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EFFECT OF PH VARIATIONS ON SHEAR STRENGTH PARAMETERS OF LIME STABILIZED CLAYEY SOIL

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Abstract This paper presents the consequences of geotechnical and mineralogical examinations on lime treated mud soils from Bhubaneswar City, India, and impacts of pH minor departure from their shear strength parameters. At first, lime was added in various rates and laboratory experiments were condcuted after curing times. The outcomes show that these soils can be stabilized sufficiently with the addition of around 8 % lime. A few labo-ratory tests were performed on treated and untreated clay soils with lime blended in with pore liquids with various pH esteems including 3, 5, 7 and 9. The after effects of shear strength tests demonstrated that the undrained shear strength boundaries for untreated clays expanded impressively if the pore liquid had a high (pH = 8) or a low (pH = 2). It can likewise be discovered that for lime-treated soils, maximum cohesion and friction angle values are accomplished at pH = 8.

Keywords Clay · Lime · pH · Shear strength ·

Introduction

Clay soils are commonly stiff in the dry state, but lose their stiffness when saturated with water. Soft clays are characterized by low bearing capacity and high compressibility (Mohamed et al. 2009). The reduction in strength and stiffness of soft clays causes bearing capacity failure and excessive settlement, leading to severe damage to buildings and foundations.

The usual method for soil stabilization is to remove the unsuitable soil and replace it with a stronger material. The high cost of this method has driven researchers to look for alternative methods, and one of these methods is the process of soil stabilization. In recent years, scientific techniques of soil stabilization have been introduced (Bell 1993; Rogers et al. 1997). Stabilized soil is, in general, a composite material that results from combination and optimization of properties in individual constituent materials (Basha et al. 2005). The techniques of soil stabilization are often used to obtain geotechnical materials improved through the addition of such cementing agents as cement, lime or industrial by-products such as fly ash and slag, into soil. Extensive studies have been carried out on the stabilization of soils using various additives such as lime and cement. Lime is widely used in civil engineering applications such as road construction, embankments, foundation slabs and piles (Al Rawas and Goosen 2006).

Extensive studies have been carried out on the stabilization of clay soils using lime (Basma and Tuncer 1991; Bell 1996; Kassim and Chern 2004; Mohamed et al. 2009; Sherwood 1993). As investigated by Sabry (1977), many significant engineering properties of soft soils can be beneficially modified by lime treatment, as lime decreases the plasticity index, increases the workability and shrinkage limit, reduces shrinkage cracking, eliminates almost all swelling problems, increases the California Bearing Ratio (CBR) and soil strength, as well as increases permeability of soils. In addition, lime can be extended at deep in situ levels, either in the form of lime column or lime injection (Okumura and Terashi 1975).

Quick lime treatment on soft clayey soil improves stability and bearing capacity of soft clay. Croft (1967) found that the addition of lime significantly reduces the swelling potential, liquid limit, plasticity index and maximum dry density of the soil, and increases its optimum water content, shrinkage limit and strength. Bell (1996) indicated that the optimum addition of lime needed for maximum modification of the soil is normally between 1 and 3 % lime by weight, and further additions of lime do not bring changes in the plastic limit, but increase the strength. However, other studies reported the use of lime between 2 and 8 % in soil stabilization (Basma and Tuncer 1991).

When lime is added to clay soils in the presence of water, a number of reactions occur leading to the improvement of soil properties. These reactions include cation exchange, flocculation, carbonation and pozzolanic reaction. The cation exchange takes place between the cations associated with the surfaces of the clay particles and calcium cations of the lime. The effect of cation exchange and attraction causes clay particles to become close to each other, forming flocs; this process is called flocculation. Flocculation is primarily responsible for the modification of the engineering properties of clay soils when treated with lime. The lime–clay reactions depend on several factors, such as the mineralogical composition of the clay soil, the quantity of lime employed for treatment, the moisture content of the soil, the curing time and the temperature (Sherwood 1993).

Broderick and Daniel (1990) reported that the lime and cement stabilized soils are less vulnerable to attack by organic chemicals in comparison to untreated soils. Furukawa et al. (1994) investigated the variation of the engineering properties of freshly cement-stabilized decomposed granite soil cured in water and in 0.2 N acid solution, and indicated that the CBR obtained from the specimens cured in the 0.2 N acid solution was lower than that cured in water. The strong alkaline conditions were able to release silica and alumina from the clay mineral and eventually react with lime to form new cementation products. The success of the lime treatment process is highly dependent on the available lime content, curing time, soil type, soil pH and clay minerals (Kassim and Chern 2004). Limited research has been conducted to determine whether pH variations will affect properties of lime-stabilized soils. Additional studies are therefore necessary to explain the erosion mechanism of lime-stabilized soils due to pH variations. Before studying pH variation effects on strength parameters of clay soils, the additive content of lime required was determined, based on the uniaxial compressive strengths and compaction tests obtained from stabilized soils having various addi- tive contents.

Materials and methods

The soil used for the study was clay collected from southwest of Hamedan City, Iran (Fig. 1). The studied soil is a residual soil that is collected at a depth of about 0.5 to 1 m, and is normally consolidated. The disturbed soil was excavated, placed in plastic bags, and transported to the laboratory for preparation and testing. Laboratory tests were performed on the clay soils to determine basic properties. The clay obtained was light brown in color, and extreme precautions were taken during sampling to keep the clay in its natural water conditions. A particle size distribution curve of Hamedan clay is shown in Fig. 2. The grain size distribution of untreated (natural) soil samples indicates that the soil is composed of 12 % sand, 65 % silt and 23 % clay, which can be classified, according to ASTM (American Society for Testing and Materials) D422 (1990), as CL. Properties of untreated clay are shown in Table 1. The lime used for the study is hydrated lime or $Ca(OH)_2$ in the form of fine powder.

In this work, a number of specimens from the natural clay samples were investigated. To investigate the effect of lime on geotechnical properties of these soils, lime was added to each specimen at room temperature, in the order of 1, 3, 5 and 7 % by weight. The lime was thoroughly mixed by hand until homogeneity was reached, and the mixture was quickly stored in a large plastic bag to prevent loss of moisture content. After preparing the mixture of soil and lime, curing time was allowed. At the end of the curing time (7, 15, 30 and 45 days), the remolding operation for specimens' preparation for uniaxial compressive and direct shear test in maximum dry density was performed, and lime-treated soil specimens were tested. The mineralogy of the clay and non-clay minerals of the soil used were identified by the X-ray diffraction technique (XRD). Semi- quantitative estimation of clay minerals was based on peak areas, and on peak height for non-clay minerals, as pro- posed by Pierce and Siegel (1969).

The geotechnical experiments conducted in the present study include grain size analysis, unconfined compressive tests and compaction test. All tests were conducted in accordance with the ASTM (1990–2000).

Results and discussion

Mineralogical analysis

In this section, the results of XRD on the soil used are briefly presented. The results of XRD on the untreated soil speci- mens indicated that kaolinite, illite and cholorite were the principal clay minerals of the soil sediment (Fig. 3). Other non-clay minerals were also detected in the bulk samples,

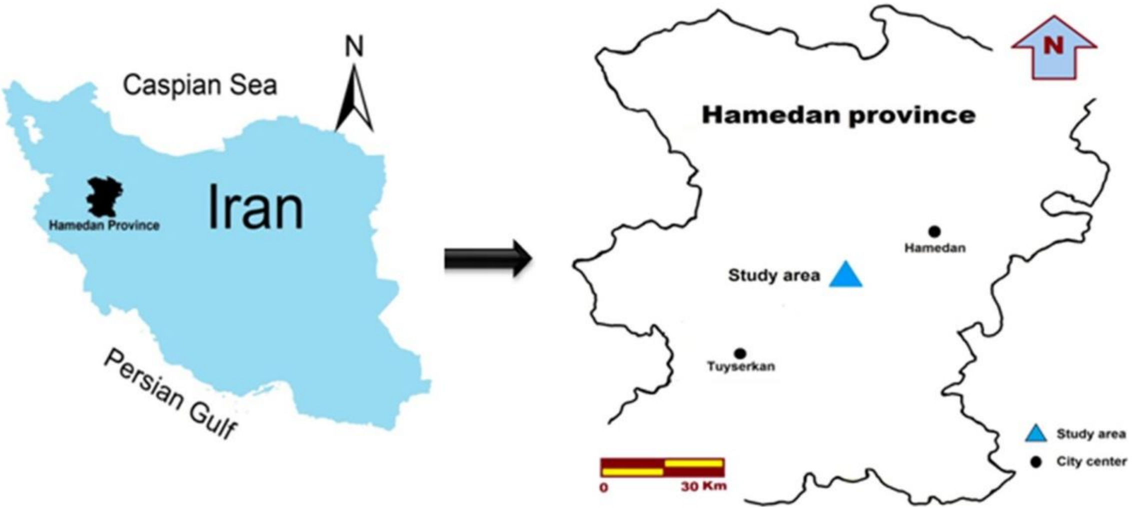


Fig. 1 Location map of the study area

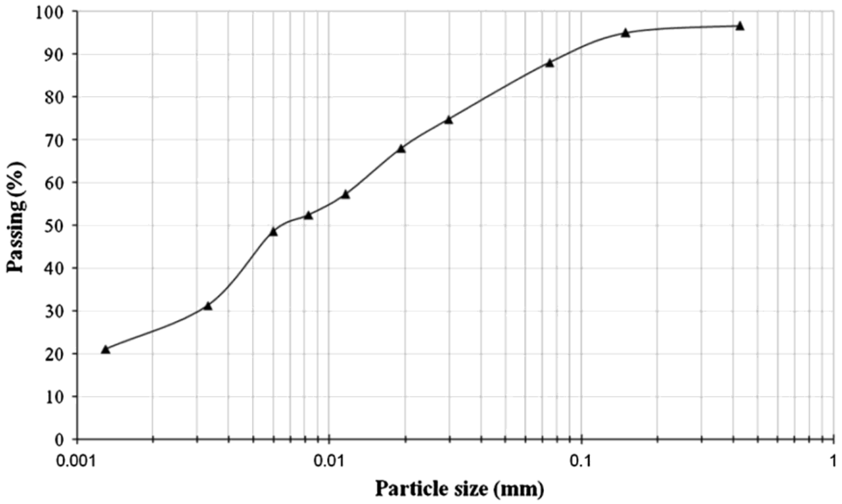


Fig. 2 Grain size distribution of Hamedan clay

including quartz and feldspar. As can be seen in Figs. 4, 5 and 6, XRD of the lime-treated soil illustrated that a relative decrease in peak intensities of kaolinite, illite and cholorite was observed with increasing lime percent. This is attributed to the pozzolanic reactions of lime with these minerals, leading to the destruction of their structure. Meanwhile, kaolinite showed a lesser rate of decreased relative peak intensity with increasing lime content than those of illite and cholorite, which can be attributed to the relative stability of kaolinite compared with other clay minerals.

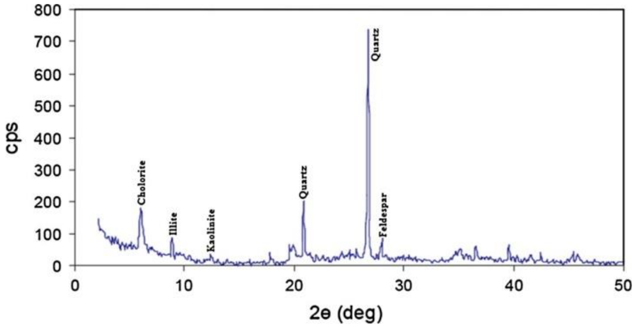


Fig. 3 XRD results for natural clay

Compaction test

The compaction characteristics of clay soils were studied in the laboratory using standard Proctor test based on the ASTM D698 (2000). Compaction tests to determine the effect of lime on maximum dry density and optimum moisture content were carried out on soils after 7, 15, 30 and 45 days, after mixing with 1, 3, 5 and 7 % lime by weight. The results are plotted in Fig. 7a, b in the form of maximum dry density and optimum moisture content

Table 1 Basic properties of untreated clay

Property	Value
Natural moisture content (%)	9.2
Color	Light brown
Clay (%)	23
Silt (%)	65
Sand (%)	12
LL (%)	32
LP (%)	22
IP (%)	10
Specify gravity	2.55
Maximum dry density (g/cm^3)	1.74
Optimum moisture content (%)	19.6
Uniaxial compressive strength (KPa)	14.2
Soil classification	CL

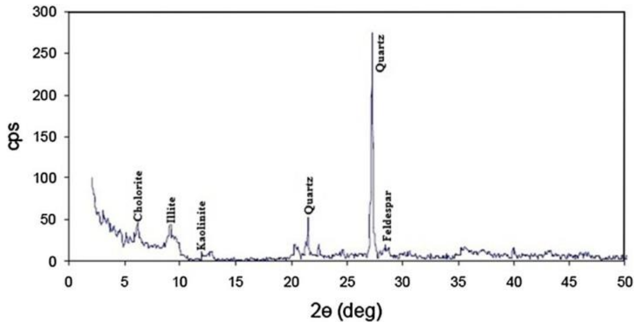


Fig. 4 XRD results for treated clay with 3 % lime

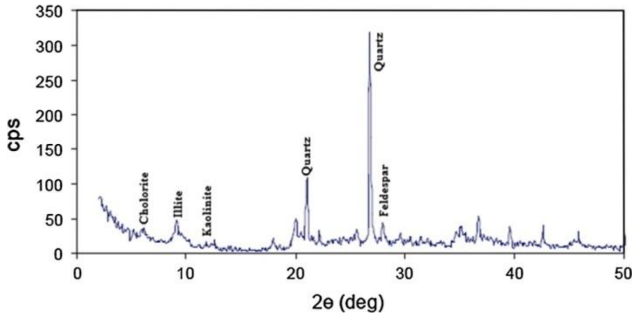


Fig. 5 XRD results for treated clay with 5 % lime

versus lime content. The results obtained from the study show that with increasing lime content, maximum dry density shows a decreasing trend and reduced ratio depending on the lime content and curing time. It can also be seen from Fig. 7b that optimum moisture content increases with the increase of lime percent and curing time. Similar behaviour was observed by other researchers for lime-stabilized clayey soils (Hossain et al. 2007; Rahman 1986; Ola 1977; George 1976; Bell 1996; Gay and Schad 2000).

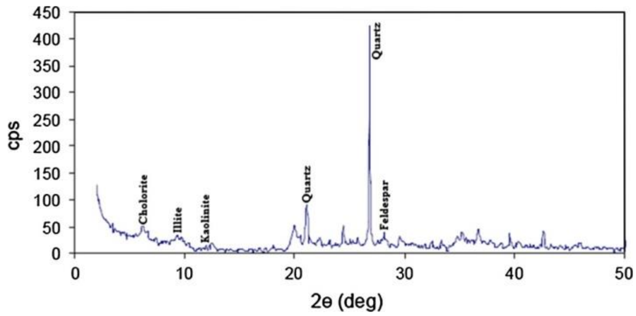


Fig. 6 XRD results for treated clay with 7 % lime

The following reasons could explain this behavior: (1) the lime causes aggregation of the particles to occupy larger spaces, and hence alters the effective grading of the soils; (2) the specific gravity of lime is generally lower than the specific gravity of soils tested; (3) the pozzolanic reaction between the clay present in the soils and the lime is responsible for the increase in optimum moisture content.

Uniaxial compressive strength

The uniaxial compressive strength (UCS) of untreated clay was estimated to be around 14.24 kPa, which indicates a very soft soil. In order to investigate the effect of lime on uniaxial compression strength of these soils, tests were carried out according to ASTM D2166 (2000) on clayey samples mixed with different percentages of lime. The amount of lime added to the clay was in the range of 1–7 %. To prepare the specimens for uniaxial compressive strength test, at the end of the each curing time, the samples were remolded in maximum dry density derived from compaction test (1.74 g/cm^3), and then samples were tes- ted. The results show that the stress–strain curves of untreated soils exhibit a continuous deformation until a steady state is reached; with no true failure points observed (Fig. 8). This is in agreement with the behavior of normally consolidated soils, which do not exhibit pronounced stress– strain peaks. Figure 8 also shows that the stress–strain curves of lime-treated soils exhibit gradual pronounced peaks, depending on the lime percent and curing time, which are attributed to the cementation of soil particles due to pozzolanic reactions mentioned earlier.

It can also be seen from Fig. 9a, b that UCS increases with the increase of lime percent and curing time. For example, with the addition of 7 % lime, a considerable improvement in UCS was achieved after a curing time of 30 days. Therefore, the optimum lime content and proper curing time for lime-treated soils is at least 7 % and 30 days, respectively. Figure 10 also shows that elastic modulus (Es) increases with the increase of lime content. As shown in Fig. 9b, an increase in curing time has not

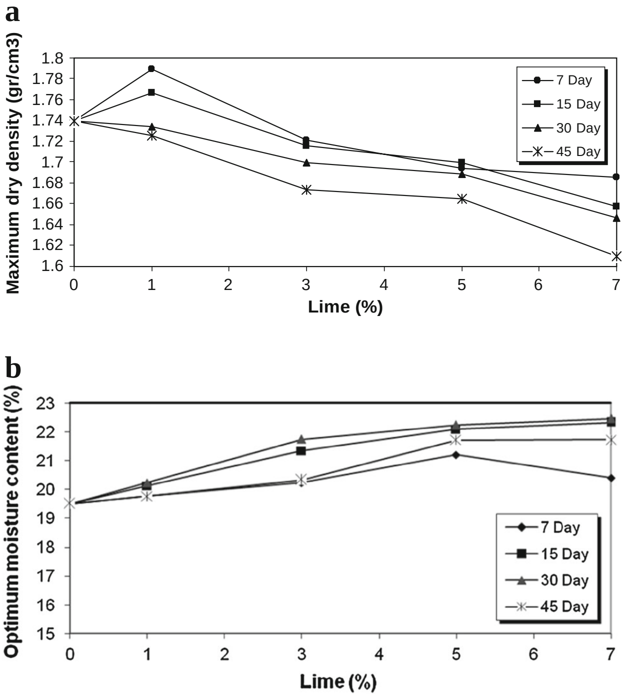


Fig. 7 The effect of lime content on a maximum dry density, b optimum moisture content

resulted in any significant increase in strength of treated soil, and also there is a reduction in strength when curing time is 45 days. The reason for this phenomenon could be that because sample preparation, compaction and remolding is done after curing period, the bonds and cohesion between soil particles caused by the addition of lime may be destroyed.

Statistical analysis of test results

A multiple regression analysis using SPSS software, version 17 was carried out to obtain the relationships that correlate the geotechnical properties of lime-treated soils (i.e. unconfined compressive strength, modulus of elasticity, maximum dry density and optimum moisture content) with the curing time (*t*) and lime content (%LC). The following equations were derived:

UCS¼29:216þ6:93LCð%Þ—0:146tðDaysÞ ð1Þ

*E*¼0:164þ0:033LCð%Þ—0:009tðDaysÞ ð2Þ

c_d¼1:8—0:016LCð%Þ—0:001tðDaysÞ ð3Þ

x_{opt} ¼ 19:33 þ 0:317LCð%Þ þ 0:029t ðDaysÞ ð4Þ

Strong coefficients of correlation, *r*, between the measured and predicted values using the above equations were obtained and found to be equal to: 0.83, 0.80, 0.92 and 0.73

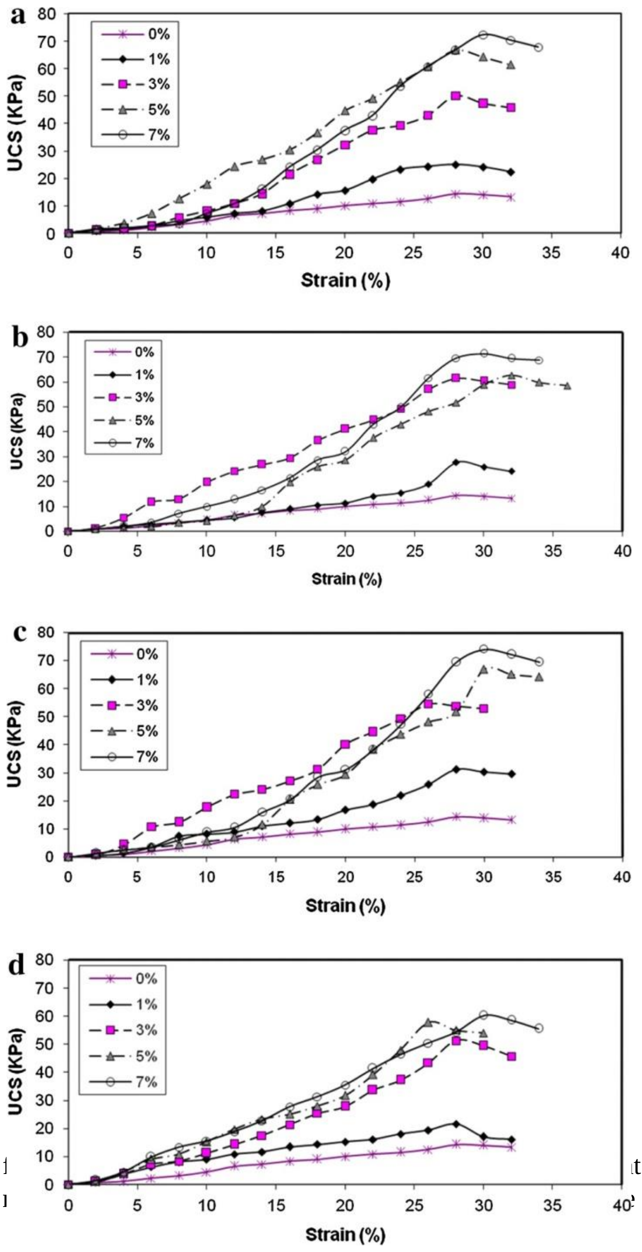


Fig. 8 Stress-strain curves of untreated and lime-treated clay soils for curing time of a 7 days, b 15 days, c 30 days and d 45 days

useful in the sense that they give a quick guide to the characteristics of lime-treated soft clay soils.

Effect of pH variations on soil shear strength parameters

The undrained shear strength of clays is an important geotechnical parameter used during construction processes. It is also important for foundations in clayey soil, as it is often assumed that a clayey deposit will take longer to consolidate than the construction period/application of

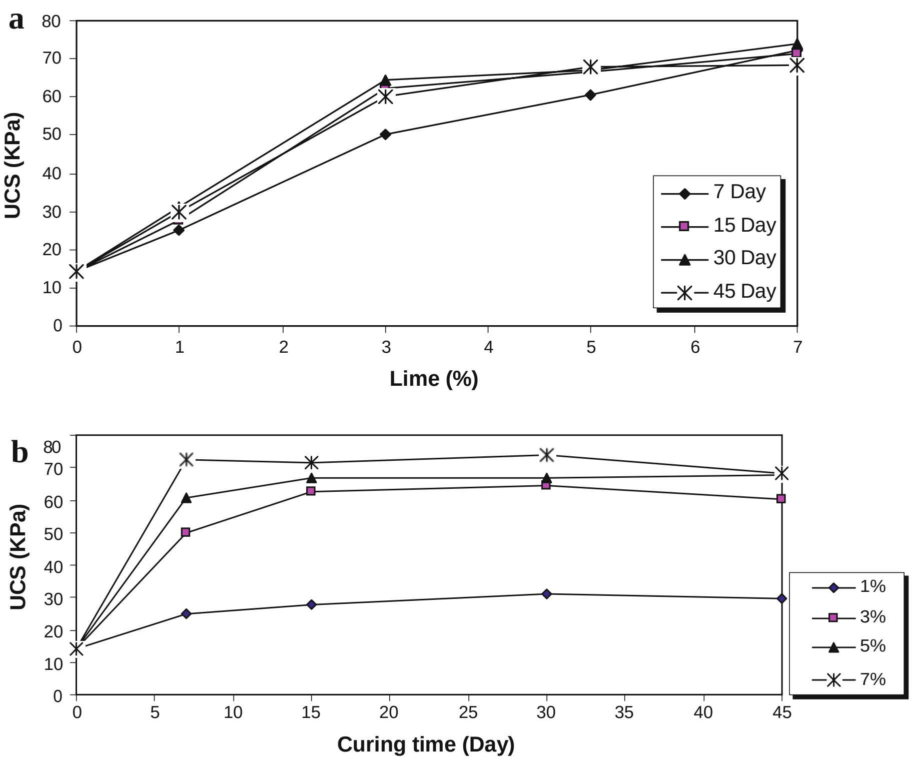


Fig. 9 a Effects of lime percent and b Effects of curing time on unconfined compressive strength

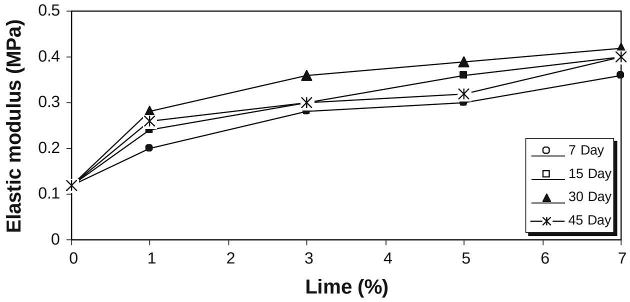


Fig. 10 Effects of lime percent on the modulus of elasticity

load. In view of this, enhancement of the undrained shear strength by varying the pH of the pore fluids could be a useful way of accelerating the construction process, but very little data regarding such a relationship have been found in the literature. Wang and Siu (2006) observed that kaolinite increases its compressibility at high pH values due to edge-to-face (EF) association. Gori (1994) studied the influence of pH on the Atterberg limits of kaolinite and concluded that the liquid limit of kaolinite is not dependent upon the pH of pore fluids, because it is not related to the double layer of such clays (Sridharan and Prakash 1999; Gori 1994).

From this brief literature review, it is suggested that pH potentially influences the mechanical resistance of clays. It

dissolution processes and changes in the surface electrical properties of clays in response to changes in pH are involved. The influence of pH on kaolinite dissolution works in two different ways: at low pH, aluminum dissociates preferentially (Wieland and Stumm 1992), while at high pH, silica dissociates preferentially (Brady and Walther 1989). For kaolinite, the isomorphic substitutions are negligible as they show few permanent charges (5–25 cmol kg^{-1}), i.e. the overall surface charge of kaolinite is neutral. However, edge charges are of great significance. For a kaolinite edge face area of 1–10 m^2/g, the development of one positive charge amounts to
is not clear, however, which main mechanisms are leading to such changes. Santamarina et al. (2002) suggest

0.4–4 cmol kg^{-1} (White 1997; Gajo and Maines 2007).

Therefore, highly pH-dependent edge surface charges characterize the behavior of such clays. The edge surfaces become positive at low pH values due to the adsorption of $H^?$ ions, and more negative at high pH values due to the adsorption of OH^- ions (Gratchev and Sassa 2009). As a consequence of bonding or the elimination of protons, the charge of the edges becomes dependent on the pH values. In acid ranges, positive edge charges are generated through an excess of protons, which are compensated through anions. With increasing pH, the density of charge decrea- ses. The edge becomes slowly uncharged, because increasing negative edge charges generate through dissociation of Si–OH, and in the stronger alkaline range, through Al–OH dissociation. This is a typical situation for kaolinite. Therefore, the edge-to-face (E–F) flocculation

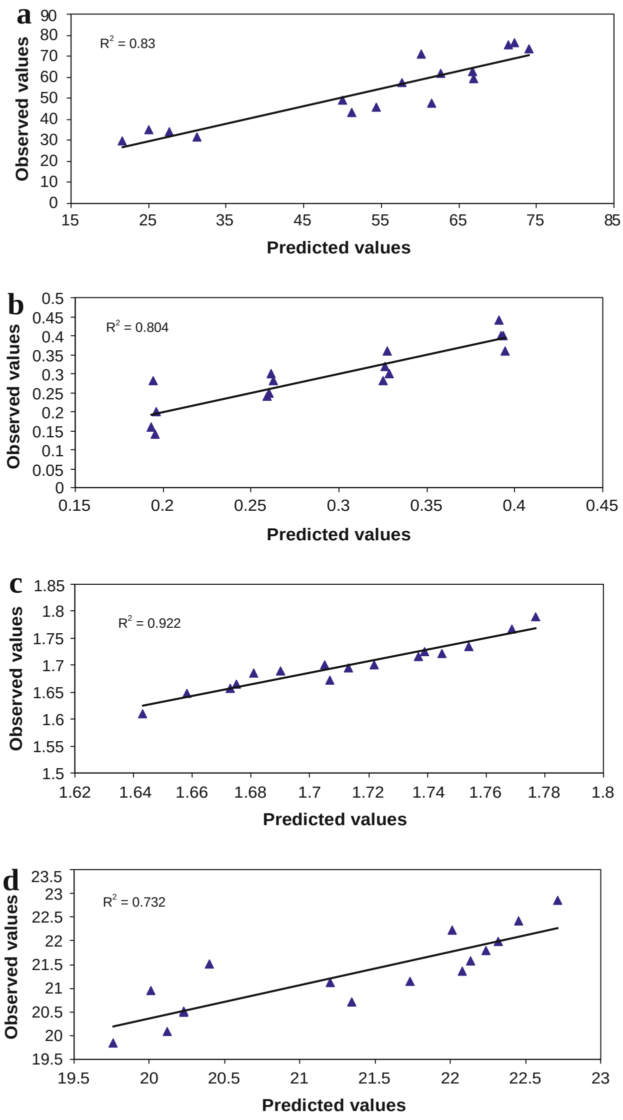
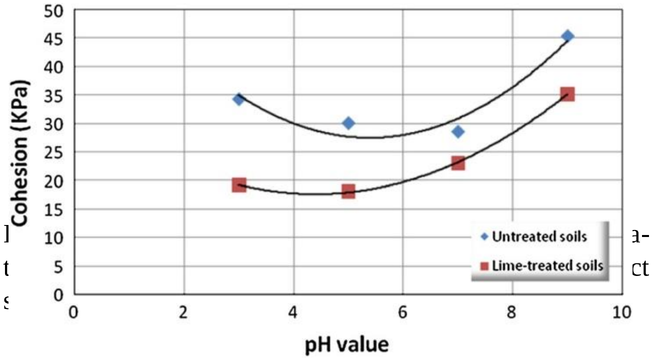


Fig. 11 The relationship between observed and predicted values: a UCS, b elastic modulus, c dry density and d optimum moisture content

Table 2 The effect of pH variations on cohesion and friction angle values of Hamedan untreated clay soils

pH	Cohesion (KPa)	Friction angle (deg)
3	34.21	17
5	30	13
7	28.5	12
9	45.26	19



prevails at low pH, while the face-to-face (F–F) associations predominate at high pH. In this research, several laboratory tests were performed on untreated and treated lime clay soils mixed with pore fluids with different pH values. The pH was determined using a combined glass electrode (portable pH-meter). The pH values that were used in this study varied from 3 to 9 using 1 M HCl or 1 M NaOH solutions to control the pH.

Effect of pH variations on untreated soils

Fig. 12 The relationship between pH pore fluids and undrained cohesion of clay soils

and were conducted on treated and untreated samples compacted at maximum dry density and optimum moisture content. The normal stress was chosen to be 0.5, 1.0 and 2.0 kg for all the specimens. The results of tests indicate that the undrained shear strength parameters for untreated clays increased considerably if the pore fluid had a high pH (pH = 9) or a low pH (pH = 3). The results of undrained shear strength for untreated soils are shown in Table 2 and Figs. 12 and 13.

As can be seen in Fig. 12, for untreated clay soils at high and low pH, the undrained shear cohesion reaches 35 and 45 kPa. According to Jasmund and Lagaly (1993), through the addition of NaOH, a negative charge at the edges arises and edge (–)/face (?) contact occurs, such that the viscous resistance increases. This phenomenon has led to an increase in shear strength parameters of soils. The possible mechanism that could be accepted in relation to increasing shear strength parameters in low pH values has been explained by Brandenburg and Lagaly (1988). According to this assumption, due to occurrences of edge-to-face flocculation at pH lower than 4 and an increment in $H^{?}$ concentration, the materials become slightly stiffer than when the pore fluid is only water.

Effect of pH variations on lime: treated soils

In order to investigate the pH effect on lime-treated soils, soils treated at curing time of 30 days and lime percent of

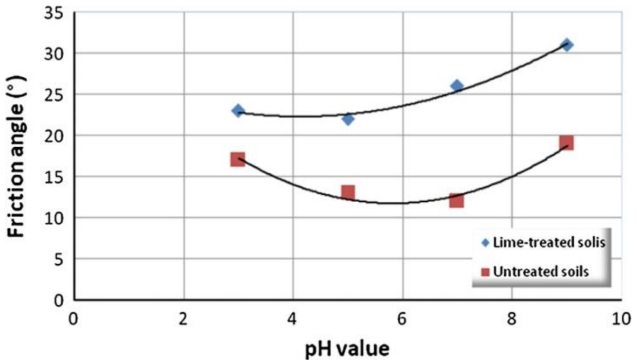


Fig. 13 The effect of pH variations on the friction angle of clay soils

Table 3 The effect of pH variations on cohesion and friction angle values of Hamedan clay soils

pH	Cohesion (KPa)	Friction angle (deg)
3	19.2	23
5	18	22
7	23	26
9	35.17	31

7 % were selected. Shear strength parameters of these soils were determined using direct shear tests in different pH values of pore water (pH = 3, 5, 7 and 9). The results of direct shear tests performed on lime treated soils are shown in Table 3. With a decrease in pH, the free $Ca^{2?}$ ions were almost completely leached and the adsorbed $Ca^{2?}$ ions began to leach. This change resulted in a significant decrease in the strength of the stabilized soils. The shear strength parameters decreased considerably when the pH values decreased to less than 3.0. The free and absorbed, even hydrated, $Ca^{2?}$ ions were sharply released to leach under the increased acidic condition (pH = 3) and this reaction caused a great decrease in strength (Kamon et al. 1996). As can be seen in Figs. 12 and 13, the values of undrained cohesion and friction angle increased with an increase in the pH values of the pore fluid. The maximum cohesion and friction angle values were achieved at pH 9. This relationship explained the fact that the neutralization of lime-stabilized soils resulted in a decrease in shear strength parameters. It is evident that the alkalinity is an effective agent for stabilization of clay soils.

Conclusions

The results of geotechnical and mineralogical investigation on lime-treated soft clay soils from Hamedan City, west of Iran, were investigated and discussed. Lime was added in the order of 1, 3, 5 and 7 % by weight, and experiments after 7, 15, 30 and 45 days were conducted. Relationships that correlate the geotechnical properties of lime-treated soils were developed. In addition, the research explored the influence and the effect of the pH of pore fluids on the shear strength of clay soils. The study has led to the following conclusions regarding lime-treated clay soil.

X-ray diffraction technique of the lime-treated soil illustrated that a relative decrease in peak intensities of kaolinite, illite and cholorite was observed with increasing lime percent. This is attributed to the pozzolanic reactions of lime with these minerals, leading to the destruction of their structure. The results obtained from the study show that with increasing lime content, maximum dry density shows a decreasing trend and reduced ratio depending on the lime content. In addition, the unconfined compressive strength of soil can be increased by nearly five times by the addition of at least 7 % lime after a curing time of 30 days. Also, a remarkable improvement in modulus of elasticity can be achieved by the addition of lime, depending on the curing time. Overall, the research reported in this study proves that soft Hamedan clay can be stabilized satisfac- torily with the addition of at least 7 % lime after 30 days of curing time.

In order to investigate the effect of pH on shear strength of treated and untreated soils, shear strength parameters of these soils were determined using direct shear test in dif- ferent pH values of pore water (pH = 3, 5, 7 and 9). Based on the results of undrained shear strength tests for untreated clays, it was found that the undrained shear strength parameters would increase considerably if the pore fluid had a high pH (pH = 9) or a low pH (pH = 3). At an acid pH, this behavior could be related to the increased disso- lution of $Al^{3?}$, which acts as a coagulant increasing the internal resistance, whereas at an alkaline pH, the increasing ionic strength favors face-to-face aggregation.

In order to investigate the pH effect on lime-treated soils, soils treated at a curing time of 30 days and lime percent of 7 % were selected. The results of direct shear test in different pH values of pore water (pH = 3, 5, 7 and

9) indicated that with a decrease in pH, the free $Ca^{2?}$ ions were almost completely leached and the adsorbed $Ca^{2?}$ ions began to leach. This change resulted in a significant decrease in the strength of the stabilized soils. The shear strength parameters decreased considerably when the pH values decreased to less than 3.0. It was also found that maximum cohesion and friction angle values were achieved at pH 9. It is evident that the alkalinity is an effective agent for stabilization of clay soils.

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