Effects of Potassium Solutions on Swell Potential of Mae Moh Expansive Soil

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Abstract

This paper presents a field experiment of using potassium solutions to reduce swelling of expansive soil in the area of Mae Moh District, Lampang Province, Thailand. Based on the fact that the difference between montmorillonite in expansive soil and illite in non-expansive soil is the silica-gibbcite structure of the former was bonded by water molecules but those structures of illite was bonded by potassium ions. Therefore, an assumption of this research was if the expansive soil were soaked in potassium solution, monmorillonite may change to illite, and the soil should no longer swell. The field experiment was conducted by drilling holes of approximately 2 meters depth. Then, released potassium hydroxide in the forms of solution and flakes as well as potassium chloride solution and potassium nitrate solution into the holes. Kept the holes fill with the solutions at all time. After 30 days and 90 days, drilled other holes nearby the solution-fill holes to collect soil samples for laboratory tests. The investigation revealed that only the 20% potassium hydroxide can reduce the swelling of Mae Moh expansive soil. The X-ray diffraction test discovered that after 30 days of applying KOH solution to the expansive soil stratum, only illite and muscovite but montmorillonite was found, then after 90 days only muscovite was found. Based on academic articles in chemistry and geology, the transformation of montmorillonite to illite, and transformation of illite to muscovite are possible. The study of using potassium hydroxide solution should be studied extensively because it will be useful for existing buildings.

Keywords: Expansive soil, Soil improvement, Potassium hydroxide, Potassium chloride, Potassium nitrate

1. Introduction

Expansive soil is generally recognized as one of the most problematic soils around the world. This type of soil shrinks and swells significantly when moisture content in the soil mass changes. The swelling can induce very high pressure and cause damages to structures built on or in the expansive soil layers.

In Thailand, expansive soil is rare. It can be found only in some areas. Mae Moh District of Lampang Province, is one of those few areas where expansive soil can be generally found. The swelling of this soil has caused damages to some buildings as well as road embankments. There have been several attempts to solve this problem such as designing pile foundations with uplift resistance, and replacing the expansive soil layers with compacted wasted ash from the local power plants before the construction. These approaches, however, are not appropriate for solving problems of existing buildings damaged by the swelling of the supporting expansive soil. An example is a workshop built on layers of expansive soil which underwent heaving for more than 10 years, and until now the heaving is still going on. Differential heaving occurred all over the building and, therefore caused a lot of problems, especially, for machine operation in the workshop. The ongoing heaving prevents the building owner to repair all the damages. Stopping the swelling or stabilization of the underneath expansive soil must be done first without demolishing the workshop building.

After reviewing several approaches of reducing the swelling potential of expansive soils, chemical injection was considered an appropriate approach in this case. There have been a number of research involving chemical treatment on expansive soils throughout the world. For instances: lime, lime-fly ash, and other conventional additives such as cement had been studied for more than 60 years [1–7]. However, these materials must be in the form of slurry which has difficulty in penetrating through the voids around expansive clay particles, and thus they need fissures and cracks to be more effective [8].

As a result, treatment with substance in the form of solution should be more effective. For example, gypsum solution was brought in to the improvement [9] as well as some other chemicals such as chloride salts [10–14], and potassium carbonate [15]. These treatments shown some promising trends, however, the authors would like to try another idea as following.

It is widely known that there are two types of clayey soils which are very similar in their mineral structures: one is illite which is non-expansive, another is montmorillonite which is expansive soil. As illustrated in **Figure 1**, their basic mineral structures consist of a gibbsite (O) sheet sandwiched by two silica (T) sheets. The only difference between them is that illite layers are bonded by potassium ions while montmorillonite layers are bonded by water and exchangeable cations [16]. The surfaces of those silica sheets are negative charges, and hence attract cations with positive charge such as K^+, Na^+, and etc. Therefore, soaking expansive soils with K^+ solutions could possibly transform montmorillonite to illite.

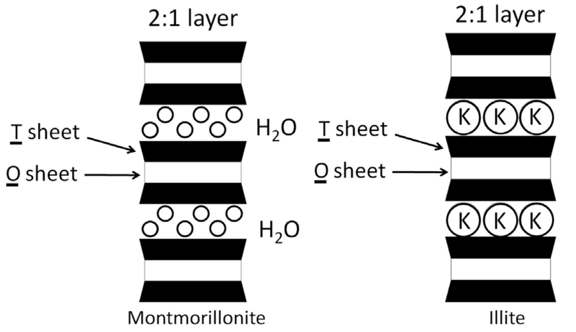

Figure 1. Comparison of symbolic structures of Montmorillonite and Illite.

It was demonstrated that the highly expansive Na-montmorillonite can be transform to illite through the following chemical process [17], was shown in eq. (1).

$$\begin{aligned}&(Na^{+})_{0.3}(Al_{1.7}{}^{VI}Mg_{0.3})(Si_4O_{10}) + 0.6K^{+} + 0.15Al_2O^{3} => \\ &K_{0.6}(Al_{1.7}{}^{VI}Mg_{0.3})(Si_{3.7}Al_{0.3}{}^{IV}O_{10}) + 0.3SiO_2 + 0.3Na^{+}\end{aligned} \quad (1)$$

Solutions of K^+ can be simply made by dissolving potassium substances in water [18]. Kruadsungnoen and Sethabouppha found their laboratory test on K-substances such as potassium hydroxide (KOH), potassium chloride (KCl), and potassium nitrate (KNO_3) has shown some good trends on improvement of Mae Moh expansive soil samples [19]. Therefore, this research was an extensive study focused on the effect of stabilizing expansive soil using these solutions in a field.

2. Mae Moh Expansive Soil

Prior to this pilot field study, there were some laboratory tests on a number of Mae Moh expansive soil samples. With clay content around 90%, and variety of ranges of liquid limit and plastic limit, the soil can be classified based on Unified Soil Classification System mostly as CH, and CL. Meanwhile some portions can be classified as MH, and ML as shown in **Figure 2.** The figure shows that Mae Moh expansive soil poses a wide range of swelling potential from low to very high. Those classified as CH and MH have higher potential of swelling. **Figure 3** demonstrates a sample of Mae Moh expansive soil in a consolidation ring after completing a free swell test under the pressure of 1 psi (6.89 kN/m^2).

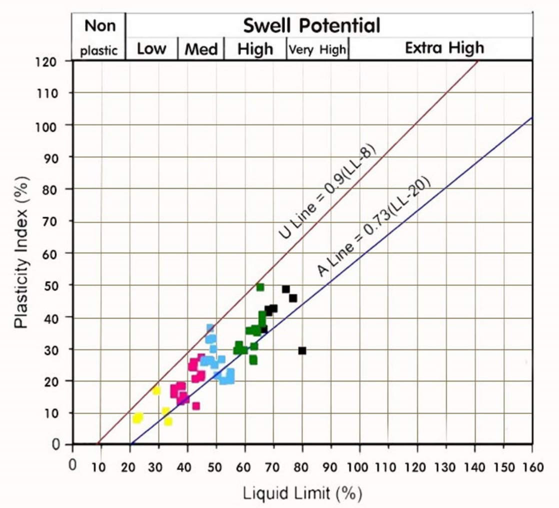

Figure 2. Plot of some Mae Moh expansive soil samples in the plasticity chart and swelling potential.

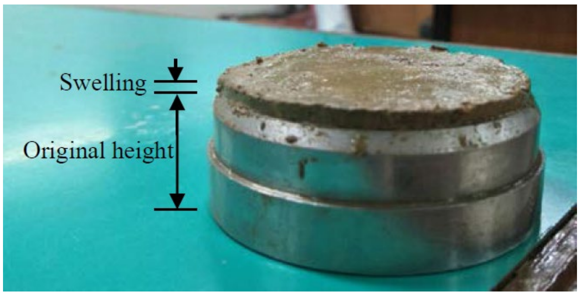

Figure 3. Swelling of an expansive soil sample in a consolidation ring after a free swell test.

Result from free swell test revealed that Mae Moh expansive soil samples swelled approximately 6–10% by volume in average, with the maximum value almost reach 20%. Swell pressure of this soil was found within a wide range with the maximum value of nearly 200 kN/m^2. Another noticeable behavior of this soil was its sensitivity to water. When water content increased beyond the soil's plastic limit, shear strength of the soil decreased significantly. Therefore, buildings in Mae Moh area have been damaged either by heaving caused by swelling of the soil when moisture increased from the natural or original water content or by collapsing caused by shear failure when moisture content increased beyond the soil's plastic limit.

3. Design of Experiment

From the previous sections, it can be seen that potassium solutions might have good potential for treatment of expansive soils. There are several kinds of potassium substances available, however, as mention earlier, potassium hydroxide (KOH) which is an ingredient for soap manufacturing, potassium chloride (KCl) and potassium nitrate (KNO_3) which are main composition in fertilizer for some agricultural plants. These 3 following experiments were conducted respectively.

1) Laboratory test for free swell index (FSI) based on [21]. The objective of this test was to investigate a suitable water-solution concentration of each K-substance for the field test. Section 4 shows more detail of this test.

2) Field study of drilled holes, made by continuous flight auger, to investigate the effects of those three K-solutions of certain concentration found from FSI test. K-solutions were poured in the holes. The approach of drilled-hole test was employed because it could be the method of applying solution to expansive soil stratum. It was planned that 30 days after the pouring, soil samples near the holes would be collected by a hand auger and then would be tested and compared with the natural samples. Section 5 elaborates this field study.

3) Transformation of Mae Moh expansive clay minerals treated by KOH solution was investigated in laboratories. The details is shown in Section 6.

4. Free Swell Index Test

As described above, free swell index test was conducted in order to determine an appropriate concentration of those 3 K-solutions. For this test, soil samples passing sieve#40 were put in graduate cylinders containing water, K-solutions, and kerosene as shown in **Figure 4**. Because expansive soils do not swell in kerosene, therefor, the volume of the soil in this substance was used as reference for the comparison with the others. The soil samples must be kept in the fluids for at least 24 hours or until no change in soil volume can be observed. The value of swell indices can be calculated as eq. (2).

$$Swell\ index = \frac{V_d - V_k}{V_k} \times 100\% \quad (2)$$

Where V_d = volume of the soil in distilled water or the tested solution (expanded soil) in the cylinder

V_k = volume of soil sample in kerosene.

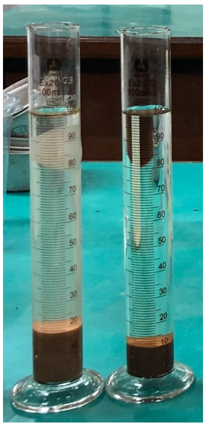

Figure 4. Free swell index test of soil samples.

The results of experiments from laboratory studies as shown in **Figure 5**. The trend of the appropriate concentration proportion to use Potassium solution.

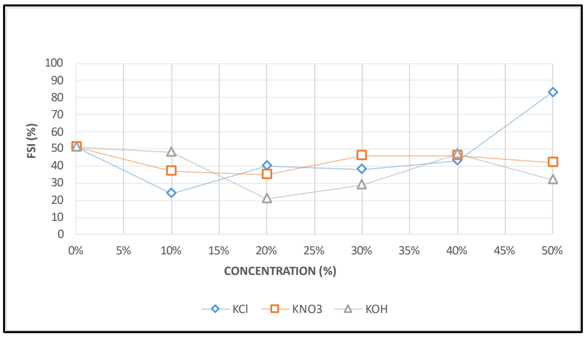

Figure 5. Result of free swell index test.

As shown in **Figure 5**, Mae Moh expansive soil, when submerged in distilled water expanded about 50% of its original volume. The best concentration of KCl-solution, KNO_3-solution, and KOH-solution yielding the lowest swell of the soil samples were 10%, 20%, and 20%, respectively. These were used in drilled-hole test later.

5. Effects of KOH, KCl, and KNO_3 Solutions in Drilled Holes

This field experiment was conducted by drilling 6 holes of approximately 3 inches in diameter and 2 meters in depth in expansive soil stratum in Mae Moh area. All 6 drilled holes were filled with different solutions or substances differently as shown in **Figure 6**.

Figure 6. Drilled holes with potassium solution containers.

As seen in **Figure 6**, the solution in each hole was kept full to the ground surface by connecting to a container of the corresponding solution. This field test were divided into two stages as described here. Stage I was to investigate the effectiveness of all 3 solutions. Stage II was to examine the use of KOH flakes in expansive soil with high water content after it was found the best from Stage I.

5.1 Stage I: Test of KCl, KOH, and KNO3 Solution

The objective of this stage was to investigate and compare the effects of those 3 solutions with their best concentration previously found from FSI test. Holes 1, 2, and 3 were filled with KOH, KCl, and KNO_3 solution of those concentration determined in section 4, respectively. Immediately after drilling, the solutions were poured into the holes. It was planned that after

30 and 90 days soil samples would be collected by drilling holes nearby the soaked holes and tested in the laboratory to investigate the changes. After 2–4 weeks the following conditions was observed.

Hole 1, filled with KCl-solution, was found closed up to approximately 1 meter as shown in **Figure 7**.

Figure 7. The depth of Hole 1 (KCl solution) was only 1 m after 2 weeks.

For Hole 2 (filled with KOH-solution), the depth was still approximately 2 meters as shown in **Figure 8**.

Figure 8. The depth of Hole 2 (KOH) still remained at about 2 meters.

For Hole 3, filled with KNO_3, the hole was closed up to the depth of 1 meter after 4 weeks as shown in **Figure 9**. Note that cracks were also found around the top of this hole unlike Holes 1 and 2.

Figure 9. Depth of KNO_3 hole was measured about 1 m after 4 weeks.

According to the remaining good shape of Hole 2, it could be concluded that KOH-solution was better than other KCl and KNO_3. Therefore, the drilled-hole test was conducted using only KOH.

5.2 Test of KOH Application Method

After KOH-solution has shown more promising from Stage I, it was thought that applying KOH flakes should be easier than in the form of solution or not. Moreover, it was concerned that the water content or the degree of saturation of the surrounding soil might affect the use of KOH-solution. Therefore, in this stage, three more drilled holes with different forms of KOH were applied.

In order to investigate the effect of using KOH flakes directly rather than making solution, the experiment of Hole 4 was conducted by, just after the drilling was completed, pouring KOH flakes of about 20% volume of the hole before filling with water. It was found that this hole was closed up to about 60 cm below the ground surface as shown in **Figure 10**.

Figure 10. Depth measurement of a hole filled by KOH flakes and water after 2 weeks.

Figure 12. The remaining depth of the hole full with KOH flakes and water was about 0.60m.

Hole 5 was to investigate the effect of applying KOH to the expansive soil with high water content. Therefore, conversely to Hole 4, this hole was filled with water for one week first and then put KOH flakes of 20% by volume in the hole. After 2 weeks, it showed that the hole was also closed up as shown in **Figure 11**.

Figure 11. The remaining depth of water-soaked hole followed by KOH flakes 20% by volume was about 80 cm.

The treatment of Hole 6 was similar to Hole 5 but fully fill KOH flakes in the hole after soaking the hole for one week. As shown in **Figure 12**, this hole was also closed up to about 0.6 m below the ground surface after 2 weeks.

These results of Stage II suggested that applying KOH in the form of flakes was not effective. This might be the result of the incomplete melting of the flake in the water. More importantly, any KOH in any form were likely to be ineffective when the expansive soil was with high water content or saturated. It must be mentioned here that experiment in Stage I was conducted in expansive soil with natural water content of not more than 25%.

6. Property and Mineral Changes of Mae Moh Expansive Soil by KOH Treatment

This section provides the investigation of property and mineral changes of the soil treated by KOH solution of 20% concentration based on the result of treatment by using KOH solution in Hole 2 as described previously in Section 4.

6.1 Investigation of Soil Samples beside Hole 2

Soil samples were collected from two holes (Hole A, and Hole B as shown in **Figure 13**) beside Hole 2 at the depth of approximately 2 meters by using a hand auger. Hole A, and Hole B was drilled 30 days, and 90 days respectively after the KOH solution was fully filled in Hole 2. Those KOH-treated soil samples were examined in geotechnical engineering laboratory for general and index properties as well as some swelling properties. Free swell volume was tested by conventional consolidation apparatus with a pressure of 1 psi (6.89 kN/m^2). Swell pressure was defined as the pressure capable of not allow the expansive soil to swell or constant volume test using the consolidation test apparatus as well [22]. Both swelling tests were on remolded soil samples passing sieve#40. XRD (x-ray diffraction) in a chemical laboratory was also run to investigate the minerals in the soils with the results shown in **Table 1**.

Results of free swell volume in **Table 1** reveals that the index properties were not much different. But surprisingly, the free swell volume was increased in contrast with the swell pressure which was decreased. For mineral point of view, KOH treatment tends to increase the free swell values, however, the swell pressure was reduced. The treatment seemed not to generate illite. Instead, muscovite was presented while montmorillonite was disappeared, and quartz was decreased. **Figures 14–16** show results from XRD test.

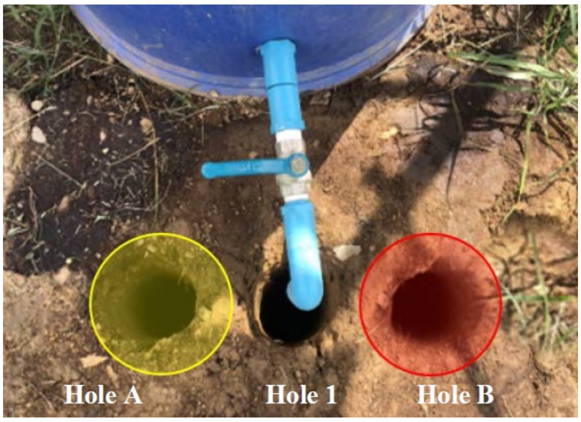

Figure 13. Hole A and B for collecting KOH-treated soil samples beside Hole 1 where KOH solution was released.

Table 1 Properties and minerals of natural Mae Moh expansive soil without and with KOH treatment.

Hole	**2**	**A**	**B**
Condition of soil samples	Before KOH treatment	30 days after KOH treatment	90 days after KOH treatment
Dry density (kN/m^3)	14.50	14.96	13.18
Water content (%)	24.41	26.96	36.54
Liquid limit (%)	63.94	65.76	57.71
Plastic limit (%)	30.49	37.49	29.87
Plastic index (%)	33.49	28.27	27.84
Free swell volume (%)	2.05	3.59	5.71
Swell pressure (kN/m^2)	134.48	121.21	90.18
Minerals (%)			
- Quartz	48.20	38.40	36.70
- Calcite	47.90	58.00	49.50
- Kaolinite	1.10	1.30	7.00
- Illite	0.80	0.80	0.00
- Muscovite	0.00	0.00	6.80
- Montmorillonite	2.00	1.60	0.00
- Orthoclase	0.00	0.00	0.00
Minerals total	100.00	100.00	100.00

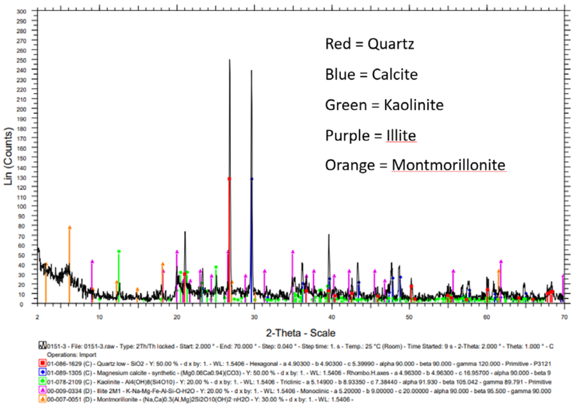

Figure 14. Result of XRD test on soil sample from Hole 1 without KOH treatment.

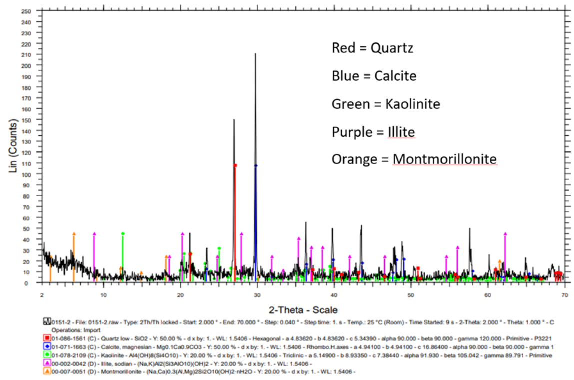

Figure 15. Result of XRD test on soil sample from Hole A 30 days after KOH treatment.

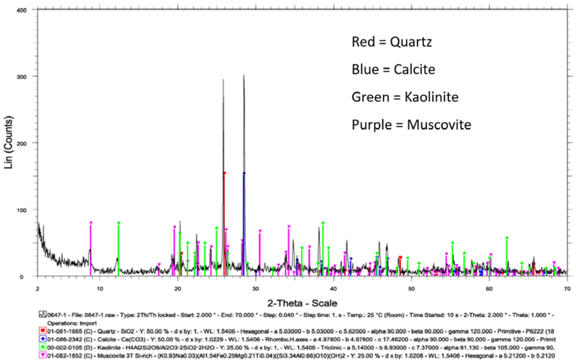

Figure 16. Result of XRD test on soil sample from Hole B 90 days after KOH treatment.

As shown in **Table 1** as well as shown in **Figures 14–16**, montmorillonite disappeared from the soil as expected, and illite was detected. However, after 90 days there was muscovite shown up rather than illite. However, to confirm the result, another series of field test was run nearby.

6.2 Effect of Bored Hole Lay out

To confirm the result found in Section 6.1, another set of 7 bored holes was drilled. The holes formed in hexagonal shape with 6 holes surrounding one hole at the center as shown in **Figure 17**. Other than to confirm the previous result, this design was to imitate a formation of holes possibly used in practice. Hole AH-7 was drilled to pick up the treated soil samples after 30 days, and Hole BH-4 was drilled to collect the treated soil samples after 90 days of releasing KOH solution into those 7 bored holes. Result of laboratory test on samples from series 2 shown in **Table 2**. The results from XRD tests are demonstrated in **Figures 18–20**.

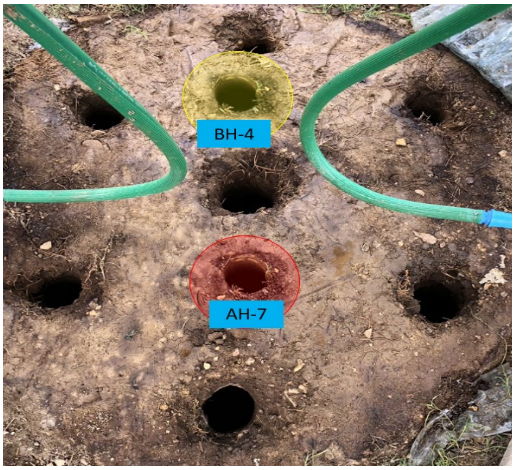

Figure 17. Bored holes AH-7 and BH-4 drilled between seven KOH-treated holes in a hexagonal formation.

Table 2 Properties and minerals of natural Mae Moh expansive soil from holes among hexagonal formation.

Hole	**Middle**	**AH-7**	**BH-4**
Condition of soil samples	Without KOH	30 days with KOH	90 days with KOH
Dry density (kN/m^3)	15.62	14.26	14.91
Water content (%)	38.35	26.23	25.47
Liquid limit (%)	67.85	74.75	71.33
Plastic limit (%)	24.61	31.06	25.47
Plastic index (%)	43.24	43.69	45.86
Free swell volume (%)	6.51	6.01	2.54

Table 2 Properties and minerals of natural Mae Moh expansive soil from holes among hexagonal formation. (*cont.*)

Hole	Middle	AH-7	BH-4
Swell pressure (kN/m^2)	282.00	151.34	49.67
Minerals (%)			
- Quartz	48.20*	55.70	36.70
- Calcite	47.90*	26.40	47.10
- Kaolinite	1.10*	8.20	2.20
- Illite	0.80*	0.00	0.00
- Muscovite	0.00*	5.20	2.20
- Montmorillonite	2.00*	0.00	0.00
- Orthoclase	0.00*	4.50	0.00
Minerals total	100.00*	100.00	100.00

* Mineral data from Hole 2

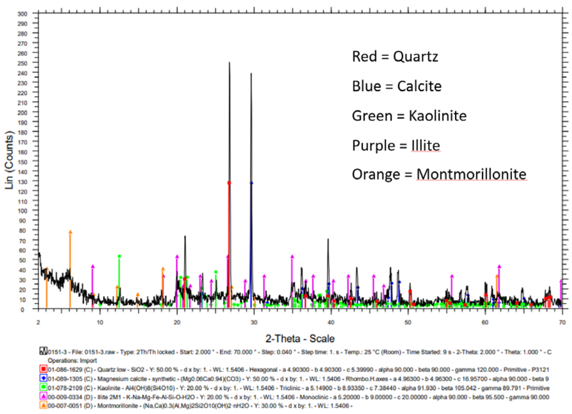

Figure 18. Result of XRD test on soil sample from Hole X without KOH treatment.

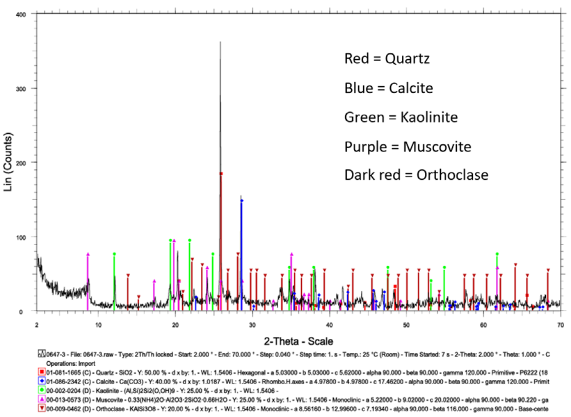

Figure 19. Result of XRD test on soil sample from Hole AH-7 30 days after KOH treatment.

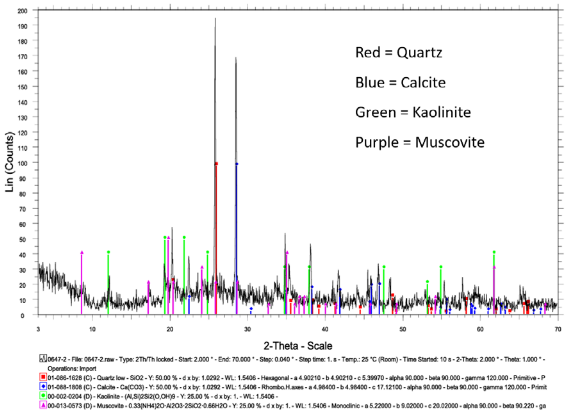

Figure 20. Result of XRD test on soil sample from Hole BH-4 90 days after KOH treatment.

The results of this set of investigation were somewhat similar to those shown in **Table 1**. The better result was the swell volume was reduced conforming to the swell pressure. Only muscovite was found in this case. This set of experiment demonstrate that this hexagonal might help accelerate the transformation process.

7. Conclusion and Discussion

The research presented in the article was an early study of using potassium chemicals to reduce or stop swelling of Mae Moh expansive soil. KCl, KOH, and KNO_3 were used as the swelling reduction agents in this study. Some conclusions and discussions are presented as following.

1) Among the three K-substances, KOH solution has demonstrated better potential for reducing the swell volume and pressure of Mae Moh expansive soil. However, it only worked well when moisture content was in natural condition: below 25% as found in this study. When the soil had higher moisture content, especially when soaked, KOH may not work.

2) KOH solution, when released into expansive soil mass tends to change montmorillonite to illite as reviewed earlier in this article. Moreover, illite possibly transform to muscovite later. This was possible by several processes [23],[24]. In fact, illite and muscovite are quite similar in

chemical structures [25]. Muscovite is sometimes called common mica or potash mica [26] while illite is also known as hydromuscovite or hydromica [27] which means "wet mica." It was possible that when illite dried out it changed to muscovite.

Though the use of KOH solution to reduce swell potential of expansive soils is promising, this research was just at the beginning. The study was still limited quantitatively. More drilled holes and more data should be performed and obtained in order to reduce the variance of natural soils. In the future, extensive experiments or research should be conducted such as its effectiveness against the water content or how to reduce water content in the expansive soil mass, KOH's impact to environment, etc.

Current practices deployed by an authority in Mae Moh area is replacing expansive soil layer of 6-8 m thick with submerged ash from nearby coal power plant. The success of further research as indicated above should be competitive to this current practice. The approach of KOH solution originated from this article will be even more useful for the existing buildings damaged by the supporting expansive soil.

8. Acknowledgement

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References

[1] C. McDowell, "Stabilization of Soils with Lime, Lime-FlyAsh and other Lime Reactive Minerals," *Highway Research Board Bulletin*, vol. 231, pp. 60–66, 1959.

[2] W. G. Holtz, "Volume Change in Expansive Clay Soils and Control by Lime Treatment," *Proc of 2nd International Research and Engineering Conference on Expansive Clayey Soils*, TX, USA, 1969, pp.157–174.

[3] K. V. Gokhale, "Mechanism of Soil Stabilization with Additives," in *Proc. of the First National Symposium on Expansive Soils*, HBTI, Kanpur, India, 1977, pp.10-1–10-5.

[4] T. C. Hopkins, D. Q. Hunsucker and T. Beckam, "Selection of Design Strengths of Untreated Soil Subgrades and Subgrades Treated with Cement and Hydrated Lime," Transportation Research Record-1440, Lexington, KY, USA, Rep. KTC-93-33, 1993.

[5] G. A. Miller and M. Zaman, "Field and Laboratory Evaluation of Cement Kiln Dust as a Soil Stabilizer," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1714, no. 1, pp. 25–32, 2000, doi: 10.3141/1714-04.

[6] F. Zha, S. Liu, Y. Du and K. Cui, "Behavior of Expansive Soils Stabilized with Fly Ash," *Natural Harards*, vol. 47, pp. 509–523, 2008, doi: 10.1007/s11069-08-9236-4.

[7] M. M. E. Zumrawi, "Stabilization of Pavement Subgrade by Using Fly Ash Activated by Cement," *American Journal of Civil Engineering and Architecture*, vol. 3, no. 6, pp. 218–224, 2015, doi: 10.12691/ajcea-3-6-5.

[8] M. R. Thompson and Q. L. Robnett, "Pressure-Injected Lime for Treatment of Swelling Soils," in *54th Annual Meeting of the Transportation Research Board*, Transportation Research Board, Washington DC, USA, Jan. 13–17, 1976, pp.24–34.

[9] I. Kousa and M. Jaksa, "Treatment of Expansive Soils Using Gypsum Solution," in *Proceedings of 3rd International Conference on Problematic Soils*, Adelaide, Australia, Apr. 7–9, 2010, pp. 197–206.

[10] M. M. E. Zumrawi, A. M. M. Mahjoub and I. M. Alnour, "Effect of Some Chloride Salts on Swelling Properties of Expansive Soils," *University of Khartoum Engineering Journal*, vol. 6, no. 2, 2016, pp.35–41.

[11] T. O. Durotoye and J. O. Akinmusuru, "Effects of Sodium Chloride on the Engineering Properties of Expansive Soils," *International Journal of Research in Engineering and Technology*, vol. 5, no. 9, 2016.

[12] R. Al-Omari, S. Ibrahim, and I. Al-Bayati, "Effect of Potassium Chloride on Cyclic Behavior of Expansive Clays," *International Journal of Geotechnical Engineering*, vol. 4, no. 2, pp.231–239, 2013, doi: 10.3328/IJGE.2010.04.02.231-239.

[13] A. Lemi, "Stabilization of Expansive Clay Soils Using Potassium Chloride," M.S. thesis, Dept. Civ. Environ. Eng., Addis Ababa Univ., Addis Ababa, Ethiopia, 2015.

[14] R. P. Shukla, N. S. Parihar and A. K. Kupta, "Stabilization of Expansive Soil Using Potassium Chloride," *The Civil Engineering Journal*, vol. 27, no. 1, 2018, Art. no. 3, doi: 10.14311/CEJ.2018.01.0003.

[15] F. Zhang, L. Zhang and W. Hong, "Stabilization of Expansive Soil with Polyvinyl Alcohol and Potassium Carbonate," *Advances in Civil Engineering*, vol. 2019, 2019, Art. no. 7032087, doi: 10.1155/2019/7032087.

[16] B. M. Das and K. Sobhan, "Origin of Soil and Grain Size," in *Principles of Geotechnical Engineering*, 8th ed., Stamford, CT, USA: Cengage Learning, 2012, ch. 2, sec. 2.5, pp.39–47.

[17] S., Kaufhold and R. Dohrmann, "Stability of Bentonites in Salt Solutions II. Potassium Chloride Solution – Initial Step of Illitization?," *Applied Clay Science*, vol. 49, no. 3, pp.98–107, 2010, doi: 10.1016/j.clay.2010.04.009.

[18] W. Breslyn, *Equation for KOH + H_2O (Potassium hydroxide+Water).* (Oct 2, 2018). Accessed: Nov.8, 2023. [Online Video]. Available: https://www.youtube.com/watch?v=i7ViM9Yp1gc.

[19] S. Kruadsungnoen and S. Sethabouppha, "Effect of Potassium Solutions on Swelling Properties of Expansive Soil in Mae Moh Area," in *the 27th National Convention on Civil Engineering (NCCE27*, Chiang Rai, Thailand*)*, Aug. 24–26, 2022, pp. GTE38-1–GTE38-6.

[20] S. N. Abduljauwad, and G. J. Al-Sulaimani, "Determination of Swell Potential of Al-Qatif Clay," *Geotechnical Testing Journal*, vol. 16, no. 4, pp. 469–484, 1993, doi: 10.1520/GTJ10287J.

[21] *Method of Test for Soils: Determination of Free Swell Index of Soils,* IS 2720 (Part-40): 1977 (Reaffirmed 2021), 2021.

[22] B. M. Das, "Foundations on Difficult Soils," in *Principles of Foundation Engineering*, 8th ed., Stamford, CT, USA: Cengage Learning, 2014, ch.11, sec.11.9, pp. 571–576.

[23] J. C. Hunziker, M. Frey, N. Clauer, R. D. Dallmeyer, H. Friedrichsen, W. Flehmig, K. Hochstrasser, P. Roggwiler and H. Schwander, "The Evolution of Illite to Muscovite: Mineralogical and Isotopic Data from the Glarus Alps, Switzerland," *Contributions to Mineralogy and Petrology*, vol. 92, pp. 157–180, 1986, doi: 10.1007/BF00375291.

[24] C. Verdel, N. Niemi and B. A. van der Pluijm, "Variations in the Illite to Muscovite Transition

Related to Metamorphic Conditions and Detrital Muscovite Content: Insight from the Paleozoic Passive Margin of the Southwestern United States," *The Journal of Geology*, vol. 119, no. 4, pp.419–437, 2011, doi: 10.1086/660086.

[25] USGS, "A Laboratory Manual for X-Ray Powder Diffraction: Illite Group," U. S. Geological Survey, Woods Hole, MA, USA, Rep. no. 01-041, Accessed: Sep. 3, 2023., [online] Available: https://pubs.usgs.gov/of/2001/of01-041/htmldocs/clays/illite.htm.

[26] *Muscovite Mineral*, Encyclopædia Britannica, Inc., Sep. 3, 2023. [online] Available: https://www.britannica.com/science/muscovite-mineral.

[27] *Hydromuscovite*, Hudson Institute of Mineralogy Sep. 3, 2023. [online] Available: https://www.mindat.org/min-9603.html.