Shear strength behaviour of mining sand treated with clay and hydrated lime

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ABSTRACT

The purpose of this study is to investigate the effect of hydrated lime in clean sand and sand-clay specimens. In order to illustrate the improvement of shear strength behaviour of soil by hydrated lime addition, kaolin clay at different percentages is added in soil specimens containing mining sand with 5% of hydrated lime because lime reacts well with clayey soil. It is observed that lime reacts with clay by increasing the strength of clayey soil. Lime appears to have little influence on clean mining sand and soil specimens containing less than 10% of kaolin clay. It is interesting to note that 30% clay content in treated (5% hydrated lime) soil specimen is needed to increase the deviator stress of soil as compared to untreated soil specimen with the same clay content.

Keywords: Mining sand, clay, hydrated lime, shear strength, soil modulus.

1. Introduction

Due to the rapid development and the lack of land resources, more construction is built on weak or soft soil, which leads to various techniques of ground improvement such as soil stabilization and reinforcement. Lime treatment has been used widely to stabilize soft soils, to be used as foundations, roadbeds, embankments and piles. In practice, improvements in engineering properties of clay can be achieved instantaneously with small additions of lime to clayey soils. However, the effectiveness of such improvement depends on the quantity of lime as well as the mineralogical composition of soil.

Soil stabilization using lime is a common method due to its effective and economic usage. When lime is added to clay soils in the presence of water, a number of reactions occur leading to the improvement of soil properties. These reactions are cation exchange, flocculation agglomeration, lime carbonation and pozzolanic reaction. Cation exchange and flocculation agglomeration reactions take place rapidly and bring almost immediate changes in soil properties, but pozzolanic reactions are time dependent. It can be categorised as short-term reactions, also called modification (cation exchange and flocculation), and long-term reactions which cause stabilisation (pozzolanic reaction).

The addition of lime increases the soil pH and forms less soluble compounds (Sivapullaiah, P.V, 2005). Lime addition causes significant improvement in a short time in clayey soil properties by reducing plasticity and increasing strength of soil. Bell (1996) indicated that the optimum gain of strength in clay is achieved with the lime addition of 4-6%. The increase in strength is affected by the amount of mix water, the curing time length, and the temperature at which curing takes place. When the mix water content is just in excess of the
optimum moisture content, the gain in strength is the highest. According to the tests conducted by Bell, the most notable increase of strength occurs within the first 7 days.

Studies have shown that 5% lime is sufficient for the short term reaction referred to as the initial lime consumption. From X-ray diffraction, Al-Mukhtar et al. observed that the additions of hydrated lime at 8% and 10% were consumed after 7 days and 28 days, respectively. It is concluded that lime was consumed more quickly when it was added in a smaller quantities. However, hydrated lime addition must not be less than the amount needed for the soil to develop pozzolanic reaction. The pozzolanic reaction development lasts longer with more lime available. The optimum hydrated lime addition to kaolinite clay varies between 4 and 6%. Strength does not increase linearly with lime content, the excessive addition of lime reduces strength of soil altogether because lime itself has no neither apparent friction nor cohesion.

Lime treatment is one of the most economical techniques to improve the engineering behaviour of soil. The granular soil may not have pozzolanic reactions as what happens when lime is added in clay soil, but it is useful to investigate how lime could affect the strength of mining sand.

2. Experimental programmes

2.1 Soil constituents

Mining sand is chosen as the host material for soil mixture and kaolin clay is used to mix together with mining sand in different proportions. Figure 1 shows the sieve analysis for mining sand and kaolin clay while Table 1 indicates the basic properties of kaolin clay.

![Sieve analysis for mining sand and kaolin clay](image)

**Table 1:** Liquid limit, plastic limit, plastic index, specific gravity, dry density and optimum moisture content of kaolin clay

<table>
<thead>
<tr>
<th>Liquid Limit (%)</th>
<th>Plastic Limit (%)</th>
<th>Plastic Index (%)</th>
<th>Specific Gravity, $G_s$</th>
<th>Dry Density (kg/m³)</th>
<th>Optimum moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>61</td>
<td>34</td>
<td>27</td>
<td>2.69</td>
<td>1350</td>
<td>38</td>
</tr>
</tbody>
</table>
Standard Proctor test was carried out on mining sand to determine its optimum moisture content. The minimum and maximum dry density of mining sand obtained are 1413 kg/m$^3$ and 1565 kg/m$^3$, respectively. The optimum moisture content was found to be about 13%. The coefficient of uniformity ($C_u$) of the mining sand is 2.08 while the coefficient of curvature ($C_c$) is 1.47. The mining sand is classified as well-graded.

Hydrated lime (i.e. Ca(OH)$_2$), manufactured by local company, is used in this study. The properties of hydrated lime are shown in Table 2.

**Table 2: Hydrated lime properties**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium Hydroxide (Ca(OH)$_2$)</td>
<td>92% min</td>
</tr>
<tr>
<td>Calcium Carbonate (CaCO$_3$)</td>
<td>5% max</td>
</tr>
<tr>
<td>Magnesium Oxide (MgO)</td>
<td>2% max</td>
</tr>
<tr>
<td>Silica (SiO$_2$)</td>
<td>0.7% max</td>
</tr>
<tr>
<td>Iron (Fe$_2$O$_3$)</td>
<td>0.2% max</td>
</tr>
<tr>
<td>Moisture</td>
<td>0.5% max</td>
</tr>
<tr>
<td>Arsenic (As)</td>
<td>5ppm max</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>5ppm max</td>
</tr>
</tbody>
</table>

2.2 Soil specimens preparation

Soil specimens with lime treatment were prepared by first estimating the weights of sand, clay and lime needed for desired content. The oven dried sand, kaolinite clay and lime were mixed manually in dry state. The dry mixing process continued until the mixtures were observed to be visually homogeneous, then water was added until it was equivalent to optimum moisture content of soil mixture of lime, clay and sand. The soil-lime-water was thoroughly mixed. After mixing, the specimens were compacted in PVC molds at a relative density of about 70% and they were sealed tightly.

All the tests were carried out on specimens compacted at optimum moisture content with 2% excess of water, because the highest gains in strength occur when the mix water content is just in excess of the optimum moisture content. All the samples stabilized with hydrated lime were cured for 7 days at constant room temperature since the most notable increase of strength occur within the first 7 days.

Soil specimens with or without hydrated lime were prepared in the similar way. The soil specimens were then compacted into the triaxial cells to be tested without curing.

2.3 Testing procedures

Monotonic undrained triaxial compression (CIU) tests are conducted on isotropically consolidated treated (with 5% hydrated lime) and untreated (without 5% hydrated lime) sand samples with 0%, 10%, 30% and 50% clay contents. Untreated soils are fully saturated before being tested. The average $B$-values of the untreated soil specimens after back pressure saturation is always higher than 0.95. After 7 days of curing, the treated soil specimens are removed from the molds and placed in the triaxial apparatus. Both treated and untreated soil
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specimens are isotropically consolidated at different confining pressures of 100kPa and 200kPa.

The triaxial apparatus is computer-controlled, and the test data are recorded using data acquisition equipment as shown in Figure 2. A total of 16 undrained triaxial compression tests are performed to determine the effect of different clay contents in mining sand containing 5% hydrated lime. The triaxial tests for this study are carried out at axial strain rate of 0.4mm/min to approximately 25% axial strain (ε). Summary of the tests conducted is shown in Table 3.

Figure 2: Computer-controlled Virtual Infinite Stiffness (VIS) Triaxial Equipment

Table 3: Summary of tests

<table>
<thead>
<tr>
<th>No.</th>
<th>Sand content (%)</th>
<th>Clay content (%)</th>
<th>Lime content (%)</th>
<th>Confining pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>95</td>
<td>0</td>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>95</td>
<td>0</td>
<td>5</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>85</td>
<td>10</td>
<td>5</td>
<td>100</td>
</tr>
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<td>4</td>
<td>85</td>
<td>10</td>
<td>5</td>
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</tr>
<tr>
<td>6</td>
<td>65</td>
<td>30</td>
<td>5</td>
<td>200</td>
</tr>
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<td>7</td>
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<td>50</td>
<td>5</td>
<td>100</td>
</tr>
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<td>8</td>
<td>45</td>
<td>50</td>
<td>5</td>
<td>200</td>
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<tr>
<td>9</td>
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<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td>11</td>
<td>90</td>
<td>10</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>12</td>
<td>90</td>
<td>10</td>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td>13</td>
<td>70</td>
<td>30</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>14</td>
<td>70</td>
<td>30</td>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td>15</td>
<td>50</td>
<td>50</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>16</td>
<td>50</td>
<td>50</td>
<td>0</td>
<td>200</td>
</tr>
</tbody>
</table>
3. Results and discussion

3.1 Mining sand with 5% hydrated lime

Figures 3 shows the comparison of CIU test results for clean mining sand and mining sand with 5% lime at 100kPa and 200kPa confining pressures. When clean mining sand is mixed with 5% of lime, the shear strength of soil mixture decreases. The soil mixture appears to be brittle and needs to be set up with care. Decrease in strength of soil specimens is caused by reduction in moisture-holding capacity in the soil samples due to the presence of hydrated lime [10]. In practice, hydrated lime is not used to improve sandy soil, but clayey soil. From the result, it is clear that hydrated lime is not suitable to increase the strength of sand. However, lime and sand could be mixed together to form autoclaved lime-sand concrete [11], but this type of concrete is cured under high temperature and high pressure steam (170°C~190°C, 0.8MPa~1.2MPa) in an autoclave. During autoclaving process, Ca(OH)$_2$ reacted with the dissolved SiO$_2$ from the surface of the sand in solution to form various types of calcium silicate hydrates [11]. In this study, the mining sand is cured at room temperature and did not undergo autoclaving process. Therefore, the mining sand mixed with lime does not display higher strength as compared to clean mining sand.

The treated soil specimens has almost negligible pore water pressure due to its brittle behavior as compared to that of clean mining sand. Clean mining sand generated negative pore pressure due to the tendency of sand particles to dilate.

(a) $\sigma'_c = 100$ kPa

(b) $\sigma'_c = 200$ kPa

Figure 3: CIU results for clean mining sand and mining sand with 5% hydrated lime for (a) $\sigma'_c = 100$ kPa, and (b) $\sigma'_c = 200$ kPa
3.2 Mining sand with different clay content and 5% hydrated lime

Figures 4 shows the CIU test results for treated and untreated soil specimens containing 10% clay content at 100kPa and 200kPa confining pressures. The strength of treated specimens is almost similar as untreated specimens. The hydrated lime treatment neither increases nor decreases the strength of sand-clay specimens. This implies that hydrated lime does not contribute to strengthen the sand-clay specimen.

Positive pore pressure of treated soil specimen with 10% clay content increases with confining stresses throughout the test indicating contractive behaviour. Untreated soil specimens with 10% clay exhibit contractive behaviour initially, followed by dilative behaviour till the end of shearing tests, because the mining sand particles in untreated soil specimen are dominant and control the soil behaviour. Clean mining sand is dilative, as shown in Figure 4.

\[ (a) \quad \sigma' = 100\text{kPa} \]

\[ (b) \quad \sigma' = 200\text{kPa} \]

**Figure 4:** CIU results for mining sand with 5% hydrated lime containing 10% clay content for (a) \( \sigma' = 100\text{kPa} \), and (b) \( \sigma' = 200\text{kPa} \)

The stress-strain and pore pressure curves shown in Figure 5 are the comparison of CIU results for treated and untreated soil specimens containing 30% clay content at 100kPa and 200kPa confining pressures. It is noted that an increase in clay content increases the strength of the treated soil specimens. As discussed earlier, the modification of treated soil specimens with clay content is induced by hydrated lime in the presence of clay. Lime reacts with the
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Silicate tetrahedral and aluninate octahedral of the lattices of the clay minerals, especially at the edges of clay particles. This pozzolanic reaction takes place over a long period of time. During the process, the highly alkaline environment produced by the addition of lime induces the dissolution of the silica and the alumina of the clay minerals which produce new cementitious compounds once it is combined with calcium in lime. When clay content is higher (i.e. 30%), such pozzolanic reactions increases with the increase of clay particles between the sand particles. The cementitious products contribute to flocculation process between the lime and clay particles by bonding adjacent soil particles together and as curing takes place, the soil is strengthened. Pore pressure of treated soil specimens with 30% clay content behaves almost similar with untreated specimens. However, the pore water pressure built up for treated soil specimen with 30% clay content is slower when they are sheared initially, and the pore pressure increases steadily throughout the test. Untreated soil specimens with 30% clay content has higher rate of increase in pore water pressure especially when confining stress is high, and the pore pressure has little changes after the peak deviator stress of soil sample is reached.

(a) \( \sigma'_{c} = 100 \text{kPa} \)

(b) \( \sigma'_{c} = 200 \text{kPa} \)

Figure 5: CIU results for mining sand with 5% hydrated lime containing 30% clay content for (a) \( \sigma'_{c} = 100 \text{kPa} \), and (b) \( \sigma'_{c} = 200 \text{kPa} \)

Figures 6 shows the similar results indicating that the treated soil specimens with 50% clay content have higher deviator stress than untreated soil specimens when they are subjected to 100 and 200 kPa confining pressures. Strength improvement in the soil is due to the formation of new cementation compounds such as calcium silicate hydrate and calcium aluninate hydrate. These cementitious compounds can be in a “gel state” during the initial
stages and these products can become crystalline as curing takes place. These cementitious compounds may bind the particles together and improve the engineering behaviour of the soil effectively.

The positive excess pore pressure of untreated soil specimens with 50% clay content is much higher as compared to treated soil specimens with the same amount of clay. When lime is added to clay soils with the presence of water, cation exchange begins to start almost immediately after mixing. Clay particles are surrounded by a diffuse hydrous double layer which is modified by the ion exchange of calcium. Thus, the density of the electrical charge around the clay particles is altered and they are attracted closer to each other to form flocs. When there is an increase in flocculation between clay particles and lime, it results in increase of void ratio and larger soil particles due to reduction in repulsive forces among clay particles. As lime is added into the clay particles, aggregation effect takes place, forming larger units of particles. Consequently, pore size area has increased, resulting in well aggregated crumbs. This may cause the strength increase of treated specimens with 50% clay content and suppress the pore pressure built up in the specimens.

![Graphs showing CIU results for mining sand with 5% hydrated lime containing 50% clay content for different deviator stresses](image)

(a) $\sigma'_c = 100kPa$

(b) $\sigma'_c = 200kPa$

**Figure 6:** CIU results for mining sand with 5% hydrated lime containing 50% clay content for (a) $\sigma'_c = 100kPa$, and (b) $\sigma'_c = 200kPa$

3.3 Normalized deviator stress and pore pressure

Figure 7(a) indicates the normalisation of deviator stress for soil specimens, which is the ratio of strength for treated soil specimens with different clay contents to untreated soil specimens.
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with different clay contents \(\left(\frac{Q_{\text{soil +lime}}}{Q_{\text{soil}}}\right)\). The normalized deviator stress increases as the clay content increases. Many clay minerals like montmorillonite and kaolinite could react favourably well with lime to form the cementation compounds (calcium silicate hydrate and calcium aluminate hydrate). In fact, montmorillonite and kaolin clay respond well to lime. The cementation compound bind the particles together and form aggregates. Through SEM technique, the formation of large floccules with a dominant porous system can be seen. Strength and deformation behaviour of clay soil are improved with the presence of lime. When the clay content increases from 10% to 50%, the normalized deviator stress also increases significantly. This indicates that hydrated lime works well with clay soil.

Figure 7(b) shows the variation of normalized excess pore pressure \(\left(\frac{\Delta u_{\text{soil+lime}}}{\Delta u_{\text{soil}}}\right)\) with clay content. The normalized excess pore pressure is about 0.2 when clay content is 0% (i.e. clean sand), indicating that the excess pore pressure for the treated sand with no clay content is almost negligible as compared to clean sand. When 10% clay content is added, the normalized excess pore pressure increases. Untreated soil specimens containing 10% clay specimens yield a minimal excess pore pressure, which causes the normalized pore pressure to increase. Treated soil specimens with 10% clay content have high positive excess pore pressures and they do not experience dilation once they are mixed with hydrated lime. It is apparent that hydrated lime has effect on the pore pressure generation in the treated soil specimen with 10% clay content. However, when clay content is more than 10% (i.e. 30% and 50%), the normalized pore pressure decreases. This indicates that the pore pressure for untreated soil specimens is higher than that of treated soil specimens when clay content is more than 10%. The increase of clay content does not lead to an increase of normalized pore pressure due to the presence of 5% hydrated lime.

![Figure 7](image)

(a) Normalization of deviator stress and (b) excess pore pressure for soil specimens

3.4 Initial tangent and secant modulus

The results of initial tangent modulus \(\left(E_t\right)\) for soil specimens with different clay contents at confining pressures of 100kPa and 200 kPa are shown in Figure 8. The results show that the initial tangent modulus for treated soil specimens with different clay contents is higher than untreated soil specimens with different clay contents. This is due to the 5% hydrated lime addition that has made the soil to be more compressible when it was sheared at small axial strain.

The initial tangent modulus for all treated or untreated soil specimens with different clay contents decreases with the increase of clay content for the two confining pressures. However,
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when clay content exceeds 30%, the declining rate of initial tangent modulus reduces significantly. At clay content 30% and more, the initial tangent modulus for treated and untreated soil samples with different clay contents are almost similar. This indicates that the clay is reacting with lime to increase the strength of the soil instead of acting as fines or lubricant in the soil particles and causes the soil to be more compressible. This behaviour can be attributed to the changes in the particle organisation resulting from the short term and long term reactions when the soil is treated with lime. The exchange of cation by calcium induces a more stable, less compressible structure which gives the clayey soil greater rigidity (short term reactions). The development of a cementitious bonding between particles produced by the pozzolanic reaction induces high rigidity and increases the strength of the soil specimens (long term reactions).

Figure 8: Initial tangent modulus of treated and untreated soil specimens

Figure 9 shows the secant modulus ($E_{s0}$) at 50% maximum deviator stress for treated and untreated soil specimens with different clay contents. At both confining pressures (100kPa and 200kPa), the secant modulus decreases with increasing clay content for treated and untreated soil specimens. When clay content is less than 30%, the secant modulus of untreated soil specimen is higher than that of treated soil specimens. When clay content is further increased, the secant modulus for both treated and untreated soil specimens becomes progressively similar. This is because sufficient clay ($\geq 30\%$) is required for hydrated lime to react upon in order to strengthen the clay, and consequently increases the deviator stress of soil specimens. The cementing products produced from the addition of lime in clayey soil form a well-knit framework between clusters (grouping of clay particles into larger fabric units). They bond each cluster together, like bridge between clusters, and it is called “bound bridge”. They hydration and cation exchange reactions in the soil induce the clay particles to larger lumps. These reaction products are responsible for strength development. The resistance to compressibility may be attributed to creation of bonds between the soil particles and within the soil matrix.
3.5 Soil friction angle and cohesion

Figure 10 (a) indicates the comparison of variation of soil friction angle with clay content for both treated and untreated soil specimens. For soil specimens treated with hydrated lime, the friction angle increases with increasing clay content. There is an increased internal angle of friction between the agglomerates, and hence greater aggregate shear strength under any given normal stress conditions. A textural change takes place from a plastic clay to a friable material that is granular in nature. For untreated soil specimens, the friction angle decreases with increasing clay content. The compressible kaolin clay causes the sand particles to be separated and lose contact with one another. Hence, when loading is applied, the static stresses could not transfer effectively through the fines. Untreated soil specimens with less than 10% clay has higher friction angle than lime treated soil specimens. Cation exchange cannot be carried out in the treated soil specimens when clay content is insufficient, and thus, pozzolanic reaction is retarded in these specimens containing less than 10% clay contents.

The comparison of soil cohesion between treated soil specimens and untreated soil specimens with different clay contents is shown in Figure 10 (b). The soil cohesion of both treated and untreated soil specimens increases with the increase of clay contents. However, the soil cohesion of treated soil specimens is higher than untreated soil specimens with the same clay contents. This may be due to the 5% hydrated lime in the treated soil specimens, which also contributes as fines in the granular material, and increase the cohesion of soil.
4. Conclusions

1. The strength in treated soil samples increases as the clay content increases from 30% to 50%. However, reaction between lime and sand occur only in autoclaving process (high pressure and temperature) to form autoclaved lime-sand mixture.

2. Lime treatment in soil induces changes in the pore size distribution which affects the pore pressure of the soil specimens. The pore volume increases with a refinement of the pore structure. The increase of clay content does not lead to an increase of normalized pore pressure, but it leads to an increase in normalized deviator stress.

3. Initial tangent modulus for untreated soil specimens is higher than that of treated soil specimens with different clay contents. It decreases with the increase of clay content for 100 kPa and 200 kPa confining pressures. However, the decreasing rate reduces significantly when clay content exceeds 30%.

4. Secant modulus of untreated soil specimens with different clay contents is higher than treated soil specimens when clay content is less than 30%. When clay content exceeds 30%, treated soil specimens with different clay contents have similar secant modulus values with those untreated soil specimens.

5. For treated soil specimens with different clay contents, the soil friction angle increases as clay content increases. The soil cohesion of treated soil specimens with different clay contents is higher than that of untreated soil specimen with the same clay content, and the soil cohesion for both treated and untreated soil specimens increases with increasing clay content.

5. References


5. Ng Pui Ling., (2005), Determination of optimum concentration of lime solution for soil stabilization, Thesis of master degree civil engineering, Universiti Teknologi Malaysia.


