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Research Article

Soil Stabilization Using Lime: Advantages, Disadvantages and Proposing a Potential Alternative

[1, 2]Ibtehaj Taha Jawad, [1]Mohd Raihan Taha, [1, 2]Zaid Hameed Majeed and [1]Tanveer A. Khan
[1]Department of Civil and Structural Engineering, Universiti Kebangsaan Malaysia, Malaysia
[2]Department of Civil Engineering, College of Engineering, University of Babylon, Iraq

Abstract: This study is an overview of previous studies on lime (quick and hydrated) -treated soil. Lime is the oldest traditional stabilizer used for soil stabilization. The mechanism of soil-lime treatment involves cation exchange, which leads to the flocculation and agglomeration of soil particles. The high pH environment then causes a pozzolanic reaction between the free Ca^{+2} cations and the dissolved silica and alumina. Lime-treated soil effectively increases the strength, durability and workability of the soil. Such treatment also improves soil compressibility. A fluctuation behavior was observed on the influence of lime on soil permeability. However, the factors affecting the permeability of the soil-lime mixture should be extensively studied. Nonetheless, lime treatment has a number of inherent disadvantages, such as carbonation, sulfate attack and environment impact. Magnesium oxide/hydroxide are thus proposed as a suitable alternative stabilizer to overcome at least some of the disadvantages of using lime in soil stabilization.

Keywords: Lime, magnesium oxide, soil stabilization, treatment mechanism

INTRODUCTION

Soil stabilization is the process of the alteration of the geotechnical properties to satisfy the engineering requirements (Attoh-Okine, 1995). Numerous kinds of stabilizers were used as soil additives to improve its engineering properties. A number of stabilizers, such as lime, cement and fly ash, depend on their chemical reactions with the soil elements in the presence of water (Azadegan *et al*., 2012; Mallela *et al*., 2004; Ramadas *et al*., 2011). Other additives, such as geofiber and geogrid, depend on their physical effects to improve soil properties (Alawaji, 2001; Viswanadham *et al*., 2009). In addition, It can be combined both of chemical and physical stabilization, for example, by using lime and geofiber or geotextile together (Yang *et al*., 2012; Chong and Kassim, 2014).

Lime is the oldest traditional chemical stabilizer used for soil stabilization (Mallela *et al*., 2004). However, soil stabilization using lime involves advantages and disadvantages. This study provides details of advantages and disadvantages of using lime as soil stabilizer. In addition, to control the disadvantages inherent to lime treated soil, proposing an alternative material was discussed.

LITERATURE REVIEW

Chemical reactions and treatment mechanism: Water absorption is the first activity that occurs when lime (particularly quick lime) is added to soil. According to Eades and Grim (1960), lime-soil chemical reaction has two stages. The first stage, which is known as immediate or short-term treatment, occurs within a few hours or days after lime is added (Locat *et al*., 1990; Abdi and Wild, 1993). Three main chemical reactions, namely, cation exchange, flocculation-agglomeration and carbonation occur at this stage. The second stage requires several months or years to complete and is thus considered the long-term treatment. Pozzolanic reaction is the main reaction at this stage. The drying of wet soil and the increase in soil workability is attributed to the immediate treatment, whereas the increase in soil strength and durability is associated with the long-term treatment (Locat *et al*., 1990; Wild *et al*., 1996; Mallela *et al*., 2004; Kassim *et al*., 2005; Geiman, 2005).

The addition of lime to the soil water system produces (Ca^{+2}) and (OH^-). In cation exchange, bivalent calcium ions (Ca^{+2}) are replaced by monovalent cations. The Ca^{+2} ions link the soil minerals (having negative

Corresponding Author: Ibtehaj Taha Jawad, Department of Civil and Structural Engineering, Universiti Kebangsaan Malaysia, Malaysia, Tel.: 0060172378410

charge) together, thereby reducing the repulsion forces and the thickness of the diffused water layer. This layer encapsulates the soil particles, strengthening the bond between the soil particles. The remaining anions (OH^-) in the solution are responsible for the increased alkalinity (George *et al*., 1992; Mallela *et al*., 2004; Geiman, 2005). After the reduction in water layer thickness, the soil particles become closer to each other, causing the soil texture to change. This phenomenon is called flocculation-agglomeration (Locat *et al*., 1990; Geiman, 2005). The silica and alumina that exist in the soil minerals become soluble and free from the soil when pH exceeds 12.4. The reaction between the released soluble silica and alumina and the calcium ions from lime hydration creates cementitious materials such as Calcium Silicate Hydrates (C-S-H) and Calcium Aluminate Hydrates (C-A-H) (Eades and Grim, 1960; Eisazadeh *et al*., 2012a). These pozzolanic reactions can be clarified using the following chemical equations (Mallela *et al*., 2004; Yong and Ouhadi, 2007; Chen and Lin, 2009):

$$Ca\,(OH)_2 + SiO_2 \rightarrow CaO\text{-}SiO_2\text{-}H_2O \quad (1)$$

$$Ca\,(OH)_2 + Al_2O_3 \rightarrow CaO\text{-}Al_2O_3\text{-}H_2O \quad (2)$$

Pozzolanic reactions are time dependent and require long periods of time (years) because such reactions are functions of temperature, calcium quantity, pH value and the percentage of silica and alumina in the soil minerals (Eades and Grim, 1960; Kassim *et al*., 2005). In addition, the impurities present on the surface of clay minerals are inversely affected on lime stabilized soil (Eisazadeh *et al*., 2012b). Consequently, the use of lime as an additive stabilizer is more effective for montmorillonite than for kaolinite (Eisazadeh *et al*., 2010; Lees *et al*., 1982).

Effect of lime treatment on the geotechnical properties of soil: The drying of wet soil and the increase in soil workability are attributed to the immediate treatment, whereas the increase in the strength, durability and compressibility of the soil are associated with the long-term treatment (Locat *et al*., 1990; Wild *et al*., 1996; Mallela *et al*., 2004; Geiman, 2005). The following applications and benefits can be accomplished by lime-treated soil.

Water content-density relationship: When lime is used as soil treatment additive, soil particles became large-sized clusters, resulting in texture change (Terrei *et al*., 1984). This flocculation-agglomeration process results in floc formation. The enlarged particle size causes the void ratio to increase (Kinuthia *et al*., 1999). This increase in void ratio reflects the decrease in maximum dry density. The moisture content for the soil-lime mixture compaction increased. Thus, the required density can be easily achieved for a broad range of water content, thereby conserving time, effort and energy (Thompson, 1965; Tabatabi, 1997; Mallela *et al*., 2004).

Decreased plasticity index: Most plastic soils show significant reduction in plasticity index. This reduction results from the decrease in liquid limit and the increase in plastic limit (Little *et al*., 1995; Mallela *et al*., 2004). Moreover, a number of high plasticity soils can be modified into non-plastic soils through lime addition (Holtz, 1969). This modification can be achieved by reaching the maximum increase in plastic limit and the maximum decrease in the liquid limit. The lime fixation point is the percentage of lime required to achieve these values (Bergado *et al*., 1996). Nevertheless, the lime fixation point alone cannot be used to obtain the adequate strength (Hilt and Davidson, 1960). The reduction in the plasticity is attributed to the change in soil nature (granular nature after flocculation and agglomeration) and the modified soil is as crumbly as silt soil, which is characterized by low surface area and low liquid limit because of the plastic nature of the lime (Osinubi, 1995).

Jan and Walker (1963) and Wang *et al*. (1963) stated that the reduction in soil plasticity is maintained in the second stage (because of cementitious formation). Bell (1996) investigated the effects of lime addition on the engineering properties of clay minerals. Three clay mineral deposits, namely, montmorillonite, kaolinite and quartz, were considered in this study. He found that after lime treatment, the liquid limit of montmorillonite decreased, whereas those of kaolinite and quartz increased. Parsons *et al*. (2001) used five types of soils to evaluate the mixing procedure of soil modification using lime. In their study, the soil was mixed with 2.5 and 5.0% lime and the results showed that the liquid limit decreased with increasing lime content, together with the decrease in plastic limit and plasticity index.

The decrease in liquid limit with increasing lime content has been reported by Jan and Walker (1963) and Wang *et al*. (1963). Meanwhile, Zolkov (1962) reported that lime content increased the liquid limit. Croft (1964) explained that the increase in the liquid limit of lime-treated soil is related to the modification of the affinity of the clay surface to water; such modification is caused by hydroxyl ions. In the same context, Lund and Ramsey (1958) and Taylor and Arman (1960) reported that the increase or decrease in the liquid limit of lime-treated soil depends on the soil type. Nonetheless, the final resultant in all cases is a reduction in plasticity index. Consequently, the soil is converted into a more workable material for excavation, loading, discharging and leveling. In addition, the sensitivity of soil strength to moisture is reduced.

Increase in soil strength: Several researchers have used various methodologies to evaluate the evolution of uncured and cured soil strength (determined in the laboratory) with respect to lime content. The predominant methods were Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR). A number of researchers also used triaxial test and indirect or flexural tensile strength to evaluate the shear strength (Little, 2000). Thompson (1965) and Beubauer Jr. and Thompson (1972) stated that plasticity reduction and compaction feature improvement result in instantaneous strength gains (uncured) and that UCS strength increased up to 60% because of pozzolanic reaction after curing for 28 days. The researchers demonstrated that using lime as additive to treat fine-grained soils yields a significant increase in soil cohesion and a slight improvement of the internal friction angle.

Eades and Grim (1966) conducted UCS on six soils with different mineralogies. They established that the percentage of added lime and the soil mineralogy are the most important factors that affect the maximum strength gain. Mallela *et al*. (2004) stated that the properties of treated soil affect the strength gain over time. These properties are soil pH, Organic carbon content, natural drainage, excessive quantities of exchangeable sodium, clay mineralogy, degree of weathering, presence of carbonates, extractable iron, silica-sesquioxide ratio and silica-alumina ratio. The acidic soil stabilization using lime displayed less UCS evolution compared with that of alkaline soil (Kassim and Chern, 2004). Doty and Alexander (1968) found identical strengths for the soil sample cured for seven days at 38°C and that cured for 28 days at 23°C. The curing environment, curing period, soil mineralogy and amount of added lime significantly affect the strength gain.

Increase in fatigue strength: The number of load cycles that a material can tolerate at a constant stress level reflects the fatigue strength of that material (Mallela *et al*., 2004). Swanson and Thompson (1967) studied the curve between the applied stress-to-static strength ratio and the number of cyclic loads to describe fatigue strength. The number of cyclic loading increases adversely to the ratio of applied stress to static strength. They downplayed the importance of fatigue in lime-treated soil because strength gained over time balanced the fatigue effect. In addition, Mallela *et al*. (2004) reported that the strength developed over time reduces the stress-to-strength ratio, thereby increasing fatigue strength.

Increased durability: Durability is the capability of lime-treated soil to resist the adverse effects of the wet-dry and freeze-thaw cycles resulting from the changes in environmental conditions during a year. This is to assure the sustainability of strength gain achieved by soil treatment (Al-Amoudi *et al*., 2010). In the laboratory, durability can be evaluated in numerous ways, such as soaking combined with strength test and cyclic freeze-thaw test (Mallela *et al*., 2004). Thompson (1970) performed a compressive strength test on immersed and non-immersed soil samples treated with lime and found that the ratio between immersed and non-immersed soil strengths ranged from 0.7 to 0.85, which was significantly high. Other studies have analyzed the effects of freeze-thaw cycles on lime-treated soil and found that durability is a function of the immediate strength, that is, a higher immediate strength corresponds to a greater number of freeze-thaw cycles bound to failure. Therefore, the researchers recommended the use of a low strength before the first freeze-thaw cycle to accommodate strength loss (Dempsey and Thompson, 1968; Tabatabi, 1997). Thompson and Dempsey (1969) demonstrated the ability of the lime-soil mixture to cure provided that the pozzolanic reaction persists. The change in soil specimens and strength along several wet/dry cycles can be illustrated in.

Decreased swell potential and volume change: Expansive soils are considered problematic because of their swell potential and volume change, which apply uplift pressure and cause substantial damage to the structures (particularly for the light-weight structure). Mallela *et al*. (2004) defined the percent of swell as the volume change that the soil has endured when the moisture content approaches saturation level. Little *et al*. (1995) stated that a significant reduction in swell potential and swell pressure can be achieved in lime treated expansive soil. This reduction in swell potential is associated with the decrease in plasticity index caused by lime treatment. Furthermore, the reduction in swell potential is attributed to the reduction in the thickness of the diffused double layer (Rogers and Glendinning, 1996). Such characteristic, along with the immediate water absorption and the immediate reduction in plasticity index, indicates that the yields from lime-treated soil have a significant role in reducing the swell potential instantaneously. In addition, curing and pozzolanic reaction provide additional reduction in the swelling during the long-term treatment (Dempsey and Thompson, 1968; Thompson, 1969; Little *et al*., 1995). The swell potential decreased to 0.1% in the lime-treated soil and to 8% in the original soil (Tabatabi, 1997).

Effect on permeability: The literature does not provide information on the precise effect of lime treatment on soil permeability. A number of studies found that the hydraulic conductivity increases when the soil is mixed with lime. However other studies reported that soil permeability significantly decreases when lime content is increased.

Broms and Boman (1977) created in situ cylindrical columns by mixing quick lime with clay in Finland and Sweden. They tested these columns as vertical drains and demonstrated that unslaked lime increases the hydraulic conductivity of clay soil by 100 to 1000 times that of the surrounding untreated soil. Therefore, these cylindrical columns can be used as vertical drains.

El-Rawi and Awad (1981) investigated the behavior of two soil types, namely sandy silty clay and poorly graded river sand, when stabilized by lime. They divided each soil type into two groups, namely, optimum dry and optimum wet. The researchers found that the permeability of clayey soil increased as the flocs were formed.

McCallister and Petry (1992) designed a multi leach operation cell and tested the permeability of 70 expansive clay samples treated with different lime contents, compacted with varying water contents and subjected to continuous accelerated leaching. The results indicated that the permeability of the soil samples substantially increased due to lime treatment.

Rajasekaran and Narasimha Rao (2002) studied the effect of lime column-treated marine clay on the hydraulic conductivity and a number of other soil engineering properties. The researchers found that the permeability significantly increased up to 15 to 18 times that of virgin soil.

Nalbantoglu and Tuncer (2001) performed a series of permeability test on an expansive soil in Cyprus with lime percentage ranging from 0 to 7%. They found that higher permeability was obtained from lime soil mixture because of soil aggregation and flocculation.

Khattab *et al*. (2008) conducted permeability test on clayey soil by using variable head method. A group of soil samples was mixed with 2 to 6% lime pecentage, whereas the other group of soil samples was mixed with 2 to 8% industrial (by-product) lime content. They applied 25°C as curing temperature and 2, 7, 28 and 90 days, respectively as curing periods. For all cases, the results showed that the hydraulic conductivity increased to reach the maximum value with lime content of 2 and 4% for lime and by-product lime, respectively. After which the hydraulic conductivity decreased. However, for all cases, the hydraulic conductivity of the treated soil was greater than of that of the untreated soil.

Singh *et al*. (2008) investigated the effect of mixing lime to the soil collected from the Nawanshahar area, in India, where the roads suffer from dramatic settlement. Three samples were respectively collected from the subgrade soil, the roadside and the road, in which differential settlements and undulations have been observed. The dry soil was mixed with lime equal to 2 and 4% of the weight of the soil. The samples were prepared for consolidation test by compacting the soil-lime mixture at optimum water content and maximum dry density. The results indicated the increase in soil granularity resulting from lime treatment caused the increase in permeability coefficient. This theory was confirmed by Brandl (1981) and Buensuceso (1990), who attributed the increase in permeability coefficient increase to the floc formation, which produced small pores (these pores were absent before lime was added), resulting in the increase in hydraulic conductivity. Nonetheless, a number of authors (Onitsuka *et al*., 2001; Milburn and Parsons, 2004; Alhassan, 2008) have stated that the permeability was decreased by lime addition.

Onitsuka *et al*. (2001) conducted a falling head permeability test on two remolded clays from Ariake City. The samples were mixed with three lime contents, namely, 5, 10 and 20%, respectively by weight of dry soil. All the samples were compacted using hand vibration with moisture content of 185%. They concluded that although permeability is a function of pore space, the hydraulic conductivity decreased because of the contraction of the pore space when the cement products were formed. Tedesco (2006) stated that although the grain size distribution was modified toward the sand fraction, the hydraulic conductivity decreased when soil was treated with lime.

Milburn and Parsons (2004) combined lime with other chemical additives in eight soil samples classified as CH, CL, ML, SM and SP. Leaching test was applied to the soil samples under constant head using distilled water. The results showed that the lime-treated samples had reduced hydraulic conductivity; this reduction was attributed to the formation of bonds between the soil particles.

Alhassan (2008) investigated the effect of lime treatment on Lateritic soil treated with rice husk ash. The tested soil was classified as A-7-6 and tested for hydraulic conductivity by using falling head test and UCS. The results indicated that the permeability decreases with increasing lime content. All of these researchers have adopted the same explanation proposed by Onitsuka *et al*. (2001).

Nonetheless, another group of researchers (Locat *et al*., 1996; Kassim and Chow, 2000; De Brito Galvão *et al*., 2004) believe that hydraulic conductivity increases with increasing lime content until a specified percentage or a certain age is reached; then, the hydraulic conductivity declines.

Locat *et al*. (1996) conducted two types of tests to evaluate the mechanical and hydraulic conductivities of dredged sediments using Louisville clay. The first was the odometer standard test and the second was large Sedimentation-Consolidation cells (SEDCON cells), which was designed to imitate the sediment formation in a basin. Lime content ranging from 0 to 10% was mixed with the soil samples with moisture content ranging from 122 to 650%. The results indicated that the permeability increased for the specimens with lime content of up to 2%. A substantial reduction in permeability that is less than that for the origin soil was observed in the specimens with lime content of at least 5%.

Kassim and Chow (2000) choose three different soil types, tapah kaolin, Sungai Buloh clay and UTM clay to study the effects of adding 6% hydrated lime on the compressibility and permeability of these soils. The design mixture adopted was as follows: Initial Consumption Lime (ICL) plus 3% to ensure that pozzolanic reactions occur. Therefore, the average value of the mixture for the three soils was 6%. After soil compaction on optimum moisture content and one hour of settlement period, odometer test was conducted. The results indicated that the coefficient of permeability was higher in stabilized soil than that in non-stabilized soil at the early stage. As the mixture aged, the permeability decreased because of the formation of cementitious gel.

De Brito Galvão *et al*. (2004) investigated the effect of adding 2 to 8% of high quality hydrated lime on the permeability and compressibility of two different tropical soils obtained from Belo Horizonte City (Brazil). The tested samples were compacted to the maximum dry density with optimum moisture content according to proctor tests. Then, triaxial cell with two back pressure systems was used to conduct the permeability test on the treated and untreated soils. The results showed that soil permeability increased until lime content was equal to 2% and decreased when additional lime was added.

These researchers defined the inflection point of lime content as Lime Modification Optimum (LMO). They attributed this behavior to the flocculation stage, in which the hydraulic conductivity increases. Further addition of lime results in the formation of cementitious minerals, which modifies the micropore network and reduces the hydraulic conductivity.

Alhassan (2008) believed that the differences in soil behavior with respect to permeability is attributed to soil mineralogy. Therefore, further comprehensive studies must be conducted to elucidate the issue.

Effect on compressibility: Similar to permeability studies, limited studies have dealt with the effect of lime on soil compressibility (Rajasekaran and Rao, 1997; Tremblay *et al*., 2001; Rao and Shivananda, 2005). Locat *et al*. (1996) conducted a series of tests on inorganic clayey sediment to evaluate the influence of lime addition on the mechanical and hydraulic soil properties as described previously. The results of the odometer test demonstrated that as the pozzolanic reactions began, the Pre-consolidation pressure (Pc) increases linearly with increasing lime content. Kassim and Chow (2000) demonstrated that as the curing period progressed, the lime-treated soil modified the compression index and reduced the coefficient of compressibility settlement.

Rajasekaran and Narasimha Rao (2002) investigated whether the compressibility characteristics of marine clay can be improved using lime as chemical additive by means of two methods, namely, lime column work and injection technique. After 30 to 45 days of curing period, the researchers conducted a standard consolidation test on the samples obtained from different radial distances from the lime column and the lime injection points. The test results indicated substantial improvement in soil compressibility from 1/2 to 1/3 of untreated soil. The Pre-consolidation (Pc) value increased from 36 kN/m^2 (untreated) to 82 kN/m^2, whereas the Compression index (Cc) value decreased from 0.85 to 0.36.

Rao and Shivananda (2005) explored the compressive behavior of saturated lime-treated soil. They collected black cotton soil samples from Karnataka State, India. After soil pulverization, the samples were hand-mixed with 4, 7 and 10%, respectively lime and cured for 10 days. After compaction, 1D consolidation test was performed. The researchers found that the compression curve of the tested samples had two stages. In the first stage, no axial strain accompanied the specimen loading pursued by elastic axial deformation with little yield. In the second stage, a plastic deformation appeared with significant yield. In addition, the soil specimens treated with lime had the same value of strain per unit pressure increase before and after yield.

De Brito Galvão *et al*. (2004) used one dimensional consolidation test to evaluate the consolidation characteristics of soil samples treated with 4 and 8% lime and cured for one day. The strain-load curves obtained from the tests results showed that the resistance against the compression substantially increased. The strain corresponding to the maximum load decreased by more than 3% for samples treated with 4% lime; however, no improvement was observed for the specimens treated with lime greater than 4%. These researchers have stated that the bond formation was the main cause of the resistance to the compression.

Tedesco (2006) studied soil compressibility before and after lime treatment with respect to the effects of initial moisture content of compacted soil sample, the curing time and the test procedure. He used a unique percentage of lime equal to 3% for all tested soil specimens. Using standard and modified Proctor tests, the samples were prepared with moisture content corresponding to optimum water content, optimum dry and optimum wet. In addition to the odometer, he developed a delayed procedure, which involved tests with constant curing time of 7 and 28 days. He pointed out that the lime-treated soil samples exhibited lower compressibility, particularly for samples compacted on the dry side and that dramatic over consolidation was obtained by dynamic compaction. Moreover, he found that the samples tested using delayed procedure showed more compression than those tested using standard procedure. Therefore, he concluded that lime addition had no effect on curing time. The remarkable decrease in compressibility related to the lime addition was associated with short-term reaction. Further, the pozzolanic reaction had limited influence.

Singh *et al*. (2008) investigated the effect of lime on the consolidation of soil samples collected from Nawanshahar roads in India as explained previously. They indicated that the Cc value significantly decreased because of the lime treatment and the increase in coefficient of Consolidation (Cv), which is considered a sufficient improvement in consolidation characteristics. The lime-treated soil exhibited significant effects on the soil compressibility. The compression Index significantly decreased with the increase in pre-consolidation stress and Cv. Most researchers attributed this improvement to the bond formation between soil particles.

Disadvantages inherent to lime treated soil: The reviewed literature indicated the advantages of soil-lime mixture. However, a number of disadvantages that are inherent to lime-treated soil can be identified as follows.

Deleterious chemical reactions: Two undesirable (deleterious) chemical reactions probably occur in the lime-treated soil. The first is lime carbonation and the second is the reaction with the sulfate salt existing in the soil. Carbonation is the reaction that occurs between free lime and atmospheric carbon dioxide, as shown in the equation below (Umesha *et al*., 2009):

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad (3)$$

According to Cizer *et al*. (2006), the factors that controlling carbonation reaction are carbon dioxide diffusion through pores, calcium hydroxide and carbon dioxide dissolution in water, as well as the reaction of Ca^{+2} with CO_3^{-2} ions to form the $CaCO_3$ crystals. $CaCO_3$ is considered cementing material (Arman and Munfakh, 1970), however, it is recommended to control its formation. This is due to three main reasons. First, it has weak bonding. Second, calcium carbonate is soluble salt and may pulverize when exposed to air for a long time period (Umesha *et al*., 2009; Tedesco, 2006). In addition, carbonation process consumes calcium ions which affected negatively on pozzolanic reaction.

When soil treated with lime or any calcium-based additives containing soluble sulfate salt, soil distress, heaving and disintegration may occur, resulting in strength loss (Mitchell, 1986; Hunter, 1988; Nair and Little, 2011). The source of sulfate is either from soil minerals, water used for mixing or from ground water (Kinuthia *et al*., 1999; Obika and Freer-Hewish, 1990). Sridharan *et al*. (1995) reported that soil treated with lime in the presence of sulfate increased the compressibility of soil. Sivapullaiah *et al*. (2000) studied the lime-treated montmorillonite containing different percentages of sulfate and had long curing period. They observed a reduction in effective cohesion intercept, which means reducing shear strength. This serious threat to soil treatment is due to the chemical interaction between calcium and aluminum existing within the soil mineralogy in the presence of soluble sulfate and water, which produces ettringite and/or thaumasite (Braga Reis, 1981; Hunter, 1988). Littleton (1995) stated that the detrimental effects of sulfate on lime-soil mixture depends on the type, amount, sulfate solubility and clay minerals. They stated some hypotheses to elucidate the swelling mechanism:

- Volume change (increase) because of ettringite formation, which possesses higher volume than the elementary reactive materials.
- Water adsorption by ettringite's high surface area and high surface potential.
- Flow of water caused by osmosis (Wild *et al*., 1993; Nair and Little, 2011).

The most successful method to minimize the heaving accompanying ettringite formation is to force deleterious reaction to occur prior to compaction through the following steps:

- Increase the optimum water content required to achieve the maximum dry density by 3 to 5%.
- Increase the mellowing time periods from as low as 24 h to as much as 7 days on the basis of the percentage of soluble sulfate in the soil.

These conditions provide the opportunity to dissolve the maximum possible percentage of sulfates in the soil (Mallela *et al*., 2004; Little and Nair, 2009). The technical memorandum of National Lime Association (NLA) (2000) provided some recommendations for lime-stabilized soil containing sulfates. These recommendations were divided according to the sulfate level in the soil. NLA proposed progressive (double) application of lime to minimize the heave effect. The method involves adding lime into two increments, mixing soil with the first increment and leaving the mixture to settle for three to seven days to provide adequate time for ettringite formation before compaction. Then, the soil is mixed with the second lime increment. This method is cost effective.

EFFECT OF ORGANIC MATERIALS

Morrill *et al*. (1982) classified the organic materials in the soil into two groups, namely, humic and non-humic. Humic acid is one of the strongest organic materials causes inhibition the solubility of silica and alumina minerals where the dissolution process needs pH more than 12 (Hampton and Edil, 1998). Chan and Heenan (1999) indicated that the presence of high microbial biomass in organic soil induced the increasing rates of decomposition in organic soils treated with lime, resulting in a decrease in pH value. Furthermore, clay minerals itself are usually low in the organic soil. Consequently, the organic materials inhibit the pozzolanic reaction required to gain soil strength (Hampton and Edil, 1998; Ling *et al*., 2013a). The organic soil characterized by high water retention capacity, which may lead to minimizing the available water for the hydration reaction. Moreover, organic materials encased the additive particles to hinder hydration process (Kamon *et al*., 1989).

According to Bonomaluwa and Palutnicowa (1987), the reaction between black humic acid and calcium ions could be liberated from lime to produce insoluble calcium humic acid. Hampton and Edil (1998) stated that the organic material decomposition blocked the polymerization of silicate. Obviously, soil stabilizer cementitious reaction was hampered by organic materials. However, it is important to know that not all organic materials inhibit cementitious formation. For instance, chloronaphthalene has no effects, whereas ethylene glycol, benzoic acid and cellulose retarded hydration reaction but did not affect soil strength gain (Tremblay *et al*., 2002). Consequently, not only the quantity but also the nature of the organic materials should be considered in soil treatment.

To solve these difficulties of lime-treated organic soil, bentonite-lime mixture was used to treat organic soil. This treatment has two benefits. First, bentonite has good water retention, which can be advantageous for lime hydration. Second, bentonite provides the source of silica for pozzolanic reaction and can serve as a filler (Chikyala, 2008). Zeolite (a kind of pozzolan) may also be used with lime to treat the soil containing humic acid (Ling *et al*., 2013a, b). This is to provide sufficient amount of silica required for pozzolanic reaction.

Impact on environment: The production of any calcium-based material such as lime involves the calcination of calcium carbonate. This calcination process occurs at very high temperature. Therefore, the process is responsible for a considerable percentage of carbon dioxide emission in addition to high energy consumption (Birchal *et al*., 2000; Shand, 2006). Hence, the production of calcium based additives has a negative impact on the environment.

RESULTS AND DISCUSSION

Finding an alternative material is perhaps the better way to overcome the disadvantages of soil stabilization using lime. Magnesium-based additives particularly reactive Magnesium Oxide (MgO) and Magnesium Hydroxide ($Mg(OH)_2$) may be the suitable alternative material for lime. Magnesium oxide has less environmental impact compared with lime, in which the production process is conducted at a temperature far less than that of lime. Therefore, magnesium oxide has less environment impact and less energy consumption, chemically more stable and more resistant against sulfate attack. In addition, magnesium carbonate is more strength than calcium carbonate (Birchal *et al*., 2000; Shand, 2006; Harrison, 2008; Al-Tabbaa, 2012; Mo and Panesar, 2012; Panesar and Mo, 2013). A few studies were conducted to evaluate the magnesium-based additives treated soil. Based on the results of these studies, magnesium-based additives is a promising material to improve soil properties (Xeidakis 1996a, b; Seco *et al*., 2011a, b; Ureña *et al*., 2013; Yi *et al*., 2013). It exhibits a considerable ability to increase soil strength, durability and improve soil workability. Therefore, comprehensive studies are required to disclose and evaluate the efficiency of magnesium-based additives treated soil.

CONCLUSION

Lime-treated soil was studied extensively in the literature. Numerous field and laboratory studies were conducted to evaluate the improvement of geotechnical properties by lime. Several types of soils, lime contents and curing conditions and methodologies were used for this purpose. The mechanism of treatment comprised hydration, cation exchange, flocculation-sagglomeration of soil particles and pozzolanic reaction to form Calcium Silicate Hydrate (C-S-H) and Calcium Aluminate Hydrate (C-A-H) as cementitious materials. The factors affecting lime treated soil are lime content, curing time, curing temperature and soil mineralogy. Soil-lime mixtures have advantages and disadvantages. Its advantages comprise significantly increase soil strength, reduce plasticity (increase workability) and increases soil durability. In addition, a considerable reduction in consolidation settlement and improve compressibility characteristics were observed. Unclear behavior was noted for the permeability of soil-lime mixture when compared with the original soil. Carbonation, sulfate attack and environment impact are a number of the disadvantages of lime-treated soil. Some studies were conducted to provide some guidelines to reduce the deleterious effects of these cons. Magnesium oxide and hydroxide can be proposed as alternative for lime since they posses chemical characteristics make them eligible to overcome the mentioned cons. Moreover, the result of few conducted studies used magnesium based additives to stabilize the soil was significant improvement achieved in soil strength, workability and durability. Therefore, it is need to conduct extensive studies to determine the efficiency of this material in soil stabilization.

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