Behaviour of Mixed Expansive Soil and Additive Minerals as Subgrade Layer

F Sitepu¹, T Harianto¹, R Ridwan² and N Marfuah¹

¹ Civil Engineering Department, Hasanuddin University, Makassar, Indonesia
² Directorate General of Highway Construction and Maintenance Department, Ministry of Public Works and Housing, Palangkaraya, Indonesia

nurulmarfuah.nm@gmail.com

Abstract. South Sulawesi is one of eastern Indonesia area covered with coastal line which have growth fast of industries. Infrastructure builds and developed in a row of industries population. Most coastal are lowland areas with expansive soil as primary soil forms. Exhaustive laboratory test conducts for clay taken from lowland area in south Sulawesi and lime up to 10% and volcanic up to 25% as stabilizers to know the Physical-mechanical properties and mineralogical when the expansive soil stabilized. The extensive soil stabilized with 5% lime + 15% Volcanic ash presents better performance and pass the roadbed materials requirements. Chemical reactions between soil and the stabilizers increase the pH and electrical conductivity. X-ray diffraction (XRD) and transmission electron microscope (TEM) confirmed new cementing agents' findings regarding the results of chemical reactions. An explicit effect on controlling the soil deformation and the moisture change shows by the expansive soil stabilized with 5% lime + 15% volcanic ash. The research results find the optimum combination of stabilizers to reduce cost to improve expansive soil from the South Sulawesi lowland area.

1. Introduction

In recent years, construction in Indonesia’s eastern region has grown fast, such as land expansion, reclamation, railways, roads, airport expansion, and opening of new industries. Engineers will encounter geotechnical engineering issues when subgrade construction for road embankment in the expansive soil. Expansive soil in the lowland area is a type of clay with high swelling potential when exposed to water and shrinks if it loses moisture and has a feeble soil strength [1], [2]. This condition became a severe problem in embankment road construction if the engineers do not give any stabilization to improve the soil strength or excavated to cut away and fill with the better soil.

Expansive soil in the lowland areas containing clay minerals such as montmorillonite, chlorite and illite which is susceptible to volume change due to changing of water content [3]. The best solution of the high swelling potential and plasticity of expansive clay is soil stabilization such mixed with resins, hydrated lime, portland cement and fly ash is the most commonly used for stabilizers [4]. The soil stabilization method could improve the durability and strength of the soil [5]. The physical and mechanical properties of expansive soil mixed with lime significantly improved, founds in Al-Rawas [6] research using Atterberg limits, swell pressure and swell percent tests. Lime and soil mixed reaction shown over the short term, and over a long time, the pozzolanic progression also seems after conducting a test of pH, electrical conductivity, and X-ray diffraction (XRD) at the Al-Mukhtar [7,8] research.
2. Material

2.1. Expansive Soils from South Sulawesi Lowland Area
Expansive soil sample taking from southern Makassar, South Sulawesi. Expansive soil is characterized by its high plasticity, low strength, and free swell index. The physical and chemical properties of this clay are presented in Table 1. The soil has a high potential for moisture absorption because it is contained high clay and cation exchange capacity (CEC) denote that the grounds have a high surface activity. The X-ray diffraction pattern measured following SY/T 5163-2010 [9] is presented in Figure 1. The soil contained montmorillonite as a primary clay mineral with few of illite and kaolinite.

![Figure 1: X-ray diffraction of the expansive soil sample](image)

Table 1. The Soil physical properties and Cation exchange capacity (CEC)

| Physical Properties               | Values   |
|-----------------------------------|----------|
| Liquid limit (%)                  | 65.4     |
| Plastic limit (%)                 | 33.5     |
| Plasticity Index (PI)(%)          | 31.9     |
| Free Swell Index (%)              | 165      |
| Maximum Dry Density (g/cm3)       | 1.35     |
| Optimum Moisture Content (%)      | 31.2     |
| CBR (%)                           | 1.6      |
| UCS (Mpa)                         | 0.212    |
| Cation Exchange Capacity (meq/100g)| 58.3    |
| Calcium (Ca)(%)                   | 47.2     |
| Magnesium (Mg)(%)                 | 4.88     |
| Sodium (Na)(%)                    | 2.75     |
| Potassium (K)(%)                  | 1.66     |

2.2. Hydrated Lime
The lime was taken from a local lime company. The composition was 96.2% Ca(OH)2 and 3.8% other oxides, and the passing rate of 80 m sieve was 100%. Hydrated lime is also used as an additive material to stabilize the expansive soil.

Table 2. Chemical composition of expansive soil and volcanic ash

| Oxides (%) | CaO | MgO | Fe2O3 | Al2O3 | SiO2 | K2O | Na2O | SO3 | P2O5 | Mn O | TiO2 | LOIa |
|------------|-----|-----|-------|-------|------|-----|------|-----|------|------|------|------|
| Expans.    | 1.8 | 0.85| 9.44  | 16.78 | 50.4 | 1.22| 0.63 | 0.2 | 0.03 | 0.33 | 0.8  | 17.5 |
| Soil       |     |     |       |       |      |     |      |     |      |      |      |      |
| Volcan. Ash| 10.47| 11.91| 12.43 | 13.35 | 43.2 | 6.13| 2.76 | 0.0 | 0.54 | 0.17 | 2.85 | 0.32 |

*a* loss on ignition

![Figure 1: X-ray diffraction of the expansive soil sample](image)
2.3. Volcanic Ash

Natural pozzolans samples were from Soputan Mount, South East Minahasa district. Table 2 has presented the chemical compositions of the expansive soil and volcanic ash due to X-ray Fluorescence (XRF, ADVANT’XP, Thermo, United States).

3. Experimental Methods and Test

3.1. Physical and Mechanical Properties Measurements

Expensive soil's physical and mechanical properties stabilized with additive minerals measured, including Atterberg limits, compaction characteristics, California Bearing Ratio (CBR), and unconfined compressive strength (UCS). The laboratory test was conducted according to JTG E40-2007 [10], and Indonesian Pavements Design for Highway Manual-2007 [11], and JTG E51-2009 for materials stabilized [12]. First of physical and mechanical properties testing the expansive soil particles passed through 0.5 mm and 2 mm sieves, and for the natural pozzolans, particles passed through 75 m sieves. Continued with mixed and cured the soft soil, volcanic ash, and lime following JTG E40-2007, then cured for one day. Afterward is performed Atterberg limits and standard proctor test, then optimal moisture content (OMC) and the maximum dry density (MDD) of the stabilized soft soil sample could be determined. The CBR specimens for testing prepared with the OMC under the compaction effort per volume and soaked for four days. CBR value is determined by penetration testing with a rate of 1.25mm/min after 2.5 mm of penetration. UCS test for the sample of stabilized soft clay based on JTG E51-2009.

3.2. Mineralogical Phase Measurements

Stabilized soil sample oven-dried and pounded until particle passes through 40 m sieves. Data recorded in the two theta ranges of 5-60o with a speed of 0.02o / the 20s per step determine the XRD patterns. Transmission electron microscope characterization determined using a JEOL JEM-2100F apparatus by putting the stabilized soil slurry to the glass sheet.

3.3. Measurements of pH and Electrical Conductivity

The pH and electrical conductivity (EC) of the slurry were measured based on JTG E40-2007. Particles of stabilized soil passing a 1 mm sieve as much as 10 g of oven-dried quantity dispersed in 50 mL of distilled water. Then the sample is put into the small container and shakes it for 3 minutes. pH and EC were measured in the 25 mL of the slurry sample after 1 and 3 hours and 1,2,7 and 28 days.

4. Results and Discussion

4.1. Physical and Mechanical Properties

4.1.1. OMC and MDD.

The OMC and MDD results based on JTG E51-2009 of the stabilized soil are shown in Figure 2. Increasing lime content will also increase OMC and decreased MDD. Contrarily tendency presents when soft soil stabilized by volcanic ash since volcanic ash coats soft soil unreacted and forms large aggregates and improves the dry density of the soil mixes. According to the conventional conclusion, volcanic ash's pozzolanic reaction with the soil constituents tends to increase the optimum moisture content [13]. The samples of all types of mixes are cured for 24 hours before the testing. In such a short time, the pozzolanic reaction might only just starting. Due to the low content of calcium oxide (10.47%) in volcanic ash, a small number of reaction products could be generated. Specific gravity and the grain size distribution contributed to the soil's compaction characteristic stabilized with volcanic ash. The soil mix's dry density increases as the results of the unreacted of the volcanic ash and large aggregates are formed by soft soils coated by the volcanic ash.

4.1.2. They are determining Lime and Volcanic Ash Content.
The Atterberg limits and plasticity index of stabilized soft soil are presented in Table 3. Soil mixed with 10% of lime decreasing liquid limit from 65.4% to 58.2%. The liquid limit of soil mixed with 25% volcanic ash also reduced from 65.4% to 51.5%. Soil samples, which are integrated with 5% lime and 20% volcanic ash, present the largest decrease of liquid limit value from 65.4 to 46.5%. Using lime, cement, and artificial pozzolan as soil additives shows an identical behavior observed by Al Rawas et al. [6]. Soil stabilized with 10% lime, 25% volcanic ash, and a combination of 5% lime + 20% volcanic ash presents the decreasing of plasticity index from 31.9% to 9.5%, 22.8%, and 22.4%, respectively. The highest of decreasing plasticity index is lime stabilized the soil.

Table 3. CBR Requirement of Roadbed Materials [14].

| Traffic Classification          | Depth Under Pavement (M) | Expressway/First-class Highway | Second-class Highway | Third/fourth-class Highway |
|---------------------------------|--------------------------|--------------------------------|----------------------|---------------------------|
| Any level of traffic           | 0.0-0.3                  | 8%                             | 6%                   | 5%                        |
| Light/medium traffic           | 0.3-0.8                  | 5%                             | 4%                   | 3%                        |
| Heavy/very Heavy Traffic       | 0.3-1.2                  | 5%                             | 4%                   | 3%                        |

Figure 2. Lime and volcanic ash effect to the optimum moisture content (OMC) and maximum dry density (MDD) of the expansive soil.

Figure 3. Presents the variation of the California Bearing Ratio (CBR) of the stabilized soil. The lime stabilized soil 1% to 10% increase the CBR from 4.7% to 25.2%, and the expansion ratio decrease from 3.1% to 0.3%. The soil mixed with volcanic ash presents lower CBR compared to soil mixed with lime. Volcanic ash 10% to 25% stabilized soil increase the CBR from 2.2% to 4.5% and decrease the expansion ratio from 2.6% to 2.1%. Composite lime and volcanic ash stabilized soil show a rapid increase of CBR. With the addition of 5% lime + 20% volcanic ash, the CBR reach 29%.

According to the JTG D30-2015 [14], subgrade soils must have less than 50% for the liquid limit and 26% for the plasticity index. Table IV shows the CBR requirement for roadbed materials. The soil stabilized with volcanic ash only can be used as roadbed materials for a low-volume road. The soil...
stabilized with lime can pave a high-grade road, and soil stabilized with 3% lime meet the highest CBR requirement.

![Graph showing CBR and expansion ratio](image)

**Figure 3.** The effects of stabilizer content on the expansive soil on the California Bearing ratio (CBR) and expansion ratio

**Table 4.** Atterberg Limits of the natural soil and soil with stabilization

| Samples                | Liquid Limit (%) | Plastic Limit (%) | Plasticity Index (%) |
|------------------------|------------------|-------------------|----------------------|
| Natural Soil           | 65.4             | 33.5              | 31.9                 |
| 1% Lime                | 65.5             | 35.7              | 29.8                 |
| 5% Lime                | 63.4             | 45.8              | 17.6                 |
| 10% Lime               | 58.2             | 48.7              | 9.5                  |
| 10% Volcanic Ash       | 58.3             | 30.6              | 27.7                 |
| 15% Volcanic Ash       | 56.5             | 31.6              | 24.9                 |
| 20% Volcanic Ash       | 53.3             | 30.2              | 23.1                 |
| 25% Volcanic Ash       | 51.5             | 28.7              | 22.8                 |
| 1% Lime + 15% Volc.Ash | 58.6             | 30.5              | 28.1                 |
| 1% Lime + 20% Volc.Ash | 59.2             | 32.3              | 26.9                 |
| 5% Lime + 15% Volc.Ash | 48.4             | 25.1              | 23.3                 |
| 5% Lime + 20% Volc.Ash | 46.5             | 24.1              | 22.4                 |

4.1.3. Unconfined Compressive Strength (UCS).

Soil stabilized with lime showed the highest UCS increase from 0.212 MPa to 2.2 MPa and 3.5 MPa with the additions lime of 5% and 10%, respectively. Interaction of the soft soil and lime mixing, cation exchange, flocculation, carbonation, and pozzolanic reaction contribute to this behavior. The volcanic ash shows a lower performance on increasing UCS comparing to the lime as a stabilizer. After 28 days of curing, soil stabilized with volcanic ash offers only 0.212 MPa to 0.81 MPa. The pozzolanic reaction's slow progress is caused by few hydroxyl ions (OH-) on volcanic ash-soil mixed. Low pH can be observed in the volcanic ash-stabilized soil.
The better result of Unconfined Compression Strength is shown by a combination of lime and volcanic ash as a soil stabilizer compared to the single stabilizer. After curing for 28 days, the soft soil stabilized with a mixture of 5% lime and 15% volcanic ash presents the UCS reaches 1.95 MPa, while soft soil stabilized with 5% lime only is 1.5 MPa or 15% volcanic ash is 0.56 MPa. The results most likely because of the pozzolanic reaction between clay and volcanic ash was accelerated by calcium hydroxide in lime. Harichane [15] found similar results in stabilizing the clay taken from sites near the town of Chlef in west Algeria.

4.2. Mineralogical Changes of Stabilized Expansive Soil

4.2.1. Movement of pH and Electrical Conductivity.

Figure 5 presents the variation of pH with stabilizer content and curing time. The solubility of aluminate and silicate in soil increases indicates by increasing pH value, which can accelerate the pozzolanic reaction between the soil and stabilizers. Increasing curing time due to a higher quantity of stabilizers will decrease the pH.

Figure 4. Effect of stabilizer on the UCS a). Lime, b) Volcanic Ash, c) Mixed Lime and Volcanic ash

Figure 5 presents the variation of pH with stabilizer content and healing time. The solubility of aluminate and silicate in soil increases indicates the rise of pH value, which can accelerate the soil and stabilizers’ pozzolanic reaction. Increasing curing time due to a higher quantity of stabilizers will decrease the pH. The electrical conductivity experience incisive drop due to cation exchange and declining due to the pozzolanic reaction.
Figure 5. pH of stabilized soil changes with curing time

Figure 6. The electrical conductivity of stabilized soil with curing time

Figure 7. X-ray diffraction of natural expansive soil and stabilized soil. (Annotations M = montmorillonite, Q = quartz, F = feldspar, A = augite, Z = zeolite, W = wollastonite, L = lime)
4.2.2. Mineralogy Phase Analysis.

Figure 7 shows the pattern of the X-ray diffracton of the soil stabilized with volcanic ash and lime. The expansive soil stabilized 15% volcanic ash presents a similar diffractogram to the soil without stabilizer. Because only a small amount of volcanic ash reacts with clay, only a few minerals are found in the soil mixtures, such as augite and wollastonite. New diffraction peaks in soil stabilized with 3% lime and 15% volcanic ash found at two theta angles of 18.20°, 34.25, 47.20, 50.95, and 54.45 ascribed to Ca (OH)2. Due to the consumption of Ca (OH)2, this diffraction disappeared after 28 days. Moreover, at two theta angles of 19.85, there is a new mineral found, calcium aluminate hydrate.

Transmission electron microscopy images of soil, soil mixed with 15% volcanic ash, and soil mixed with 3% lime + 15% volcanic ash presented in Figure 9. A multilayer sheet structure is observed in the soil with no stabilizer, which shows a typical clay mineral contour [16]. Clay minerals dominated this type of expansive soil. The soil stabilized with volcanic ash shows block-shaped particles are ascribed to volcanic ash. The volcanic ash seems no effect on the soil’s physical and mechanical properties. Soil mixed with five % lime and 15% volcanic ash still shows a sheet structure even after 28 days of curing.

![Figure 8. TEM images of Soil Stabilized a) soil stabilized with 5% lime + 15% volcanic ash, b) new minerals formed.](image)

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5. Conclusion

Compaction, Atterberg limits, CBR, and UCS tests were used to investigate the physical and mechanical properties of the expansive soil stabilized with lime and volcanic ash in this research. The mineral phases change observed with pH, EC, XRD, and TEM tests, and the conclusions following are:

1) The expansive soil from the lowland area in Makassar city of South Sulawesi province is typical of expansive soil, which is having a high plasticity index, swelling potential, and clay mineral content.
2) Expansive soil stabilized with volcanic ash could increase CBR and UCS and decrease the liquid limit and PI but not significantly with lime mixed stabilization. A combination of lime and volcanic ash as additive minerals for soil stabilization presents better improve the physical and mechanical properties of expansive soil.
3) Soil stabilized with 5% lime + 15% volcanic ash presents a better effect in controlling the road foundation's moisture and soil movement. This combination of stabilizers meets the JTG D30-2015 and SNI Road Foundation's technical requirements for roadbed materials in Indonesia.
4) XRD and TEM observed the reaction of the stabilizers with the soil, which is formed new minerals.

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