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Permeability of Expansive Soils Modified/Stabilized with lime (Review Paper)

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ABSTRACT

The aim of this paper was to review the mechanism of the expansive soil-lime reactions: short term and long-term reactions in both lime modification and lime stabilization. The focus of the study was the effect of curing time for a certain centigrade 25C curing temperature in both lime modification / stabilization-expansive soils on the coefficient of permeability. Peer reviewed articles published between 2000- and 2019 were collected and relevant data were extracted. Results of this review study showed that the coefficient of permeability of expansive soils modified with lime increased during the first 7 days of curing time at curing temperature 25C and it remains constant or slightly decreased for longer curing time periods. However, for expansive soils stabilized with lime, it was found that the coefficient of permeability increased during the first 7-day curing time at curing temperature 25C, then decreased during the longer curing time periods (pozzolanic reaction). It is also noted that even though the coefficient of permeability decreased during pozzolanic reaction, it remains higher than that of the untreated soils.

1. Introduction

In most engineering geotechnical problems, water is a critical factor. Engineering behavior of soils specifically clayey soils will be affected by the water presence [1]. Expansive soil, predominantly composed of clay, is highly affected by water. It suffers from volume change when its water content change. Further, fabric of soils greatly varies depending on the mineralogy of the soil. Montmorillonite is considered the most critical mineral because its tendency to absorb water more than other types of minerals resulted in significant volume changes. Clay particles absorb water and tend to swell, or they lose water due to evaporation and tend to shrink [2]. That causes to severe distress to various infra structures and residential houses built on expansive soils resulted in significant economic losses. It was reported that the annual cost resulted from the damaged of the civil engineering structures constructed on expansive soils is estimated at $1000 million in the United State, £150 million in the United Kingdom, and many billions of dollars worldwide [3, 4].

This kind of soils is widespread around the world and more common in arid and semi-arid regions. In fact, it covers large areas in many countries such as Unites States, United Kingdom, Canada, Australia, China, India, Turkey, South Africa, Egypt, Sudan, Jordon, and Iraq [5]. It is inevitable to avoid dealing with this kind of soils when the planned projects located in such areas. Expansive soils are used either as a sub-grade material carrying the constructed structures or as a construction material in some projects (e.g., earth dams,

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levee, and highway embankment). Geotechnical researchers who interested in expansive soils tried to improve the expansive soil properties. The common method that they have used is the additives or what is called soil stabilization. Additive materials are mixed with soils to improve its engineering characteristics [6-8]. The types of additives commonly used are lime, cement, fly ash, sodium chloride, and others [5, 9-11]. Usually, the lime either quick lime (CaO) or hydrated lime (Ca (OH)2) is commonly used with the expansive soils especially if it is locally manufactured and relatively cheap. The basic fundamental mechanism of adding lime to the expansive soil had been proven by researchers [6, 12-15]. They found that when the lime mixed with soil in the presence of water, two kinds of reactions would be initiated. The short term or instantaneous reactions are responsible for improving the workability, reducing the plasticity and swelling of soils. In this case the process is called soil modification. The amount of lime required for modification is called initial consumption lime (ICL). However, the second reaction is the long-term reaction. This reaction is responsible for increasing soil strength and durability [16]. In this reaction more lime is required. The process is called lime stabilization [6-7, 15, 17-18]. Due to such reactions between lime and soil, the soil fabric and structure would change. In this case, water percolates into the soil instead of absorbed by the soil. That leads to another problem which is the permeability-based problem. The permeability is an important hydraulic parameter that should be studied when the expansive soil modified or stabilized by lime. Researchers have done studies on the permeability of lime-expansive soil. The effect of lime modification/stabilization on the permeability is not clear. Conflict in the researchers' findings has been reported. Some studies had found that the permeability increased with lime, others; however, found that the permeability decreased with lime [15, 19-21].

The objective of this study is to collect data from previous studies on expansive soils modified or stabilized with lime, monitor the progression of the lime-soil reactions to recognize the change in soil structure. It is also to study the relation between the permeability and curing time for both lime modification and lime stabilization. In other words, monitor the change in permeability with curing time due to the change in the soil structure and soil fabric.

2. Methodology

2.1. The way of collecting papers

Since this paper is a review, the major works is to collect papers from other's works. Collecting papers requires search by websites and libraries or any other sites where the scientific publications are. In this study, searching process lasted around two months. It happens mostly in March and April, 2020. The collected papers included only publications that had been published from 2000 to 2019. The collected papers included just the papers that had been conducted on expansive soils. Experimental laboratory works are only included in this review paper. At the beginning, lots of papers have been collected to identify a gap of knowledge that related to the chosen topic and then to develop a research question. Inverted triangle and literature map are the tools that used to develop a research question. Collected papers are mostly peer reviewed papers that collected from several journals.

2.2. Selecting papers and design work procedure

Not all papers that have been collected are relevant to the specified chosen topic. After many articles had been read and gaps of knowledge had been discovered, it came up with a research question(s). After that, only papers that directly related to the topic were used in this review study (see Table. 1).

The focus should be on the previous works that uses high technology such as scanning electron microscopy (SEM) to monitor the change in soil structure during the reaction's initiation and reaction's development.

Lime modification is the process of adding adequate lime to fully develop the short-term reactions. It is usually used when the goal is to use the expansive soil as a construction material [18]. In this case, the lime percent that enough to develop the short-term reactions called initial consumption lime (ICL). The ICL can be assessed by measuring the pH value because the pH creates an alkali environment that leads to generate the reactions between lime and soil. Based on the collected papers, it was noted that a typical lime percent of ICL was ranged between (2-4%). The relation between the coefficient of permeability and the curing time would be generated based on the data from previous works.

Lime stabilization, however, is the process of adding lime percent more than ICL to ensure that it is enough to develop the pozzolanic reaction. This reaction is responsible for increasing the soil strength. The reactions take long-time and continue as long as there is lime and clay minerals in the soil-lime mixture [22].

In this review the goal was to study the effect of lime modification/stabilization on the permeability of expansive soil. The effectiveness of lime modification/stabilization directly related to the plasticity of the soils. Since the expansive soil classified as (CH) according to unified classification system, the lime was appropriate stabilizer that react with it. Due to lime-expansive soil reaction, soil structure would be changed and that would affect the soil permeability [18]. To better understanding the effect of lime modification/stabilization of expansive soils on the permeability, it was important to study the mechanism of lime-expansive soil reactions. Based on the collected papers, it was noted that a typical percent of lime stabilization was ranged between (4-7%). The relation between the coefficient of permeability and the curing time would be generated from data collected from previous works used lime content sufficient to develop the pozzolanic reactions. Lime stabilization is usually implemented when the main goal is to increase the soil strength.

Table 1: Information about the selected data

Author's name	Locations	Clay minerals	Type of compaction	Lime (%)	Curing time (day)	Permeability test device
Di sante, et.al (2015)[15]	Italy	60%Montmorillonite 20%Illite 10%Chlorite 10%Kaolinite	Standard Proctor	5	0-90	Flexible wall
Tran, et.al. (2014)[19]	France	85%Smectite-Illite 10%Quartz 5%Feldspar	Static	5	0,1,2,3,4,5,7	Falling head
Nalbantoglu and Tuncer (2001)[20]	Turkey	17% Montmorillonite 21% Kaolinite 20%Quartz 23%Chlorite 19%Others	Standard proctor (dynamic)	0,3,5,7	0,7,30,100	Oedometer
Khattab, et.al (2008)[21]	Iraq	Not measured	Standard proctor	0,2,4,6	0,2,7,28,90	Falling head
Al-Mukhtar, et.al (2012)[26]	France	80%Smectite 4%kaolinite 60%Quartz 6%Goethite	Standard proctor	0,1,4,10	7,90	Flexible wall
Galvao et al (2004)[27]	Brazil	Not measured	Static	0,2,4,8	1	Triaxial cell
Khattab and Aldaood (2009)[28]	Iraq	Not measured	Static	0,2,4,6	0, 2,7,28,56,90	Falling head
Jha and Sivapullaiah	India	Not measured	Static	0, 2, 4, 6, 8	0, 7,14,28	Oedometer

(2015)[29]						
Ali and Mohammed (2018)[30]	United Kingdom	Mainly Montmorillonite	Static	5,7,9,11,13	0.25,0.5,1,1.5,2,2.5,3	Oedometer
Onitsuka, et.al. (2001)[31]	Japan	Not measured	Static	10	7	Falling head
Yildiz, and Sogancl (2012)[32]	Turkey	Not measured	Standard proctor	6	0,1,3,7,21,28	Falling head
Milburn and Parsons (2004)[33]	U.S.A (Kansas)	Not measured	Standard proctor	0,1,2,3,4,6	0,7,14,21,28	Flexible wall permeameter
Elsharief, et.al. (2013)[34]	Sudan	90%Montmorillonite 10%Kaolinite	Standard Proctor	0,3,7	7	Triaxial cell
Khattab and Aljboury (2012)[35]	Iraq	Not measured	Standard proctor	0,2,4,6,8	0,7,14,28	Falling head

In both lime modification and stabilization, the coefficient of permeability was the dependent variable, and the curing time was the independent variable. Both variables were governed by the reactions between expansive soil and lime. It should be important to note that this review study was limited to the data that have similar initial conditions: curing temperature was 25C, specimens were prepared at optimum moisture content and maximum dry density, lime was added to the soil as a percent by weight of the soil, and the added lime was a hydrated lime ($Ca(OH)_2$). The control specimens that the researchers compare their results with were the untreated expansive soil specimens. So, in this study the coefficient of permeability, (k) of lime modification and lime stabilization would be compared with the coefficient of permeability of untreated expansive soils.

On the other hand, the method of running the permeability test, the method of compaction, the geological formation, and clay mineralogy of the tested soils were presented in Table (1) to provide more information about the experimental conditions of the collected data from each paper. These factors probably do not affect the general behaviour of lime-soil reactions, but it may cause variation in the magnitudes of the coefficient of permeability. The effect of these parameters on the coefficient of permeability was ignored in this review study.

3. Interpretation and discussion of collected data

The collected data were categorized into two main branches: mechanism of lime-expansive soil reactions and effect of lime modification/stabilization process on the coefficient of permeability of expansive soils.

3.1. Mechanism of lime-expansive soil reactions

Generally, the process of mixing lime with soil that include clay in it (i.e., expansive soils) passes through three main reactions: cation exchange (CE), flocculation and agglomeration reactions. These two reactions happen in short time, so it is better to put them under one category which is short-term reactions. However, the other reaction called pozzolanic reaction takes longer time. That is why most sources put the latter under the long-term reaction.

3.1.1. Short-term reactions

As lime added to the soil, the pH will raise up to 12.4 then almost remain constant with increasing lime content. The lime content caused to raise pH value to 12.4 is the initial consumption lime (ICL). It creates alkali environment that helps to start cation exchange process. When lime mixed with expansive soil in the presence of water, the lime will be separated to calcium (Ca) and hydroxyl (OH) ions. The highest replacement power ion, calcium ion, will replace the sodium ion Na before other ions that have a lower replacement power than the Ca. The replacement process leads to reduce the diffuse double layer of the clay particles. Consequently, the clay particles will be attracted to each other and created flocculated structure due to flocculation and agglomeration. This process continues for the first 7 days curing time under 25C curing temperature [6, 18]. Adding (ICL) lime percent to the expansive soil helps to improve the workability, reduce the plasticity index, and reduce or eliminate the swelling potential of the expansive soils [23]. So, expansive soil becomes no longer expansive soil instead it transfers to friable soil [24]. Since the goal of this study was to dig deeper in soil structures and soil pores that helped to understand the change in the coefficient of permeability, studies used advanced technology such as Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and Mercury Intrusion Porosimetry (MIP) have been selected.

In 2010, [4] did their study on highly expansive soils. They added lime percentages to the soil to raise the pH to 12.5 to ensure that the short-term reactions are going to occur. They found that the ICL equal to 4%. This percent is sufficient to exchange the soil structure, but it is not sufficient to increase soil strength because more lime is needed to develop the pozzolanic reaction. Performing TEM, researchers observed that the flocculated structures of soil particles due to cation exchange would occur. They also observed that the clay particles become larger in size indicating the increase in the micro pores of the soil particles. In 2014, [13] performed a study on stabilization of expansive soil using lime. They added lime percentages to raise the pH up to 12.4. They found that the ICL was 4%. After this percent the pH remained constant. They used SEM to study the change in clay structure and soil textures. They found that the microstructure pores increased in their size implying that the flocculation and agglomeration have been occurred after cation exchange capacity. They also measured the surface area of the clay particles. They found that the surface areas decreased with curing time, meaning that the particles size increased, and the void ratio increased too. In 2014 another study had done by [12] using SEM to monitor the change in clay structures when they added lime more than ICL to the expansive soil. They added 5% lime and found that the soil structure that detected by SEM becomes highly pores. To observe the microstructure changes due expansive soil modified by lime, [24] performed a SEM analysis. Figure (1a) showed the micrograph of natural expansive soil and Figure (1b) showed lime- modified expansive soil cured for 7 days. It is observed that for a treated soil, it cannot recognize the original structure of clay. Large flat polygonal thick sheets formed from small to large size. The new structures have been formed due to short-term reactions between the clay minerals and lime. Moreover, it is found that the clay particles of lime stabilized soil broke down and became close to each other during the first week of curing and created a cluster particle which was called agglomeration.

In all previous studies, it was noted that the pH value remained constant during the short-term reaction which was 12.4 because the hydroxyl ions probably have not reacted yet with clay minerals [25].

3.1.2 Long term reaction

This reaction is also called pozzolanic reaction. To initiate and develop the reaction, more lime content than the ICL is needed. ICL is necessary to generate the short-term reactions and the extra lime is responsible for developing the pozzolanic reaction. This reaction is responsible for increasing the soil strength. The reaction continues as long as there is a lime and clay minerals with auxiliary factors such as curing time and temperature [18]. In 2010 and 2014, [6-7, 22] found that the lime would be consumed during the curing time and a new material has been created due to the pozzolanic reaction between the calcium ions from lime and the dissolved silicate and aluminate minerals in the alkali environment. The new materials were calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH).

In hydraulic conductivity point of view, the change in the soil texture, soil structure and pore sizes of the lime-expansive soil mixtures are important. In 2014, [24] used the SEM in their study conducted on expansive soil. The results of SEM analysis are illustrated in Figure 2. Figure (2a) showed micrograph of a 28 days curing time. The image displayed the severely broken structure of expansive clay with larger size indicating that particles agglomerate together during curing. For longer curing period (i.e., 90 days), figure (2b) showed that a fibrous structure was formed indicating that a pozzolanic reaction, the CSH and CAH were formed and caused to reduce the void porous because a cementing material between clay particles has been generated. Same results were found by [26].

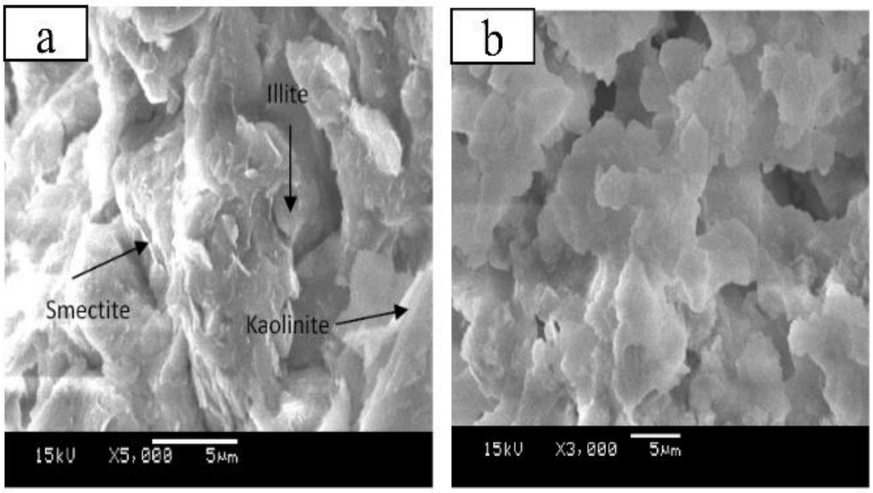

Figure 1. SEM micrograph: **a.** Untreated expansive soil **b.** Lime-expansive soil cured for 7 days [24]

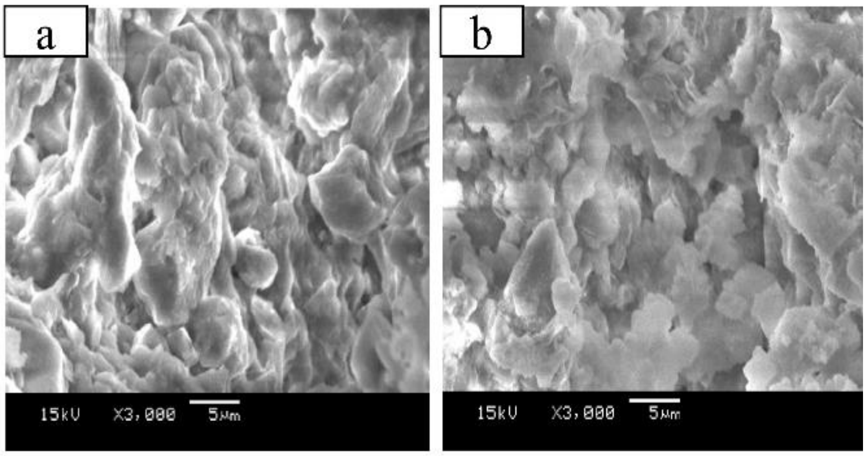

Figure 2. SEM micrograph: **a.** Lime-expansive soil cured for 28 days; **b.** Lime-expansive soil cured for 90 days [24]

In all previous studies researchers found that the lime consumption continued due to reactions. It continued as long as the pozzolanic reaction under development. In their study, [12, 13] measured hydroxyl ions in terms of pH after the pozzolanic reaction have been developed. They found that the hydroxyl ions decreased with increasing the curing time. The reason was that the hydroxyl ions and calcium ions reacted with the dissolved silica and alumina to create CSH and CAH.

3.2 Effect of curing time on the coefficient of permeability of expansive soils

In both lime modification/stabilization, the permeability will change during the curing time period. The change in the permeability of the two cases will be discussed based on collected data from previous works.

3.2.1 Effect of curing time on the coefficient of permeability under lime modification

Researchers studied the effect of curing time on the coefficient of permeability during the reactions period. They added ICL to the expansive soils and over different curing time, they evaluated the change in the coefficient of permeability (k). The selected curing temperature was only at 25C. They focused on the first week because the short-term reactions mainly occurred in the first few days [13]. Collected data were plotted on Figure (3). These data came from several studies. A study by [20] used ICL equals to 3%, the reported curing time were 0 ,30, and 100 days. They studied the effect of curing time on the coefficient of permeability of the expansive soil. They found that the coefficient of permeability increased with increasing the curing time as illustrated in Figure (3). They explained the behaviour of increasing the coefficient of permeability by the change in clay structure from sheets to granular-like particles and getting stronger with increasing the curing time. In 2004, a study by [27] was performed to investigating the permeability of lime modification of expansive soil. The ICL was 4 % with curing time 1 day. The results showed that the coefficient of permeability increased with the curing time. Figure (3) shows that the increase in the coefficient of permeability in the [27] data was much higher than the increase in that of [20] study. The reason probably referred to the clay minerals type. A slight increase in the coefficient of permeability was reported by [29] for a study of adding 2% lime on expansive soil and cured for 0, 7, 14 and 28 days. In 2008, [21] used 2 % ICL added to the expansive soil. Curing time were 0, 7, 28, 90 days. They found that the coefficient of permeability increased with curing time to reach the maximum value at 7 days then almost remained constant after 7 day curing time. They explained that the short-term reactions resulted in creating an open structure and large void space would be formed (flocculation and agglomeration). Another study has been done by [28], they found approximately similar results as shown in Figure (3). Same behaviours confirmed the previous results found by [19] when they used expansive soil treated with lime. They monitored the reactions between lime and expansive soil using the SEM and they measured the micro pores by MIP. Results plotted in Figure (3) showed that using ICL of 4% helped to increase the coefficient of permeability within the first 7 days curing time. This increase was due to short-term reactions: cation exchange and flocculation agglomeration that ended up at 7 days. After the 7 days curing time, it is to be expected that there was no change in the coefficient of permeability will be occurred. However, if more lime is added, the expectation is to decrease the coefficient of permeability due to develop the pozzolanic reaction. A study by [30] found that adding more lime to an expansive soil (i.e., 7%) and cured for only 3 days cause to a slight decrease in the coefficient of permeability. The explanation for that probably because the extra lime may work as a filler material that cause to decrease the soil permeability.

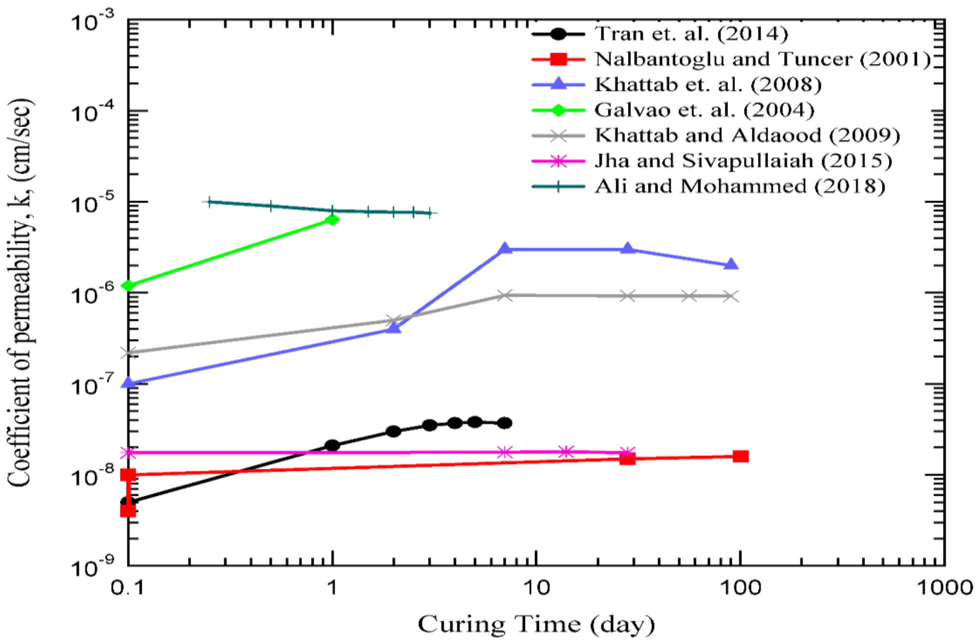

Figure 3. Effect curing time on the coefficient permeability of lime modified expansive soils

From the general observation of the data plotted on Figure (3), it was seen that there was agreement among researchers. They found that the coefficient of permeability increased up to 7 days curing time when ICL is used. The best justification for this behaviour was that adding lime to the soil, the pH value would rise to 12.4. The alkali environment helped to initiate the short-term reactions: the cation exchange between Ca from lime and Na from clay and led to decrease the diffuse double layer which is a function of the amount of clay and mineral type. The clay particles attracted to each other and created a flocculated structure that had larger void ratio resulted in decrease the coefficient of permeability. However, there was disagreement among some researchers about the coefficient of permeability after 7-day curing time. A study by [20] found that the coefficient of permeability increased after the 7-day curing time. They reported the reason for the increment in the coefficient of permeability due to the flocculated structure continued after this period. Others such as [21, 28], however, found that the coefficient of permeability remained constant after the 7 days curing time because the short time reactions stopped at 7 days due to fully develop the cation exchange and there was no extra lime to generate the pozzolanic reaction.

3.2.2 Effect of curing time on the coefficient of permeability under lime stabilization

In this scenario, the goal of adding lime to the expansive soil was to enhance the soil strength, so that the required lime content should be higher than that required for modification (the short-term reactions: cation exchange and flocculation/agglomeration). Lime stabilization percent is a function of percent and type of clay minerals [24]. The required lime content for stabilization is typically between 4-7% and rarely react up to more than 10%. Since the pozzolanic reaction develops with time (time-dependent), the expectation is that the coefficient of permeability will change with the curing time due to the change in soil structure. From previous studies, data were collected and re-plotted as shown in Figure (4).

Figure (4) showed the relationship between the curing time and the coefficient of permeability for the data collected from the previous studies. A study by [31] used 10% lime as a stabilizer and curing time of 7 days. They found that the coefficient of permeability decreased with increasing the curing time. Their explanation was that cementing bonds creating between particle caused to decrease the pore space then the permeability decreased. This results totally different from the expectation for the first week of curing time. The coefficient of permeability was anticipated to increase rather than decreased according to most of the other findings. The explanation for that probably because too much lime had used and some of it worked as filler material that caused to decrease the soil permeability.

In contrast, in 2012, a study by [32] used lime stabilized of 6% and different curing time 0, 1, 3, 7, 21, 28 days. The data plotted on Figure (4) showed that the permeability significantly increased with curing time up to 3 days and it continued increase with curing time slightly. No justification has been given for the change of the soil permeability. Similar behaviours found by [20]. They used 5% lime and curing time of (0,30, 100 days) as shown in Figure (4). Their explanation was that the increase in the coefficient of permeability back to the change in clay structure to larger particles in size and higher pore spaces. This structure became stronger with curing time.

However, a study by [33] used 6% lime stabilization. The coefficient of permeability measured after 7, 14, 21, and 28days curing time. They found that the coefficient of permeability increased up to 7 days curing time then decreased with curing time. Their explanation of increasing the permeability was due to the short-term reactions that helped to form flocculated structure. Consequently, the void ratio increased, and the permeability increased. However, the decrease in the permeability might be due to forming permanent interlocking bonds between soil particles due to the reactions between lime and clay minerals. Similar findings with different magnitudes of coefficient of permeability changes were reported by [28]. The study showed that by adding 4% lime, the coefficient of permeability increased for the first 7 days curing time and decreased afterword.

A study by [34] found that the permeability increased with increase curing time for 7% lime and 7 days curing time. The reason was that the lime reacted with the clay mineral creating different sizes of aggregate. This kind of structure had higher porosity than that of untreated soils, thus the permeability increased. Nothing mentioned about the behaviour of the coefficient of permeability after 7 days curing time as shown in Figure (4). A study by [35] used 4% lime content and curing time of 2, 7, 14, 28 days. They found that the coefficient of permeability increased up to 7 days curing time then decreased slightly beyond this period as shown in Figure (4). They noted that the increase in the coefficient of permeability for the first few days backed to the flocculation process. However, the decrease in the permeability was due to formation of pozzolanic reaction that caused to close some of water paths.

More recent, SEM and MIP have been performed to investigate the effect of curing time on the coefficient of permeability of lime stabilized expansive soil. A study by [15] used 5% lime and curing time between 0-90 days. The results were plotted on Figure (4) and showed that the soil permeability increased up to 7 days curing time then decreased. The justification was that a flocculated structure has been detected under SEM and this structure was responsible for increasing the permeability. After 7 days curing time when the pozzolanic reaction progress, the micro voids would be reduced in their size due to creating cementing material. These new materials have been detected under SEM. Similar behaviours found by [26]. They used 4% lime content. In their study, they monitored the change in the coefficient of permeability at the first week and after 90 days curing time. The monitor process conducted under SEM. They were also using MIP to measure the pore spaces during the curing time. Their explanation was that the increase in the coefficient of permeability refers to the increase in the particle size and pore spaces due to flocculated structure. The decrease, however, was due to the cementing materials that formed because of developing pozzolanic reaction. These cementing materials (e.g., CAH and CSH) helped to reduce the pore spaces and increased the tortuosity and consequently, the coefficient of permeability would be reduced.

The general observation from Figure (4) was that the majority of the curves going up to reach the maximum values of the coefficient of permeability at 7 days curing time then decreased slightly with the curing time. The general behaviour was similar to that in the lime modification because in both cases short-term reaction would be occurred. However, in case of lime stabilization, the coefficient of permeability decreased after 7 days curing time for the majority of the collected data. The best explanation was that the extra lime might help to initiate and progress the pozzolanic reaction resulted in creating cementing materials. The created cementing materials (CAH and CSH) would help to reduce the pores sizes, reduce the connecting pores, and increase the length of water paths and consequently, the coefficient of permeability would be reduced.

From Figure 4, it was also observed that even though the majority of the curves behave similarly, there were variation in the magnitudes of the coefficient of permeability due to the types and amount of clay minerals and the method of conducting the permeability test as shown in Table 1. Finally, it was observed that even though the coefficient of permeability decreased during long-term reactions, it did not reach the values of untreated soil.

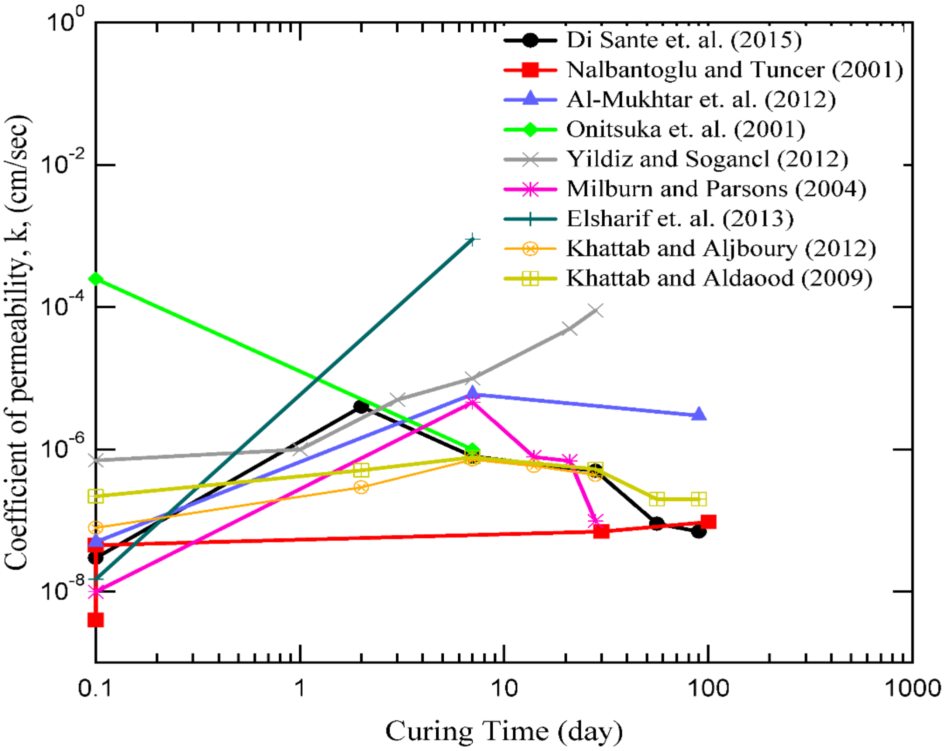

Figure 4. Effect curing time on the coefficient permeability of lime stabilized expansive soils

4. Conclusions

Based on the data selected from previous works, the following conclusions can be driven from this review paper:

1. For lime modification, the initial consumption lime (ICL) is added to the expansive soil sand caused to increase the coefficient of permeability (k) during the first 7-day curing time at 25C curing temperature. Beyond the 7 days curing time, the coefficient of permeability may remain constant or slightly decreased.
2. For lime stabilization, adding lime content to the expansive soils must be more than ICL. This percent of lime will attribute to increase the coefficient of permeability (k) for the first 7 days curing time. After that (longer curing time), the pozzolanic reaction will develop. The coefficients of permeability decreased and continue decrease as long as the pozzolanic reaction has been developing. But the final magnitude of the coefficient of permeability remains higher than that of the

untreated soils even at very long curing time.

3. High technologies such as Scanning electron microscopy (SEM) showed that the inter-particle pores are in charge of the change in the coefficient of permeability of lime modification/stabilization of expansive soils.
4. An average value of increasing permeability for all studies at curing time 7 days and 28 days can be determined and its ratio to initial average value can be quantified to assess the amount of increasing in soil permeability at different stage.

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