Predicting the UCS of Lime–Stabilized Clayey Soils

B. Sari-Ahmed[1], M. Ghrici[1], and K. Harichane[1]
[1]*Geomaterials Laboratory, University Hassiba Benbouali of Chlef, Chlef, Algeria*
E-mail: m.ghrici@univ-chlef.dz

ABSTRACT: This study was made in order to develop a statistical model for predicting the unconfined compressive strength (UCS) of lime-stabilized clayey soils. The obtained results showed that the developed model (UCS–Model) is very efficient and can be used as a reliable tool for predicting the UCS of lime–stabilized clayey soils. Indeed, both the (*F*-test) and (*t*-test) showed that the significance value of UCS–Model was found to be less than 0.05 which indicates that the lime content and curing time significantly contribute to the constructed model and lead to a better prediction of UCS. In addition, the comparison study between predicted values and experimental data indicated that the UCS model can be reasonably applied to explain the effect of lime content below 10%, and curing time between 0 and 90 days on UCS of clayey soils and to design new mixtures without making an experimental study.

KEYWORDS Clayey soils, Lime, Unconfined compressive strength (UCS), Curing time, Statistical model.

1. INTRODUCTION

Clayey soils are mainly distributed throughout the world (Goodarzi et al., 2015; Gadouri et al., 2017a), which possess deprived geotechnical characteristics and pose serious construction problems resulting in large settlements detrimental to structures constructed over them, and they have to be improved by chemical stabilization for acceptable performance (Kavak and Baykal, 2012; Yilmaz and Civelekoglu, 2009). Chemical stabilization using mineral additives such as lime is usually used to improve the mechanical performance of problematic soils around the world (Harichane et al., 2012). According to Kavak and Baykal (2012), cementitious compounds formed upon mixing clay with lime during pozzolanic reactions are responsible for the improvement in strength and durability. The addition of lime (quicklime; CaO) or hydrated lime; $Ca(OH)_2$) to problematic soils has a better effect, which reduces their expansion (Afès and Didier, 2000) and improves their strength (Hossain et al., 2007). Such behavior of treated soil may be attributed to the pozzolanic reactions: reaction between the silica and alumina present in the clay minerals and the calcium from the lime to form new cementing agents such as calcium silicates hydrates (C–S–H), calcium aluminates hydrates (C–A–H) and calcium alumino-silicates hydrates (C–A–S–H) (Mitchell 1986). Generally, cation exchange takes place by initial addition of 1 or 2% lime (by dry weight of soil), further addition of lime is responsible for pozzolanic activity (Kate, 2005).

The unconfined compressive strength (UCS) of soil is considered one of the most important designing parameters used for pavement design especially for highway construction (Gadouri et al., 2017c). It was also used to verify the effectiveness of the soil stabilization, to assess the importance of influencing factors on strength of stabilized clayey soils, and to choose the best stabilizer percentage. However, clayey soils usually exhibit significant increases in strength when treated with lime (Bell, 1996; Cerato et al., 2011; Etim et al., 2017). The strength of such soil mixtures is influenced by the behavior of the soil, the amount of lime added, the length of time available for curing and the conditions under which this takes place (i.e., temperature and humidity), moisture content, and the time elapsed between mixing and compaction (Gadouri et al., 2016a).

On the other hand, it is known that the time required for laboratory tests and costs of compilation projects is very important. For this reason, some studies have been made on computer-based models using analytical methods (Sari Ahmed et al., 2018) and artificial neural networks (Taleb Bahmed et al., 2017) for predicting the physico-mechanical properties of additives-stabilized clayey soils without making laboratory tests. In addition, some investigations have been made in order to develop some statistical models for predicting the effect of lime and curing time on UCS of stabilized clayey soils (Ling et al., 2014; Naveena et al., 2017; Baldovino et al., 2018; Consoli et al., 2009; Consoli et al., 2012; Sharma and Singh, 2018) where it can be seen that there is no validation study made for their developed models. In fact, Naveena et al. (2017) have studied the critical factors influencing the UCS development of clayey soil stabilized with additives where they have found in their study that both the clay-water/lime ratio and curing period are the main parameters controlling the UCS development. Also, Baldovino et al. (2018) have developed some empirical equations that present an exponential relation between UCS and lime content and a linear relationship with the logarithm of curing time. Moreover, Sharma and Singh (2018) have established empirical equations for UCS using simple and multiple linear regression methods where all the developed models have shown the highest prediction capacity based on several independent parameters such as lime content, curing time, plastic limit, liquid limit, potential of hydrogen, primary ultrasonic wave velocity, optimum moisture content and maximum dry density.

However, as a disadvantage, these researchers have used in their studies a few databases (some results collected from a single experimental study) to make their statistical models, which are difficult to be used and not always with the range of the engineer. For this reason, many data sources were collected from several laboratory studies published in the literature made on lime-stabilized problematic soils and used as a database in this work. The goal of this paper is to develop a statistical model in order to predict the UCS of lime-stabilized clayey soils, to validate the proposed model (UCS–model), to make a comparison study between predicted values and experimental data, and finally to evaluate the effect of lime and curing time on UCS based on a parametric study.

2. GEOTECHNICAL PROPERTY STUDIED

It is known that the most frequent problem for all earth structure projects is the presence of unsuitable soils such as gypseous soils, organic soils and clayey soils of high plasticity (Gadouri et al., 2017c). These problematic soils caused severe problems for constructions like a high sensitivity to water due to the presence of high clay particles fraction, high expansion linked with the presence of sulphates, organic matter, and/or expansive clay minerals such as montmorillonite and illite, low bearing capacity related to the high compressibility of the soil, etc. According to Kolias et al. (2005), chemical stabilization using mineral additives such as cement, lime, and FA was used for several years with the main aim to make the problematic soils capable of meeting the requirements of specific engineering projects. However, some geotechnical tests made on stabilized soils like compaction, UCS, and free swell are not economic and require much time for their achievement. For these reasons, it is necessary to develop statistical models for resolving this problem based on the results published in the literature and consequently to predict suitable geotechnical properties. In fact, the geotechnical property investigated in this paper is the UCS of lime-stabilized clayey soils, which is very essential in practices of civil engineering projects such as roadway subgrades, road embankments, trench backfills, landfill liners, and earth dams. Thus, the UCS of clayey soils is also one of the most important designing parameters used for pavement design, especially for highway construction. It can be used to verify the effectiveness of soil stabilization, to assess the importance of influencing factors on strength of stabilized soils, and to choose the best stabilizer percentage. On the other hand, this selection was also based on the availability of data published in the literature in order to develop a best-fit model (UCS–model) to make a rapid and better prediction of UCS of lime-stabilized high plasticity clayey soils, and consequently the reduction of both the time consumption and costs. This empirical model describes the relationship between the UCS of stabilized clayey soils and some factors dominating this property, such as the lime percentage and the curing time. These were selected as predictors in the proposed model. Several factors control the UCS of lime-stabilized soils in addition to lime content and curing time (which have the most important effects on the strength of stabilized soils). Among these factors we can cite the type and content of clays, plasticity and other factors. Several of these factors have been considered indirectly in the selection of the database used for the fitting of the proposed model. Indeed, a high number of data was collected from the literature about the utilization of lime as an additive for several applications in engineering construction.

3. DATA COLLECTION AND TREATMENT

The database used in this study was collected from many laboratory studies of different types of soil stabilized by various lime contents. In fact, this step is very important for obtaining suitable database where several factors were taken into account at this stage such as soil classification, lime type and the presence of organic matter in natural soils. These factors can considerably affect the quality of the collected database.

For these reasons, numerous results were collected from many previous works but only the results of soils classified as the clayey soil of high and medium plasticity and stabilized with hydrated lime $Ca(OH)_2$ were considered in this study as a database. In addition, Al-Taie et al. (2016) have reported that the presence of organic matter (humic or fulvic acid) caused a high decrease in the pH value of the stabilized soil and consequently affected the dissolution of clay minerals (SiO_2 and Al_2O_3) responsible for the formation of cementing agents by pozzolanic reactions between them and calcium. For this reason, all the soils containing a high amount of organic matter were not considered in this study. Also, it should be noted that the constructed database was collected by taking into account the above factors. In fact, the number of data points used in this study is 496 points which were obtained from 52 research studies (Table 1). But, the experimental data points used for the validation of proposed UCS–model are 32 points which were extracted from four research works (Gadouri et al., 2017a; Little et al., 1987; Dayioglu et al., 2017; Noorzad and Motevalian, 2018). Also, UCS results were obtained from different standards that were used for carrying out UCS tests, namely: ASTM standard (56%), BIS Standards (8%), Chinese, French, British, Australian, New Zealand and Indonesian Standards (21%), and unspecified standards (15%). Table 1 depicts the collected results used to develop the UCS-model.

4. DEVELOPMENT OF UCS–MODEL

Four relationships between UCS as a dependent variable and both the lime contents and curing time as independent variables were proposed, examined and presented in Table 2. Data analysis was considered in two stages (learning and validating). A total of 496 data points was used during the learning stage for developing all the empirical models. The coefficient of determination is an efficient tool to evaluate the constructed models where the higher the precision of the models is reflected by the higher the R^2 (close to 1) (Jafer et al., 2016).

Table 1 Data used for developing a statistical model to predict the UCS of lime-stabilized clayey soils

Data source	Lime content range	UCS range (kPa)	Time range (days)	Number of data
Neubauer (1972)	0–06	25.7–154.0	-	04
Prasade (1972)	0–10	365.8–1933.9	0–60	21
Quilici (1972)	0–10	965.3–1634.1	0–03	06
Harty and Thompson	0–10	489.5–2840.6	0–56	12
Medhani (1983)	0–09	503.3–1427.2	0–28	05
Hopkins and Allen (1986)	0–06	94.1–756.5	0–14	06
Rahman (1986)	0–12	210.7–732.3	0–07	13
Petry and Lee (1988)	0–2.5	455.1–1377.0	0–28	06
Tehrani (1988)	0–04	190.0–625.0	0–14	04
Tuncer and Basma (1991)	0–09	200.0–1737.0	0–28	24
Bell (1996)	0–08	178.0–1597.0	0–07	10
Beckham and Hopkins (1997)	0–10	205.6–782.4	0–07	11
Sridharan et al. (1997)	0–03	160.6–1121.7	0–28	13
Pinero Rivera (2001)	0–10	931.5–2637.3	0–28	05
Kate (2005)	0–03	253.7–473.8	-	13
Cai et al. (2006)	0–08	90.0–660.0	0–28	04
Ismaiel (2006)	0–8.5	131.2–1221.7	0–07	04
Nalbantoglu (2006)	0–07	718.4–2493.6	0–30	07
Osinubi (2006)	0–08	490.0–1500.0	0–28	13
Osinubi and Nwaiwu	0–08	310.0–1449.0	0–28	10
Khattab et al. (2007)	0–04	300.0–1400.0	0–07	02
Alhassan (2008)	0–08	295.0–1450.8	0–28	13
Sharma et al. (2008)	0–05	202.2–650.0	0–28	05
Sirivitmaitrie et al. (2008)	0–12	94.5–1394.8	0–07	06
Bozbey and Garaisayev (2010)	0–09	309.0–1529.0	0–28	07
Behak (2011)	0–09	253.4–1718.2	0–28	05
Cerato et al. (2011)	0–05	216.5–1527.2	0–14	26
Siddique and Hossain	0–15	565.0–4600.0	0–112	26
Solanki et al. (2011)	0–06	175.8–892.9	0–07	10
Al-Mukhtar et al. (2012)	0–10	300.0–2400.0	0–90	06
Kavak and Baykal (2012)	0–10	123.5–1068.0	0–28	16
Portelinha et al. (2012)	0–03	303.4–780.6	0–28	07
Baglari and Dash (2013)	0–16	233.2–2048.0	0–28	21
Khalid et al. (2014)	0–03	470.5–629.3	0–28	04
Samantasinghar (2014)	0–13	295.0–3069.0	0–56	21
Goodarzi et al. (2015)	0–15	315.0–3060.0	0–28	16
Jha and Sivapullaiah	0–06	312.0–1350.0	0–28	13
Önal (2015)	0–08	120.8–294.3	0–07	07
Yilmaz et al. (2015)	0–06	118.5–1072.2	0–28	02
Al-Taie et al. (2016)	0–08	283.0–1251.8	0–28	09
Damoerin et al. (2016)	0–10	557.0–1023.0	0–07	04
Kavak and Bilgen (2016)	0–05	406.7–1420.5	0–28	09
Sharma and Hymavathi (2016)	0–05	373.4–1165.1	0–28	07
Wang et al. (2016)	0–06	564.6–1397.9	0–90	06
Behak and Núñez (2017)	0–05	214.0–1600.0	0–90	07
Etim et al. (2017)	0–08	107.2–1689.6	0–28	13
Harish (2017)	0–09	230.0–1302.7	0–28	13
Jahandari et al. (2017)	0–08	407.0–1389.3	0–28	07
James and Pandian (2017)	0–07	115.8–1181.3	0–07	07
Negawo et al. (2017)	0–09	1438.0–1799.0	0–07	04
Shen et al. (2017)	0–03	65.6–164.7	0–07	04
Soltani et al. (2017)	0–09	422.5–1526.2	0–28	02
Total number of data				**496**

Table 2 A summary of the statistical analysis of the four proposed UCS–models of lime-stabilized clayey soils

N°	Equations	Models parameters	t-test results	Signif.	R^2	F value	P_r	Signif.
(1)	$UCS = a * UCS_0 * (b + L)^{(c*t+1)}$	a = 0.14	Std. Err. = .012591 t value =11.61 $P > \lvert t \rvert = 0.000$ [95% Conf. Interval] .1215 .1709	Yes	0.67	339.85	0.000	Yes
		b = 8.64	Std. Err. = 1.1444 t value = 7.56 $P > \lvert t \rvert = 0.000$ [95% Conf. Interval] 6.398 10.892	Yes				
		c = 0.003	Std. Err. = .000179 t value = 16.65 $P > \lvert t \rvert = 0.000$ [95% Conf. Interval] .00263 .00333	Yes				
(2)	$UCS = a * L + b * UCS_0 + c * t + d$	a = 82.03	Std. Err. = 3.987 t value = 20.57 $P > \lvert t \rvert = 0.000$ [95% Conf. Interval] 74.195 89.865	Yes	0.75	739.42	0.000	Yes
		b = 1.041	Std. Err. = .0743 t value = 14.00 $P > \lvert t \rvert = 0.000$ [95% Conf. Interval] .894 1.186	Yes				
		c = 17.17	Std. Err. = .807 t value = 21.27 $P > \lvert t \rvert = 0.000$ [95% Conf. Interval] 15.587 18.761	Yes				
		d = -105.76	Std. Err. = 33 .266 t value = -3.18 $P > \lvert t \rvert = 0.002$ [95% Conf. Interval] −171.129 −40.405	Yes				
(3)	$UCS = UCS_0 + (1 + a * L) * e^{(b*\sqrt{t}+1)}$	a = 20.0	Std. Err. = .8234 t value = 24.30 $P > \lvert t \rvert = 0.000$ [95% Conf. Interval] 18.387 21 .623	Yes	0.78	895.72	0.000	Yes
		b = 0.169	Std. Err. = 0.0061 t value = 27.78 $P > \lvert t \rvert = 0.000$ [95% Conf. Interval] .1573 .1813	Yes				
(4)	$UCS = UCS_0 + a * L * (t + 1)^b$	a = 28.97	Std. Err. = 1.916 t value = 15.12 $P > \lvert t \rvert = 0.000$ [95% Conf. Interval] 25.207 32.737	Yes	0.80	1008.66	0.000	Yes
		b = 0.488	Std. Err. = .0186 t value = 26.19 $P > \lvert t \rvert = 0.000$ [95% Conf. Interval] .451 .524	Yes				

UCS_0 is the unconfined compressive strength of natural soil (kPa); L is the lime (%); t is the curing time (days) and a, b, c, and d are the model's parameters

As shown in Table 2, the determination coefficients of all models are between 0.67 and 0.80. An important part of assessing the adequacy of an empirical model is testing statistical hypotheses about the model parameters and constructing certain confidence intervals. In this context, statistical tests (*t*-test and *F*-test) were performed in order to examine the significance of the regression models. The contribution of each independent variable to the constructed model was investigated by calculating its statistical significance (signif.).

The statistical significance indicates whether the studied independent variable contributes to the model or not, any independent variable with (signif.) value more than α (α = 0.05) will not contribute to the model, but it plays an important role in the prediction process when its (signif.) value is less than α (Jafer et al., 2016). A type I error (α) of 0.05 was used as a reference value for all the statistical tests. As shown in Table 2, the proposed UCS–models and their parameters are sufficient for a better prediction of UCS based on curing time (t, days), lime content (L, %) and unconfined compressive strength of unstabilized clayey soil (UCS_0, kPa). The coefficients of variables are in the range of 95% confidence level. As shown in Table 2, the proposed UCS−model N°4, gives the best correlation ($R^2 = 0.80$) as compared to other proposed UCS−models N°1, 2 and 3, which were presented low coefficient of determination of 0.67, 0.75 and 0.78, respectively.

The results of the comparison between predicted values from UCS–model, and validation of new data records are summarised in Table 3 and Figure 1. The total average error of 8.75% (Table 3) found between experimental results and predicted values of UCS indicated that the proposed UCS–model can be used as a reliable tool for predicting the UCS of clayey soils stabilized with different lime contents. It is important to note that clayey soil that fits better to the proposed model, are the soils classified as clayey soil of high and medium plasticity (CH or CL) and stabilized with hydrated lime $Ca(OH)_2$. The proposed UCS-model (Eq. 4) is valid in the following conditions:

- $25.7 \leq UCS_0 \leq 1438.0$ (kPa);
- $0 \leq t \leq 90$ (days); and
- $0 \leq L \leq 10$ (%).

Table 3 Error between experimental results and predicted values of UCS based on other research studies

Data source	Lime (%)	Time (days)	UCS_{Exp} (kPa)	UCS_{Pred} (kPa)	Error (%)	RME (%)
Little et al. (1987)	00	0	558.48	558.48	00.00	10.40
	03	28	1385.85	1007.97	27.30	
	05	28	1461.69	1307.63	10.50	
	07	28	1330.69	1607.29	-20.80	
	00	0	489.53	489.53	00.00	
	03	28	1158.32	939.02	18.90	
	05	28	1123.85	1238.68	-10.2	
	07	28	1544.43	1538.34	00.40	
	00	0	703.27	703.27	00.00	
	03	28	1537.53	1152.76	25.00	
	05	28	1489.27	1452.42	02.50	
	07	28	1606.48	1752.08	-09.10	
Dayioglu et al. (2017)	00	0	1363.36	1363.36	00.00	09.60
	04	1	1388.06	1525.88	-09.90	
	08	1	1537.83	1688.40	-09.80	
	12	1	1672.16	1850.92	-10.70	
	04	7	1584.15	1683.04	-06.20	
	08	7	1843.54	2002.72	-08.60	
	12	7	2096.76	2322.40	-10.80	
	04	28	2047.35	1962.68	04.10	
	08	28	2383.94	2562.00	-07.50	
	12	28	2471.95	3161.32	-27.90	
Gadouri et al. (2017a)	00	0	100.00	100.00	00.00	09.50
	08	7	1110.00	739.36	33.40	
	08	30	1330.00	1338.29	-00.60	
	08	60	1910.00	1822.98	04.60	
	08	120	2750.00	2506.79	08.80	
Noorzad and Motevalian (2018)	00	0	274.50	274.50	00.00	05.50
	10	3	935.65	844.34	09.80	
	10	7	1056.85	1073.70	-01.60	
	10	15	1510.91	1395.38	07.60	
	10	28	1630.62	1772.80	-08.70	
Total RME						$\pm$**08.75**

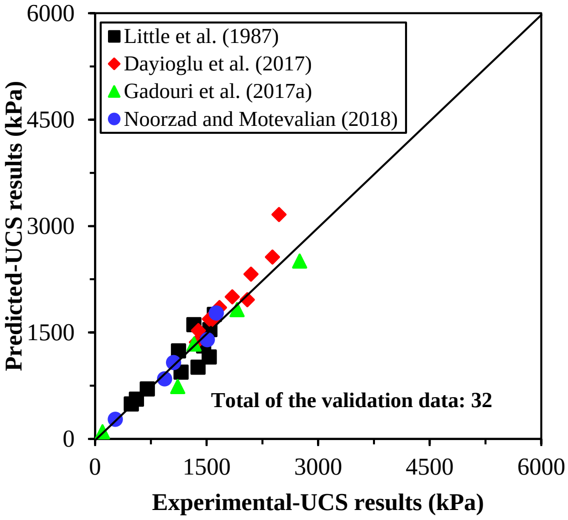

Figure 1 Error between experimental results and predicted values of UCS of lime-stabilized clayey soils

5. PARAMETRIC ANALYSIS BASED ON RESULTS OBTAINED FROM DEVELOPED MODEL

A parametric analysis was carried out in order to check the ability of this model (Equation N°4 given in Table 2) for evaluating the effect of lime on UCS of stabilized clayey soils. The results of UCS gain with respect to the curing time are shown in Figure 2. The parametric analysis was based on UCS_0 value (350 kPa), curing time (7, 14, 28 and 90 days) and lime content (0–12%).

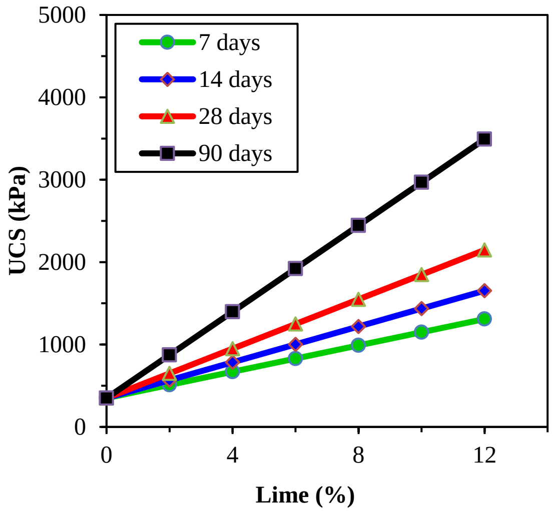

Figure 2 Effect of different lime content on the UCS of stabilized clayey soils for different curing periods

It is known that the addition of lime as an additive to clayey soils improves their strength which can be reflected by the significant increase in the UCS value of stabilized clayey soils (Bozbey and Garaisayev, 2010; Behak, 2011). It is obvious to see that the UCS increases with increasing lime content and curing time.

For example, for a clayey soil with UCS_0 = 350 kPa and for 14 days curing time, the UCS of lime-stabilized clayey soil increases from 350 kPa up to 785 and 1219 kPa with the addition of 4 and 8% lime, respectively. This corresponds to increases of 124 and 248% in UCS values when adding 4 and 8% lime, respectively (Figure 2).

However, after 28 days curing time, the UCS increases from 350 kPa up to 950 and 1549 kPa when adding the same lime contents (4 and 8% lime). This corresponds to increases of 171 and 342% in UCS values respectively with 4 and 8% lime. It should be noted that among the different variables affecting the strength of lime-stabilized clayey soils, curing is of major importance. Similar observations have been found by Bell (1996).

According to Etim et al. (2017), the increase in UCS values was primarily due to micro-fabric changes and the formation of cementitious compounds (C–S–H and C–A–H) by pozzolanic reactions, which are responsible for the strength development, especially with curing period. Similar findings were reported by several researchers when compared their experimental results to predicted values from UCS–model. For example, Hussey et al. (2010) reported that the UCS of a clayey soil increased from 369 kPa up to 841 kPa when using 4% lime for 14 days curing time. This reflected that the UCS value increased by 128%. Furthermore, for 8% lime addition, Manasseh and Olufemi (2008) have reported that the UCS of clayey soil increased from 360 kPa up to 1400 kPa. This revealed that the UCS value increased by 289% for 8% lime. For 28 days curing period, Nicholson et al. (1994) have reported that the UCS of a clayey soil increased from 444 kPa up to 1276 kPa when using 5% lime as an additive. When using 8% lime, Manasseh and Olufemi (2008) found that the UCS of clayey soil increased from 360 kPa up to 1479 kPa. This reflected that the UCS value increased by 311% when adding 5% lime.

Several researchers have reported the same behaviors (Tuncer and Basma, 1991; Chikyala et al., 2008; Sirivitmaitrie et al., 2008; Harichane et al., 2011; Etim et al., 2017).

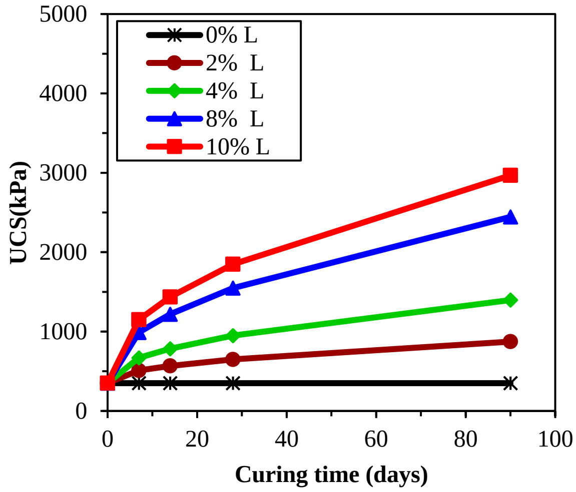

Figure 3 Effect of curing periods on UCS of stabilized clayey soils for different lime contents

As shown in Figure 3, it is obvious to see that the UCS value of stabilized soil was substantially increased by increasing the curing time from 7 to 90 days. Moreover, a nonlinear trend of UCS increasing was observed. A similar trend was observed by Jahandari et al. (2017). It is clear to observe that with 2 and 4% lime as additives, there is no significant increase in UCS values when the curing period increases from 7 to 28 days. However, beyond 7 days curing time, a considerable increase can be noticed for clayey soils treated with 8 and 10% lime contents. A similar finding was reported by Al-Taie et al. (2016) and Cheng and Huang (2019). It has been confirmed that the pH parameter can be used as an indicator to track the pozzolanic reactions process with curing time (Gadouri et al., 2017d), and consequently, the development of soil strength with curing time as the mechanism of reaction between lime and clay particles (Al-Taie et al., 2016).

In fact, according to Al-Taie et al. (2016), two opposite processes can be observed during lime-clay particles reaction. The first process is the ionization of lime in contact with water to produce OH− ions which raise the pH concentration of the environment. As a second process, the dissolution of silica (due to high pH value) reduces the content of OH− ions and consequently the decline in the pH concentration of the environment. Also, the speed of lime dissolution is high up to 7 days and then decreases after this curing time. All the same, the pH concentration decreases because the consumption of OH− ions during silica dissolution is always very higher as compared to the supply of OH− ions during lime dissolution. This decrease can be higher during the period between 7 and 28 days. This behavior shows that the enhancement of soil properties will depend on the pH value after the reduction. If the pH value after the reduction is about or higher than 12.3, the long-term reactions will continue and consequently, the improvement in soil properties will also continue. Figure 4 shows a comparison study which was made between the developed UCS–model (Eq. 4) and two existing models proposed by Ghobadi et al. (2014) (Eq. 5) and Gupta and Prasad (2018) (Eq. 6) using experimental-UCS results obtained from three research studies (Little et al., 1987; Dayioglu et al., 2017; Noorzad and Motevalian, 2018) after a curing period of 28 days.

$$UCS = 321.21\ (L)^{0.7272} \quad (\text{at } t = 28 \text{ days}) \tag{5}$$

$$UCS = 44.22\ (t)^{0.45}\ (L)^{1.0} \tag{6}$$

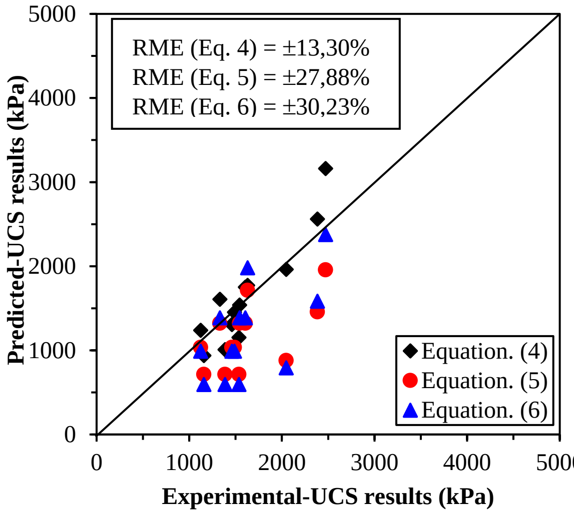

Figure 4 A comparison of proposed and existing models with experimental observations

From the results shown in Figure 4, it is quite clear to see that the two existing models of by Ghobadi et al. (2014) and Gupta and Prasad (2018) show a significant scatter (a high dispersion) from the line of equality. In contrast, the UCS predicted by the proposed model (Eq. 4) is generally closely distributed around the line of equality for lime contents lower than 10% and therefore is much closer than existing models. This reflected that the proposed UCS–model is accurate enough to be used as a simple tool to approximate the UCS of lime-stabilized high plasticity clayey soils as compared to the precision made by those suggested by by Ghobadi et al. (2014) and Gupta and Prasad (2018). However, for lime more than 10%, this model will overestimate the strength. This overestimation of strength is explained by the fact that in the majority of the studies summarized in Table 1 (used to fit the proposed model) lime contents have not exceeded 10%.

6. CONCLUSIONS

This work was undertaken in order to develop best-fit models for predicting the unconfined compressive strength of lime stabilized clayey soils. Based on obtained results, the following conclusions can be drawn:

- The proposed UCS–model was successfully tested using (*t*-test) and (*F*-test), trained and validated. This model can be used for assessing the UCS of lime-stabilized clayey soils.
- The obtained results showed that the statistical analysis of geotechnical data could be one of the suitable techniques for developing new statistical models which can present the best understanding of problematic soils behavior.
- The comparison study between experimental results and predicted values indicated that the constructed model can be reasonably applied to explain the effect of lime percentage below 10%, and curing time between 0 and 90 days on UCS of clayey soils, and to design new mixtures without making experimental studies.
- Both the (*t*-test) and (*F*-test) showed that the significance values of all the developed models are less than α (α = 0.05) which indicates that all the studied parameters considerably contribute to the constructed UCS–model and lead to the better prediction of UCS.
- It was found that the existing UCS–models showed a low preciseness and poor correlation at 28 days and for different lime percentages as compared to the proposed UCS–model where the measured UCS values are closely distributed around the line of equality.
- The coefficient of determination and validation study showed a better accuracy of the constructed UCS–model for predicting the UCS for lime with percentage between 0% and 10% and curing time less than or equal to 90 days. This model (Eq. 4) is recommended to be used in practices of civil engineering projects such as roadway subgrades, road embankments, trench backfills, landfill liners and earth dams for preliminary design. However, laboratory testing is recommended to verify the results for detailed design.
- The proposed model should be limited to use in preliminary design as a simple tool to estimate the unconfined compressive strength (UCS) of clayey soils stabilized with below 10% lime and for curing times varying from 0 to 90 days.
- It is suggested as a perspective to develop predictive models for the rest of the properties (e.g. shear strength, California bearing ratio (CBR), compressibility, plasticity etc.) of stabilized problematic soils using lime and other mineral additives such as cement, fly ash, slag, and natural pozzolana.

7. ACKNOWLEDGMENTS

This research was funded by the General Directorate for Scientific Research and Technological Development (DGRSDT) of the Algerian Minister of Higher Education and Scientific Research.

8. REFERENCES

Afès, M., and Didier, G. (2000) "Stabilization of expansive soils: the case of clay in the area of Mila (Algeria)", Bulletin of Engineering Geology and the Environment, 59, Issues 1, pp75-83.

Alhassan, M. (2008) "Permeability of lateritic soil treated with lime and rice husk ash", Assumption University Journal of Thailand, 12, Issues 2, pp115–120.

Al-Mukhtar, M., Khattab, S., and Alcover, J. (2012) "Microstructure and geotechnical properties of lime-treated expansive clayey soil", Engineering Geology, 139, pp17-27.

Al-Taie, A., Disfani, M., Evans, R., Arulrajah, A., and Horpibulsuk, S. (2016) "Impact of curing on behaviour of basaltic expansive clay", Road Materials and Pavement Design, pp1-22. DOI: 10.1080/ 14680629.2016.1267660.

Baglari, D., and Dash, S. (2013) "Improvement of expansive soil by lime and reinforcement", Indian Geotechnical Conference, Roorkee, pp1-6.

Baldovino, J., Moreira, E., Teixeira, W., Izzo, R., and Rose, J. (2018) "Effects of lime addition on geotechnical properties of sedimentary soil in Curitiba, Brazil", Journal of Rock Mechanics and Geotechnical Engineering, 10, Issues 1, pp188-194.

Beckham, T., and Hopkins, T. (1997) "Stabilization of an airport subgrade using hydrated lime and fly ash", Kentucky Transportation Center College of Engineering University of Kentucky, Lexington, Research Report, KTC-97-20.

Behak, L. (2011) "Performance of full-scale test section of low-volume road with reinforcing base layer of soil-lime", Transportation Research Record: Journal of the Transportation Research Board, 2204, pp158-164. DOI: 10.3141/2204-20.

Behak, L., and Núñez, W. (2017) "Mechanistic behaviour under traffic load of a clayey silt modified with lime", Road Materials and Pavement Design, pp1-17. DOI: 10.1080/14680629.2017.1296884.

Bell, F. (1996) "Lime stabilization of clay minerals and soil", Engineering Geology, 42, Issues 4, pp223-237.

Bozbey, I., and Garaisayev, S. (2010) "Effects of soil pulverization quality on lime stabilization of an expansive clay", Environmental Earth Sciences, 60, Issues 6, pp1137-1151. DOI: 10.1007/s12665-009-0256-5.

Cai, Y., Shi, B., Ng, C., and Tang, C. (2006) "Effect of polypropylene fiber and lime admixture on engineering properties of clayey soil", Engineering geology, 87, Issues 3-4, pp230-240. DOI: 10.1016/j.enggeo.2006.07.007.

Cheng, Y, and Huang, X. (2019) "Effect of Mineral Additives on the Behavior of an Expansive Soil for Use in Highway Subgrade Soils", Applied sciences, 9, Issues 1, 30. DOI:10.3390/app9010030

Cerato, A., Miller, G., Snethen, D., and Hussey, N. (2011) "Validation and Refinement of Chemical Stabilization Procedures for Pavement Subgrade Soils in Oklahoma-Volume 1", University of Oklahoma, School of Civil Engineering and Environmental Science,Final ReportESL-TR-86-19.

Consoli, N., Dalla Rosa Johann, A., Gauer, E., Dos Santos, V., Moretto, R., and Corte, M. (2012) "Key parameters for tensile and compressive strength of silt–lime mixtures", Géotechnique Letters, 2, Issues 3, pp81-85. DOI: 10.1680/geolett.12.00014.

Consoli, N., Da-Silva, L., Jr, L., and Heineck, K. (2009) "Key parameters for the strength control of lime stabilized soils", Journal of Materials in Civil Engineering, 21, Issues 5, pp210-216. DOI: 10.1061/(ASCE)0899-1561(2009)21:5(210).

Damoerin, D., Hadiwardoyo, S., and Minaroy, T. (2016) "Characteristics of lime-stabilized Depok residual soil", ARPN Journal of Engineering and Applied Sciences, 11, Issues 1, pp554-558.

Dayioglu, M., Cetin, B., and Nam, S. (2017) "Stabilization of expansive Belle Fourche shale clay with different chemical additives", Applied Clay Science, 146, pp56-69. DOI: 10.1016/j.clay.2017.05.033.

Etim, R., Eberemu, A., and Osinubi, K. (2017) "Stabilization of black cotton soil with lime and iron ore tailings admixture", Transportation Geotechnics, 10, pp85-95. DOI:10.1016/j.trgeo.2017.01.002.

Gadouri, H., Harichane, K., and Ghrici, M. (2017d) "Assessment of sulphates effect on pH and pozzolanic reactions of soil–lime–natural pozzolana mixtures", International Journal of Pavement Engineering, pp1-14. DOI: 10.1080/10298436.2017.1337119.

Gadouri, H., Harichane, K., and Ghrici, M. (2017a) "Effect of calcium sulphate on the geotechnical properties of stabilized clayey soils", Periodica Polytechnica Civil Engineering, 61, Issues 2, pp256-271. DOI: 10.3311/PPci.9359.

Gadouri, H., Harichane, K., and Ghrici, M. (2017c) "Effect of sodium sulphate on the shear strength of clayey soils stabilised with additives", Arabian Journal of Geosciences, 10, Issues 10, pp218-235. DOI: 10.1007/s12517-017-3016-y.

Gadouri, H., Harichane, K., and Ghrici, M. (2016a) "Effects of Na_2SO_4 on the geotechnical properties of clayey soils stabilised with mineral additives", International Journal of Geotechnical Engineering, 11, Issues 5, pp500-512. DOI: 10.1080/19386362.2016.1238.

Ghobadi, M. H., Abdilor, Y., and Babazadeh, R. (2013) "Stabilization of clay soils using lime and effect of pH variations on shear strength parameters", Bulletin of Engineering Geology and the Environment, 73, Issues 2, pp611-619. DOI 10.1007/s10064-013-0563-7.

Goodarzi, A., Goodarzi, S., and Akbari, H. (2015) "Assessing geo-mechanical and micro-structural performance of modified expansive clayey soil by silica fume as industrial waste", Iranian Journal of Science and Technology, Transactions of Civil Engineering, 39, Issues C2, pp333-350.

Gupta, C., and Prasad, A. (2018) "Variables controlling strength of lime stabilized jarosite waste", International Journal of Geo-Engineering, 9, Issues 1, . doi.org/10.1186/s40703-018-0074-2.

Harichane, K., Ghrici, M., and Kenai, S. (2012) "Effect of the combination of lime and natural pozzolana on the compaction and strength of soft clayey soils: a preliminary study", Environmental Earth Sciences, 66, Issues 8, pp2197-2205.

Harichane, K., Ghrici, M., Kenai, S., and Grine, K. (2011) "Use of natural pozzolana and lime for stabilization of cohesive soil", Geotechnical and Geological Engineering, 29, Issues 5, pp759-769. DOI: 10.1007/s10706-011-9415-z.

Harish, G. (2017) "Studies on Stabilization of Black Cotton Soil Using Lime", International Research Journal of Engineering and Technology (IRJET), 4, Issues 6, pp1725-1727. Retrieved from https://www.irjet.net/archives /V4/i6/ IRJET-V4I6326.pdf.

Harty, J., and Thompson, M. (1973) "Lime reactivity of tropical and subtropical soils", Highway Research Record, 442, pp102-112.

Hopkins, T., and Allen, D. (1986) "Lime Stabilization of Pavement Subgrade Soils of Section AA-19 of the Alexandria-Ashland Highway", Kentucky Transportation Research Program: UKTRP.-86–24. 1986, Research Report, URL: http://dx.doi.org/10.13023/ KTC.RR.1986.2.

Hossain, K., Lachemi, M., and Easa, S. (2007) "Stabilized soils for construction applications incorporating natural resources of Papua New Guinea", Resources, Conservation and Recycling, 51, Issues 4, pp711-731. DOI: 10.1016/j. resconrec.2006.12.003.

Hussey, N., Cerato, A., Grasmick, J., Holderby, E., Miller, G., and Tabet, W. (2010) "An assessment of soil parameters governing soil strength increases with chemical additives", Florida 2010: Advances in Analysis, Modeling & Design, Florida, USA, pp2702-2711.

Ismaiel, H.A.H. (2006) "Treatment and improvement of the geotechnical properties of different soft fine-grained soils using chemical stabilization", Doctoral dissertations, Martin-Luther-Universität Halle-Wittenberg, Allemagne.

Jafer, H., Hashim, K., Atherton, W., and Alattabi, A. (2016) "A statistical model for the geotechnical parameters of cement-stabilised High town's soft soil: a case study of Liverpool, UK", World Academy of Science, Engineering and Technology, International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering, 10, Issues 7, pp16-921.

Jahandari, S., Saberian, M., Zivari, F., Li, J., Ghasemi, M., and Vali, R. (2017) "Experimental study of the effects of curing time on geotechnical properties of stabilized clay with lime and geogrid", International Journal of Geotechnical Engineering, pp1–12. DOI: 10.1080/19386362. 2017.1329259.

James, J., and Pandian, P. (2017) "Role of phosphogypsum and ceramic dust in amending the early strength development of a lime stabilized expansive soil", International Journal of Sustainable Construction Engineering and Technology, 7, Issues 2, pp38-49.

Jha, A., and Sivapullaiah, P. (2015) "Mechanism of improvement in the strength and volume change behavior of lime stabilized soil", Engineering Geology, 198, pp53-64. DOI: 10.1016/j.enggeo.2015.08.020.

Kate, J. (2005) "Strength and volume change behavior of expansive soils treated with fly ash", Geo-Frontiers Congress: Innovations in Grouting and Soil Improvement.,Austin, Texas, United States. doi.org/10.1061/40783(162)19.

Kavak, A., and Baykal, G. (2012) "Long-term behavior of lime-stabilized kaolinite clay", Environmental earth sciences, 66, Issues 7, pp1943-1955. DOI: 10.1007/s12665-011-1419-8.

Kavak, A., and Bilgen, G. (2016) "Reuse of ground granulated blast furnace slag (GGBFS) in lime stabilized embankment materials", IACSIT International Journal of Engineering and Technology, 8, Issues 1, pp11-14. DOI: 10.7763/IJET.2016.V8.850.

Khalid, N., Mukri, M., Kamarudin, F., Sidek, N., and Arshad, M. (2014) "Strength of Soft Soil Stabilized Using Lime-POFA Mixtures", InCIEC 2013, Springer, Singapore, pp501-510

Khattab, S., Al-Mukhtar, M., and Fleureau, J. (2007) "Long-term stability characteristics of a lime-treated plastic soil", Journal of Materials in Civil Engineering, 19, Issues 4, pp358-366.

Kolias, S., Kasselouri-Rigopoulou, V., and Karahalios, A. (2005) "Stabilization of clayey soils with high calcium fly ash and cement", Cement and Concrete Composites, pp301-313. DOI:10.1016/j.cemconcomp.2004.02.019.

Ling, F., Kassim, K., Karim, A., Tarmizi, A., and Ho, S. (2014) "Evaluation of contributing factors on strength development of lime stabilized artificial organic soils using statistical design of experiment approach", Advanced Materials Research, pp362-368. DOI: 10.4028/www.scientific.net/AMR. 905.362.

Little, D., Thompson, M., Terrell, R., Epps, J., and Barenberg, E. (1987) "Soil stabilization for roadways and airfields", Engineering & Services Laboratory :Air Force Engineering & Services Center. Tyndall Air Force Base, Florida, USA,Final Report, ESL-TR-86-19.

Manasseh, J., and Olufemi, A. (2008) "Effect of lime on some geotechnical properties of Igumale shale", Electronic Journal of Geotechnical Engineering, 13, Issues 6, pp1-12. DOI: 10.1.1.534.4790.

Medhani, R. (1983) "Stabilization of Ponca city shale", Doctoral dissertations, University of Oklahoma. Retrieved fromhttps://shareok.org/bitstream/handle/11244/5049/8302454 .PDF?sequence=1&isAllowe d=y.

Mitchell, J. (1986) "Practical problems from surprising soil behaviour", Journal of Geotechnical Engineering, 112, Issues 3, pp274-279. DOI: 10.1520/STP15529S.

Nalbantoglu, Z. (2006) "Lime stabilization of expansive clay", Expansive soils: recent advances in characterization and treatment, Taylor & Francis, pp139-148.

Naveena, P., Dinesh, S., Gowtham, B., and Umesh, T. (2017) "Prediction of Strength Development in Black Cotton Soil Stabilised with Chemical Additives", Indian Geotechnical journal, 47, Issues 3, pp286-302. DOI: 10.1007/s40098-016-0209-3.

Negawo, W., Di Emidio, G., Bezuijen, A., Verastegui Flores, R., and François, B. (2017) "Lime-stabilisation of high plasticity swelling clay from Ethiopia", European Journal of Environmental and Civil Engineering, pp1-11. DOI: 10.1080/19648189.2017.

Neubauer. (1972) "Stability properties of uncured lime-treated fine-grained soils", Highway research record, 381, pp20-26.

Nicholson, P., Kashyap, V., and Fujii, C. (1994) "Lime and fly ash admixture improvement of tropical Hawaiian soils", Transportation Research Record, 1440, pp71-78.

Noorzad, R., and Motevalian, S. (2018) "Improvement of Clayey Soil with Lime and Industrial Sludge", Geotechnical and Geological Engineering, pp1–10. DOI: 10.1007/s10706-018-0515-x.

Önal, O. (2015) "Lime Stabilization of Soils Underlying a Salt Evaporation Pond: A Laboratory Study", Marine Georesources & Geotechnology, 33, Issues 5, pp391-402. DOI: 10.1080/1064119X.2014.909 297.

Osinubi, K. (2006) "Influence of compactive efforts on lime-slag treated tropical black clay", Journal of Materials in Civil Engineering, 18, Issues 2, pp175-181. DOI: 10.1061/ (ASCE)0899-1561(2006)18:2(175).

Osinubi, K., and Nwaiwu, C. (2006) "Compaction delay effects on properties of lime-treated soil", Journal of Materials in Civil Engineering, 18, Issues 2, pp250-258. DOI: 10.1061/(ASCE)0899-1561(2006)18:2(250).

Petry, T., and Lee, T. (1988) "Comparison of Quicklime and Hydrated Lime Slurries for Stabilization of Highly Active Clay Soils", Transportation Research Record, 1190, pp31-37.

Pinero Rivera, C. (2001) "Use of high volume fly ash cement for stabilization of expansive soils with high soluble sulfates content", Doctoral dissertations, Texas A & M University.

Portelinha, F., Lima, D., Fontes, M., and Carvalho, C. (2012) "Modification of a lateritic soil with lime and cement: an economical alternative for flexible pavement layers", Soils and Rocks, São Paulo, 35, Issues 1, pp51-63.

Prasade, G. (1972) "Role of fly ash in soil-lime stabilization", Master of technology, Indian Institute of Technology, Kanpur. Retrieved from https://archive.org/details/in.ernet. dli.2015.223276.

Quilici, F. (1972) "The Characteristics and uses of Montana fly ash", Master of Science, Montana College of mineral science and technology, Butte, Montana, USA.

Rahman, M. (1986) "The potentials of some stabilizers for the use of lateritic soil in construction", Building and Environment, 21, Issues 1, pp57-61. DOI: 10.1016/ 0360-1323(86)90008-9.

Samantasinghar, S. (2014) "Geo-engineering properties of lime treated plastic soils", Doctoral dissertations, National Institute of technology, Rourkela, India. Retrieved from http://ethesis.nitrkl.ac.in/6523 /1/e-9.pdf.

Sari Ahmed, B., Gadouri, H., Ghrici, M., and Harichane, K. (2018) "Best-fit models for predicting the geotechnical properties of FA–stabilised problematic soils used as materials for earth structures", International Journal of Pavement Engineering, pp1-15. DOI:10.1080/10298436.2018.1517874.

Sharma, L., and Singh, T. (2018) "Regression-based models for the prediction of unconfined compressive strength of artificially structured soil", Engineering with Computers, 34, Issues 1, pp175-186. DOI: 10.1007/s00366-017-0528-8.

Sharma, R., and Hymavathi, J. (2016) "Effect of fly ash, construction demolition waste and lime on geotechnical characteristics of a clayey soil: a comparative study", Environmental Earth Sciences, 75:377, Issues 5, pp1-11. DOI: 10.1007/s12665-015-4796-6.

Sharma, R., Phanikumar, B., and Rao, B. (2008) "Engineering behaviour of a remolded expansive clay blended with lime, calcium chloride and rice- husk ash", Journal of Materials in Civil Engineering, 20, Issues 8, pp509-515.

Shen, Z., Cao, Y., and Fang, L. (2017) "Experimental Investigation of Rapid Stabilization of Soft Clay Soils Using Chemical Admixtures", Soil Mechanics and Foundation Engineering, 54, Issues 3, pp202-210. DOI: 10.1007/s11204-017-9459-z.

Siddique, A., and Hossain, M. (2011) "Effects of lime stabilization on engineering properties of an expansive soil for use in road construction", Journal of Society for Transportation and Traffic Studies, 2, Issues 4, pp1-9.

Sirivitmaitrie, C., Puppala, A., Chikyala, V., Saride, S., and Hoyos, L. (2008) "Combined lime and cement treatment of expansive soils with low to medium soluble sulfate levels", In GeoCongress 2008: Geosustainability and Geohazard Mitigation, New Orleans, Louisiana, United States, pp646-653.

Solanki, P., Zaman, M., and Khalife, R. (2011) "Tube suction test for evaluating durability of cementitiously stabilized soils", Oklahoma Transportation Center, Midwest City, Oklahoma,Technical report: OTCREOS7.1-52-F.

Soltani, A., Taheri, A., Khatibi, M., and Estabragh, A. (2017) "Swelling potential of a stabilized expansive soil: a comparative experimental study", Geotechnical and

Geological Engineering, 35, Issues 4, pp1717-1744. DOI: 10.1007/s10706-017-0204-1.

Sridharan, A., Prashanth, J., and Sivapullaiah, P. (1997) "Effect of fly ash on the unconfined compressive strength of black cotton soil", Proceedings of the Institution of Civil Engineers-Ground Improvement, 1, Issues 3, pp169-175. DOI: 10.1680/gi.1997.010304.

Taleb Bahmed, I., Harichane, K., Ghrici, M., Boukhatem, B., Rebouh, R., and Gadouri, H. (2017) "Prediction of geotechnical properties of clayey soils stabilised with lime using artificial neural networks (ANNs)", International Journal of Geotechnical Engineering, pp1-13.

Tehrani, B. (1988) "Chemical stabilisation of Whaka Terrace loess Christchurch", Master of technology, University of Canterbury. Retrieved from https://ir.canterbury.ac.nz/ bitstream/ handle/10092/6705/tehrani_thesis .pdf.

Tuncer, E., and Basma, A. (1991) "Strength and stress-strain characteristics of a lime-treated cohesive soil", Transportation Research Record, 1295, pp70–79.

Wang, D., Zentar, R., and Abriak, N. (2016) "Temperature-Accelerated strength development in stabilized marine soils as road construction materials", Journal of Materials in Civil Engineering, 29, Issues 5, 04016281. DOI: 10.1061/(ASCE)MT.1943-5533.0001778.

Yilmaz, F., Kamiloğlu, H., and Şadoğlu, E. (2015) "Soil stabilization with using waste materials against freezing-thawing effect", Acta Physica Polonica, 128, Issues 2B, pp392-394. DOI: 10.12693/APhysPolA.128.B-392.

Yilmaz, I., and Civelekoglu, B. (2009) "Gypsum: an additive for stabilization of swelling clay soils", Applied Clay Science, 44, pp166-172. DOI: 10.1016/j.clay. 2009.01.020.