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BEARING CAPACITY OF STRIP FOOTING ON LIME STABILIZED EXPANSIVE CLAYEY SOIL

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ABSTRACT

To investigate and understand the effect of lime on the engineering properties of an expansive clayey soil, 4% lime by weight of the dry soil have been added. The stabilized soil specimens were subjected to unconfined compression, swelling potential and pH value tests. Also, a finite element analyses using PLAXIS-2D software were conducted. The studied parameters include the footing size and thickness of lime stabilized soil, and then compared with the natural soil. It was proved that lime content and curing duration had a significant effect on the engineering properties of lime-treated soil. The curing duration had significantly enhanced the strength properties of the lime stabilized soil specimens, where, unconfined compressive strength has significantly improved. Also, the pH value was decreased with increasing curing durations. Moreover, it was found that the swelling potential of the lime-treated soil specimens was reduced by lime addition and increasing of the curing duration. The results of numerical analysis show that the stress-settlement behaviour and ultimate bearing capacity of footing can be considerably enhanced as the thickness of lime-treated increases, and the influence of footing width seems to be insignificant.

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قابليـــة تحمـــل الأســـس الشـــريطية المقامـــة علـــى تربـــة طينيـــة انتفاخيـــة مثبتة بالنورة

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الخلاصة

لغرض فهم تأثير النورة على الخصائص الهندسية لتربة طينية انتفاخية ، تم إضافة نسبة 4% منها مقاسة من وزن التربة الجافة. تم إجراء بعض الفحوصات المختبرية على نماذج التربة المثبتة بالنورة وشملت فحص الانضغاط غير المحصور وفحص نسبة الانتفاخ وفحص الرقم الهيدروجيني pH. كذلك تم إجراء تحليل نظري بطريقة العناصر المحددة وذلك باستخدام برنامج PLAXIS-2D، حيث تم تحليل نتائج سلوك الإجهاد-الهبوط ومقارنة النتائج التي ظهرت مع النتائج الخاصة بالتربة الطبيعية غير المثبتة. شملت العوامل المدروسة تأثير حجم الأساس وتأثير سمك طبقة التربة المثبتة بالنورة. تم ملاحظة التأثير الواضح لكل من محتوى النورة ومدة الإنضاج على الخصائص الهندسية للتربة الطينية الانتفاخية. إن لمدة الإنضاج تأثير واضح على مقاومة الانضغاط غير المحصور، حيث لوحظ تحسن القيمة بشكل واضح مع زيادة مدة الإنضاج. في حين لوحظ بأن الرقم الهيدروجيني pH ونسبة الانتفاخ يقلان مع زيادة محتوى النورة ومدة الإنضاج. إن دراسة التحليل النظري باستخدام طريقة العناصر المحددة بينت إمكانية تحسين سلوك الإجهاد-الهبوط وقابلية تحمل التربة بشكل واضح مع زيادة سمك طبقات التربة المثبتة بالنورة وأن تأثير عرض الأساس لم يكن ذو تأثير كبير.

الكلمات الدالة: قابلية التحمل، التربة الانتفاخية، التثبيت بالنورة، الأساس الشريطي، برنامج PLAXIS-2D، التحليل العددي.

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1. Introduction

Expansive soils are widespread around the world especially, in the arid and semi-arid regions. These soils are considered very dangerous to the engineering structures when built upon, because of their tendency to swelling and shrinkage during wet-dry seasons [1-4] Higher volume change and cracks propagation of expansive soils represented a challenging task for the geotechnical engineers during construction of the embankment, highways and foundation of structures (especially light weight structures) on such soils. The alteration of soil with lime addition to enhance its engineering properties is very well recognized and widely practiced. Through lime stabilization, the soil plasticity is decreased, while its shear strength, compressive strength and bearing capacity are enhanced [2, 5-9]. Such improvements are due to the number of chemical processes taking place in the presence of lime [10]. At the initial time of the lime addition, Ca^{++} ions fixes to the surface of the clay mineral and the calcium ions replace most of the available exchangeable cations [11]. This reaction is called cation exchange leads to flocculation and agglomeration [6]. As a result of this reaction workability and plasticity is going to be enhanced [7, 12, 13]. The long term reaction consists of pozzolanic reaction, where calcium existing in lime reacts with alumina and silica existing in clay particles to make stable calcium aluminate hydrate CAH, calcium silicate hydrate CSH, also calcium aluminate silicate hydrate CASH, where they are responsible for the improvement of soil properties such as compressive strength, compressibility and volume change [2, 5-7]. This reaction continues for months or may be years to complete, which depends on the rate of chemical decomposition and the hydration of aluminates and silicates existing in the clayey soil [2]. A number of experimental and theoretical studies have been conducted to analyze the bearing capacity of footing constructed on soils [14-17]. The building structures might have suffered from many problems like cracking and spalling when constructed on expansive soils.

The objective of this research is to investigate the role of lime stabilization on enhancing the bearing capacity of footing constructed on expansive clayey soil. The study is divided into two parts. Firstly, experimental tests were conducted on the soil specimens represented by unconfined compression, free swell, and pH tests. Secondly, a numerical study using PLAXIS 2D software program was conducted to investigate the bearing capacity behaviour and factor of safety against failure of footing constructed on natural and lime stabilized clayey soil.

2. Experimental Program

2.1 Materials

Two components were used in this study for specimens' preparation: clayey soil and lime. The clayey soil was taken from Mosul city, north of Iraq at depth varied between (1.5–2.0) *m* under the surface ground. Index and physical properties of the soil i.e. Atterberg limits, specific gravity, hydrometer analysis and compaction tests were conducted in accordance with ASTM specifications [18]. These properties are exhibited in Table 1. According to USCS classification, the soil can be calssified as CH, i.e. fat clay. From the grain size distribution analysis the percentage of sand, silt and clay was (5, 46 and 49) % respectively. The hydrated lime used in the research has been obtained from Al-Meshrag Sulphur factory, which is a high fine product and passes through #40 sieve, its activity was 73%. Its chemical composition is exhibited in Table 2.

Table 1. Index, chemical and physical properties of natural soil

Properties		Values
Liquid Limit (%)		86
Plastic Limit (%)		32
Plasticity Index (%)		54
pH		7.97
Specific Gravity		2.75
Sand (%)		5
Silt (%)		46
Clay (%)		49
Standard Compaction Characteristics	Optimum Moisture Content, OMC (%)	26
	Maximum Dry Unit Weight (kN/m^3)	14.25
Soil Classification (USCS)	Group Symbol	CH
	Group Name	Fat Clay

Table 2. Chemical composition of lime

Chemical composition	$Ca(OH)_2$	CaO	$CaCO_3$	AL_2O_3	Fe_2O_3	SiO_2	MgO	H_2O	L.O.S
Weight (%)	73.0	6.1	5.2	0.17	0.04	10.1	4.19	0.09	1.11

L.O.S: Loss of Ignition

2.2. Specimens Preparation

A standard Proctor compaction effort ASTM D-698 [18] was specified in the preparation of soil specimens. The oven-dried soil (2 days at 60 °C) was ground initially and sieved through #4 (4.75 *mm*) sieve, thereafter, a required amount of water which represents OMC was gradually added to the dry soil. Mixing continued manually with sufficient time and care until getting a homogeneous mix. The mixture was kept in polyethylene bags for 24 *hrs.* To achieve uniform mixing of soil with water [7]. For the lime stabilized soil, 4% lime which represents the optimum percentage according to the Eades and Grim procedure [19], was added and thoroughly mixed with soil in a dry state, then, the previous procedure for the natural soil specimens was followed to get a homogeneous mix. The mixture was kept in polyethylene bags for 1 *hr* as mellowing time [7]. Thereafter, the soil specimen was compacted with a temping rod inside a specific mold which corresponds to the desired test to reach the maximum dry density. After that, the soil specimen was immediately extracted from the mold and then kept in polyethylene bags to keep moisture content without change. For the lime-treated soil specimens, they are immediately covered with cling film and paraffin wax to keep moisture without change, then put in desiccators to cure at 25 °C until tested at 2, 7 and 28 days.

2.3. Experimental Tests

2.3.1. Unconfined Compression Test

The unconfined compressive strength is considered one of the most important design parameters in road construction and earthwork applications [20]. The unconfined compressive strength was conducted in accordance with ASTM D-5102 [18] specification with cylindrical specimens 50 *mm* in diameter and 100 *mm* in height. The strain rate of 0.1 *mm/min* was used for the testing, and the loading process continued until the failure of the specimens occurred.

2.3.2. pH Test

The procedure recommended by Eades and Grim [19] was adopted. In this procedure, 20 *gm* of dried soil sieved through #40 (425 *µm*) sieve was mixed with 100 *ml* of distilled water and the solution was continuously shaken for a half *min* duration every 15 *min*. After 1 *hr.*, finally, thereafter, the pH value of the solution was measured.

2.3.3. Swelling Potential Test

A swelling potential test was conducted for natural and lime stabilized soil specimens using standard one dimensional odometer apparatus based on ASTM D-4546 specifications [18]. The compacted soil specimens were installed into the odometer apparatus within two porous stones, at the top of the odometer cell, a sensitive dial gauge was fixed in order to find the vertical displacement. The precision of the dial gage was 0.001 *mm* and the precision of the axial strain was 0.005%, which satisfies ASTM D-6026 specifications [18].

3. Finite Element Analysis

Finite element analysis using the commercial software PLAXIS 2D version 8.2 was used for the numerical analysis. The geometry of the finite element soil model adopted for the analysis is 10B × 20B with varying strip footing with (1.0, 1.5 and 2.0) *m* in width, rests on a clayey soil with varying thickness of lime stabilized (Natural soil, 0.25, 0.5, 0.75, 1.0, 2.0 and treated soil) *m*, in order to investigate the influence of the lime stabilization on the bearing capacity of footing. Fig. 1a shows the geometry model of footing.

The soil was defined by a linear elastic-perfectly plastic Mohr-Coulomb model. The kind of drainage was drained, where stiffness was modeled by drained Young's modulus (E_u) and drained Poisson's ratio (υ_u), and strength was modeled with drained shear strength (S_u). The clayey soil properties were obtained from a series of laboratory tests. The shear strength parameters (c and φ) for natural clayey soil have been obtained from direct shear test, while for lime stabilized soil the values were obtained from the unconfined compressive strength. These properties for both natural and lime stabilized clayey soil are exhibited in Table 3.

Fifteen nodes wedge element was adopted as a finite element mesh which is composed of six nodes triangles in horizontal axis and eight nodes quadrilaterals in vertical axis. The size of meshes is refined in order to obtain best and exact results. The boundary conditions were chosen such that no vertical or horizontal soil movement at the vertical boundaries. The finite element mesh of the footing is illustrated in Fig. 1b.

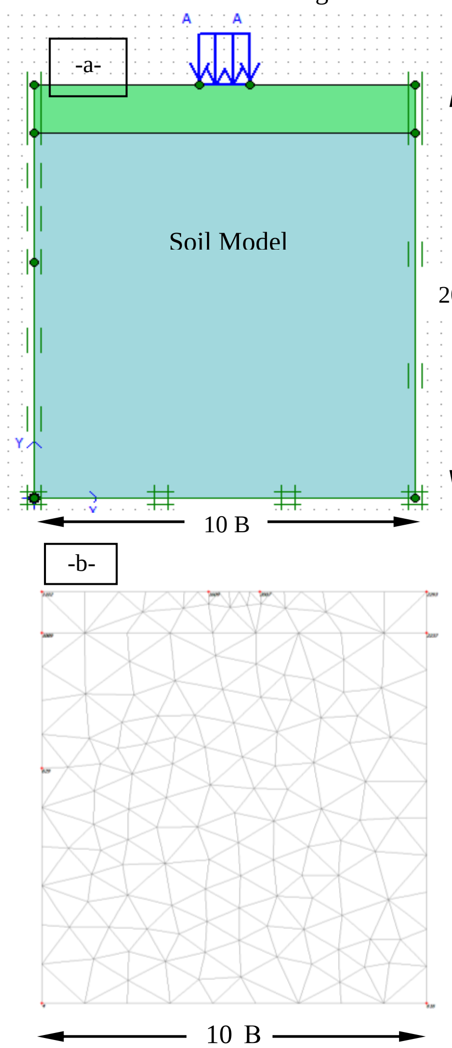

Fig. 1. Finite element model, a) Geometry model of footing resting on clayey soil layer, b) Plot of the mesh with significant nodes.

Table 3. Material properties of the study*

Parameter	Value	
	Natural clayey soil	Lime stabilized soil
Model of material	Mohr-Coulomb Model	
Secant Young's modulus, E_{ref} (kN/m^2)	15,000	50,000
Unsaturated unit weight (kN/m^3)	14.1	13.8
Saturated unit weight (kN/m^3)	18.0	17.0
Initial void ratio, e_{init}	0.5	0.5
Cohesion, c_{ref} (kN/m^2)	80	450
Friction angle, φ (°)	20	36

* All the results have been obtained from laboratory tests except Secant Young's modulus which was assumed in the analysis depending on Das, [21]

4. Results and Discussion

4.1. Variation of Unconfined Compressive Strength

The variations of the UCS values versus curing durations have been presented in Fig. 2a. As expected, the curing duration has a significant influence on the UCS of lime stabilized soil specimens, where, UCS has significantly improved until 14 days of curing, thereafter, the strength improvement seems to be slight. The improvement ratios were 4.0, 6.2, 7.3 and 7.8 time that of the natural soil specimen strength for 2, 7, 14 and 28 days curing durations respectively. This increase can be explained by the combined action of two factors. First, the given curing duration yields an amount of hydration materials like (CSH) and (CAH) gels due to hydration processes, the cementitious materials fill the pores and bond with each other to create solid network leading to a denser composition. Second, the reduction in the moisture content of soil specimens during curing durations causes gain in strength, since the moisture content correlate oppositely with UCS. The reduction in moisture content is due to the hydration process of lime. As well as, when the curing duration increased, the amount of pozzolanic compounds increased, leading to an increase in the unit weight of the material. The variation of the pH values with the UCS values of soil specimens is exhibited in Fig. 2b. Generally, the pH values decreased with increasing UCS of soil specimens and the relationship was polynomial with the coefficient of computation, R^2 equal to 0.97, however, a slight amount of scatter have been found in the data, which is due to the strength of lime stabilized soil primarily depends on the soil structure and chemical reactions products i.e. CSH and CAH, while, the pH of soil primarily depends on the calcium ions concentration in the pore fluid. Thus, the UCS of the soil specimens is not directly related to the pH values.

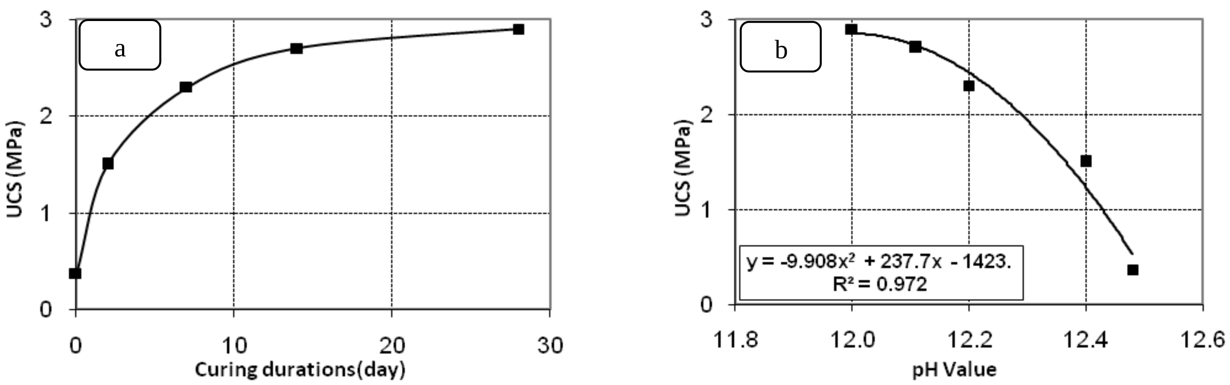

Fig. 2. Variation of UCS, a) UCS versus curing duration, b) UCS versus pH values.

4.2. Variation of pH Value

The pH value considered an important parameter in lime stabilization technique to supply suitable environment for pozzolanic compounds formation. According to the procedure suggested by Eades and Grim method [19], the minimum amount of lime required for soil stabilization was (4%). The variations in pH values of soil specimens with curing durations are exhibited in Fig. 3. It can be observed that pH value reduced with increasing curing durations and the variation curve exhibited a sharp reduce which extended to 7 days of curing, thereafter, pH values decreased with a gentle slope to reach a value of 12.0. The drop in pH value is considered an indicator for the long term reaction between lime and soil. Keller [22] stated that pH value greater than or equal to 10 is considered enough to start the formation of pozzolanic compounds in lime or cement-treated soil. The drop in pH values with curing durations is attributed to the calcium (Ca^{+2}) consumption during cation exchange and pozzolanic reactions [2, 9].

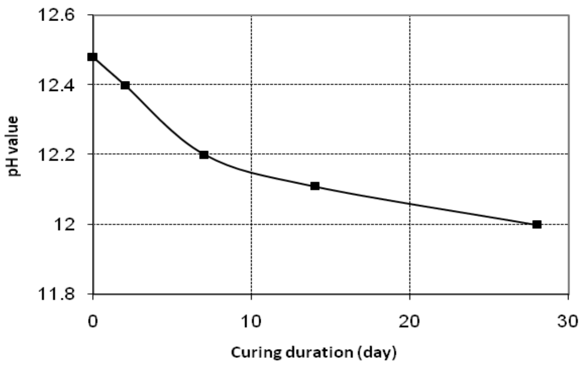

Fig. 3. Variation of pH value versus curing durations

4.3. Variation of Swelling Potential

Free swell potentials of natural and lime stabilized soil specimens are presented in Fig. 4. It is observed that swell potential decreased by the lime addition and this behaviour agrees with many previous studies [2, 9]. Further, the swell potential of stabilized soil specimens was suppressed at 28 days of curing at 20°C. This drop is due to the role of lime as an effective stabilizer that reduces the swelling potential of clayey soil. The addition of lime to clayey soil, cation exchange begins to take place immediately and leads to decrement on plasticity, workability, swelling and shrinkage properties of soil. Another reaction that causes decreasing in swell potential is a pozzolanic reaction, which is considered as the key parameter in lime stabilized soils. The Pozzolanic reaction is a time dependent reaction which results in cementitious materials (calcium silicate hydrated and calcium aluminate hydrated) which bind the adjacent soil particles together. Therefore, the value of swelling potential is going to decrease.

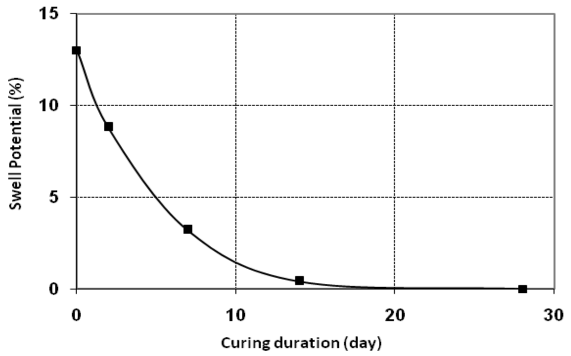

Fig. 4. Variation of swelling potential versus curing durations

4.4. Stress-Settlement Analysis

To investigate the influence of lime on the bearing capacity of footings, reference analysis using commercial software PLAXIS-2D version 8.2 was investigated on strip footings having different widths and the same soil properties. The stress-settlement relationships were exhibited for all studied cases as shown in Fig. 5 (a,b and c) for footing width (1.0, 1.5 and 2.0) *m* respectively. The failure stress was determined as the stress corresponding to displacement at (5) % of the footing width [18]. In the plate loading tests terminated at displacement less than (5) % of plate diameter, the failure stress was depended as the maximum stress applied on the plate, since at that stress the displacement increased successively without any increase in the imposed stress. The relationship between the failure stress of footing on lime stabilized soil to that on the natural soil is defined as the bearing capacity ratio, *BCR*, as exhibited in Table 4. The values of ultimate bearing capacity and *BCR* for different footing widths (1.0, 1.5 and 2.0) *m*, and different thickness of lime stabilized soil (Natural soil, 0.25, 0.50, 0.75, 1.00, 2.00 and treated soil) *m* are shown in Table 4. As the thickness of stabilized lime increases, the ultimate bearing capacity of footing increases. As a result the *BCR* increases. However, the influence of footing width on the *BCR* is observed to be slight or insignificant. The *BCR* for different footing width and different thickness of lime stabilization was ranged between (1.00-1.59), (1.00-1.52) and (1.00-1.45) for footing width (1.0, 1.5 and 2.0) *m* respectively as shown in Fig. 6.

Table 4. Bearing capacity ratio results

Footing width (*m*)	Thickness of lime stabilized soil (*m*)	Bearing capacity (kPa)	Bearing capacity ratio, *BCR*
1.0	Natural soil	333	1.00
	0.25	363	1.09
	0.50	394	1.18
	0.75	422	1.27
	1.00	448	1.35
	2.00	531	1.59
	Treated soil	> 1000	> 3.00
1.5	Natural soil	367	1.00
	0.25	388	1.06
	0.50	412	1.12
	0.75	440	1.20
	1.00	467	1.27
	2.00	557	1.52
	Treated soil	> 1000	> 3.00
2.0	Natural soil	398	1.00
	0.25	412	1.04
	0.50	428	1.08
	0.75	453	1.14
	1.00	479	1.20
	2.00	576	1.45
	Treated soil	> 1000	> 3.00

The maximum ultimate bearing capacity was recorded as (531, 557 and 576) kPa, for the thickness of lime stabilization equal to 2.0 *m*, which are equivalent to (1.59, 1.52 and 1.45) times of the ultimate bearing capacity of footing on natural soil layer. The bearing capacity ratio for the full treated soil layer can't be determined, however, it was more than 3.00 for different footing widths. This means that footings can sustain larger failure stress when the thickness of lime stabilization increases.

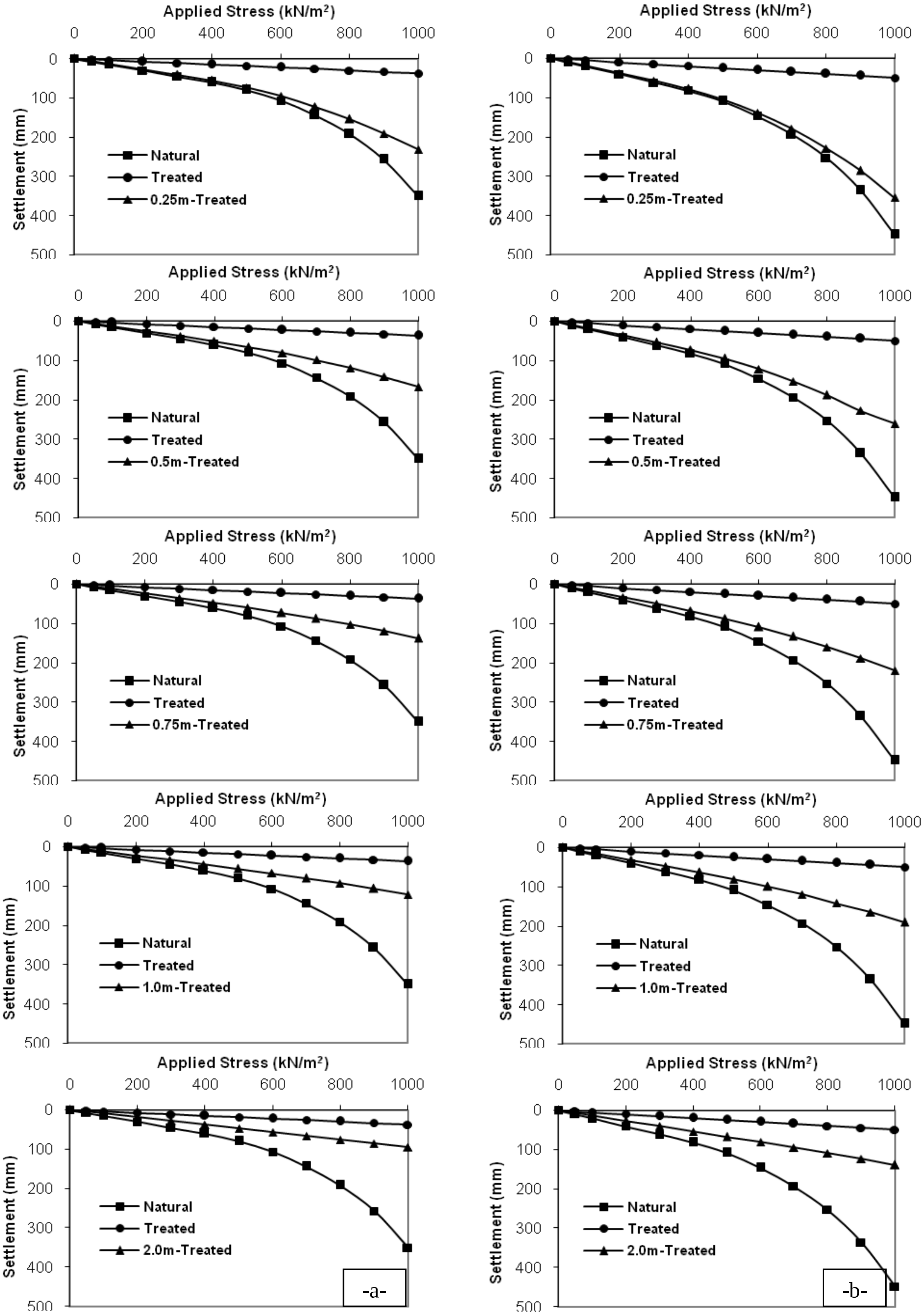

Fig. 5. Effect of lime on stress-settlement relationships with footing widths, a) B=1.0*m*, b) B=1.5*m*

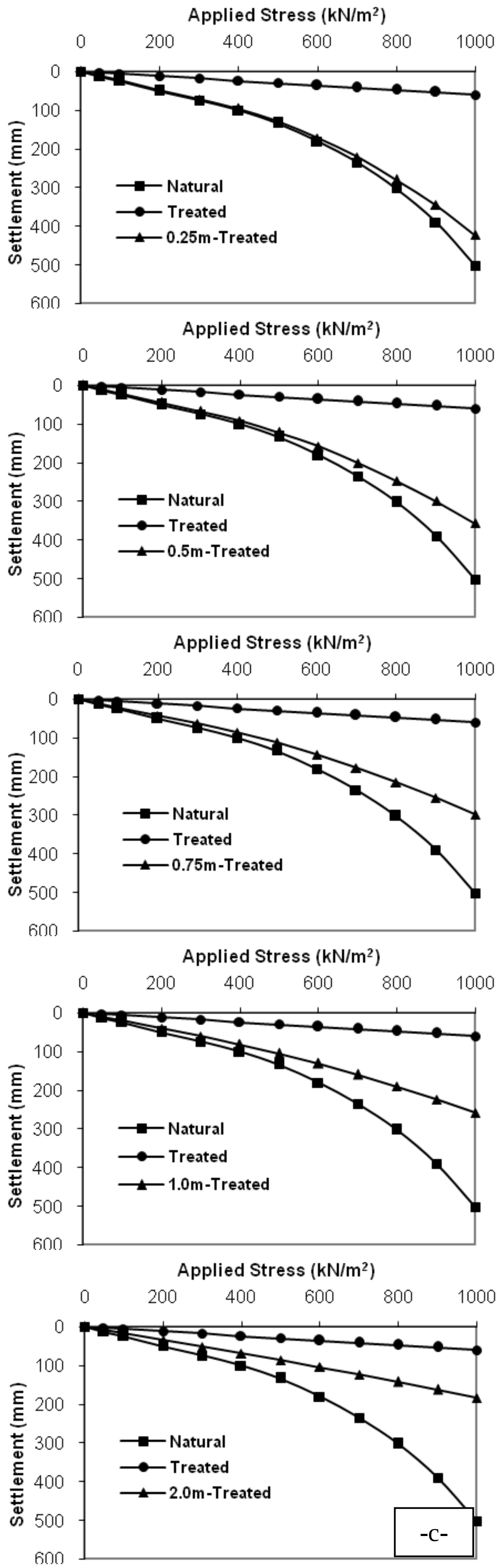

Fig. 5 c. Effect of lime on stress-settlement relationships with footing width, B=2.0 *m*

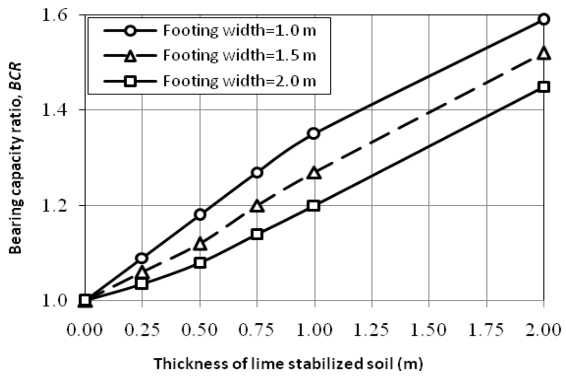

Fig. 6. Effect of lime stabilization and footing width on BCR

5. Conclusions

Based on the experimental laboratory tests conducted, and the numerical analysis using software PLAXIS-2D, the following may be concluded:

- The curing duration has a significant influence on the unconfined compressive strength of lime stabilized soil specimens, where, unconfined compressive strength has significantly improved until 14 days of curing, thereafter, the strength gain is observed to be slight.
- The pH values decreased with increasing unconfined compressive strength of lime stabilized soil specimens. This value mainly depends on the calcium ions concentration existing in the pore fluid. Also it decreased with increasing curing durations and the variation curve exhibited a sharp decrease, thereafter, is going to be a gentle slope.
- The swell potential decreased by the lime addition, and it is decreased with increasing curing duration until suppress at 28 days of curing.
- The stress-settlement relationships obtained from the finite element analysis at failure stress depends upon the thickness of lime stabilization, where footings can sustain larger failure stress as the thickness of lime stabilization increases, and the influence of footing width seems to be insignificant.

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