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Maximizing Strength of CKD – Stabilized Expansive Clayey Soil Using Natural Zeolite

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ABSTRACT

The influence of pozzolanic materials on calcium-based soil stabilization technique has recently attracted researchers' attention as such materials may catalyze the occurrence of pozzolanic reactions due to their high SiO_2 and AL_2O_3 content. In this study, the effect of adding natural zeolite, which is a common pozzolanic material, on soil stabilized with cement kiln dust (CKD) is investigated. The optimal CKD content was determined by conducting tests on soil treated with percentages of CKD (0%, 2%, 4%, 6%, 8%, 10%, and 12%), and then, the optimal CKD treatment was applied on soil replaced by different zeolite percentages (1%, 3%, 5%, 10%, and 15%). Atterberg limits, swelling, California bearing ratio and unconfined compression tests were performed on all samples to evaluate the performance of additives in stabilization. Unconfined compression test samples were cured for 0, 7, 14 and 28 days to study the effect of time. Addition of CKD resulted in reduction of soil swelling and a significant increase in the long-term strength to an optimum of 10% that resulted in 3-folds of strength value higher than the based soil. Addition of 15% natural zeolite to the optimized CKD stabilized soil, caused 21% increase of strength higher than that with CKD optimized soil, however the swelling is only slightly reduced.

1. Introduction

The presence of expansive clayey soil underneath a construction base can considerably threaten the ductility of that construction, such soils are extremely problematic as they are essentially composed of certain types of clay minerals that tend to expand in volume (swell) when presented to moisture and contract in size (shrink) when they dry out which may eventually cause differential settlements in the base of structures and thus may lead to severe distresses in constructions (Asuri and Keshavamurthy, 2016).

Over the years, diverse solutions have been proposed to limit and control expansive soil problems. One of the oldest solutions is to stabilize the soil by mixing the soil with a stabilizing additive. It is considered a highly-efficient and cost-effective method to enhance the strength and durability of expansive soils and eliminate swelling and other undesirable geotechnical properties (Firoozi et al., 2017), and hence the stabilized soil can secure an endured base for engineering structures.

Soil stabilization techniques are mainly categorized as either calcium-based or non-calcium-based depending on the chemical compounds produced through the reactions of the additive with the soil (Behnood, 2018). Calcium-based stabilizers usually contain large amounts of active quicklime (CaO) that produces cementitious gels such as C-S-H and C-A-H that create strong bonding between the soil particles resulting in stronger soil. However, the addition of non-calcium-based stabilizers, such as polymers (Mousavi et al., 2014), fibers (Sharma, 2017), alkaline activation (Shaqour et al., 2017), and nanoparticles (Sharo and Alawneh, 2016), improve the strength of soil through polymerization, soil reinforcement and other means.

In the calcium-based stabilization technique, when calcium ions are introduced to the soil with the presence of moisture, several chemical reactions occur; including firstly short-term reactions (cation exchange and flocculation), leading to immediate improvement of the soil workability and the reduction of its plasticity, and secondly long-term reactions (pozzolanic reactions), that are responsible for the noticeable increase in the soil strength (Diamond and Kinter, 1965).

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Pozzolanic reactions are time-dependent that take place between Ca^{2+} in the quicklime and the SiO_2/Al_2O_3 located on edges of clay particles to produce calcium-silicate-hydrate (C-S-H) and calcium-aluminate-hydrate (C-A-H) gels that act as cementitious materials causing increase of strength (Shaqour et al., 2017; MolaAbasi et al., 2019). The most worldwide used calcium-based stabilizers are lime and cement (Bell, 1996; Ghobadi et al., 2014; Sharo et al., 2019; Ismeik and Shaqour, 2020). Cement kiln dust (CKD) is becoming a widely used soil stabilizer. It is a highly alkaline waste material that is produced during the manufacture of cement clinker. It is considered an environmentally friendly and a cost-effective active quicklime provider since its composition is quite similar to cement and its production is estimated to be about 15% to 20% of the clinker production (Kunal et al., 2012). The suitability of utilizing it as a soil stabilizer was validated by many researches (Baghdadi et al., 1995; Solanki et al., 2009; Anwar Hossain, 2011; Hossain and Mol, 2011; Okafor and Egbe, 2013; Salahudeen et al., 2014; Ismail and Belal, 2016; Al-Homidy et al., 2017; Sharma, 2017). Solanki and Zaman (2012) and Yoobanpot et al. (2017) studied the microstructural characteristics of CKD-stabilized clayey soil and proved the formation of hydrated products within its structure using scanning electron microscope (SEM). It can be concluded from previous work that CKD reduces the plasticity and enhances the strength and the durability of the based soil. However, the optimal CKD content required to produce the best long- term strength enhancement and sufficiently reduce the plasticity is highly varying in the literature as it is a function of the amount of quicklime presented in the CKD sample and the type of the based soil under study. Sreekrishnavilasam et al. (2007) attributed the efficiency of utilizing different types of fresh and landfilled CKD in soil stabilization with the presence of free lime within their compositions.

Clearly, the amount of quicklime in the calcium-based stabilizer induces the pozolanic reactions that strengthen the stabilized soil, where the rate of such reactions is a function of silicon/aluminum availability as well as the specific surface area of particles (Massazza, 1998). The role of finely grained silicon and aluminum oxides in the pozzolanic reactions and their stabilizing effects has attracted researchers of soil stabilization (Khatib et al., 2018; Harichane et al., 2019). A main advantage of the use of pozzolanic materials in soil strengthening is them being cost effective naturally occurring and environmentally friendly. The use of such materials will reduce energy consumption and harmful gas emissions (Mola-Abasi et al., 2020b). Several studies have been carried out to investigate the efficiency of adding different pozzolanic materials, that proved to be highly effective, such as fly ash, silica fume, rice husk ash, volcanic ash and natural pozzolana to the soil with the presence of various calcium-based stabilizers (Ansary et al., 2007; Anwar Hossain, 2011; Hossain and Mol, 2011; Al-Swaidani et al., 2016; Mousavi, 2018; Sharo et al., 2018; Harichane et al., 2019).

Zeolite (ZT) is a type of pozzolanic materials that is formed as a very stable three-dimensional tectosilicate structure, it consists mainly of aluminum, silicon oxides that makes them effective pozzolanic materials. The most common zeolite minerals are clinoptilolite, faujasite, phillipsite and chabazite. Zeolite is known for its high cation exchange capacity due to its channeling system (Akimkhan, 2012). The characteristic channelings system of the zeolite makes the swell potential quite low (Yukselen-Aksoy, 2010). Poon et al. (1999) set the reactivity of clinoptilolite - zeolite between the reactivity of fly ash and silica fume. Mola-Abasi and Shooshpasha (2016) partially replaced cement by clinoptilolite - zeolite to enhance the mechanical properties of sandy soil. Turkoz and Vural (2013) found that the addition of clinoptilolite-zeolite increased the unconfined compressive strength of cement - stabilized clayey soil. MolaAbasi et al. (2020a) conducted research on cemented sand where the cement is partially replaced with zeolite resulted in the formation of more C-S-H strengthening gels and that was confirmed by the use SEM and XRD techniques in the analyses of test samples. It is worth mentioning that clinoptilolite-zeolite is the type of zeolite used in most of the fore mentioned research, while other types of zeolites are less used although they have the good potential.

It is part of the current study to investigate the use this type of zeolite in soil stabilization. Five different percentages of phillipsite zeolite (1%, 3%, 5%, 10%, and 15%) were added to the unconfined compressive strength optimized CKD – stabilized based soil. The mixture was then tested for Atterberg limits, swell, compaction, pH, unconfined compression (short and long term), and California bearing ratio (CBR), in addition to SEM tests. The results of these tests are discussed in section 3.

2. Experimental Program

2.1 Materials

2.1.1 Soil

The clayey soil used in this research was collected from Jarash – northern Jordan at a depth of about 3 m below the ground level. The soil, which is olive- green in color, is classified as CH according to the unified soil classification system (USCS), following ASTM D2487 (2017). Index geotechnical characteristics of the soil are summarized in Table 1. The chemical composition of the based soil was determined using X-ray fluorescence (XRF) as given in Fig. 1(a). X-ray diffraction (XRD) technique was used to determine the mineralogical composition of the based soil which is mainly quartz, calcite, illite and smectite clay minerals, as shown in Fig. 2.

2.1.2 Stabilizers

The natural zeolite used in this study was collected from Al-Ashqaf area from the north of Jordan. the obtained raw natural zeolite was reddish-brown in color due mainly to the presence of iron oxides. The test zeolite samples were provided by a local zeolite company with a size range between 4.25 mm down to 1 μm. Enough amount of the zeolite material was grinded in the

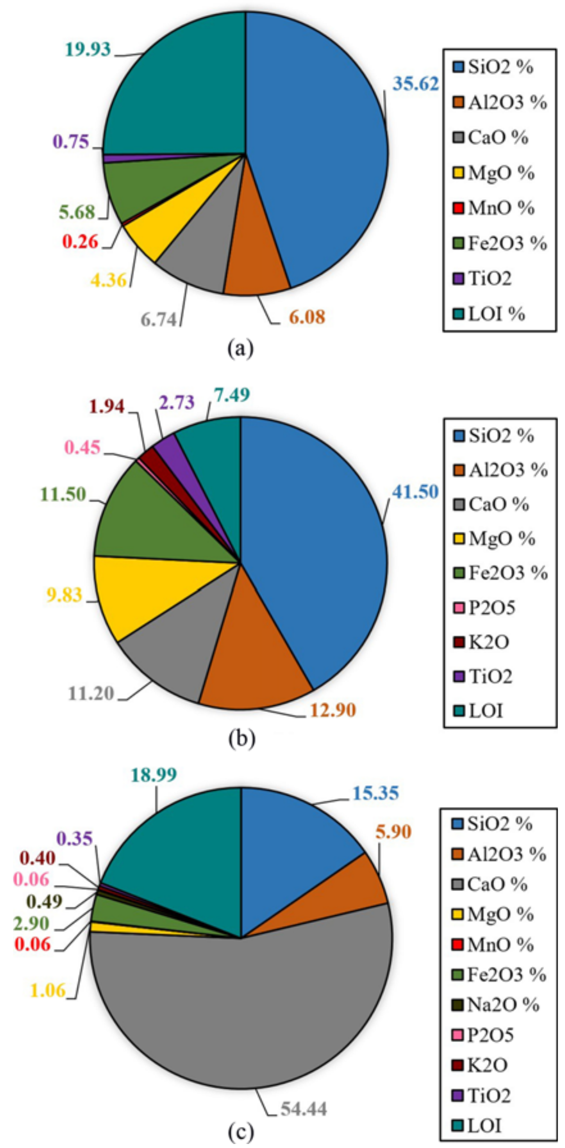

Fig. 1. Chemical Compositions of the: (a) Based Soil, (b) Natural Zeolite, (c) Cement Kiln Dust as Obtained from XRF Analyses

laboratory using a ball milling machine after which it was sieved through sieve No. 200 (< 75 μm) to be used as the stabilizing additive. The chemical and mineralogical compositions of the prepared samples of natural zeolites are presented in Figs. 1(b) and 2 respectively. The initial moisture content was 3%.

The used cement clinker dust (CKD) was obtained as very fine grained from a local cement factory and used as is, with no further processing in the test program. Its general characteristics were provided by the company. Specific gravity is 3.1 following ASTM D854 (2014), with 85.3% smaller than 71 μm. Chemical composition of the used CKD is given in Fig. 1(c).

2.2 Sample Preparation

Enough amount of the prepared based soil was oven-dried at a temperature of 105°C, then crushed by a rubber hammer before it

Table 1. Physical and Index Properties of the Based Soil

Property	Quantity	Test method
Specific gravity	2.64	ASTM D 854 (2014)
Liquid limit (%)	109.5	ASTM D4318 (2017)
Plastic limit (%)	43	ASTM D4318 (2017)
Plasticity index (%)	66.5	ASTM D4318 (2017)
USCS	CH	ASTM D2487 (2017)
Sand size fraction (%)	16.1	ASTM D422 (2007)
Particles passing No.200 sieve fraction (%)	83.9	ASTM D422 (2007)
Silt size fraction (%)	14.2	ASTM D422 (2007)
Clay size particles fraction (%)	69.7	ASTM D422 (2007)
Maximum dry density (g/cm^3)	1.336	Wilson (1970)
Optimum moisture content (%)	32.4	Wilson (1970)
Unconfined compressive strength (kPa)	252.18	ASTM D2166 (2016)
pH	8.8	ASTM D6276 (2019)
Soaked California bearing ratio (%)	1.73	ASTM D1883 (1999)
Swell potential (%)	19.85	ASTM D4546 (2014)

was sieved on sieve No. 10 (2 mm) where it was used for all geotechnical tests except for Atterberg tests where soil passing sieve No. 40 was used as per standard. The based soil was mixed thoroughly with the different percentages of additives as planned, then the optimum water content of the based soil (32.4%) by weight was added and mixed thoroughly after which, test specimens were remolded following the standard specifications of the required tests to be conducted.

Specimens for the first series of geotechnical tests were prepared from a predesigned mix samples of based soil and percentages of CKD (2%, 4%, 6%, 8%, 10%, and 12%) by dry weight of the based soil. Then unconfined compressive strength tests were conducted to specimens with the different CKD percentages and the optimum percentage to achieve the highest strength was determined.

The second series of samples for geotechnical tests were prepared by adding combinations of CKD and zeolite. The based soil was mixed with zeolite to the different percentages (1%, 3%, 5%, 10%, and 15%), and then the optimal percentage of CKD (10%) was added to each sample of the soil-zeolite mix.

The individual specimens were cured before they were tested for unconfined compressive strength in order to investigate the time-dependent effect of pozzolanic reactions. Curing was made by sealing the specimens in plastic wraps after remolding and then keeping them at room temperature for periods of 0, 7, 14 and 28 days before testing for unconfined compressive strength.

2.3 Methodology

A comprehensive series of laboratory tests were conducted to assess the performance of CKD and zeolite as soil stabilizing agents. Unconfined compression test, pH test, compaction test, California bearing ratio test, Atterberg limit tests and swell test

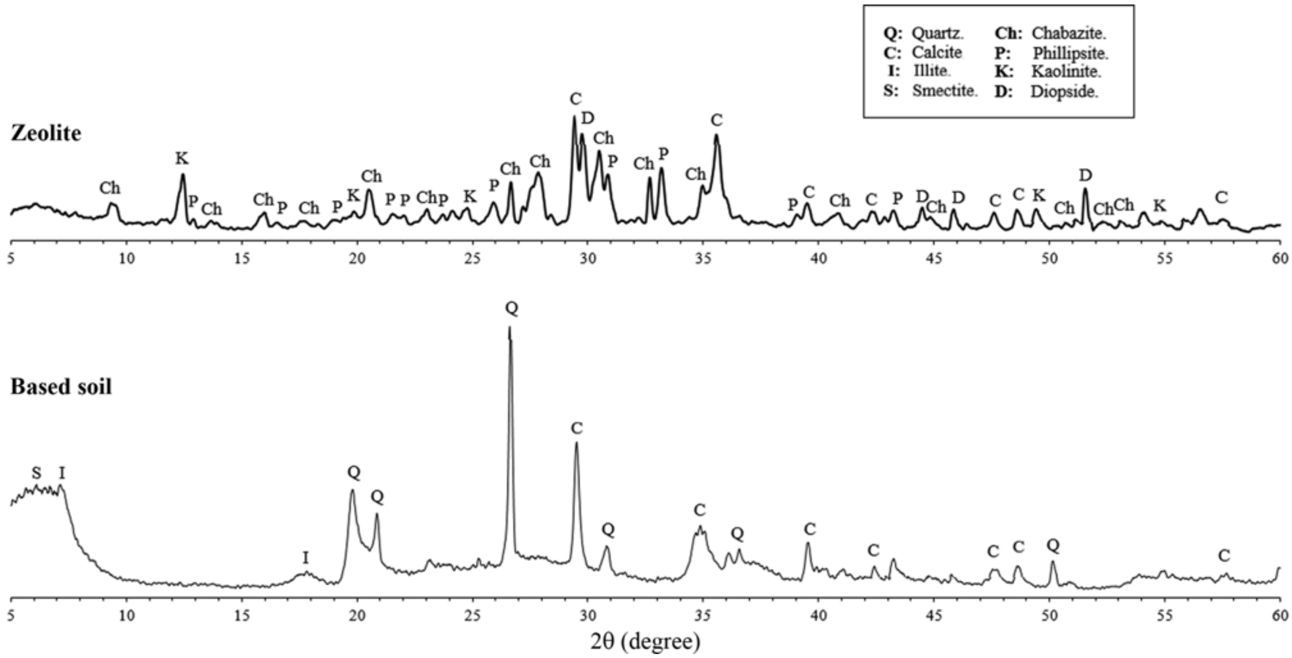

Fig. 2. XRD Patterns for the Tested Based Soil and Natural Zeolite

were performed in accordance with ASTM D2166 (2016), ASTM D6276 (2019), Wilson (1970), ASTM D1883 (1999), ASTM D4318 (2017) and ASTM D4546 (2014), respectively. Tests were performed on all soil samples before and after adding stabilizers. A total of 12 specimens were tested for each case. Three identical specimens were tested for each parameter and the average of the three results was considered representative.

The unconfined compression test is considered a good indicator to detect the effect of stabilizers on the short- and long-term strength of the soil. Samples were loaded vertically until failure, at a constant rate of strain, and the stress at failure is considered as the maximum strength of the tested specimen. Harvard miniature mold of 62.4 cm^3 volume was used to prepare the test specimens which were compacted in three layers following the standard.

pH was measured on the soil-additive mixtures by adding distilled water to a mass ratio of 5:1, shake the mixture and let it settle for one hour before measuring the pH using a pH-meter.

Compaction tests were conducted on soil mixtures with different percentages of additives to investigate the effect of additives/stabilizers on the optimum moisture content and maximum dry density of the based soil. Tests were carried out following (Wilson, 1970) method, by compacting the soil specimen in three layers within Harvard miniature mold, with 25 tamps for each layer. The compaction energy is provided by a spring that has two calibrations (89 N and 178 N). The dry densities were determined for the different moisture contents and the compaction curve is constructed for each specimen.

Soaked California bearing ratio (CBR) test was performed to provide an additional indication on the validity of the used additives in based soil stabilization. Samples are prepared by adding 5 compacted successive layers of the test soil within the 6-inch diameter standard CBR mold, after which the mold and the sample were immersed in water for 96 hours before testing. The samples were loaded until the CBR piston penetrated the soil to a depth of 2.5 mm.

Liquid and plastic limits were determined as per standards to investigate the influence of added stabilizers on such index geotechnical properties. Tests were carried out before and after adding the stabilizers to the based soil, following Casagrande method with a rate of 2 revolutions per second for the liquid limit, while for the plastic limit, the rolling rate was 80 strokes per minute.

Swell test is essential to expansive soils to evaluate the swell pressure potential, and the role of the stabilizers in reducing such a harmful property. The standard odometer mold of 7.5 cm diameter and 2 cm height, was used. The sample was then subjected to 1 psi stress while submerged in water to allow free swell of the sample. The percentage of swell is calculated by measuring the change in height of the sample divided by the original height (2 cm) and multiply by 100%.

3. Results and Discussion

3.1 Unconfined Compressive Strength Results and the Optimal CKD Content

Unconfined compression tests carried out on based soil alone and on mixture samples of based soil blended with different percentages of CKD. Test results showed that soil strength is increased with increasing percentage of added CKD up to a maximum strength value achieved at CKD percentage of 10%. Further addition of CKD resulted in decreasing the strength

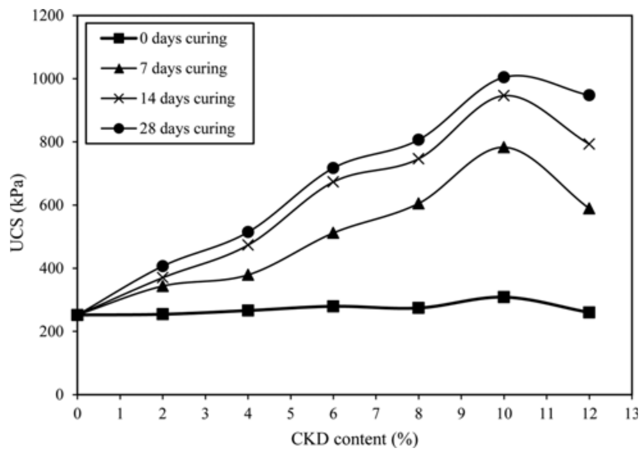

Fig. 3. Effect of CKD Addition on the Unconfined Compressive Strength (UCS)

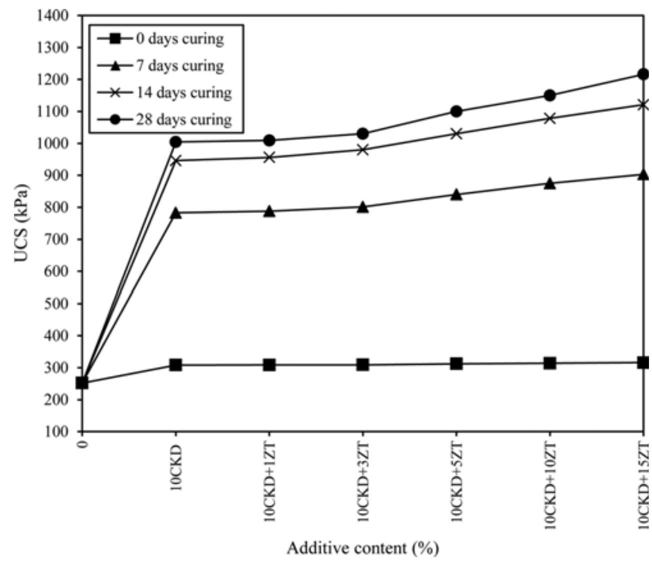

Fig. 4. Combined Effect of CKD and Natural Zeolite on the Unconfined Compressive Strength (UCS) of the Stabilized Soil

value and thus the added 10% of CKD is considered as an optimum percentage. Test results are presented in Fig. 3, that also shows the strength of the based soil to be 252.2 kPa that increased to 1,004.3 kPa as a result of adding 10% of CKD for 28 days cured samples. This clearly show that the optimal CKD resulted in an increase of strength by about 3 folds (298%). The effect of curing time found to substantial. Miller and Azad (2000) attributed this substantial increase to the nature of the pozzolanic reaction between calcium hydroxide from CKD and the aluminum-silicon oxides in the clay soil that takes long time, i.e., longer than the normal curing times of 7 to 28 days to form the binding hydrate gel material such as C-S-H and C-A-H gels.

Since the pozzolanic reactions require time to form the cementitious products, excessive amounts of added CKD to soil beyond a certain percentage (10% in our study) will increase the crowding of the unreactive CKD material between the clay particles at early stages, As the CKD material by itself have neither adequate friction nor cohesion between its particles (Bell, 1996), the accumulation of the unreactive CKD particles may cause segregation between soil particles which allows the rate of UCS to decelerate. However, it can be seen from the results that this decreasing rate is decreasing with increasing curing time as the CKD material is being consumed and more calcium hydroxide molecules react with the clay particles. A similar trend was obtained from research conducted by Sharma (2017).

Other series of tests were carried out on based soil with optimal 10% of CKD, together with different percentages of phillipsite-zeolite. Test results showed increasing unconfined compressive strength by increasing the percentage of zeolite. Results of these tests are presented in Fig. 4. Addition of 15% natural zeolite resulted in increasing the 28 days curing strength of the 10% CKD-based soil, from 1,004 kPa to 1,217 kPa that is equivalent of 21% increase. Further strength development equivalent of 347% was achieved by replacing 15% of the based soil with natural zeolite. This is with the mixture weight unit ratios of: 85:15:10; based soil: zeolite: CKD respectively. Table 2 presents these results.

Natural zeolite forms the source silicon and aluminum oxides that are necessary for the pozzolanic reactions, whereas calcium hydroxide is provided by the CKD. Similar results were obtained by a number of researchers: Turkoz and Vural (2013); Mousavi (2018) and Harichane et al. (2019), when they used additives of clinoptilolite-zeolite, silica fume and pozzolana respectively to

Table 2. Statistical Analysis of Adding Cement Kiln Dust and Natural Zeolite on Different Geotechnical Properties of Soil

		10% CKD – treated soil		(10%CKD+ 15%ZT) – treated soil	
Soil Tests	Base value	% Increase † or % decrease ‡ by adding CKD	% Absolute difference between base value and CKD - treated soil	% Increase † or % decrease ‡ by adding the (10%CKD +15%ZT)	% Absolute difference between CKD- treated and (10%CKD+15%ZT)- treated soil
28- days unconfined compressive strength, kPa	252.18	298 †	298	347 †	49
Swelling Potential, %	19.85	65 ‡	65	75 ‡	10
Plasticity index, %	66.5	56 ‡	56	52 ‡	4
CBR value, %	1.73	732 †	732	917 †	185

†: Percent increase ‡: Percent decrease

mixtures of soil and calcium based stabilizers. They recorded progressive increase of unconfined compressive strength with the increasing added amounts of zeolite. Addition of zeolite on the expense of the weak based soil could have contributed to the overall enhancement of the mixture, however this needs further investigation and analyses of the produce chemical phases as a result of the reactions between the different components and this is something that will take place in the next phase of the research.

3.2 Results of pH Value for the Different Soil Mixtures

Figure 5(a) presents the results of pH measurements due to progressive addition of CKD, that shows rapid jump by adding 2% and then gradual increase until 10% CKD. where a pH value of 12.4 was recorded. This is obvious due to the alkaline nature of CKD. However, the addition of zeolite to soil-CKD mixture resulted only in a slight reduction of pH value as compared to the effect of CKD only and that is possibly due to the neutral pH value of zeolite. The rise of pH values accompanied with the addition of CKD to the clay soil to a high value of 12.4 can be attributed to the complete dissolution of the available silicon and aluminum oxides in the clay structure and thus full activation of pozzolanic reactions (Eades and Grim, 1960). The same full activation of pozzolanic reactions continued to be constantly maintained with the addition of natural zeolite (Fig. 5(b)).

3.3 Compaction Characteristics

Compaction test results indicated a progressive increase of maximum dry density (MDD) and decrease of optimum moisture content (OMC), with the increase of CKD percentage added to the based soil as shown in Fig. 6(a). The rate of increasing MDD was lower between 0% to 4% of CKD, then higher between percentages of 4% to 8% CKD, and then slowed down from 8% to 12% of CKD that resulted to a MDD of 1.53 g/cm^3, only slightly higher than that due to 10% of CKD. Addition of 10% CKD to the based soil resulted in an optimal UCS value. The increase in density is due to the higher specific gravity of the added CKD (Anwar Hossain, 2011), while the increase of strength is related to the binding effect due to pozzolanic reactions as explained earlier, and the excess CKD have a negative impact on strength.

However, the results showed a progressive decrease of optimum moisture contents (OMC), with increasing CKD added percentages where a drop from 32.5% for the based soil, down to 20.9% for the based soil blended with 12% CKD, as shown in Fig. 6(a). The increase of MDD and decrease of OMC are attributed to the increase of fine grains in the soil mix due to the addition of the finer grained CKD to the based soil. Similar results were obtained by Kolay Parbir and Wadiah (2005) and Khalid and Rehman (2018), who they confirmed in their research that the increase of fine percentage in the soil, increases

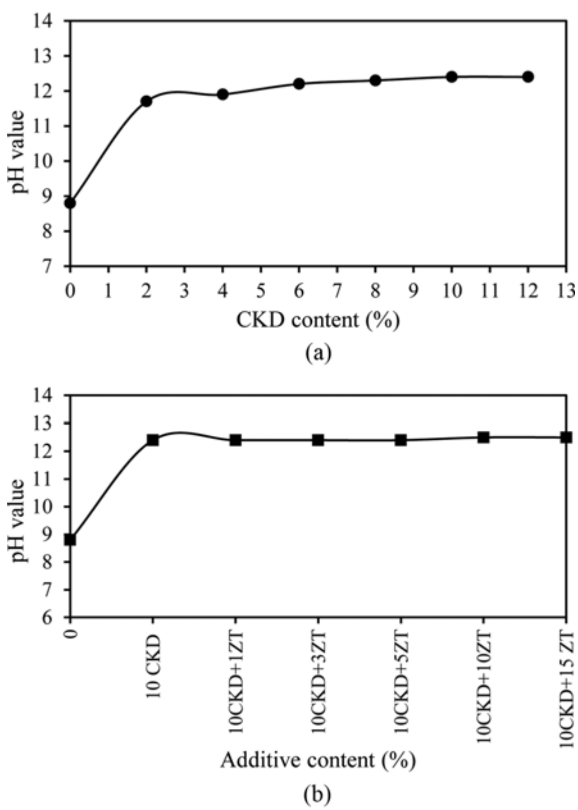

Fig. 5. Change of pH Value due to Addition of CKD and Zeolite: (a) CKD Effect, (b) Combined Effect of CKD and Zeolite

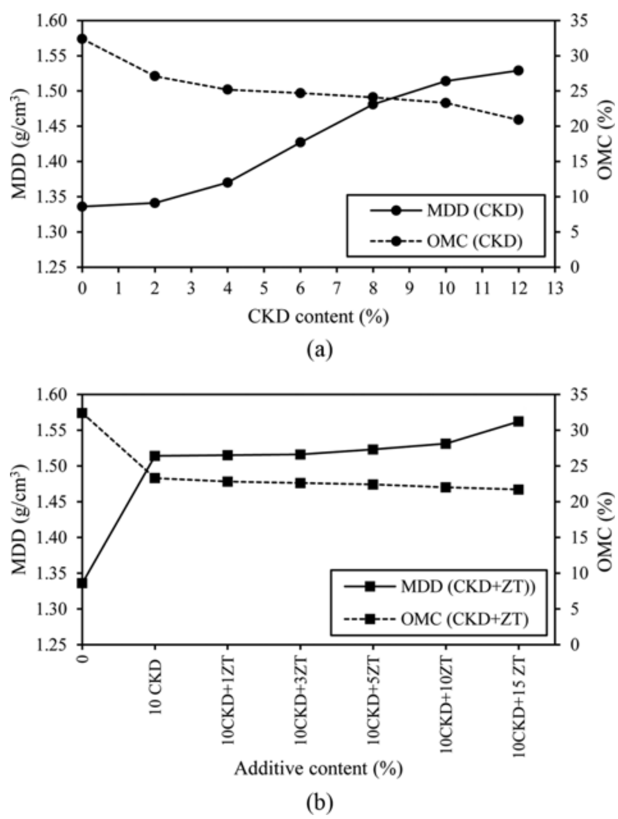

Fig. 6. Effect of Additive Content on Maximum Dry Density (MDD) and the Optimum Moisture Content (OMC): (a) CKD Only, (b) Combined CKD and Zeolite

the maximum dry density and decrease the OMC.

The effect of adding the combination of CKD and natural zeolite to the based soil, on the MDD and OMC is minor compared to the effect of 10% CKD only (Fig. 6(b)). Addition of 15% natural zeolite to the based soil blended with 10% CKD resulted to 1.56 g/cm^3 MDD and 21.7% OMC which are close to what obtained by the addition of 10% CKD only. This could be due to the coarser grains and the lower specific gravity of natural zeolite (2.15) compared to CKD (3.1).

3.4 California Bearing Ratio

Soaked California Bearing Ratio Tests were conducted on samples of the based soil before and after mixing it with different percentages of stabilizing agents: CKD and natural zeolite, under soaked condition to determine the influence of varying percentages of such additives on the CBR value. Fig. 7 presents these tests that show similar trends to the UCS test results, where CBR values progressively increased with the increasing percentages of added CKD until reached an optimum CBR value at 10% CKD. Further addition of CKD resulted in reducing the CBR values. Such a behavior is attributed to the unreactive excess of CKD as explained for UCS test results. Fig. 7(a) illustrates the increase of CBR value from 1.73% for the based soil to 14.4% for based soil with 10% added CKD and that is about 8 folds (732%) higher. Introducing about 15% natural zeolite to the CKD-based soil mix caused further enhancement of CBR from 14.4% for the CKD-soil mix to 17.6% as illustrated in Fig. 7(b) and tabulated in Table 2.

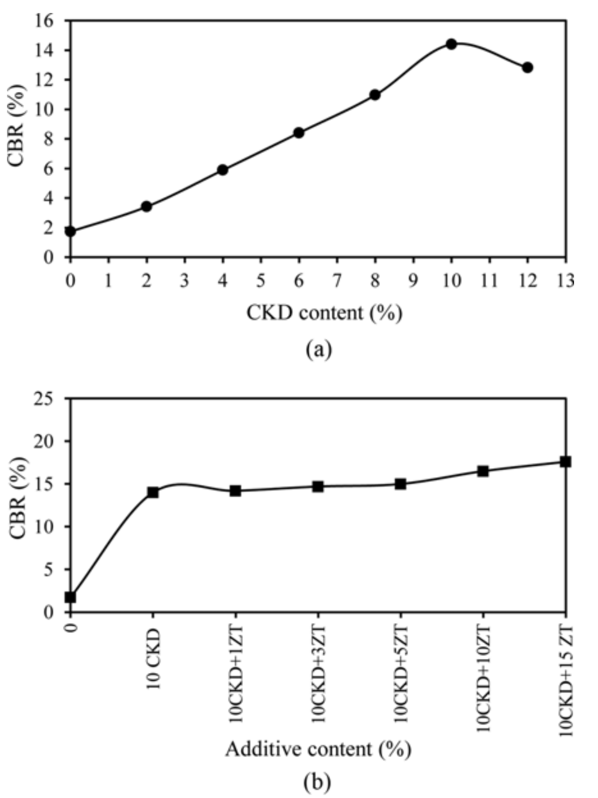

Fig. 7. Effect of Additive Content on the California Bearing Ratio (CBR): (a) CKD Only, (b) Combined CKD and Zeolite

This additional development is attributed to the pozzolanic reactivity effects of the natural zeolite.

3.5 Atterberg Limits

The results of tests on the Atterbeg limits of the based soil before and after adding the stabilizers of CKD alone and the combined CKD together with natural zeolite. Plasticity index of the based soil showed a decrease of 65% due to addition of 12% CKD (Fig. 8(a)). This is due to the cation exchange where calcium ions from CKD replaces the magnesium and other ions found on the surfaces of clay particles that leads to better flocculation-agglomeration between the clay particles (Sivapullaiah et al., 2000).

The behavior of liquid limit is sensitized to the type of the cations that exist on the clay surface in the treated soil. Calcium-saturated clays exhibit higher liquid limit values with increasing added amounts of quicklime. However, saturated clays with other cations show higher cation exchange reactions causing a decrease in the liquid limit (Diamond and Kinter, 1965). The increase of the plastic limit upon addition of CKD is mainly due to the weak and easily broken bonds during the flocculation of clay particles which increases the required amount of water necessary to reach the plastic limit, (Hilt and Davidson, 1960). The effect of adding natural zeolite to the CKD-based soil mix

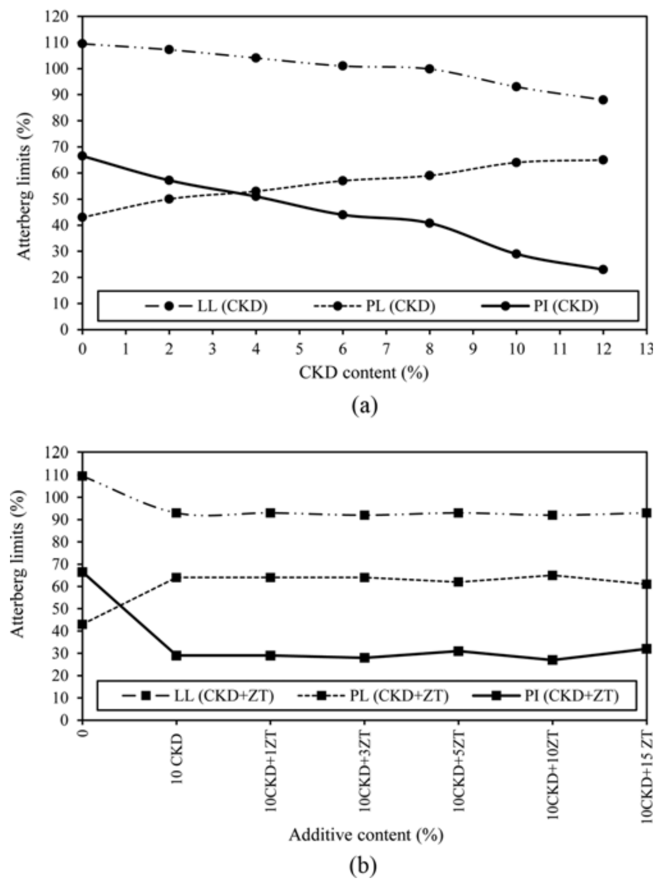

Fig. 8. Effect of Additive Content on the Atterberg Limits: (a) CKD Only, (b) Combined CKD and Zeolite

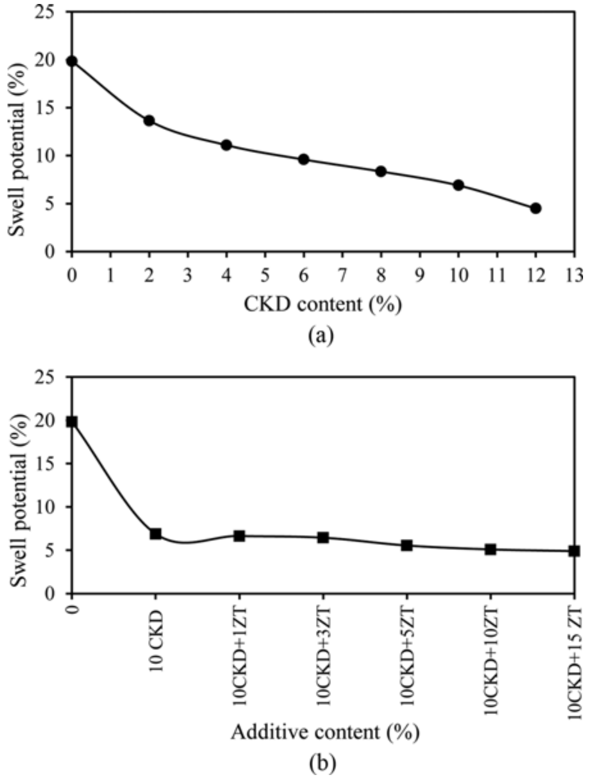

Fig. 9. Effect of Additive Content on Swell Potential: (a) CKD Only, (b) Combined CKD and Zeolite

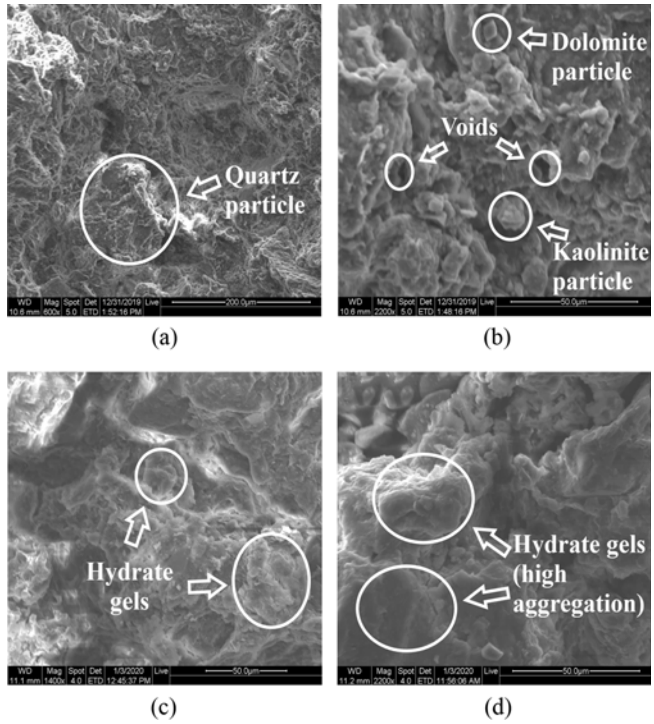

Fig. 10. SEM Micrographs of: (a) Based Soil at 200 µm, (b) Based Soil at 50 µm, (c) 10% CKD - Treated Soil at 50 µm, (d) (15% ZT + 10% CKD) - Treated Soil at 50 µm

on decreasing plasticity index is found to be minimal and negligible. This could indicate that zeolite has minimal to no effect on the cation exchange process in the system as shown in Fig. 8(b) and Table 2.

3.6 Swell Potential

Figure 9(a) presents the effect of CKD on the swelling potential. the addition of small percentages of CKD to the soil (2%) causes a drop in the swelling percentage by about 31%, after which, the rate of decreasing swell potential with the addition of CKD became less. It was noticed that most of the reduction in the swelling percentages occurred within the first two hours of adding even small percentages of CKD. A reduction of swell potential by 77% was recorded due to addition of 12% CKD. Such a reduction in swell potential is attributed to less double layer cation exchange with the existence of CKD (Bell, 1996). Negligible further reduction of the swell potential was recorded by adding natural zeolite, where addition of 15% zeolite to the CKD (10%) - based soil, only resulted in decreasing the swell potential from 6.9% to 4.9% (Fig. 9(b)) and (Table 2). Similar results were obtained by Turkoz and Vural (2013) due to addition of clinoptilolite-zeolite to cement-stabilized soil.

3.7 Microstructure of the Stabilized Soil

SEM micrographs of based soil given in Fig. 10 illustrate mineral composition of dolomite, kaolinite, quartz, and poorly crystalline minerals of illite-smectite clay minerals. The dispersive structure of the soil with large voids is evident.

Figure 10(c) presents the SEM micrograph for the 10% CKD - treated soil. The formation of hydrates gels such as C-S-H and C-A-H gels is evident. As the curing time increases, these gels build a network between soil particles and bond them together that eventually results in increasing the strength of the treated samples.

Figure 10(d) presents SEM micrograph of treated soil with a combination of 15% natural zeolite and 10% CKD that illustrates the formation of hydrated gels with more aggregation than the case with CKD addition only, explaining the higher values of UCS caused by the addition of zeolite which contributed to the additional formation of cementitious material.

4. Conclusions

Based on the conducted laboratory experiments on based expansive soil and based soil before and after adding stabilizing agents of CKD and natural zeolite, the following conclusions are made:

1. CKD proved to act as an effective stabilizing agent that fundamentally improved the strength of the tested expansive soil by 3 folds. Addition of 10% CKD found to be an optimum percentage to achieve the maximum unconfined compressive strength within 28 days of curing.
2. The increase of UCS due to the stabilizing agent of CKD is a function of curing time and curing process.
3. CKD reduces plasticity index and swelling potential of the based expansive soil to make it more liable for construction

purposes, whilst limited effect is noted on these two parameters by adding natural zeolite to the mix.

4. Phillipsite natural zeolite and its pozzolanic activity, proved to be an additional value stabilizer to expansive soil where it contributes to further enhancing and maximizing the strength and other geotechnical properties of such expansive soils.

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Not Applicable

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