



## Research paper

# The effects of lime content and environmental temperature on the mechanical and hydraulic properties of extremely high plastic clays

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## ABSTRACT

This paper focuses on monitoring the evolution of lime-clay reactions using geotechnical parameters as a function of lime content and environmental temperature. Lime contents of 5, 7, 9, 11 and 13% by dry weight of expansive clay powder were added to prepare lime-clay specimens. The specimens were prepared at the same dry unit weight of 12.16 kN/m<sup>3</sup> and moisture content of 40% except for tests aimed at the determination of dry unit weight as a function of mellowing period. Prepared specimens were mellowed or cured at two different ambient temperatures of 20 °C and 40 °C. Results attained from Unconfined Compressive Strength and permeability tests were employed to assess the impact of lime content on the mechanical and hydraulic properties of lime treated expansive clays. The results revealed that at the beginning, the rate of strength gain is remarkably fast for a particular period of time which is dependent on lime content. Furthermore, the strength gain on specimens cured at 40 °C is 8 times higher than that observed on specimens cured at 20 °C which highlights significant effect for the environmental temperature on accelerating the chemical reactions. Reduced dry unit weight due to increased resistance to compactability is observable with increasing lime content and higher environmental temperature. Accelerated pozzolanic reaction at higher environmental temperature resulted in permeability coefficient of specimens mellowed for 24 h at 40 °C to be higher than those mellowed at 20 °C. The results also highlighted that the permeability coefficient would be relatively stable when expansive clays were treated with small amounts of lime e.g. 5%.

## 1. Introduction

The presence of expansive clays in construction sites poses major concerns to both design and site engineers due to their substantial volumetric changes with drying and wetting cycles. As a result of this volume change, distress and damage of infrastructure may be inevitable. Montmorillonite minerals group that has a voracity to absorb water is responsible for the volumetric behaviour of such expansive clay (Sridharan and Prakash, 2000; Estabragh et al., 2014 and Thyagaraj et al., 2016). Over the past few decades, a number of preventative techniques have been proposed and implemented to reduce and/or limit potentially destructive impacts of the volumetric change of expansive clays on structures such as; replacement of near surface expansive clay, control of compaction and water content, addition of fibrous materials (Mirzababaei et al., 2013), stabilization using chemical agents (Mirzababaei et al., 2009 and Soltani et al., 2017) and traditional chemical treatment using lime, cement and fly ash (Schanz and Elsway, 2015 and Thyagaraj et al., 2016). Due to its low cost, technical efficiency and abundant availability; lime treatment is by far the most

common way to suppress volumetric change and enhance strength of expansive clays. Quick lime (CaO) and hydrated lime Ca(OH)<sub>2</sub> are typically considered for stabilization of expansive clays. The reactions following the addition of lime to such a clay in the presence of water have been extensively described by many researchers (Diamond and Kinter, 1965; Diamond and Kinter, 1966; Rogers and Roff, 1997; Boardman et al., 2001; Di Di Sante et al., 2014; Beetham et al., 2015 and Zhao et al., 2015). There is a consensus that cation exchange, flocculation and agglomeration, carbonization and pozzolanic reaction are responsible for the changes in the clay characteristics. The added lime decomposes partially into hydroxyl ions and calcium ions. Calcium ions tend to replace the monovalent cations such as sodium or any native cations in a process called cation exchange which takes place on the clay particle surfaces. Thus, the surface of clay particle could be balanced by lesser number of hydrated cations (Strawn et al., 2015). This leads to a reduction in the thickness of diffuse double layer that surrounds the clay particles which in turn enhances the bonding with each other to form the flocs (Beetham et al., 2015). Hydroxyl ions increase the pH value in the pore water to nearly 12.4 and as the pH value

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increases the number of negatively charged sites rises (Al-Mukhtar et al., 2014). The aggressive alkaline environment in the pore water partially destroys the clay layers launching silica and alumina anions in the pore water. Concentration and availability of silica and alumina ions are dependent upon the mineralogy of clay (Cristelo et al., 2012). Alumina and silica anions react with calcium and hydroxyl ions forming desirable cementitious compounds in the form of calcium-silicate-hydrates (CSH), calcium-aluminate-silicate hydrates (CASH) and calcium-aluminate-hydrates (CAH). The formation of the cementitious compounds strengthens the convergence points between particles within the flocs and between the flocs within the aggregates. The immediate formation of such compounds and their role in enhancing the flocculation and agglomeration were reported by (Diamond and Kinter, 1965 and Vitale et al., 2017). This is contradictory to the outcomes of studies that refer to the late formation of the cementitious compounds (see for example; Boardman et al., 2001). Disagreement is also notable with the concept of initial lime consumption which is still used in the British Standard, BS 1942-2 (1990) for the determination of the minimum required percentage of lime to satisfy the cation exchange phenomenon based on the pore water alkalinity as an indicator. Of note, the British Standard, BS 1942-2 (1990) assumes that the reactions are to occur as distinct processes. This assumption was one of the main criticisms that were raised by Rogers and Roff (1997). In contrast, Rogers and Roff (1997) used the plastic limit as an indicator rather than the pH value and proposed a new concept called modified initial lime consumption that is based on simultaneous occurrence of all reactions. More recently, these main reactions have been examined and monitored by many studies (see for example; Al-Mukhtar et al., 2014; Tran et al., 2014; Zhao et al., 2015 and Vitale et al., 2017) using chemical and geotechnical parameters but conflicting opinions still exist.

The efficiency of lime treatment is dependent on many factors such as mineralogical composition of clay, curing time, ambient temperature, mellowing period and lime content. Over the past three decades, contradictory conclusions were reached for the impact of adding various percentages of lime on the mechanical and hydraulic properties of expansive clays. For instance, Bell (1996) stated that the addition of lime to montmorillonitic soil beyond 4% leads to a decline in the strength attributing this behaviour to the lime which is considered as a bad fill and does not have marked cohesion or friction. Similarly; Dash and Hussain (2012) noted that strength gain declines on lime stabilized bentonite specimens if they were treated by more than 9% of lime. In contrast, a study conducted on bentonite clay by Al-Mukhtar et al. (2010) indicated that as the lime content (0–20%) increases; the strength gain increases attributing the initial strength gain to the flocculation induced by cation exchange whereas the long term gain was attributed to the pozzolanic reaction. Both short and long term behaviours were considered as being distinct processes. Al-Mukhtar et al. (2010) attributed the elevated strength gain after the first day to the pozzolanic reaction which was found to be 6 times higher when the temperature is increased from 20 °C to 50 °C. Ali and Mohamed (2017) observed that the strength gain measured on 7% lime treated expansive clay specimens was temperature and mellowing period dependent in particular during the first day of treatment. This corresponds with the observation made by (Vitale et al., 2017) that the formation of cementitious compounds starts since the very short time from the addition of lime. The current study, therefore, examines and evaluates the rate of strength gain under two different environmental temperatures over a curing period of 7 days on specimens treated with various percentages of lime. Moreover, since the ongoing formation of cementitious compounds causes an increased resistance to compaction (Osinubi, 1998), the compaction test will be conducted with view to track down the effects on dry unit weight as a function of lime percentage, temperature and compaction delay. Furthermore, the changes in the hydraulic properties are investigated to assess the impact and extent of growing cementitious compounds due to increased lime content. Earlier studies (see for example; McCallister and Petry, 1992; Metelková et al.,

**Table 1**

Chemical analysis of used clay as provided by the supplier.

Element and amount (%)								
SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	Na <sub>2</sub> O	CaO	FeO	LOI <sup>a</sup>	Trace
63.02	21.08	3.25	2.67	2.57	0.65	0.35	5.64	0.72

<sup>a</sup> Loss of ignition.

2011; Al-Mukhtar et al., 2012) suggested that the ongoing formation of cementitious compounds in the available pores leads to a gradual decline in the permeability of treated expansive clays but further quantification of the time-dependent changes is needed.

## 2. Materials

Expansive clay in the form of Pure Wyoming Sodium Bentonite powder was selected for the testing programme. The used clay composed primarily of montmorillonite mineral in addition to a small amount of non-clay minerals e.g. Quartz, calcite and feldspar. The used clay is classified as extremely high plastic clay due to its high liquid limit of 330% and plastic limit of 43%. The used expansive clay was supplied by Potclays Ltd., UK and its chemical analysis is illustrated in Table 1. The results of standard Proctor Compaction tests revealed that as the water content increases the dry unit weight decreases. Neither maximum dry unit weight nor optimum moisture content could be determined by conduction of the compaction tests due to the expanding lattice of used bentonite clay with increasing water content. An optimum water content was, therefore, estimated according to the correlation suggested by Sridharan and Nagaraj (2005) as a function of the plastic limit. As a result, moisture content of 40% was taken as the optimum moisture content and the corresponding dry unit weight was found to be 12.16 kN/m<sup>3</sup>. Fine hydrated lime which was passed through 425 µm sieve and stored in a sealed container, was utilized. In this investigation, percentages of lime were selected to be 5, 7, 9, 11, and 13% of the dry weight of clay.

## 3. Experimental Programme

Lime-clay mixtures were prepared by the addition of specific percentage of lime to clay in a powder form. Subsequently, a pre-determined amount of water was added gradually whilst the mixture was manually mixed and kneaded. To ensure high degree of pulverization and uniform treatment each mixture was passed through 2 mm sieve. Furthermore, the mixture was mechanically mixed to ensure complete and thorough mixing. In this paper, three series of experiments have been conducted to assess the evolution of reactions and impacts on physical, mechanical and hydraulic properties. Table 2 demonstrates the variable and fixed parameters in each series of tests following the initial mixing. In order for preparation of specimens under controlled laboratory conditions to be carried out, an environmental cupboard that is capable of controlling both temperature and humidity, is used in this investigation. In all experiments a relative humidity of 90% was maintained and found to be adequate to prevent loss of water from specimens during mellowing and curing periods.

### 3.1. Compaction tests

A total of 70 compaction tests have been conducted in this series according to the parameters illustrated in Table 2. Fig. 1 shows the newly developed purpose made mould and hammer by the authors and reported in Ali and Mohamed (2017). The newly developed mould and hammer were designed to prepare specimens under relatively comparable compactive energy as in the standard Proctor Compaction test whilst making significant saving in materials, time and effort. Specimens were compacted in 6 layers of which each layer has received 15

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