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# INVESTIGATION OF THE STRENGTH DEVELOPMENT USING MAGNESIUM ALKALINIZATION FOR SUBGRADE

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**Abstract**: The stabilization of problematic soils with chemical additives has become popular globally. Others studied the use of the magnesium chloride ($MgCl_2$) for improving weak soil properties, but the $MgCl_2$ mixed with the alkaline solution as a chemical additive have not been investigated. This paper studied the factors that contribute to the strength development of silty sand, a typical subgrade soil in Kamloops BC, Canada, using the $MgCl_2$ with different ratios of alkalinization solution ($Na_2SiO_3$/NaOH). The total of 65 samples included the untreated sample were examined using standard compaction and the unconfined compressive strength (UCS) tests under a curing period of 7, 14, 28, and 60 days. Results revealed that the chemical additive was improving the density and the compressive strength of the silty sand. This increase in strength was subjected to the formation of the new cementitious product, which was the combination of the chemical additive that filled up voids and reinforces the particles in the soil.

## 1 INTRODUCTION

Statistically, the investment cost in maintaining and rehabilitating the road subgrade in British Columbia, Canada is extremely expensive. BCMoTI (2015) had reported in the B. C on the Move; A 10-year Transportation Plan bulletin, an additional $270 million is needed to improve the condition of provincial side roads which includes hard surfacing, gravelling base construction, dust control, shoulder widening, and other safety improvements over the next three years. Moreover, problematic soil subgrade greatly contributes a major event on the road pavement like potholes, rutting, and pumping on the road surface. Most of BC highways laid on the problematic soil such as clay, organic and silt. The selection of the best option like optimizing the pavement layer by thinning while still achieving the strong subgrade can result in reducing the material and construction cost. Many methods that can be applied to strengthen the weak subgrade but chemical stabilization method has become a vital method that most researchers were tried to applied and produce a product that is practical to the environment and cheap.

The chemical stabilization process is complete when the chemical additive reacts with the soil by changing or altering the soil minerals properties and engineering properties. This process involved the cation exchange, flocculation, crystallization, and dissociation with the result in improvement of the soil strength parameters and the loading capacity (Zhu and Liu 2008). However, the proposed stabilizer agent in most research were targeting the clay soil using lime, fly ash, cement or ordinary Portland cement as the additive (Hashemi et al. 2015, Khater 2010, Saadeldin and Siddiqua 2013, Sukmak et al. 2013). Scientifically, the cement product such as the Ordinary Portland Cement (OPC) and lime is not practically safe for the environment. As for every ton of OPC prepared, the cement manufacturing process discharges almost 0.85 to 1.0 tons of carbon dioxide into the air (Davidovits 2015). The accrue discharges of $CO_2$ may be jeopardizing the environment; hence the industry as well as the researcher shall discover new solutions on replacing the traditional cementitious additives which is safer to the environment.

Lately, the introduction of the alkaline solution to the industry scarcely to be a good competitor of the OPC as is it significantly reduce the emission of $CO_2$. The dissolution of high alkali content can promote the silica and alumina minerals that originally presence in the soil to generate a three-dimensional chain linked structure that is a –Si-O-Al-O bond. The mineral polymers have cross-linked units of $SiO_4$ and $AlO_4$- tetrahedral tends to combine with alkali metals such as $Na^+$, $K^+$, $Li^+$, $Ca^{2+}$, $Ba^{2+}$ or $H_3O^+$in order to get neutral species (Davidovits 1991). This process was known by its eco-friendliness in developing the structural strength of the material. As far as concerned, the sodium hydroxide (NaOH) had also been used as an additive that helps to improve the density of soil that has high aluminium such as kaolinitic soil (Olaniyan et al. 2011). In addition, the potential of alkalis as a reagent usually used with metakaolin, fly ash or slag for improving the microstructure of the soil.

Many researchers have tempted to apply a salt in order to improve the mechanical properties of high sensitive clays, high swelling clays, tropical soil, and residual laterite soil (Sarkar and Siddiqua 2016, Latifi et al. 2015, Latifi et al. 2016a, Latifi et al. 2016b, Helle et al. 2016). Salt is a natural type of chemical additive that improves the soil engineering properties e.g. calcium chloride, sodium chloride, potassium chloride, and magnesium chloride. Nevertheless, it was depended on the concentration of the salt in order to change the behaviour of certain materials. Latifi et al. (2016) found the changes on the mineralogical, morphological, and the development of the mineral molecules chains linked off the problematic soil when mixing it with the $MgCl_2$. This results on the improvement of the engineering properties for the untreated soil. In fact, the bentonite clay can be used as a sealing radioactive waste material with the aid of salt and result revealed that the volume of micro-pores sizes, porosity, and hydraulic conductivity is increased (Sarkar and Siddiqua 2016).

Few decades ago, $MgCl_2$ has been widely used as a green binder; and, recently the attention has shifted to a soil stabilizer. In industry, this salt is used as road material stabilizer and dust controller due to properties of higher moisture absorption. The $MgCl_2$ practically safe to the environment. Studied made by environmentalist (William et al. 2009) found the $MgCl_2$ was not harmful to the aquatic life as it below the ranges that could be considered as deleterious based on the standards set by Environment Canada (2001). Same studied had revealed the solid asphalt itself extracted the carbon but not the $MgCl_2$. Meanwhile, result on distilled water leached from the recycled asphalt pavement with aluminium, boron and silicon to the environment rather than the $MgCl_2$. Few studies have focusing the $MgCl_2$ directly mixed with the problematic soil, but no studies have been conducted on applying the $MgCl_2$ with the aid of alkaline solution as a chemical additive to improve the strength of silty sand soil.

Three material are introduced in the development of the chemical formulation, which were magnesium chloride, sodium hydroxide, and sodium silicate. The production of new chemical additive by mixing all these materials is to provide a modification and amendment on the element contains in the silty sand. The present work investigates the compaction behaviour of untreated soil with the new proposed green additive and the strength characteristics of the treated soil through the unconfined compressive strength (UCS) test. The results are conceptually analyzed for each different ratios of the soil, magnesium chloride, and alkalinization solution and the measurement is based on the curing time.

## 2 MATERIALS AND METHODOLOGY

In this experiment, the silty sand soil had been selected, as it is the main subgrades soil in British Columbia. Canada. The collected sample was an original subgrade layer from the road construction site, which located in Kamloops at Trans-Canada Highway 1 near the Thompson River (50.7376, -119.7626). Fig. 1 shows the particle size distribution of the studied soil that consists of 53.3%, 40.9% and 5.8% of sand, silt and clay, respectively. According to the Unified Soil Classification System (USCS), the collected silty sand used for this experiment was classified as SM. Table 1 below lists the engineering properties of the silty sand used in this experiment.

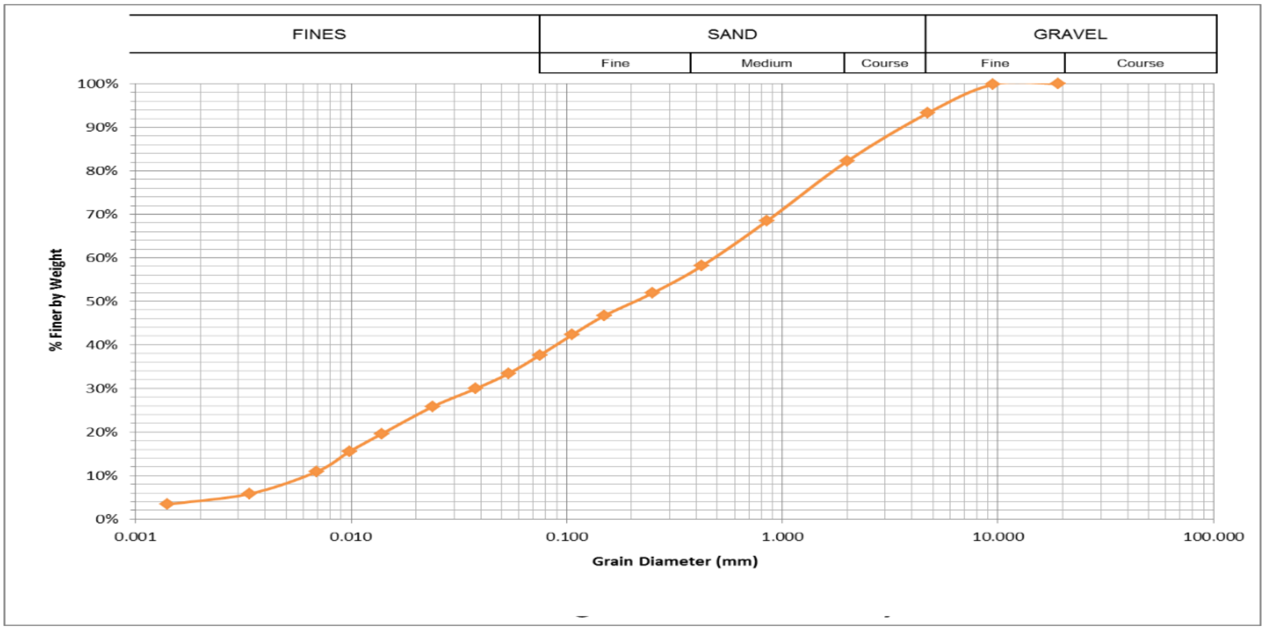

Figure 1: PSD curve for the untreated silty sand soil

Table 1: Engineering properties of silty sand

| Properties | Values |
|---|---|
| Liquid limit, LL (%) | 40 |
| Plastic limit, PL (%) | 35 |
| Plasticity index, PI (%) | 5 |
| Maximum dry density (kN/m$^3$) | 15 |
| Optimum moisture content (%) | 24 |
| Unconfined compressive strength (kPa) | 142 |

The magnesium alkalinization additive was prepared using the magnesium chloride ($MgCl_2$), sodium hydroxide (NaOH), and sodium silicate ($Na_2SiO_3$). The deionized waster was used through all the mixtures and tests. All chemicals had been purchased from Thermo Fisher Scientific Chemicals Inc., Massachusetts. The 10 M of NaOH was first prepared from the mixture of fresh NaOH pellets and deionized water and then left to stand for at least 24 hours. The water was added accordingly if the solution decreasing due to the exothermic reactions. The alkalinization solution was then prepared by mixing the 10 molar NaOH with $Na_2SiO_3$ based on decided ratios. The physical and chemical properties for each chemical as presented in Table 2.

Table 2: The physical and chemical properties of the chemical additive

| Properties | Magnesium chloride | Sodium hydroxide | Sodium silicate solution |
|---|---|---|---|
| Physical state | Solid | Solid | Liquid |
| Appearance | White | White | Viscous, Colorless |
| Odor | Odorless | Odorless | Odorless |
| pH | 5-6.5, 5% aq. Solution | 14 (5%) | 11.2 |
| Relative density | - | 2.13 | 1.4 |
| Solubility | 540 g/L (20 ºC) | Soluble in water | Soluble in water |
| Molecular weight | 95.21 | 40 | - |
| Molecular formula | $Cl_2$ Mg | NaOH | $Na_2$ $SiO_3$ |

In this study, the percentage of the $MgCl_2$-to-soil was 3%, 5%, 10%, and 15%, the alkalinization solution ratios ($Na_2SiO_3$/NaOH) were 0.5, 1.0, 1.5, and 2.0 and the alkalinization-to-$MgCl_2$ ratios were 0.3, 0.5, 0.7, and 0.9 by dry weight of the soil as describe in Table 3. The untreated soil sample was prepared first by oven dried them and sieved passing through No.10 sieve intended for removing the bigger particles. The magnesium alkalinization additive mixed with the soil using the mechanical mixer for about 10 minutes. For letting the solution to cool down because of the exothermic reactions taken place, the mixture was then allowed to cool in the high relative humidity room with controlled room temperature for at least 24 hours.

All mixtures had performed the standard compaction test using the standard compaction effort with regard to find the maximum dry density and the optimum moisture content. Each mixture will have same mixture proportion but escalation on the amount of deionized water, as to comply the method specifically in ASTM D698 Method A. In this study, the compaction has done in 38 mm diameter mold with approximate volume of 115 $cm^3$ in three layers. At least 5 point observed for obtaining the compaction curve for each sample. Meanwhile, for the unconfined compressive strength (UCS) sample preparation, all the liquid alkaline solution ($Na_2SiO_3$ and NaOH), anhydrous $MgCl_2$, and silty sand, were thoroughly mix with deionized water until reach the optimum water content. The mixture statically compressed using the Instron machine in a 38mm diameter and 76mm high mold with three equally divided layers (ASTM D 4219) at the optimum moisture content and the maximum dry density.

As the sample is compressed using the Instron machine, the compression energy should be controlled in favor of achieving a maximum dry density with an equally high level for each layer. After the samples extruded from the mold, using the hydraulic jack, and wrapped in several layers of cling film, they left to cure in the high relative humidity room with the control room temperature (25 ± 2ºC) before the UCS testing. All specimens were undergone the unconfined compressive strength (UCS) test as per the American Standard for Testing Material (ASTM D 4219) after they left to cure on 7, 14, 28, and 60 days. The rate of vertical load remained 1% mm/min until failure or reached 15% strain.

To minimize the blocking effects while preparing the samples, a few things needed to be considered. At least four samples for each soil mixture should be prepared to check the consistency of the result. The soil must be collected from the same location in a big batch. Even the soil collected from the same location at different times, the properties of the soil will be different. All samples must be wrapped with cling wrap and stored in a plastic box then placed it in the curing room with high relative humidity percentage to avoid excessive absorbance from room moisture.The control samples have no curing days as they sheared immediately, meanwhile the treated samples will only be sheared once after they reach the curing time.

Table 3: Experimental summary

| Variable | Standard Compaction test | Unconfined compressive strength test |
|---|---|---|
| Magnesium Chloride content ($MgCl_2$) | 3, 5, 10, and 15% | 3, 5, 10, and 15% |
| Sodium Hydroxide concentration (NaOH) | 10 molar | 10 molar |
| Sodium silicate to sodium hydroxide (L) ratio | 0.5, 1.0, 1.5, and 2.0 | 0.5, 1.0, 1.5, and 2.0 |
| L to $MgCl_2$ ratio | 0.3, 0.5, 0.7, and 0.9 | 0.3, 0.5, 0.7, and 0.9 |
| Soil type | Silty sand | Silty sand |
| Deionized water | Variety<br>- | Based on optimum water content |
| Curing period | | 7, 14, 28, and 60 days |

## 3 RESULTS AND DISCUSSION

### 3.1 Optimum moisture content and maximum dry density

Figure 2 illustrates the compaction behaviour between the untreated soil and treated soil samples. The observation of the compaction behaviour is crucial in determining the changing in the density of the soil especially for subgrade soil layer. The optimum moisture content (OMC) and maximum dry density (MDD) of the untreated silty sand was observed at values of 24% and 15 kN/m$^3$, respectively. Meanwhile, the chemically treated mixtures sample was found to improve the MDD and decreased the OMC with the same compaction effort. The experimental values of OMC and MDD ranged from 16.5% to 26% and 15.60 kN/m$^3$ to 17.70 kN/m$^3$, respectively. It was expected to reduce settlement and permeability, as well as increasing the shear strength of the weaker soil layer. The addition of the chemical additive literally increased the maximum dry density and decreased of the optimum moisture content.

Theoretically, the chemical additive induced the chemical reaction to the untreated soil and created a subsequent effect when the soil was compacted and resulted in the exchange of a single anion or cation. First, during the compaction effort, the chemical stabilizer may influence the pore size of the soil and later create a crystallization process between the soil particles (Marto 2014). The rapid cation exchange between the $MgCl_2$ alkalinization and soil itself may contribute to the ionic balancing, which may cause the particles to agglomerate and flocculate themselves. Thus, the particles would tend to pack closely together and reduce the specific particle surface area of the stabilized soil. Meanwhile, it would affect water capability to absorb, which may contribute to the lowering of the optimum moisture content and increasing the dry density.

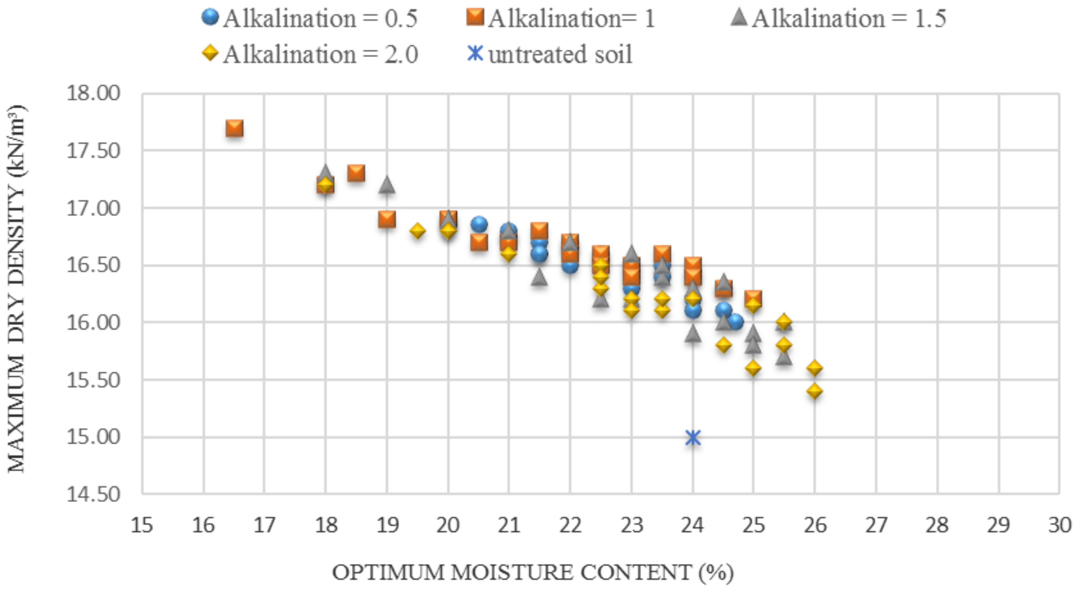

Figure 2: The optimum moisture content and maximum dry density points for all mixtures

### 3.2 Optimization of the mixture design based on UCS

The important of conducting the UCS test in this study was it can straightforwardly verify the significant improvement of strength of the soil when treated with $MgCl_2$ and alkalinization solution. In the present work, four by four (4x4) full factorial design has taken place for analyzing the result. The function of the different factors (i.e A, B, C, and D) with four levels each summarized in the Table 4 below. Each factor subjected to the chemical additive and curing time. In addition, each level subjected to the ratio of the mixture as previously explained. The total off 1024 runs with 64 samples and 4 repetitions each has shown significant improvement in the UCS. The analysis of variance shows all models (linear, 2-way interactions, 3-way interactions, and 4-way interactions) and blocks have P-value less than 0.05, which were significantly different from zero at the 95% confidence level. As the model summary revealed the R-square value was 99.88% with the adjusted R-square was 99.84%.

Table 4: Full factorial design $4^4$

| FACTORS | LEVELS | | | |
|---|---|---|---|---|
| A ($Na_2SiO_3$/NaOH) | 0.5 | 1.0 | 1.5 | 2.0 |
| B (A/$MgCl_2$) | 0.3 | 0.5 | 0.7 | 0.9 |
| C ($MgCl_2$/soil) | 0.03 | 0.05 | 0.10 | 0.15 |
| D (curing time) | 7 | 14 | 28 | 60 |

However, this statistical result had proven the effects for each factor played very important role in order to achieve the optimum design. All the effects between $MgCl_2$, alkalinization solution, soil, and curing time were fully related to each other. Figure 3 illustrates the interaction between all factors and levels on behalf of the UCS result. Intentionally, as the level of alkalinization solution increased the strength increased on behalf of the curing time. Similar patent was found for factor B, which was the ratio between the alkalinization solution and $MgCl_2$. However, the factor C shows vice versa strength pattern to the factor D. When the amount of $MgCl_2$ was added to the soil, the strength pattern shows significant drop as the curing time increased. This unpredictable results shows significant advantage as the less amount of the $MgCl_2$ used in the mixtures has better strength improvement.

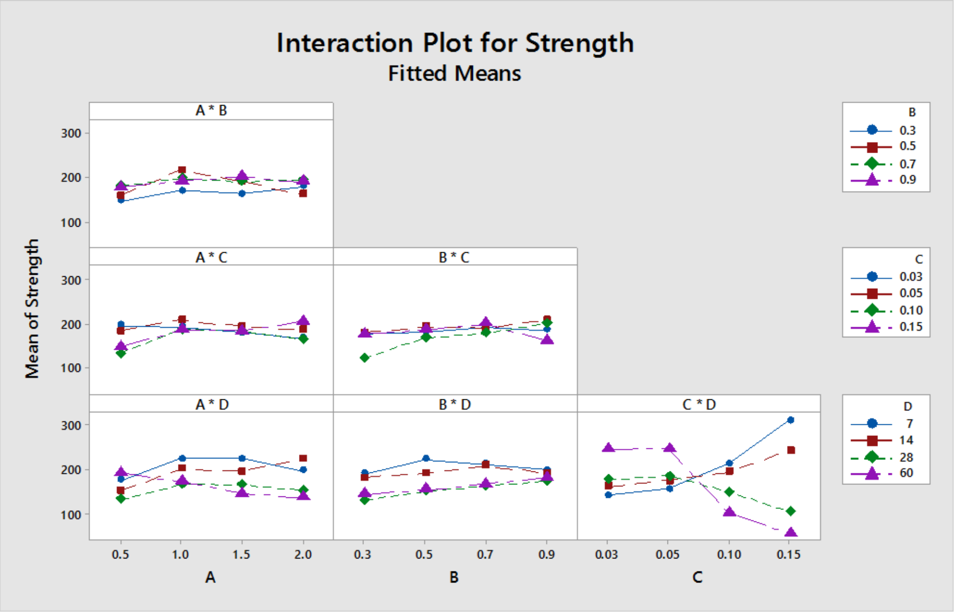

Figure 3: Interaction plot for strength between all factors and levels

In furtherance of narrowing the optimizing design mixture, the second full factorial design was conducted in defining the interactions between the significant effects of each ratio to the strength of treated soil. The full factorial design has limited into two levels or two ratios for each factors. The selected ratios based on the significant interaction plot given in previous figure. Table 5 summarizes all the factors and the levels that has considered for obtaining the optimum mixture design. Statistically, the analysis of variance shows all models were significant with the R-square of 99.80%. Figure 4 shows the result of residual plots for this statistical analysis. There was no argument as all plots were showing normality and looks good.

For better understanding, the contour plots plotted in Figure 5. The interaction between the alkalinization solution ratios with the curing time can be seen in this contour plot with the factors interaction of D (curing time) and A (alkalinization solution). Less alkalinization solution gave better strength as the curing time increases. Meanwhile, the interaction between factor C and D, which were the ratio of $MgCl_2$/soil and curing time, respectively, the strength pattern at level 0.03 shows higher strength than 0.05 as the curing time increased from 28 day to 60 day. Only small amount of $MgCl_2$ is needed in order to achieve a better strength of silty sand soil with the helps of alkalinization solution. Last but not least, the interaction between the alkalinization solution and the $MgCl_2$ itself can be understood with the aid of this contour plots (Figure 5) as well as graph plotted in Figure 6. The factors interaction between C and B suggested the higher alkalinization solution to the $MgCl_2$ ratio is required for the optimum strength to be achieved.

However, in order to find the optimum mixture design, this preliminary conclusion should be checked with the multi-criteria decision-making. Based on the weighted sum method, four alternates were selected based on four criteria (e.g 7, 14, 28, and 60 days) with estimated weighting criteria. The highest score selected as the optimum mixture design. This experiment would like to suggest the optimum design for the magnesium alkalinization additive to be used for improving the strength of silty sand is the mixture of 0.5,0.7, and 3%, of the alkalinization solution ratios ($Na_2SiO_3$/NaOH), the alkalinisation solution-to-$MgCl_2$ ratios, and the $MgCl_2$ percentage, respectively by dry weight of the soil.

Table 5: Full factorial design $2^4$

| **FACTORS** | **LEVELS** | |
|---|---|---|
| A (Na2SiO3/NaOH) | 0.5 | 1.0 |
| B (A/$MgCl_2$) | 0.7 | 0.9 |
| C ($MgCl_2$/soil) | 0.03 | 0.05 |
| D (curing time) | 28 | 60 |

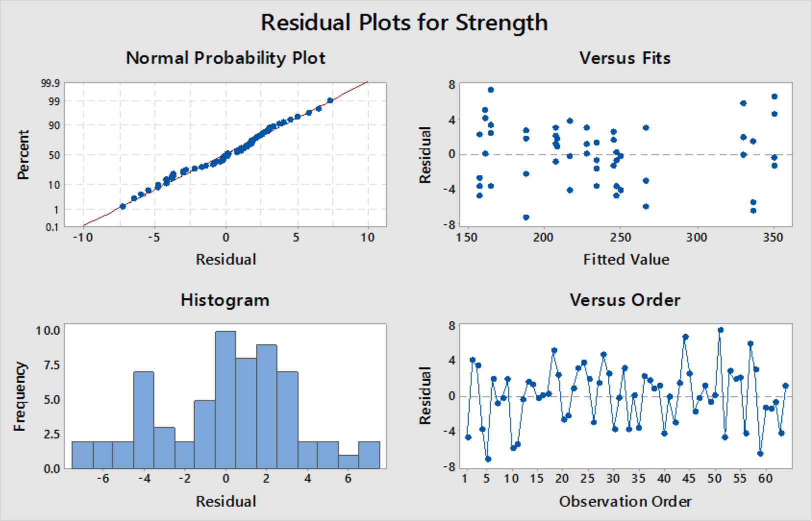

Figure 4: Residual plots for strength based on 4 factors and 2 levels

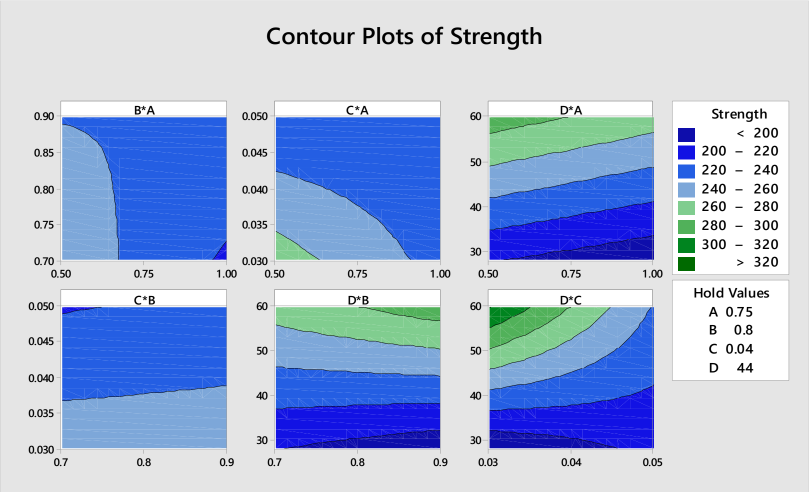

Figure 5: Contour plots of strength based on all factors

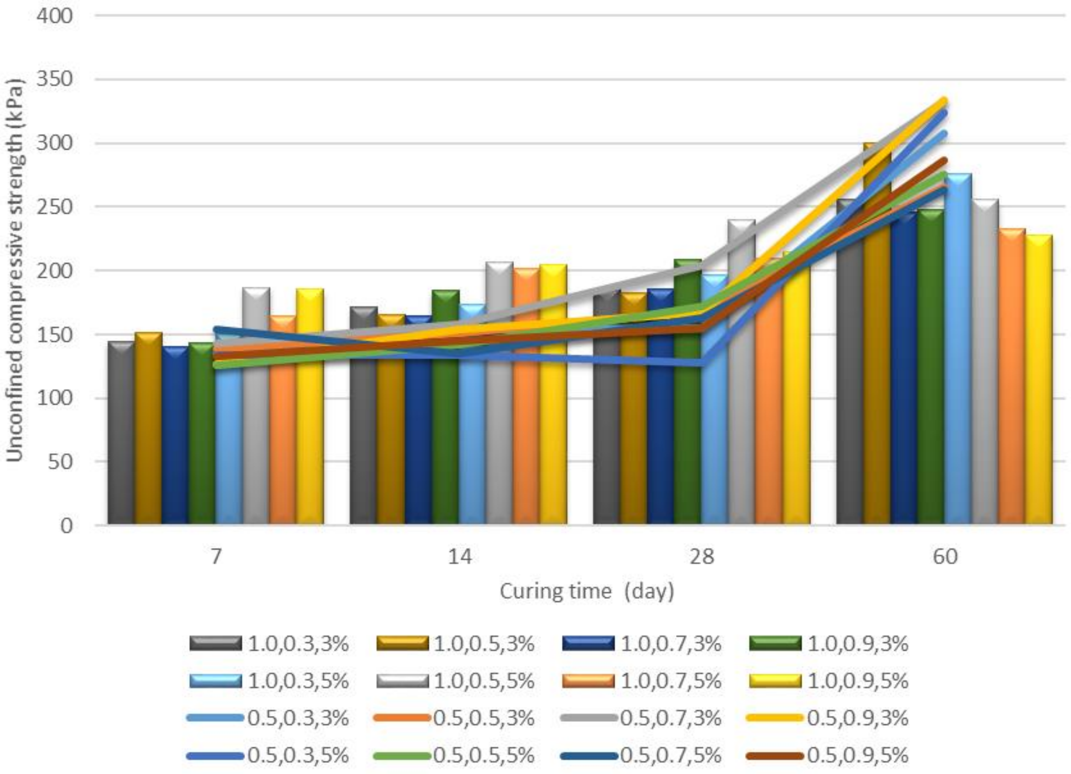

Figure 6: Effect of alkalinization ratio and percent of magnesium chloride at different curing time

Overall, the salt content plays a main role because it was a good moisture absorbance. However, absorbing too much moisture may not greatly contribute in strengthening the weak soil. As reported in Latifi et al. (2015), the UCS shows reduction in clay strength when the amount of $MgCl_2$ exceeded 8%. Much research has shown that the chemical alteration on soil may caused the positive surcharge to increase and create repulsion forces between the soil and the additive mixtures (Marto et al. 2014, Tingle and Santoni 2003, Rauch et al. 2002, Katz et al. 2001).

The presence of $MgCl_2$ was hypothesis to affect the weight ratio of alkalinization solution ($Na_2SiO_3$/NaOH). As the concentration of the $Na_2SiO_3$ increased, the strength showed a stagnant strength in between 150 kPa to 250 kPa with the respect of curing times. As far as concerned, the $MgCl_2$ and $Na_2SiO_3$ has high solubility in water. This would suggest that the existent of high water demands product has weakened the bonding between dissolution of alumino-silicate minerals and NaOH to form a chemical bond with the silty sand particles. When high amount of NaOH solution was added, it would produce the better chemical bond, which subjected to higher dissolution of alumino-silicate mineral in silty sand particles, which helps to form a new cementitious product. However, the present of the $Na_2SiO_3$ was still necessary in order to provide a good platform for generating a polymer structure.

Many studies have concluded the escalation of this phenomena related to the cementing gel material (hydrates) that formed by the pozzolanic reactions (Latifi et al. 2016, Abdullah et al. 2012). The inner particles activity such as cationic exchange and the existence of the cementitious component may be subjected to decrease in soil porosity and better strength properties. In this study, the chemical additive needs time to react with the untreated soil and the optimum curing time needed in providing the better strength was found to be after 28 days.

## 4 CONCLUSION

This preliminary study has drawn few conclusions that can be applied to the next level of research. Firstly, the higher percentage of $MgCl_2$ used may not improve the strength of the silty sand soil. The nature of the material itself as a good absorbance may be beneficial for the chemical additive if the amount used was a small portion. Secondly, significant strength improvement from the unconfined compressive strength test provide better result only when the less ratio alkalinization solution ($Na_2SiO_3$/NaOH) has applied, which means the higher NaOH solution was the better. Finally, this experiment suggests the curing time is necessary for providing a better strength of the chemically treated soil especially when they were cured up to 28 day. This outcome can contribute to the cost effectiveness and environmentally friendly. Further testing shall be employed to understand the chemically bonding between the silty sand particles and the mixture additive.

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