Study of the Mineralogical Changes of Clay Due to Cement and Lime Addition Using X Ray Diffraction Technique

M. Dafalla and E. Mutaz
Bugshan Research Chair in Expansive Soils (BRCES),
Department of Civil Engineering, King Saud University (KSU), Riyadh, Saudi Arabia

Abstract: Light structures in semi arid regions suffer from damage due to expansive subsurface soils subjected to frequent wetting and drying. The use of cement and or lime as stabilizers is a common remedy known to geotechnical engineers. This research is aimed at investigating the mineralogical changes as viewed by x-ray diffraction when lime and cement are added to expansive clay. The x-ray diffraction showed that the mineralogy is not significantly changed due to lime addition while serious alteration and peak collapse of smectite minerals reported with the addition of cement. The percentage of added cement was found proportional to the change in expanding minerals in clay. Adding 6% of cement was found to reduce the expanding minerals of Al-Qatif clay by half compared to 3% cement is added. The stabilization and soil improvement using lime was due to flocculation of clay particles while the improvement obtained by adding cement was due to the cementatious bond and alteration of the mineral structure. Flocculation of clay particles and formation of cementatious bond were found associated with a significant drop in the maximum dry density and changes in the clay compaction characteristics. The outcome of similar studies will serve as a guide to select the appropriate additive and quantity to chemically stabilize clay soils.

Keywords: Cement stabilization, lime stabilization, x-ray, minerals

INTRODUCTION

General: Heavily populated semi arid areas are generally covered by large network of roads ranging from express motorways, highways, inter-city artery, ring roads and municipal main or secondary roads. Agricultural links connecting villages and small towns and secondary roads are considered low volume roads. The secondary roads within the cities are designed for low traffic and often consist of a natural sub-grade material ranging from A-2-4 to A-1-b as per AASHTO (2004) classification and overlain by a single 200 mm sub-base layer, 70 mm Asphalt base and 50 mm asphalt wearing course. Thin surfaced pavements which have the lowest standard of any classification are used for agricultural links. These pavements consist of 50 mm of hot mix asphalt spread over top 200 mm granular material classified within A-2-4 group as per AASHTO (2004) classification. The California bearing ratio CBR required is normally 20%.

This type of pavement (secondary or agriculture roads) is very sensitive to subsurface soil conditions. Expansive soil is one of the main factors that causes this type of roads to malfunction. The use of stabilizers such as cement and lime is a known procedure to reduce the expansion caused by swelling soils. This is widely practiced and receiving a wide attention in areas struck by
expansive soils. Maintenance costs are running into multi
million United States dollars annually for a city like
Tabuk located to the North-west of Saudi Arabia.
Examples of deterioration initiated by expansive soil are
shown in Fig. 1, 2, 3 and 4.

Lime and cement are common stabilizers for the
subgrade formation. Trial sections are normally suggested
in order to observe and assess the improvement added to
the road performance. This research was aimed at looking
to the effect on the mineralogy when such stabilizers were
used. The X-ray diffraction is a widely used technology
for the study of minerals.

Smectite is a term used to define a wide range of
phyllosilicate minerals. The smectite group of minerals is
known of its expanding nature and is generally composed
of silica tetrahedral and alumina octahedral units arranged
in a three layers order with specific d-spacing separating
these units. The chemical composition of each mineral
depends on cations present and the way these units are
composed. Several forms of expanding minerals were
listed in mineral database references. Three of the most
common forms are shown as follows:

Montmorillonite: \[(Na,Ca)_{0.33} (Al,Mg)_{2} Si_{4} O_{10} (OH)_{2} nH_{2}O\]

This is a whitish, yellow or green clay mineral, composed of tetrahedral and octahedral nets of monoclinal crystal system. Silicates containing aluminum and magnesium and involve sodium and iron.

Nontronite: \[Na_{0.3} Fe_{4} (Si, Al)_{4} O_{10} (OH)_{2} nH_{2}O\] This is a green, olive-green or yellow-green mineral, composed of tetrahedral and octahedral nets of monoclinic crystal system. Silicates containing aluminum and involve sodium and iron.

Saponite: \[Ca_{0.33} (Mg, Fe)_{2} (Si, Al)_{4} O_{10} (OH)_{2} nH_{2}O\] This is a white, gray-green to bluish, yellow mineral of a greasy or soapy feel appearance composed of tetrahedral and octahedral nets of monoclinic crystal system. Silicates containing aluminum and involve calcium, magnesium and iron.

Montmorillonite is a very soft mineral formed by
deposition of volcanic ash in lakes. Montmorillonite, a
member of the smectite family, is 2:1 clay, with an
average diameter of approximately 1 micrometer. The
particle thickness is extremely small (~ 1 nm) (Sharifah,
2006). The water content of montmorillonite is variable.
Montmorillonite increases greatly in volume when it
absorbs water. Chemically it can be defined as hydrated
sodium calcium aluminum magnesium silicate hydroxide.
Potassium, iron and other cations are common substitutes
and the exact ratio of cations vary with source (Sharifah,
2006). The addition of water causes the montmorillonite
to expand to variable levels. However, based on the
chemical composition and structure, some types of
montmorillonite expand more than other types.

Lime Treatment: Lime is generally added to soils to
generate long-term strength gain through a series of
pozzolanic reactions in the presence of water. The mixture
is generally compacted to a desired water content and dry
density. The different types of lime available are: quick
lime (CaO), hydrated lime (Ca(OH)_{2}) and lime slurry
which is a suspension of hydrated lime dissolved in water.
Quicklime is manufactured by chemically transforming
calcium carbonate (limestone-CaCO_{3}) into calcium oxide.
Hydrated lime is created when quicklime reacts with
water. It is the hydrated lime that reacts with clay particles
and permanently transforms them into a strong
cementitious matrix (National Lime Association, 2004).
According to the National Lime Association Publication
(Lime-treated Soil Construction Manual, 2004) when lime
and water are added to a clayey soil, chemical reactions
occur immediately. When the quick lime is added to a soil
it will start drying and the moisture holding capacity is
then reduced to a great extent. Calcium ions start
migrating from the lime to the surface of the clay particles
and displace water and weakly bonded anions. The soil
becomes friable and starts to granulate and this makes it
easily compacted. When lime is added to the soil, the
concentration of OH⁻ ions increases and elevates the pH
level. This will result in the release of alumina and silica
into the clay fraction (Ouhadi and Yong, 2003). The
released alumina and silica phases react with calcium ions
producing CSH (3CaO·2SiO_{2}-3H_{2}O) and CAH (3CaO·Al_{2}}
O₃·Ca(OH)₂·12H₂O, which renders cohesive soils workable and less plastic (Raymond and Ouhadi, 2006). In general, the higher the clay contents in soils the higher the plasticity values. Expansive clays have high liquid limits. The addition of lime to highly plastic clay has a significant effect in reducing plasticity index, liquid limit and linear shrinkage and increases shrinkage limit and plastic limit. The compacted soil-lime mixtures have lower maximum density values compared to untreated soil and this reduction increases with the increase in the lime content. The optimum water content also increases proportionally with the increase in the percentage of the lime (Mallela et al., 2004). Lime can modify almost all fine-grained soils, but the noticeable improvement occurs in the case of clayey soils containing minerals such as; smectite, kaolinite and illite. The soil mineralogy is an important issue for the effectiveness of lime treatment. Generally, the optimum amount of lime required for soil treatment is usually between 2 and 8 % measured by dry weight of the soil (Basma and Tuncer, 1991).

Cement Treatment: Cement is a comprehensive chemical stabilizer often used in ground improvement. The most common cement type used to treat clayey soils is the Portland cement which when combined with water, hydrates to form the cementing compounds of calcium-silicate-hydrate and calcium-aluminates-hydrate, as well as excess calcium hydroxide. Calcium hydroxide released during the process of hydration reacts with soil alumina and soil silica fine-grained clay soils. This pozzolanic reaction is an important aspect of the stabilization of clayey soils. Portland cement essentially contains five main components. In their pure form, these phases are tricalcium silicate (Ca₃SiO₅ or C₃S) (Taylor, 1997), dicalcium silicate (Ca₂SiO₄ or C₂S), tricalcium aluminate (Ca₃Al₂O₆ or C₃A), a tetracalcium alumino ferrite (Ca₄Al₂Fe₂O₁₀ or C₄AF) and a sulfate phase (often given as Ca₁₀Al₂(AlSi)₂.22O₂ (OH)₁₂2.25H₂O). Calcium aluminate hydrates are formed when Ca₁₀Al₂(AlSi)₂.22O₂ (OH)₁₂2.25H₂O, a compound present in Portland cement, reacts with water (Spierings and Stein, 1978). The chemical formulation of Calcium Aluminate Hydrate (CAH) is (3CaO·Al₂O₃·Ca(OH)₂·12H₂O). CAH has many crystal structures. Richardson (2008) depicted some of the crystal structures of CAH as; Bicchulite Ca₃(Al₂SiO₇)(OH)₂, Katoite Hydrogarnet Ca₃Al₂Si₃O₉(OH)₂·5H₂O, Tobermorite Ca₉Si₆O₁₈(OH)₂·16(OH)₂ and Jennite Ca₈Si₆O₁₈(OH)₂·8H₂O.

Pozzolanic reaction and its compounds: The Pozzolanic reaction is a chemical reaction which occurs in cement or in a mixture of hydrated lime (calcium hydroxide) with amorphous siliceous materials in the presence of water. The most important reaction of the siliceous pozzolans occurs between reactive silica, lime and water to produce calcium silicate hydrate (Helmuth, 1987). A simple acid-base reaction between Calcium Hydroxide, (Ca(OH)₂) and silicic acid, (H₂SiO₄ or Si(OH)₂), can be shown as an example of pozzolanic reactions. According to Cook (1986), the reaction can be schematically represented as follows:

\[
\text{Ca(OH)}_2 + \text{H}_2\text{SiO}_4 \rightarrow \text{Ca}_2\text{H}_2\text{SiO}_4 + 2\text{H}_2\text{O} \\
\rightarrow \text{Ca}_2\text{SiO}_4 \cdot 2\text{H}_2\text{O}
\]

The above reaction can be simplified into:

\[
\text{CH} + \text{SH} \rightarrow \text{CSH}
\]

The product of (CaH₂SiO₄·2H₂O) formed is a calcium silicate hydrate, also abbreviated as CSH in cement chemist notation (Cook, 1986).

Hydration reaction is the main hardening reaction of calcium silicate binders due to the reaction of calcium silicates, calcium aluminates and calcium-silicate-aluminate phases (i.e., 2CaO·Al₂O₃·SiO₂ and 4CaO·Al₂O₃·Fe₂O₃) with water (Cizer et al., 2009). This leads to the formation of hydrated compounds such as calcium silicate hydrates (CSH), calcium aluminate hydrates (CAH) and AFm phases (AFm phase is an alumina and monosulfate phase) (Taylor, 1997).

Calcium silicate hydrates possess a remarkable level of structural complexity (Chena et al., 2004). More than 30 crystalline calcium silicate hydrate phases are known, these phases range from semicrystalline to nearly amorphous, all of which are described by the generic term, “C-S-H” (Taylor, 1997). The C-S-H formed by the hydration of tricalcium silicate (C₃S) or ß-dicalcium silicate (ß-C₂S), which together constitute about 75 % of a portland cement by weight, is particularly a disordered variety, usually called C-S-H gel to distinguish it from C-S-H phases made by ‘‘synthetic’’4 preparation routes such as the reaction of CaO and SiO₂ or the double decomposition of a Ca salt and an alkali silicate in aqueous solution (Chena et al., 2004). CSH has many crystal structures, some of which are depicted by Richardson (2008) as; Foshagite Ca₅(Si₆O₁₈)(OH)₂, Nekoite Ca₅Si₆O₁₅·7H₂O, Clinotobemorite Ca₅Si₆O₁₅·5H₂O, Tobermorite Ca₅Si₆O₁₈·16(OH)₂ and Jennite Ca₅Si₆O₁₈(OH)₂·8H₂O.

Detecting CSH and CAH Phases: This study is aimed at utilizing the x-ray diffraction technique to view the possible changes in the minerals and the new forms of compounds formed as a result of adding lime or cement. During the application of cement or lime to soil, peaks
pertaining to cementing compounds such as CSH and CAH were observed. According to Al-Mukhtar et al. (2010) new peaks corresponding to calcium aluminate hydrate (CAH) were formed Ca$_3$Al$_2$O$_6$·xH$_2$O appeared at d-spacing of 0.76, 0.376, 0.285 and 0.166 nm at 2θ = 11.6º, 23.6º, 31.3º and 55.3º; respectively in all the XRD patterns of treated sample. Two new peaks appeared at d-spacing of 0.308 and 0.279 nm at 2θ = 29.0º and 32.1º. These peaks correspond to calcium silicate hydrate (CSH) Ca$_3$Si$_2$O$_7$·xH$_2$O. The size and pattern of x-ray peaks of the expanding minerals in pure clay can be compared to clay treated with lime and cement.

MATERIALS AND METHODS

Material and Equipment: This work was carried out during the years 2010 and 2011 at King Saud University in Saudi Arabia. The soil material selected for this study was brought from Al-Qatif district from the eastern province of Saudi Arabia. The physical and geotechnical properties of Al Qatif clay is given in the Table 1:

The x-ray diffraction was carried out using SHIMADZU XRD-7000 system at 40 Kv Cu K alpha radiation source and a scanning speed of 2 degrees/minute. Divergence and scatter slit is 1 degree. Receiving slit is 0.3 mm. Continuous scanning for two theta range of 2 to 40 degrees was considered.

Sample preparation is an essential parameter that governs the intensity measurements and can be a basic factor in the quantitative analysis (Rietveld, 1969). Several other parameters can affect the intensity measurements; these include instrument related parameters (e.g., Variation in power supply, temperature and diffractometer efficiency). The intensity of reflection is also dependant on the mass absorption coefficient of the tested material. In this study sample preparation was kept identical for all tested samples and same machine was utilized with the same set up conditions applied for all tests. Air dried samples of crushed material passing sieve number 200 (size 75 μm) were used.

Testing Program: The x-ray diffraction technique is generally used in qualitative and quantitative mineralogical identification. The x-radiation is produced when high energy cathode rays rip electrons from a target element placed in the anode of an evacuated tube. The wave length produced is short and is dependent on the target material. The radiation involves two components known as kα and kβ. Screens were used to filter kβ for simplification. Crystal spacing can be determined by x-rays of a single wave length. The common radiations used in x-ray crystallography are produced by Cu, Co, Fe and Cr tubes. Powder prepared samples from Al-Qatif were tested.

Table 1: Physical Properties of Al-Qatif soil

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Limit (%)</td>
<td>136</td>
</tr>
<tr>
<td>Plastic Limit (%)</td>
<td>60</td>
</tr>
<tr>
<td>Shrinkage Limit (%)</td>
<td>12</td>
</tr>
<tr>
<td>Linear Shrinkage (%)</td>
<td>28</td>
</tr>
<tr>
<td>Plasticity Index (%)</td>
<td>76</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.70</td>
</tr>
<tr>
<td>% finer than 200 μm</td>
<td>99.1</td>
</tr>
<tr>
<td>USCS Classification</td>
<td>CH</td>
</tr>
</tbody>
</table>

The basal spacing at peaks in the range of d = 12 A° to 15 A° indicates the presence of smectite minerals. Na⁺-montmorillonite d spacing is 12 A° while Ca⁺⁺-montmorillonite is 14 to 15 A°. Other minerals including Vermiculite and Chlorite can also occur at d = 14 A°. The Illite can be observed at d = 10 A°. From the X-ray diffraction results it is possible to confirm the presence of expanding minerals belonging to smectite groups. Some techniques are commonly used to differentiate between overlapping peaks including glycolation, heating and other means. Some peaks shift or disappear when a special treatment is used. This study used Al Qatif clay, a typical semi-arid highly expansive material. Peak intensities can tell about mineral proportions when a calibrated curve is prepared for different concentrations.

The test program was planned as to have the x-ray diffraction profile for Al-Qatif clay prepared at room temperature after saturating with potassium chloride. The aim of chemical saturations was to characterize different clay minerals including smectite, illite and kaolinite. Heating the sample to 550 °C was adopted to detect the changes in d-spacing and collapse of expanding mineral peaks. The peak intensity changes were observed. Samples saturated with potassium chloride but including cement and lime as additives were investigated. The ranges tested included 3% cement, 6% cement, 4% lime and 8% lime. All preparation procedures and testing conditions were kept similar in order to enable good comparison. 1 M potassium chloride reagent was used for air dried slides.

As part of this study additional physical testing was carried out to compare the changes in compaction characteristics. One of the measures for the stabilization in clays is the compaction test and compaction characteristics. These tests describe the relationship between the moisture content and the dry density. Changes in the curve showing this relationship due to the addition of lime or cement were observed.

The compaction tests were carried out using the modified proctor approach as given in ASTM D1557. The test was carried out on pure clay and on clay treated with 4% lime, 8% lime, 3% cement and 6% cement. The moisture content and the dry density plot were obtained. Maximum dry density and optimum moisture content was defined for each sample. OPM is the optimum moisture content at which maximum dry density occurs. WOPM refers to the wet side of the curve or values of dry density when moisture content is greater than the optimum.
Al-Qatif clay was prepared at room temperature after saturating with potassium chloride. Heating the samples to 550°C was adopted to detect the changes in x-ray profile and d-spacing. Samples saturated with potassium chloride but including cement and lime as additives were investigated using the experimental system as described above.

**RESULTS AND DISCUSSION**

The swelling and volume change behavior is dependant on the clay minerals present in a soil. Adding cement or lime will affect the chemical balance and may lead to some changes in the structure of minerals or even alter or convert the mineral. Evidence of this can be detected by the use of x-ray diffraction technique. As part of this research x-ray diffraction was carried out utilizing SHIMADZU XRD-7000 system at 40 Kv Cu K alpha radiation source and a scanning speed of 2 degrees/minute.

The presence of the smectite clay minerals, illite and kaolinite was confirmed for Al Qatif pure clay sample saturated with potassium chloride. On glycolation the d-spacing was increased to 18 Å. On heating to 550°C most of the smectite minerals peaks collapsed and a maximum d-spacing of 10 Å was reported. Non-clay minerals including quartz, feldspar and calcite were also reported. The d-spacing for illite was around 9.9-10.1 Å and it remained constant with MgCl, Ethylene Glycol and KCl saturations. The d-spacing of kaolinite was 7.15 Å with MgCl, Ethylene Glycol and KCl saturations and the kaolinite peaks disappeared when heated at 550 degrees.

The intention was to see how the addition of lime (4% and 8% by weight) or cement (3 and 6% by weight) will affect the mineralogy of the swelling clay of Al Qatif. The comparison was made between the diffraction profiles of the clay-cement mixtures, clay-lime mixtures and the natural Qatif clay soaked in Potassium Chloride (KCl) at room temperature and when heated to 550 degrees. The heating cause's smectite group peaks to collapse and expanding minerals to disappear. Works of Al-Rawas et al. (2005) showed that montmorillonite, which is the main mineral responsible for swelling, collapsed on heating beyond 550 degrees and the swelling was reduced to zero. The laboratory test results of Al-Rawas et al. (2005) indicated that the swell potential and the swelling pressure converged to zero upon elevated heating (800°C). Basal spacing of smectite group is sensitive to interlayer hydration. Dehydrated montmorillonite may have a 10 to 13.6 Angstrom spacing and can move up to 18 Angstrom on full hydration. Mordome et al. (2009) compared the response of basal spacing of Ca montmorillonite and Na montmorillonite and found that differences are related to hydration powers of exchangeable cations. The peak intensity is proportional to the mineral content in the sample and measurements of peaks can provide good information for minerals quantitative analysis. It is known that varying absorption coefficient for different mineral phases in a mixture can affect the peak intensity (Al-Jaroudi et al., 2007).

One of the approaches of quantitative analysis of minerals is based on comparing the peak size or the area under the peak of the x-ray diffraction profile to that of known standard mineral concentration. The quantitative analysis for specific mineral using internal or external standard method (Dafalla and Ali, 1991) refers to the area under the peak that match the area calibrated using a known mineral. The amount of the smectite group minerals content reflected by these measures can tell about how much minerals are likely altered or collapsed. In this study the areas were measured for comparison in order to check if significant part of the smectite group minerals is altered. The percentage change in areas or intensity do not give the percentage of minerals altered but can confirm the order by which change is taking place. Two new terms are used here to define a base line; these are reference area and reference peak. The reference area is the area under the diffraction profile for the zone (two theta = 2 to 10 degrees) subtracted by the area under the pure clay diffraction profile heated to 550°C for the same zone. The reference peak is the peak height measured for the pure clay subtracted by the peak height for the heated pure clay. Table 2 summarizes the peak heights and relative areas as measured for the tested samples.

The reactions between lime and the clay include exchange of cations, flocculation, carbonation and pozzolanic reactions (Al-Rawas et al., 2005). The cation exchange causes clay particles to flocculate or getting close to each other leading to the so called flocculation. Flocculation is responsible for modification of engineering properties. In the case of adding cement, reactions due to calcium silicate and aluminates hydration gives cementitious bond within the soil particles or alter the mineral composition and/or structure.

<table>
<thead>
<tr>
<th>Prepared sample</th>
<th>Reference area</th>
<th>Reference peak</th>
<th>Area under the curve for 2θ</th>
<th>Peak intensity for 2θ = 2 to 10º</th>
<th>Area increase (%)</th>
<th>Peak increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Clay saturated in KCl</td>
<td>41</td>
<td>1372</td>
<td>41</td>
<td>3172</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Clay with 3% cement saturated in KCl</td>
<td>41</td>
<td>1372</td>
<td>30</td>
<td>2604</td>
<td>27.5</td>
<td>42.0</td>
</tr>
<tr>
<td>Clay with 6% cement saturated in KCl</td>
<td>41</td>
<td>1372</td>
<td>17</td>
<td>1764</td>
<td>58.5</td>
<td>100</td>
</tr>
<tr>
<td>Clay with 4% lime saturated in KCl</td>
<td>41</td>
<td>1372</td>
<td>41</td>
<td>3530</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Clay with 8% lime saturated in KCl</td>
<td>41</td>
<td>1372</td>
<td>36</td>
<td>2900</td>
<td>12.2</td>
<td>19.3</td>
</tr>
</tbody>
</table>
The outcome of this x-ray study indicates that adding of cement can alter some smectite minerals and reduce their expansion nature through a cementatious bond while when adding lime the expansion is reduced due to flocculation of clay particles and the mineralogy is not significantly altered. From this study we note that improvement using cement was proportional to the quantity added i.e., the quantity of added cement is a function of the level of improvement. Area increase or peak increase was not observed when adding 4% of lime. This amount may not be sufficient to produce flocculation or hold the expansion and tension stresses. The 8% addition of lime caused an increase in the area under peak and peak intensity by 12.2 and 19.3% respectively.

The results in Table 3 indicated that adding lime or cement shifts the moisture density curve to the right and increases the optimum moisture content for both lime and cement. The other clear change was the decrease in the dry density at the optimum moisture content and also wet of optimum moisture content. This reduction is attributed to the formation of lumps and aggregations of clay particles which are not breakable at the level of compaction energy commonly used in standard and conventional compaction tests.

The flocculation or aggregation caused by adding lime is not of sufficient bond to hold the clay against tensile stress. The clay-lime mixture may be friable and the improvement is function of the amount added. The influence of the pozzolanic reactions is not satisfactory to cause significant changes in the structure of the expanding minerals. The amount of lime additive that can stabilize swelling clays depends on the type of clay and its chemical composition.

From this XRD study it was indicated that, lime has an effect in changing the mineralogy of Al-Qatif soil by changing the diffraction profile at 2θ = 31 degrees. Similar outcome is reported by Al-Mukhtar et al. (2010). These cementing agents are further responsible for the improved soil strength and swelling reduction resulting from the stabilization process (Mohamed and Al-Hosani, 2000).

To evaluate the effect of cement treatment on clay mineralogy, a similar approach and concept as described in the experimental section below was used. From Fig. 6 and 7 and Table 3 for Al-Qatif soil, it is inferred that the area under the curve and the peak intensity from 2θ = 2 to 2θ = 10 degrees decreased on the addition of 3 % and 6 % cement. The reduction was more pronounced in the case of 6% cement. The outcome of this XRD study indicates that, the amount of expanding minerals were significantly reduced and the cement had an effect in changing the mineralogy of the soil as a result of pozzolanic reactions.

![Fig. 5: X- Ray profile for pure clay treated with potassium chloride](image)

![Fig. 6: X-ray profile for 3% cement clay mixture compared to pure AlQatif Clay (heated to 550º and non-heated)](image)

![Fig. 7: X-ray profile for 6% cement clay mixture compared to pure AlQatif Clay (heated to 550º and non- heated)](image)

<table>
<thead>
<tr>
<th>Properties</th>
<th>4% lime</th>
<th>8% lime</th>
<th>3% cement</th>
<th>6% cement</th>
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<tr>
<td>Increase in OMC</td>
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<td>6.2</td>
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<td>25</td>
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<tr>
<td>Increase in WOMC</td>
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<td>16.7</td>
<td>13.9</td>
<td>30.6</td>
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<tr>
<td>Decrease in Dry</td>
<td>4.8</td>
<td>9.4</td>
<td>4.2</td>
<td>5.2</td>
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<tr>
<td>Density at OMC</td>
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<td></td>
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<tr>
<td>Decrease in Dry</td>
<td>4.9</td>
<td>9.9</td>
<td>4.4</td>
<td>5.6</td>
</tr>
<tr>
<td>Density at WOMC</td>
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</tbody>
</table>

* Values given are percentage change based on untreated soil.
taking place. A strong bond was generally created which prevented the expanding minerals from causing high expansion. These cementitious compounds were responsible for the remarkable reduction in the swelling for Al-Qatif soil.

It can be concluded that by adding cement to clayey soils, the pozzolanic reactions can cause some minerals to change and form other cementatious compounds and the original concentration of expanding minerals within the clay will reduce.

Figure 8 and 9 presents the XRD profiles for the 4% and 8% lime treated clay respectively. As discussed above the influence of the pozzolanic reactions is not strong enough to cause significant mineral structure changes when considering low lime concentrations.

The compaction characteristics of lime-treated and cement-treated clays are presented in Fig. 10 and 11. The optimum dry unit weight drops significantly with the increase of lime concentrations.

**CONCLUSION**

Based on the works carried out and test results reported in this research, it can be concluded that the addition of cement to a potentially expansive clay can alter some smectite minerals and can reduce their expansion nature through forming cementatious bonds. The addition of lime to potentially expansive clay can reduce the expansion due to flocculation of clay particles and the mineralogy is not significantly altered. The change and decrease in expanding minerals when using cement is proportional to the quantity added. When adding 6% quantity of cement to a clay, reduction in area under the peak will be twice that produced by a clay with 3% cement added. The pozzolanic reactions associated with lime are of weaker influence in altering the structure of expanding minerals. Flocculation of clay particles and formation of cementatious bond were found associated with a drop in the maximum dry density of the clay and significant changes in the clay compaction characteristics.
ABBREVIATIONS

AASHTO American Association of State Highway and Transportation Officials
CBR The California Bearing Ratio
CH Highly plastic clay
CSH (3CaO·2SiO_2·3H_2O) calcium silicate hydrates
CAH (3CaO·Al_2 O_3·Ca(OH)_2·12H_2O) calcium aluminate hydrates
KCL potassium chloride
OMC optimum moisture content
WOMC wet of optimum moisture content
°A Angstrom
°C degree in Centigrade
Al Aluminum
C Carbon
Cu Cupper
Ca Calcium
Fe Iron
H Hydrogen
Mg Magnesium
Na Sodium
Si Silicon
O Oxygen
kα Radiation component
kβ Radiation component

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