder, and acrylic acid

Into optimum content of marble powder, acrylic acid solution is added with variation ranging from 5%, 7%, 10%, 13% and 15% of water that added to the mixture. The varied percentage was used to obtain optimum percentage of solution.

The test is divided into 3 parts i.e. testing for Original soil, soil that has been stabilized with marble powders, and with acrylic acid solutions. To the original soil the tests were carried out for physical, compaction and mechanical properties of soil. For the soil that has been stabilized, mechanical properties testing (CBR and UCS) were performed.

8.4. Physical Properties Test

Physical properties test aims to determine the soil index properties. The index properties are needed for classification and identification of soil which is then used in determining suitable stabilizing material and in determining the initial estimate of the level of powder material needed for stabilization. Physical properties tests list is shown in **Table 6**.

Table 6. Indonesian Standard for Soil Property Tests

No	Testing	Standard
1	Liquid Limit Test	SNI 1967:2008
2	Plastic Limit Test	SNI 1966:2008
3	Shrinkage Limit	SNI 3422:2008
4	Soil Density Testing	SNI 1964-2008
5	Water content Testing	SNI 1965:2008
6	Sieve Analysis	SNI 3423:2008

8.5. Mechanical Properties Test

This test is generally done to determine the strength and bearing capacity of soil. The mechanical tests conducted are compaction test, unconfined compression test, and CBR test. The modified compaction test is conducted according to SNI 03-1742-1989 or SNI 03-1744-1989. Unconfined compression test is conducted according to SNI 03-3638-1994/ASTM D 2166. CBR (California Bearing Ratio) is conducted according to SNI 03-1744-1989.

8.6. X-Ray Diffraction and SEM

X-ray diffraction tests for morphology and soil mineral composition include the use of Scanning Electron Microscope (SEM) and X-Ray Diffraction (XRD) testing.

9. Results and Discussion

9.1. Physical Properties of Original Soil

The results of the original physical soil test performed can be seen in **Table 7**.

Table 7. Original Soil test Results

No	Type of test	Value	Unit
1.	Water content	45,1	%
2.	Specific Gravity	2,63	-
3.	Sieve Analysis		
	a. Coarse Grain	36,4	%
	b. Fine Grain	63,6	%
4.	Atterberg Limits		
	a. Liquid Limit	79,07	%
	b. Plastic Limit	20,03	%
	c. Plasticity Index	59,04	%
	d. Shrinkage Limit	6,76	%

The table shows that the original soil is clay that heavily influenced by moisture content, i.e. soil moisture content affects the swelling shrinking behavior. This trait often inflicts damage to buildings such as heaving of foundation, wall cracks, wavy or settlement of roads. Soil with such conditions has low strength, therefore it is necessary to improve the soil. The improvement is performed by mixing soil with additive material. **Figure 2** and **Table 7** show that the percentage of soil passing sieve no 200 is 63.6%, liquid limit is 79.07%, and plasticity index is 59.04%.

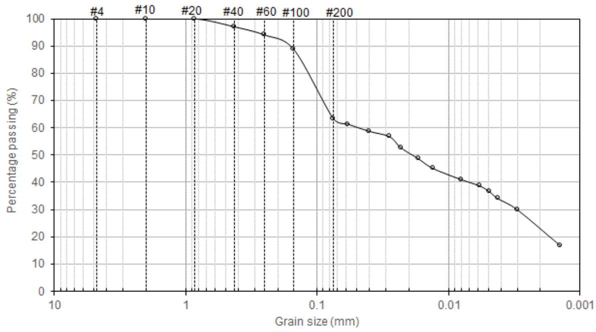


Figure 2. Gradation of original soil

9.2. Soil Classifications

9.2.1. Unified Soil Classification System (USCS)

To classify the soil with USCS, the results from Atterberg limit test, i.e. liquid limit and plasticity index, are plotted into plasticity diagram as shown in **Fig. 3**.

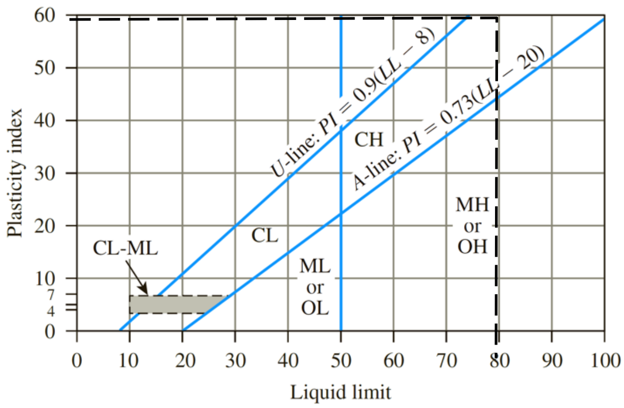


Figure 3. Plasticity Diagram (ASTM, Casagrande)

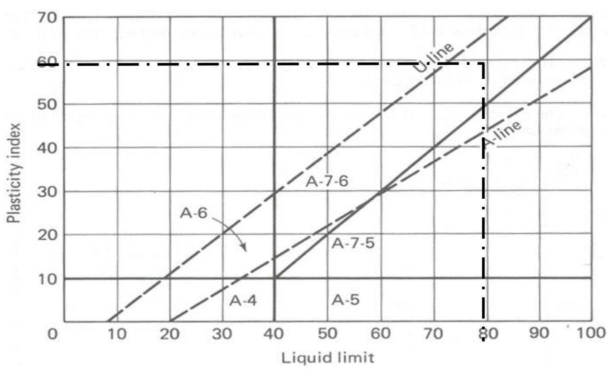


Figure 4. Classification of group A-4 to A7

From LL and PI, the soil is grouped as CH. CH is inorganic clay with a high plasticity. Soil classified as high plasticity will have some effect during construction. The soil will undergo volume changes, i.e., the soil will swell when water content increases and shrink when water content reduces. The clay with high plasticity will cause damage to road construction, especially in the base and subbase.

9.2.2. American Association of State Highways Transportations Officials (AASHTO)

AASHTO soil classification is based on the result of sieve analysis and Atterberg limits tests as follows:
- Soil passes sieve No. 200 = 63.6%
- Liquid limit (LL) = 79.07%
- Plastic limit (PL) = 20.03%
- Plasticity index (PI) = 59.04%

With these data, AASHTO classification table, and **Fig. 4**, the soil belongs to group A-7-6. To determine the level of soil reliability for road pavement layer, group index (GI) should be determined with **Eq. 3**.

$$GI = (F - 35)\,[0.2 + 0.005\,(LL - 40)] + 0.001\,(F - 15)\,(PI - 10) \quad [3]$$

Where F is the percentage of soil passes sieve# 200, then GI value is 14. Based on the AASHTO Classification System (**Table 8**) The soil is classified as A-7-6 and is a very poor soil as road pavement layer.

Table 8. Subgrade Rating, AASHTO

Subgrade Rating	Group Index
Excellent	0
Good	0 - 1
Fair	2 - 4
Poor	5 - 9
Very poor	10 – 20

9.3. The activity of fine-grained soil

The results of the index properties test can be used to identify expansive soils. Calculation of Activity of the original soil samples can be seen in **Table 9**.

Table 9. Calculation of Activity

No	Test	Value
1	Plasticity Index (IP) %	59,04
2	Percentage clay fraction less than 0,002 mm (C) %	30
3	Activity A= IP / C	1.9

The activity value is then plotted into the soil activity diagram of clay that classifies soil for its swelling potential by using **Fig. 1**, swelling potential can be concluded that the fine-grained soil tested is clay that has high potential for swelling.

9.4. Mechanical Properties Testing

9.4.1. Soil compaction test (Standard Proctor Test)

From compaction testing using standard Proctor test, the maximum dry density (MDD) is 1.43 gr/cm^3 which was achieved at optimum water content (w opt.) of 27% (**Fig. 5**).

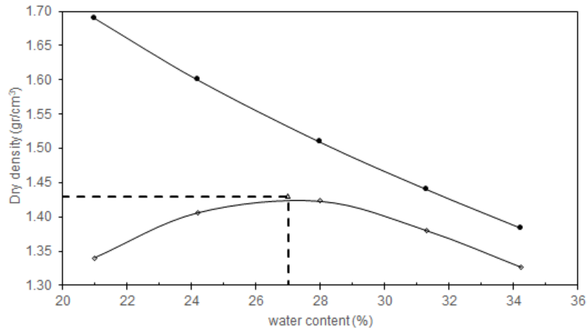


Figure 5. Maximum dry density v. Optimum water content

9.4.2. California Bearing Ratio (CBR) Testing

CBR testing aims to determine the strength of the soil surface layer which will generally be used as a sub-base (fill) or subgrade (ground surface) of road construction. The tests performed were only for CBR without soaking which were shown on **Fig. 6** and **Table 10**.

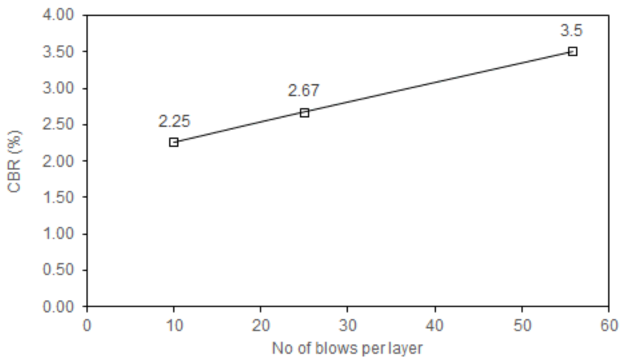


Figure 6. Number of blows per layer and CBR values

Table 10. CBR test result of original soil

Deformation	10 blows per layer			25 blows per layer			56 blows per layer		
	Load	CBR	Max	Load	CBR	Max	Load	CBR	Max
(inches)	(lbs.)	%	%	(lbs.)	%	%	(lbs.)	%	%
0.1	67.5	2.25	2.25	80	2.67	2.67	105.0	3.50	3.50
0.2	85.0	1.89		100.0	2.22		125.0	2.78	

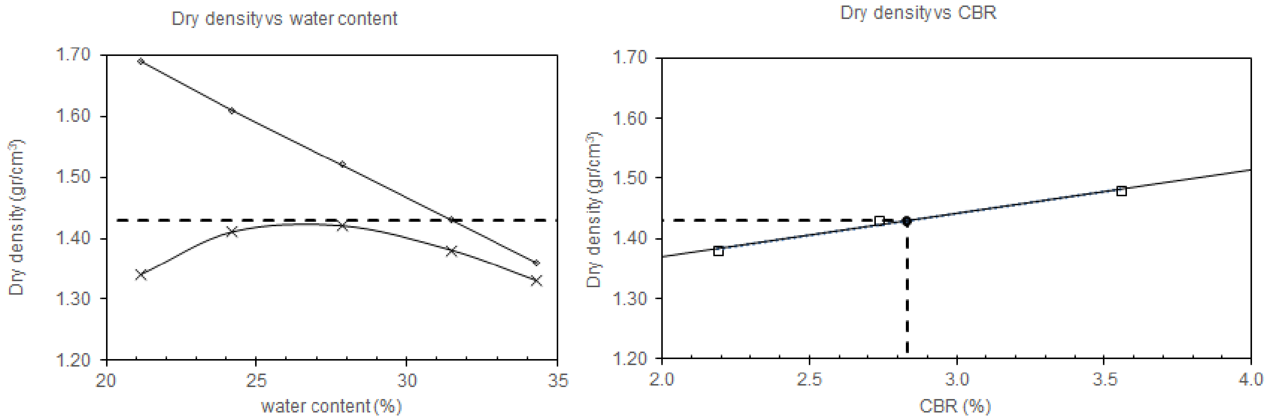


Figure 7. Determination of CBR design

Required CBR value for soil used on subgrade is 6% (ASTM D1183). From CBR testing performed on the original soil the resulted CBR design value was 2.83%. CBR design value is determined by comparing two graphs, namely graph of water content vs. dry density, and graph of CBR value vs. the dry density (**Fig. 7**).

9.4.3. Unconfined Compression Test (UCT)

This test is intended to determine the amount of unconfined compressive strength of cohesive soil in both original and remolded state (or modified with stabilization material). The test results are recorded on the **Fig. 8**. The value of qu for testing on soil samples is 0.099 kg/cm^2 (< 0.25 kg/cm^2) which is considered very soft, see **Table 11.** With that consistency the soil could not serve as road foundation. Therefore, in order to function as subgrade layer, the soil required additional materials to increase its q_u value.

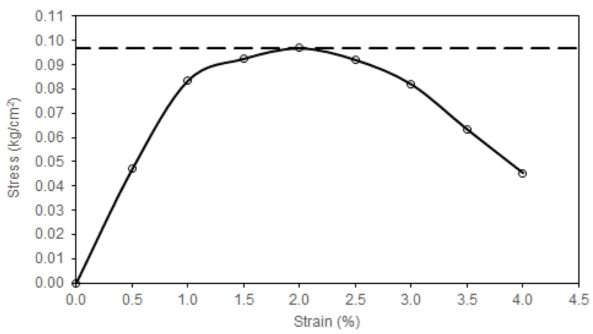


Figure 8. Stress strain from Unconfined Compression Strength test

Table 11. Soil consistency and UCS test q_u

q_u (kg/cm^2)	Consistency
< 0,25	*Very soft*
0,25 – 0,5	*Soft*
0,5 – 1	*Medium*
1 – 2	*Stiff*
2 – 4	*Very Stiff*

> 4	*Hard*

9.5. Characteristics of mixture original soil and marble powder

9.5.1. Soil compaction testing (standard proctor test)

For original soil compaction test, maximum dry density obtained was 1.43 kg/cm^3 at a water content of 27%. Further compaction tests were performed on clay soil stabilized with marble powder and the results are presented in **Table 12**. and **Fig. 9**. The value of optimum water content is used as a reference for mixing sample in subsequent tests.

Table 12. Results of compaction test with varied marble powder mixture

No.	Mixture	Optimum Water Content (ω opt) %	Dry Density (γ dry) kg/cm^3
1	100% Original soil	27,00	1,43
2	95% Original Soil + 5% marble powder	26,00	1,46
3	90% Original Soil + 10% Marble Powder	25,00	1,48
4	85% Original Soil + 15% Marble Powder	24,00	1,50
5	80% Original Soil + 20% marble powder	22,50	1,53
6	75% Original Soil + 25% Marble Powder	21,00	1,55
7	70% Original Soil + 30% Marble Powder	20,00	1,58

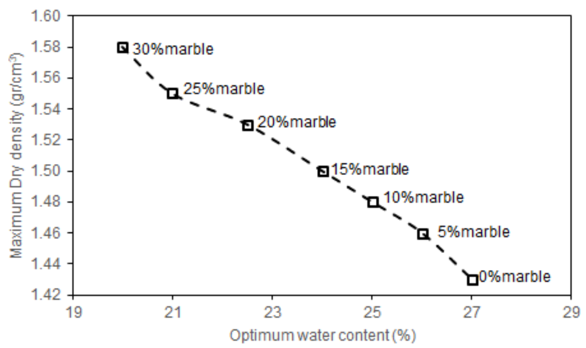


Figure 9. Max dry density and Optimum water content of soil mixed with varied percentage of marble powder

The addition of marble powder with percentage from 5% to 30% in clay soil causes the maximum dry density increases by 10.49% and the optimum water content decreases by 25.92%. This is due to the grain of marble powder bind clay soil grains and fill the pores so that the soil becomes dense and the moisture content needed to densify the soil is reduced.

9.5.2. California Bearing Ratio (CBR) Testing

CBR value obtained of original soil was 2.83% which is not qualified since it is smaller than 6%. Unsoaked CBR tests on clay soil stabilized with marble powder were performed with optimum water content. The resulted CBR values can be seen in **Table 13** and **Fig. 10**.

Table 13. Design CBR of soil with varied marble powder mixture

No.	**Mixture**	**CBR (%)**
1	100% Original soil	2,83
2	95% Original Soil + 5% marble powder	3,88
3	90% Original Soil + 10% Marble Powder	4,96
4	85% Original Soil + 15% Marble Powder	5,93
5	80% Original Soil + 20% marble powder	6,31
6	75% Original Soil + 25% Marble Powder	6,82
7	70% Original Soil + 30% Marble Powder	7,59

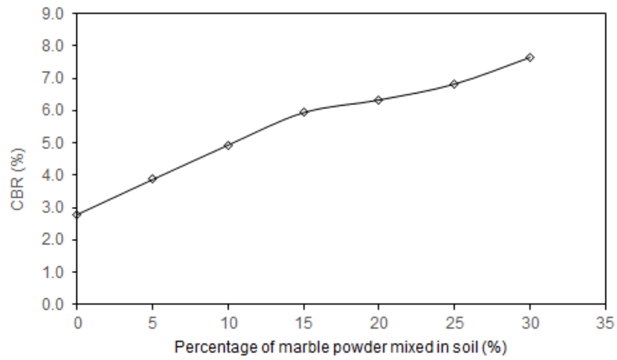


Figure 10. Design CBR values of soil mixed with varied marble powder content.

Figure 10 shows the effect of marble powder increased from 5% to 30% on the design CBR values. Mixture of soil with 20% marble powder resulted in CBR value of 6.31% which is qualified for road pavement subgrade (CBR > 6%).

The increase of CBR's value due to the marble powder fill the pore cavity which then cause interlocking between particles. The occurrence of pozzolan reaction between marble powder and soil further strengthens the bond between particles, where calcium oxide on marble powders produced at hydration will form a reaction with the soil causing hard and rigid soil mass. Increase in UCS with cement content is in good agreement with the study conducted by Osinubi (2001).

9.5.3. Unconfined Compression Test (UCT)

UCS testing were performed in order to know the mechanical characteristics of the expansive soil and its mixture with stabilizing material. The varied mixture composition of the samples, duration of sample curing period, resulted UCS values, and consistency designation are shown in **Table 14** and **Fig. 11**.

Table 14. UCS Test Results of mixture clay soil and marble powder

No	Mixture	qu (kg/cm^2) Curing 0 day	Curing 7 days	Consistency
1	100% Original soil	0,099	0,109	*Very soft*
2	95% Original Soil + 5% marble powder	0,104	0,155	*Very soft*
3	90% Original Soil + 10% Marble Powder	0,123	0,210	*Very soft*
4	85% Original Soil + 15% Marble Powder	0,131	0,251	*Very Soft/Soft*
5	80% Original Soil + 20% marble powder	0,180	0,304	*Very Soft/Soft*
6	75% Original Soil + 25% Marble Powder	0,215	0,358	*Soft*
7	70% Original Soil + 30% Marble Powder	0,306	0,450	*Soft*

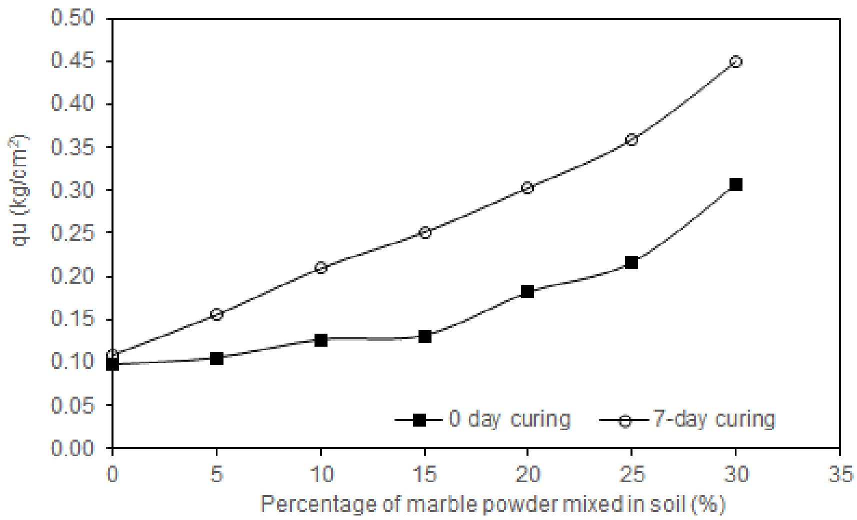


Figure 11. UCS test results (q_u) with varied marble powder mixture and curing time

Figure 11 shows that the amount of marble powder in the mixture and the curing time can increase the unconfined compression strength of the soil. The values of UCS with 7-day curing are higher than those without curing time. This is due to increased bonding of grain by process of cementation, the pore cavity in the clay soil is surrounded with harder marble powder, so that the grain is not easily deformed. Increasing amount of marble powder in the mixture consistently increases the unconfined compression strength values.

9.6. Mixture of marble and acrylic marble solution

9.6.1. Unconfined Compressive Strength (UCS)

From UCS test (qu) on mixture of soil with marble powder, the mixture's consistency is designated as soft. Further, a series of UCS test were performed on mixture of clay (70%), marble powder (30%), and varied concentration of acrylic acid solution. Concentrations of acrylic acid solutions added are 5%, 7%, 10%, 13%, and 15% of the moisture content. The mixtures underwent curing for 3 and 7 days to see effect curing duration on the strength.

9.6.2. Unconfined Compression Strength Test with 3-days curing

Results obtained after performing this test can be seen in **Table 15.**

Table 15. UCS test for samples treated with 3-day curing

No	Mixture (with 70% original soil + 30% marble powder)	qu (kg/cm^2)			Consistency
		Sample 1	Sample 2	mean	
1.	+ 5% acrylic acid	0,434	0,431	0,432	*Soft*
2.	+ 7% acrylic acid	0,455	0,444	0,449	*Soft*
3.	+ 10% acrylic acid	0,484	0,471	0,477	*Soft*
4.	+ 13% acrylic acid	0,557	0,549	0,553	*Medium*
5.	+ 15% acrylic acid	0,635	0,707	0,671	*Medium*

UCS value of original soil is 0.099 kg/cm^2, and from **Table 15** show the value increase after curing. For mixture with marble powder 30% and acrylic acid solution 15% of the water content, with 3-day curing, the UCS value increasing by 577.78%.

9.6.3. Unconfined Compression Strength Test with 7-day curing

Results obtained after performing this test can be seen in **Table 16**.

Table 16. UCS test for samples treated with 7-day curing

No	Mixture (with 70% original soil + 30% marble powder)	qu (kg/cm^2)			Consistency
		Sample 1	Sample 2	mean	
1.	+ 5% acrylic acid	0,455	0,481	0,468	*Soft*
2.	+ 7% acrylic acid	0,537	0,521	0,529	*Medium*
3.	+ 10% acrylic acid	0,609	0,609	0,609	*Medium*
4.	+ 13% acrylic acid	0,679	0,671	0,675	*Medium*
5.	+ 15% acrylic acid	0,714	0,802	0,758	*Medium*

UCS value of original soil was 0.099 kg/cm^2, and **Table 16** shows the value increase after mixing and curing. For 30% marble powder and acrylic acid solution 15% of the water content, with 3-day curing, the UCS value increased by 665.66%.

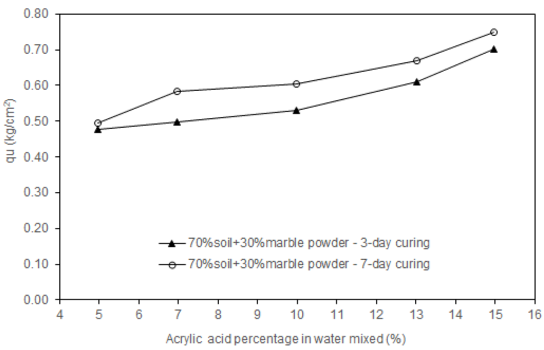


Figure 12. UCS values with 3 and 7-day curing.

Table 15 and **16** are combined in **Fig. 12** which shows consistent increase in the UCS value compared to original soil. This is due to the increase in acrylic acid solution and due to longer curing time. For example, for addition 5% of acrylic acid solution, UCS value increase 8.3% from the result 3-day curing to 7-day curing.

For 7-day curing, the UCS value of original soil qu is 0.109 kg/cm^2, then mixed with 30% marble powder, the value increase to 0.405 kg/cm^2 which is 271.56% increase. The mixture then added with acrylic acid solution, 15% of water content, UCS value increase to 0.758 kg/cm^2 which is a further increase by 87.16%.

Original soil that is mixed only with marble powder, will gain an increase in UCS value. For mixture of original soil, marble powder, and acrylic acid solution, the UCS value increases furthermore. The original soil that is only mixed with marble powder increase its UCS value by 30% and designated as soft, with the addition of an acrylic acid solution of 15% of water content, the soil has higher strength and its consistency is designated as Medium.

There occurs positive ion exchange (cation) in the clay soil (Na^+) by the positive ion in marble powder, and acrylic acid (Ca^{++}). Ion exchange reaction occurs in a relatively short time and causes the process of forming large grains (flocculation). In addition, acrylic acid solution as mixing material causes lime from marble powder become stronger. Longer curing time maximizes mixing process and causes the mixture to have much greater strength.

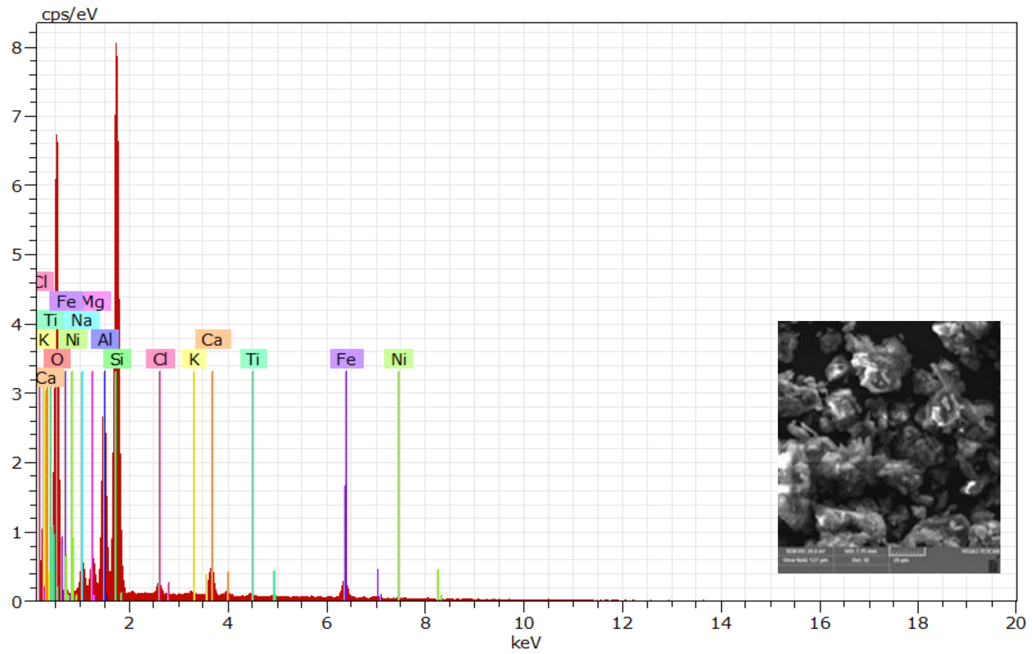


Figure 13. Scanning Electron Microscope (SEM) test result chart for clay soil

Mineral elements contained therein are 30.04% Oxygen, 17.87%Silicon, 7.17% Aluminum, 1.35% Magnesium, 3.07% Iron, and 1.88% Sodium. They formed dominant compound that is SiO_2 of 59.73% and Al_2O_3 of 21.18%. Soil mineral content are presented in **Table 17** and **Fig. 14**.

Table 17. Minerals contained in clay soil samples

Element / Compound	Portion (%)
Illite – Montmorilonite	80
Albite, calcian	15
Quartz, syn	0,8
Iron diiron (III) oxide, Magnetite	0,7
Magnesioferrite, syn	4

9.7. Characterization of original soil minerals

The original soil SEM test results is presented in **Fig. 13**. Clay soil is said to have a high swelling potential when most of these minerals forming soil are montmorillonite. Montmorillonite consists of three units of layer, i.e. two units of tetrahedral layer (containing silica ions) adheres to a single octahedral layer (containing iron ions and magnesium). Montmorillonite has chemical formula of $Al_2Mg\ (Si_4O_{10})\ (OH)_2kH_2O$. From XRD results in **Table 17**, the soil sample is categorized as an expansive clay soil. The high level of silicate in the soil is caused by high mineral alpha quartz.

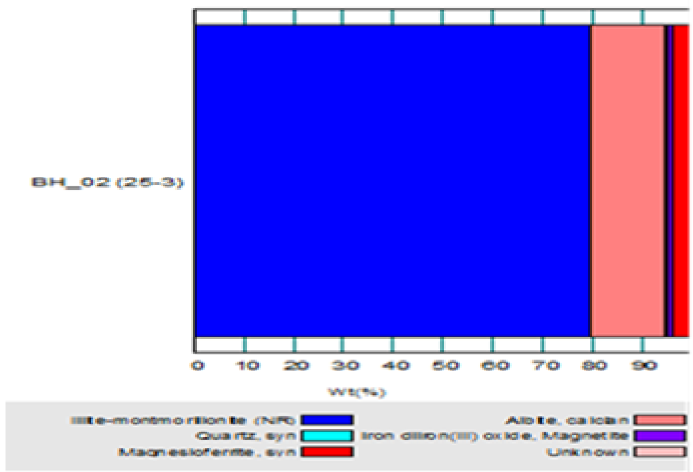


Figure 14. Test XRD mineral content of original soil sample

9.8. Chemical characterization of marble powder

Chemical characteristic of marble powder from test results are shown on **Table 18**.

Table 18. Chemical Characteristic of marble powder

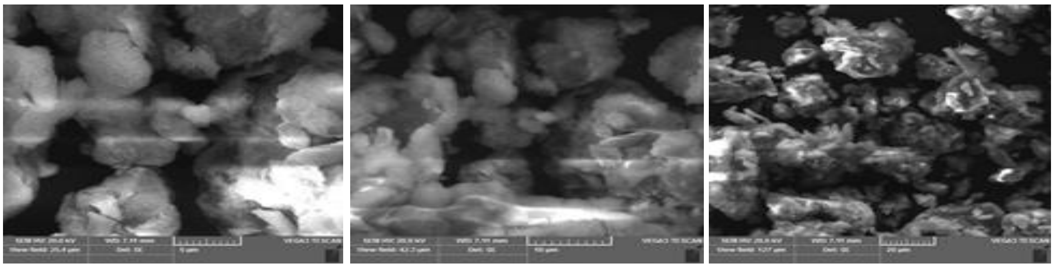
Material Name	Content (%)
CaO (Calsium oxide)	97,15
MgO (Magnesium oxide)	1,47
Al_2O_3(Aluminium oxide)	0,28
K_2O (Kalium oxide)	0,82
SiO_2 (Silica)	0,28

The result also shows calcium oxide compound (CaO) is dominant, 97.15%. The dominant compound in lime and cement are similar, both are used in the stabilization of clay soils. CaO is a compound needed in a chemical process with clay soil, which will produce high calcium ions that bind and surround clay soil particles to reduce water attraction (Al Huda & Gunawan, 2013).

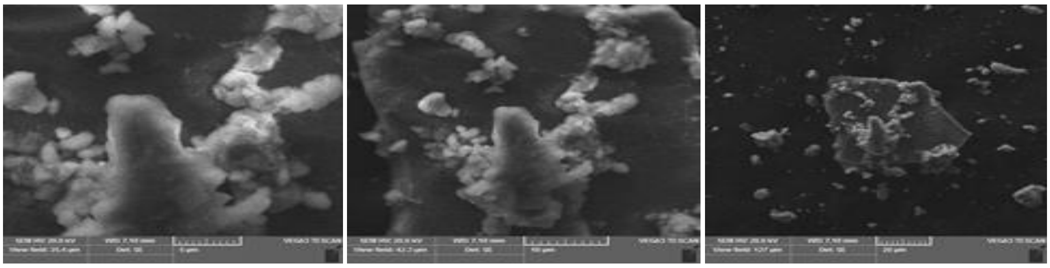
ASTM (1994) requires that for stabilizing soil, lime content (CaO) should not be less than 60%, and should pass sieve #200 with 70%-100%. Therefore, marble powder meets the requirement as a soil stabilization material.

9.9. Characterization of mixture of clay soil, marble soil, and acrylic acid

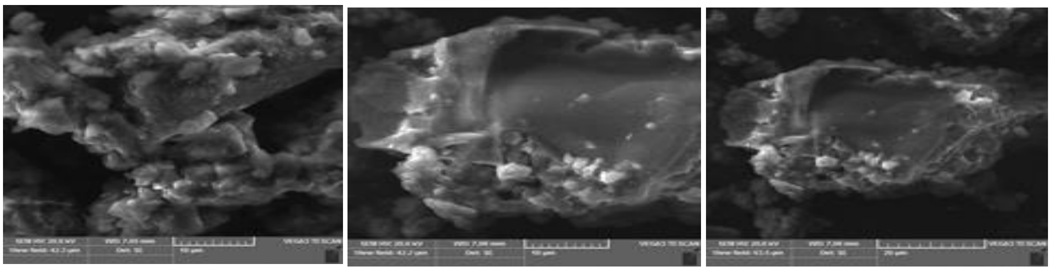
The characterization of the clay using SEM (scanning electron microscope) is to determine the morphology of the clay surface. The observations performed with SEM can be seen in **Fig. 15**.



a. Clay soil solution



b. 70% Clay soil + 30% Marble powder



c. 70% Clay soil + 30% Marble powder + 15% Acrylic acid solution

Figure 15. The result of SEM on mixture of clay soil, marble powder, and acrylic acid solution

A wide range of additives have high calcium ions or other compound elements that can bind the soil grain to form larger grains. With addition of marble powders and acrylic acid solutions (**Fig.15** (b) and (c)), It is clearly seen that the bonds between particles have been formed. It is also shown that the calcite formation occurred and is cemented by the mixture of marble powder and acrylic acid. It is proven by presence of changes in soil structure with pores that have been filled by material during the curing time. Thereby the density and strength of soil that has mixed with stabilization material increase.

The results of the minerology test of the chemical element in mixture of 70% of clay soil and 30% of marble powder can be seen in **Table 19**.

Table 19. Chemical compound in mixture of 70% of soil clay and 30% of marble powder

Component	Content (%)
SiO_2	48,37
CaO	27,26
Fe_2O_3	12,26
Al_2O_3	8,84
K_2O	2,07

Marble powder which is rich in CaO and MgO if added to montmorillonite clay will cause Ca^{++} and Mg^{++} ion exchange with Na^{+} ion (sodium) present in expansive clay. The process of exchanging positive ions will decrease the soil's plasticity index which is then followed by a decrease in soil swelling potential.

Further, test results of chemical content in a mixture of 70% clay soil, 30% marble powder and 15% acrylic acid solution can be seen in **Table 20**.

Table 20. Chemical compound in mixture of 70% of soil clay, 30% of marble powder and 15% acrylic acid solution

Component	Content (%)
SiO_2	35,92
CaO	36,66
Fe_2O_3	12,16
Al_2O_3	7,69
SO_3	3,71

It can be seen in the changes from **Tables 19** to **Table 20**, after addition of acrylic acid solution there is decrease in the content of SiO2 by 25.74% and an increase of CaO compounds by 34.48%. Si and Al in clay, if reacted with active lime (CaO) in a certain period of time, ion change reaction will occur followed by pozzolanic reaction forming Calcium silicate hydrate (C-S-H) or Calcium Aluminate hydrate (C-A-H) or even Calcium silicate Aluminate hydrate (C-S-A-H). Even CSH binding gel causes the binding between soil particle which could result in increased soil strength.

10. Conclusions

Marble Powder from Enrekang District contain 97.15% of calcium oxide (CaO) while clay soil sample used in this study contain 59.73% of SiO2 which is considered an expansive soil.

With increasing percentage of marble powder in the mixture, CBR values consistently increase. Maximum CBR value occurs in mixture with 30% marble powder with an increase of 168.2%. With addition of 20% marble powder, resulted CBR value is 6.31% which is higher than the required for road subgrade construction.

From UCS test to the mixture of clay soil and marble powder, the strength of the mixture increased by increasing amount of marble powder and duration of curing. With the addition of 30% marble to the original soil and with 7-day curing, the mixture gain in strength in term of qu value up to 354.54%, however the consistency of the mixture is still categorized as soft. Furthermore, acrylic acid solution was added to the optimum mixture of marble powder and the results showed significant increase. With addition of 15% acrylic acid solutions to the water, the mixtures can increase the value of qu from original soil by 665.66%. This increase changes soil strength from very soft consistency to medium.

From the results of minerology test to the mixture of clay soil, marble powder, and acrylic acid solution, CaO and SiO_2 compounds as well as other compounds will undergo pozzolanic reactions and will harden in a certain period that causes the increase of expansive soil strength.

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