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A Sole Empirical Correlation Expressing Strength of Fine-Grained Soils – Lime Mixtures

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ABSTRACT: This paper advances understanding of the key parameters controlling unconfined compressive strength (q_u) of lime stabilized fine-grained soils by considering distinct specimen porosities (η), different lime types and contents and several curing temperatures and time periods. A sole empirical relationship establishing the normalized unconfined compression strength for lime stabilized fine-grained materials considering all porosities, lime contents, curing temperatures and curing periods studied is proposed. From a practical point of view, this means that a very limited number of unconfined compression tests on specific lime stabilized fine-grained material specimens molded with a given lime type and amount, porosity, moisture content and cured for a given time period at a particular temperature, should be sufficient to estimate the strength for an entire range of porosities and lime contents at any given condition. Examples of the practicality of the proposed relationship are presented.

Keywords: Normalization, porosity, lime, strength, fine grained soils, porosity/lime index.

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INTRODUCTION

Previous studies of fine-grained materials–lime mixtures (Consoli *et al.* 2011, 2014a,b and 2015) have shown that their behavior is complex, and affected by many factors, such as grain size distribution of the soil, lime type and content, molding moisture content, porosity of the material, and curing temperature and time period. Consoli *et al.* (2009) were the first to establish a unique dosage methodology based on rational criteria where the porosity/lime index plays a fundamental role in the assessment of the target unconfined compressive strength. This study explores the influence of the amount of lime and the porosity on the unconfined compressive strength (q_u) of various fine-grained materials. A normalization was searched dividing every single strength value (for each material studied) by the unconfined compressive strength corresponding to a specific porosity/lime index, the result of which a unique power law function was obtained quantifying the influence of the amounts of lime, porosity, curing time and temperature in the assessment of q_u of fine-grained materials–lime mixtures. From a practical point of view, this means that carrying out a limited number of unconfined compression tests on specimens of the studied fine-grained materials molded with lime and cured for any time period, should allow the prediction of the unconfined compressive strength for an entire range of porosities and lime contents.

EXPERIMENTAL PROGRAM

The experimental program has been carried out in two parts. First, the properties of the several fine-grained materials were characterized. Then a number of unconfined compression tests were carried out for fine-grained materials - lime blends considering different amounts of lime, up to five dry unit weights varying from low to high density values, up to four moisture contents, curing temperatures and distinct curing time periods (from 1 to 360 days of curing).

Materials

Several fine-grained materials with distinct characteristics were considered in the present research, such as non-plastic and low plasticity soils, as well as industrial by-products such as powdered rock obtained from a cutting rock place and coal fly ash from a coal thermo-electrical power plant. The physical properties of the materials are presented in Table 1. Seven individual or combinations between different fine-grained materials were used as host matrix: dispersive clay, clayey sand (BRS), BRS + 25% powdered rock, BRS + 12.5% coal fly ash, BRS + 25% coal fly ash, coal fly ash, clayey soil from Italy and sulphated clay from Paraguay. The percentages of powdered rock and coal fly ash are calculated by mass of the BRS soil.

Quicklime [CaO - product of calcination of limestone, consists of the oxides of calcium], dolomitic and calcitic hydrated lime [$Ca(OH)_2$ - manufactured by treating quicklime with sufficient water to satisfy its chemical affinity for water, thereby converting the oxides to hydroxides] and calcitic carbide lime [$Ca(OH)_2$ - a by-product of the manufacture of acetylene gas] were used as binders. The combinations host material – binder used are presented in Table 2.

Methods

Molding and Curing of Specimens

For the unconfined compression tests, cylindrical specimens 50 mm in diameter and 100 mm high were used. Given a certain amount of fine-grained material (enough for molding a specimen), the amount of lime for each mixture was calculated based on the mass of dry fine-grained material. A target dry unit weight for a given specimen was then established through the dry mass of fine-grained materials-lime divided by the total volume of the specimen. As a general procedure, in order to keep the dry unit weight of the specimens constant with increasing lime content, an equivalent amount of the fine-grained material was replaced by lime. Porosity (η) is defined as the ratio of voids (in volume) over the total volume of the specimen and as shown by Eq. (1), it is a function of dry unit weight (γ_d) of the blend, lime content (L) and the unit weight of solids of host material (γs_s - see Table 1) and lime (γs_L – see Table 2) respectively

$$\eta = 100 - 100\left\{\left[\frac{\gamma_d}{1+\left(\frac{L}{100}\right)}\right]\left[\frac{1}{\gamma s_s}+\frac{\frac{L}{100}}{\gamma s_L}\right]\right\} \tag{1}$$

After each fine-grained material and lime was weighed, both materials were mixed until the mixture acquired a uniform consistency. Tap water between 13 and 18% by dry mass of host fine-grained material was then added, continuing the mixing process until a homogeneous paste was created. The specimen was then constructed in three layers each layer being statically compacted inside a cylindrical split mold, so that each layer reached the prescribed dry unit weight. In the process, the top of each layer was slightly scarified. After the molding, the specimen was immediately extracted from the split mold and its weight, diameter and height measured with accuracies of about 0.01g and 0.1mm, respectively. The specimens were cured in a humid room at specific temperatures (see Table 2) and relative humidity above 95%. The specimens were considered suitable for testing if they met the following tolerances: (i) *Dry unit weight* (γ_d): degree of compaction between 99% and 101% (the degree of compaction being defined as the value obtained in the molding process divided by the target value of γ_d); and (ii) *Dimensions*: diameter to within ±0.5mm and height ±1 mm.

Unconfined Compression Tests

Unconfined compression tests have been systematically used in most experimental programs reported in the literature in order to verify the effectiveness of the lime stabilization process or to explore the importance of influencing factors on the strength of reinforced soils. This test is largely used in practice for material strength characterization. The tests presented in this study followed Brazilian standard ASTM C39 (ASTM 2010) standard.

An automatic loading machine with maximum capacity of 50kN and a proving ring with capacity of 10kN and resolution of 0.005kN were used for the unconfined compression tests. Before carrying out testing, the specimens were submerged in a water tank for 24 hours for saturation to minimize suction (Consoli *et al*. 2012). The water temperature was controlled and maintained at 23º±2ºC. Immediately before the test, the specimens were removed from the water tank and dried superficially with an absorbent cloth. Then, the unconfined compression test was carried out and the maximum load recorded. Because of the typical scatter of data for unconfined compression tests, for each point, three specimens were tested. The testing program was chosen in such a way as to isolate, separately, the influences of the lime content, dry unit weight and porosity/lime index. The specimen molding conditions (lime contents, dry unit weights, moisture content and curing time period and temperature) of all tested fine-grained material are presented in Table 2.

RESULTS

Effect of the Lime Content, Dry Unit Weight and Porosity/Lime Index on Compressive Strength

The unconfined compressive strength (q_u) variation with lime content (L) for a dispersive clay treated with 3, 5 and 7 % of hydrated lime, water content of 13% and 28 days of curing period is shown in Fig. 1. It can be seen that an increase of both lime content and dry unit weight produces an increase of q_u. Other four fine-grained materials (clayey sand (BRS), BRS + 25% powdered rock, BRS + 12.5% coal fly ash, BRS + 25.0% coal fly ash) treated with hydrated lime and cured over periods varying from 7 to 360 days and a coal fly ash material treated with calcitic carbide lime (Consoli *et al.* 2014b) presented similar behavioral trends.

The typical unconfined compressive strength data shown in Figure 1, can further be presented function of an adjusted porosity/lime index, $\eta/(L_{iv})^C$, [expressed as porosity (η) divided by the volumetric lime content (L_{iv}), the latter given as a percentage of lime volume regarding total volume (Consoli *et al.* 2011)]:

$$q_u = A\left[\frac{\eta}{L_{iv}{}^{c}}\right]^{-B} \tag{2}$$

where *C*, *A* and *B* are material dependent parameters. Consoli *et al.* (2011) found that for the clayey sand soil (BRS) treated with hydrated lime contents between 3 and 11% and cured for 360 days at 23^o temperature, the *C* coefficient is 0.12. A similar *C* = 0.12 value appears to provide the best fit exponent for all fine-grained materials treated with lime types studied herein, as well as for all curing temperatures and curing periods, as shown in Figure 2.

Sole Correlation Determining Strength

Dividing Eq. (2) by an arbitrary specific value of the unconfined compression strength, corresponding to a given value of the adjusted porosity/lime index, $\frac{\eta}{L_{iv}{}^{0.12}} = \nabla$, leads to:

$$\frac{q_u}{q_u\left\{\frac{\eta}{L_{iv}{}^{0.12}}=\nabla\right\}} = \frac{A\left[\frac{\eta}{L_{iv}{}^{0.12}}\right]^{-B}}{A[\nabla]^{-B}} = [\nabla]^{B}\left[\frac{\eta}{L_{iv}{}^{0.12}}\right]^{-B} \tag{3}$$

If a fixed $\left\{\frac{\eta}{L_{iv}{}^{0.12}}\right\} = \nabla = 30$ value is chosen, (any ∇ value could be selected, and $\nabla = 30$ covers all fine-grained materials – lime mixtures studied), then a sole function can be obtained through a normalization process of the experimental unconfined compressive strength (q_u) values of all the studied fine-grained materials – lime blends with respect to the corresponding specific value of q_u at $\left\{\frac{\eta}{L_{iv}{}^{0.12}}\right\} = \nabla = 30$, to give:

$$\frac{q_u}{q_u\left\{\frac{\eta}{L_{iv}{}^{0.12}}=30\right\}} = 4.60x10^5\left[\frac{\eta}{L_{iv}{}^{0.12}}\right]^{-3.84} \tag{4}$$

The last column of Table 2 presents the q_u values used for normalization process for each material and curing periods, while Fig. 3 reassembles all the experimental results shown in Figure 2, including also Eq. (4).

Inevitably it can be observed the scatter of data around Eq. (4), but from a practical point of view, the meaning of relations like those given by Eqs. (3) and (4) is that carrying out a limited number of tests (in reality three identical specimens are tested in order to obtain a good representativity) with a specific fine-grained material, a given lime type and any given curing temperature and period, one could predict the effect of varying binder content and porosity across a wide range.

The validation for this unique relationship establishing the compressive strength was done considering two distinct soils: a clayey soil from Italy (Consoli *et al.* 2015) and a sulphated clay from Paraguay (Bittar 2017). The physical properties of both soils were presented in Table 1. The former soil was treated with quicklime and the latter was treated with hydrated calcitic lime Curing time period was short (7 days) from the Italian soil and long (90 and 180 days) for Paraguayan soil, validating the relationship use for distinct soils and a significant range of curing time periods.

Regarding the clayey soil from Italy, data were taken from the average of specimens with $\frac{\eta}{L_{iv}{}^{0.12}} = \nabla = 32.6$ and $q_u\left\{\frac{\eta}{L_{iv}{}^{0.12}} = 32.6\right\} = 870\ kPa$ (see Table 2 for details). Substituting the above values in Eq. (3), it results:

$$q_u\,(kPa) = 5.63\text{x}10^8\left[\frac{\eta}{(L_{iv})^{0.12}}\right]^{-3.84} \tag{5}$$

Varying $\left[\frac{\eta}{L_{iv}{}^{0.12}}\right]^{-3.84}$ from 32.0 to 42.0 in Eq. (5), a curve is drawn in Fig. 4 and plotted together with lab-testing data points from Consoli *et al.* (2015) for clayey soil of low plasticity and quicklime blends under curing period of 7 days. It can be observed in Fig. 4 that the curve obtained using Eq. (5) is describing the laboratory testing data with good accuracy.

Concerning the sulphated clay from Paraguay, information were taken from the average of specimens with $\frac{\eta}{{L_{iv}}^{0.12}} = \nabla = 23.6$ for 90 days of curing and $q_u\left\{\frac{\eta}{{L_{iv}}^{0.12}} = 23.6\right\} = 1509\ kPa$ and $\frac{\eta}{{L_{iv}}^{0.12}} = \nabla = 23.2$ for 180 days of curing and $q_u\left\{\frac{\eta}{{L_{iv}}^{0.12}} = 23.2\right\} = 2534\ kPa$ (see Table 2 for details). Substituting the above values in Eq. (3), it results:

$$q_u(kPa) = 2.80x10^8\left[\frac{\eta}{{L_{iv}}^{0.12}}\right]^{-3.84} \quad (6)$$

$$q_u(kPa) = 4.46x10^8\left[\frac{\eta}{{L_{iv}}^{0.12}}\right]^{-3.84} \quad (7)$$

Varying $\left[\frac{\eta}{{L_{iv}}^{0.12}}\right]^{-3.84}$ from 22.0 to 37.0 in Eqs. (6) and (7), respectively for 90 and 180 days of curing, curves were drawn in Fig. 5 together with lab-testing data points from Bittar (2017) for sulphated clay from Paraguay and hydrated calcitic lime blends. It can be observed in Fig. 5 that the curves obtained using Eqs. (6) and (7) are relating the laboratory testing data with sound accurateness.

CONCLUSIONS

From the data and analysis presented in this manuscript the following conclusions can be drawn:

- Taking advantage of the fact that an exclusive correlation shape expresses q_u versus $\eta/(L_{iv})^{0.12}$, as well as of a normalization of the data by dividing the values of q_u by the value of strength of a specific $\eta/(L_{iv})^{0.12}$ [see Eq. (3)] for all fine-grained materials–lime mixtures studied herein considering distinct moisture contents, porosities, amounts of lime, curing temperatures and periods studied, it was possible to establish and validate a sole relationship establishing strength of fine-grained soils with distinct characteristics (grain size distribution, plasticity index), distinct curing temperatures and curing periods up to 360 days, performing well in all studied conditions.
- From a practical viewpoint, this means that carrying out only a limited number of unconfined compression tests (in reality three identical specimens, in order to have a better representation of the average q_u value) with a specimen molded with a

specific binder and cured for a given time period, allows the establishment of an equation that controls the strength of a fine-grained soil-lime blend for distinct porosities and lime contents.

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NOTATION

D_{50}	*mean effective diameter*
L	*lime content (expressed in relation to mass of dry soil)*
L_{iv}	*volumetric lime content (expressed in relation to the total specimen volume)*
q_u	*unconfined compressive strength*
R^2	*coefficient of determination*
η	*porosity*
$\frac{\eta}{{L_{iv}}^{0.12}}$	*adjusted porosity/lime index*
γ_d	*dry unit weight of the blend*
γ_{sL}	*unit weight of lime*
γ_{ss}	*unit weight of fine-grained material*
w	*moisture content*

TABLES

Table 1. Physical properties of the soil samples

Soil Type	Dispersive Clay	Clayey Sand (BRS)	Powdered Rock	Coal fly ash	Clayey Soil from Italy	Sulphated Clay from Paraguay
Liquid limit (%)	43	23	28	-	40	33
Plastic limit (%)	19	13	20	-	20	17
Plastic index (%)	24	10	8	Non-plastic	20	16
Unit weight of solids - (γs_s) (kN/m^3)	27.4	26.4	33.3	21.6	26.7	26.9
Coarse sand (2.0mm < diameter < 4.75mm) (%)	-	-	-	1.0	-	-
Medium sand (0.425mm < diameter < 2.0mm) (%)	-	16.1	1.9	4.0	-	1.0
Fine sand (0.075mm < diameter < 0.425mm) (%)	7.0	45.5	38.4	15.0	3.0	14.0
Silt (0.002 mm < diameter < 0.075 mm) (%)	59.0	33.4	57.5	78.0	58.0	52.0
Clay (diameter < 0.002 mm) (%)	34.0	5.0	2.2	2.0	39.0	33.0
Mean particle diameter, D_{50} (mm)	0.005	0.12	0.03	0.015	0.012	0.06
USCS class	CL	SC	CL	ML	CL	CL

Table 2. Details of molding, curing and normalization data

Soil Type	Lime type	Unit weight of solids of lime γs_L (kN/m^3)	Lime contents L (%)	Molding dry unit weight γ_d (kN/m^3)	w (%)	Curing temperature (ºC)	Curing periods (days)	Normalization Index (∇)	Average q_u (kPa) for normalization
Clayey sand (BRS)	Dolomitic hydrated lime	24.9	3, 5, 7, 9 and 11	16.0, 17.0, 18.0 and 18.8	14	23	90, 180 and 360	$\frac{\eta}{{L_{iv}}^{0.12}} = 30$	250.3, 267.5 and 580.7 kPa, respectively for 90, 180 and 360 days of curing
Dispersive clay	Dolomitic hydrated lime	26.0	3, 5 and 7	16.0, 17.5 and 19.0	13	21	7, 28 and 60	$\frac{\eta}{{L_{iv}}^{0.12}} = 30$	1070, 1535.4 and 2010.5 kPa, respectively for 7, 28 and 60 days of curing
BRS + 25% Powdered Rock	Dolomitic hydrated lime	24.9	3, 5, 7, 9 and 11	16.0, 17.0, 18.0 and 18.8	14	23	28, 90 and 360	$\frac{\eta}{{L_{iv}}^{0.12}} = 30$	444.4, 873.7 and 1685.6 kPa, respectively for 28, 90 and 360 days of curing
BRS + 12.5% Coal Fly Ash	Dolomitic hydrated lime	24.9	3, 5, 7 and 9	14.0, 15.0, 16.0 and 17.0	14	23	28, 60, 90, 180 and 360	$\frac{\eta}{{L_{iv}}^{0.12}} = 30$	1206.7, 1993.4, 2649.8, 3142.3 and 2449.9 kPa, respectively for 28, 60, 90, 180 and 360 days of curing
BRS + 25.0% Coal Fly Ash	Dolomitic hydrated lime	24.9	3, 5, 7 and 9	14.0, 15.0, 16.0 and 17.0	14	23	28, 60, 90, 180 and 360	$\frac{\eta}{{L_{iv}}^{0.12}} = 30$	403.5, 3631.9, 6166.2, 6728.7 and 7083.0 kPa, respectively for 28, 60, 90, 180 and 360 days of curing
Coal Fly Ash	Carbide Lime	21.2	5, 10 and 15	11.0, 12.0 and 13.0	18	23, 40, 60 and 80	1, 3, 7 and 14	$\frac{\eta}{{L_{iv}}^{0.12}} = 30$	→ 1491.9 and 2383.0 kPa (23ºC) and 7 and 14 days of curing → 1397.3, 3341.8 and 10562.8 kPa (40ºC) and 1, 3 and 7 days of curing → 5005.9, 12216.1 and 26475.4 kPa (60ºC) and 1, 3 and 7 days of curing → 8852.6, 11540.8 and 14,970.2 kPa (80ºC) and 1, 3 and 7 days of curing
Clayey soil from Italy	Quicklime	33.7	2 to 4	16.0 to 18.0	Not known	23	7	$\frac{\eta}{{L_{iv}}^{0.12}} = 32.6$	870.0
Sulphated clay from Paraguay	Calcitic Lime	24.1	4, 6 and 8	14.5, 15.5 and 16.8	15	23	90 and 180	$\frac{\eta}{{L_{iv}}^{0.12}} = 23.6$ and $\frac{\eta}{{L_{iv}}^{0.12}} = 23.2$, respectively for 90 and 180 days of curing	1509 and 2534 kPa, respectively for 90 and 180 days of curing

FIGURES

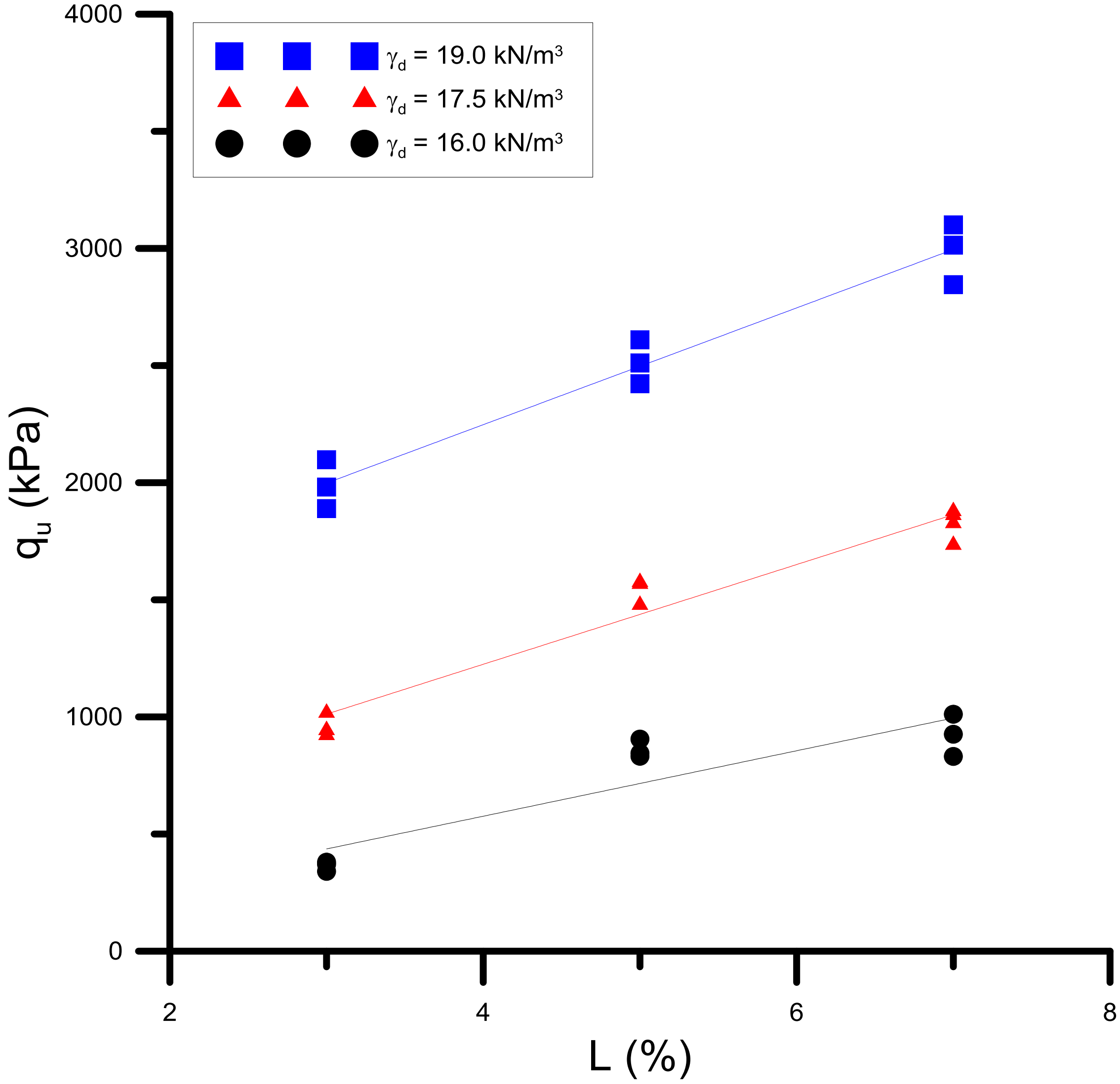

FIGURE 1: Unconfined compressive strength (q_u) of a dispersive clay with hydrated lime content (L) for 28 days as curing period and 21°C as curing temperature.

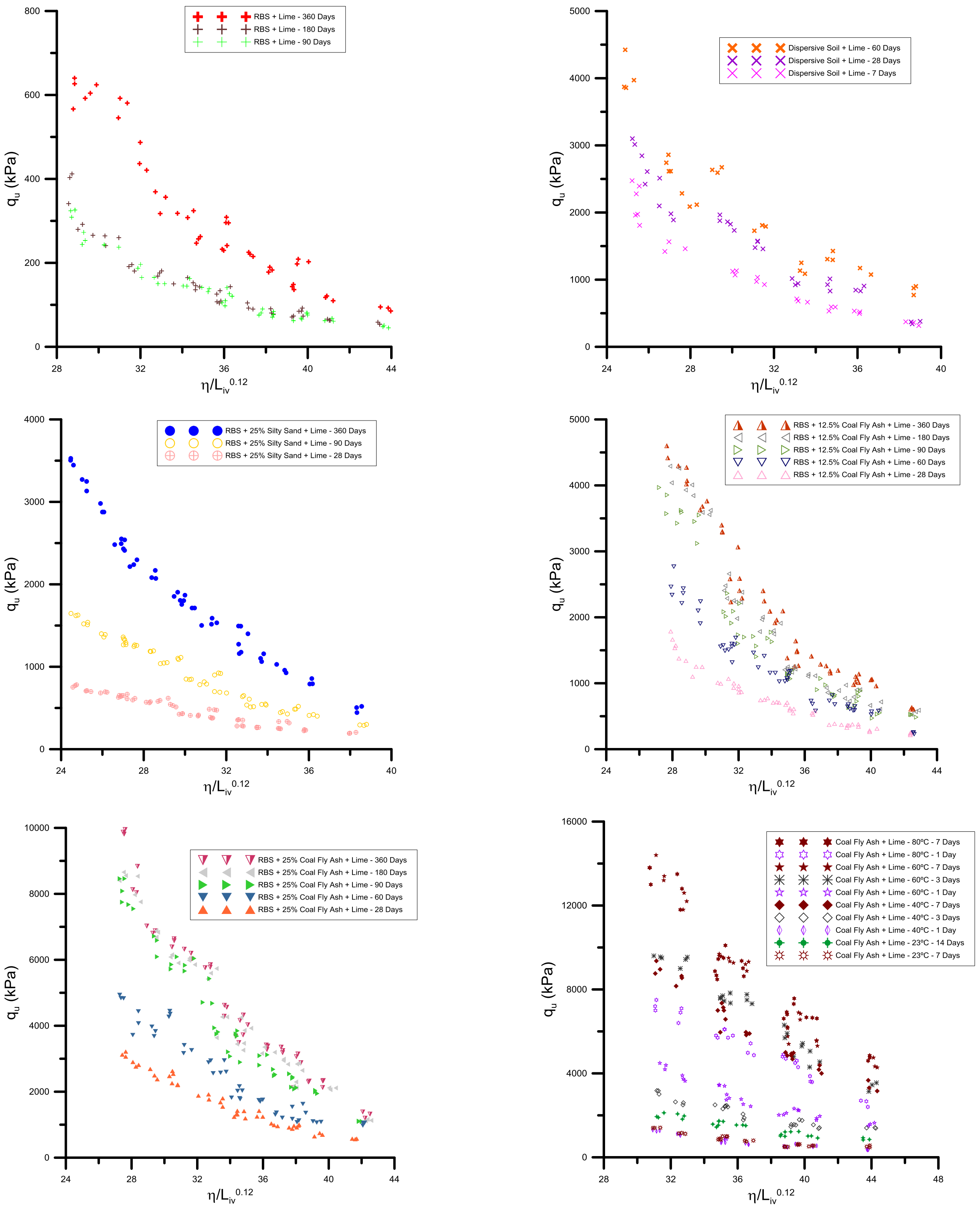

FIGURE 2: Variation of unconfined compressive strength (q_u) with adjusted porosity/lime index for all studied fine-grained soils treated with distinct lime amounts and types considering distinct curing temperatures (varying from 21°C to 80°C) and time periods (varying from 1 to 360 days).

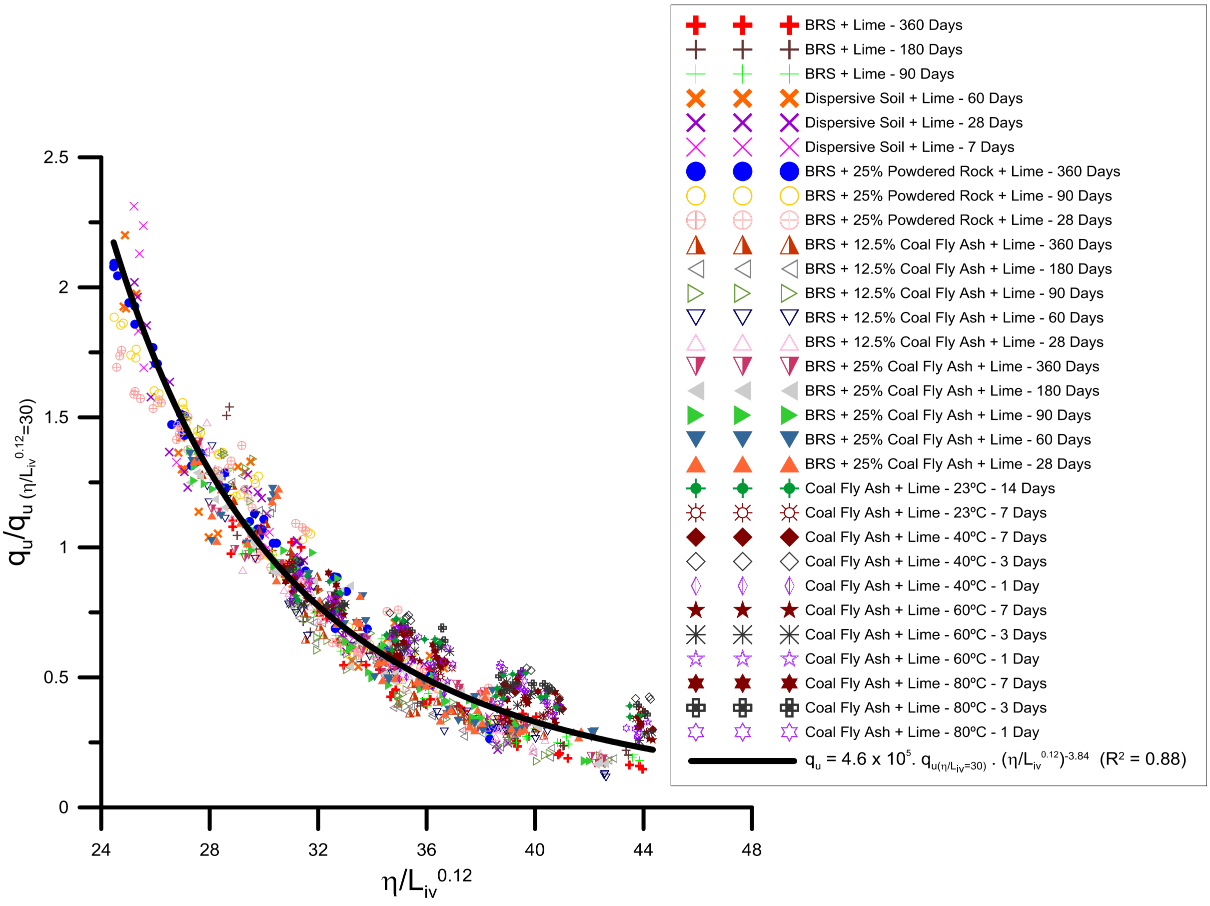

FIGURE 3: Normalization of q_u (for the whole range of $\eta/L_{iv}^{0.12}$) dividing for q_u at $\eta/L_{iv}^{0.12}$ = 30 considering distinct curing temperatures (varying from 21°C to 80°C) and time periods (varying from 1 to 360 days).

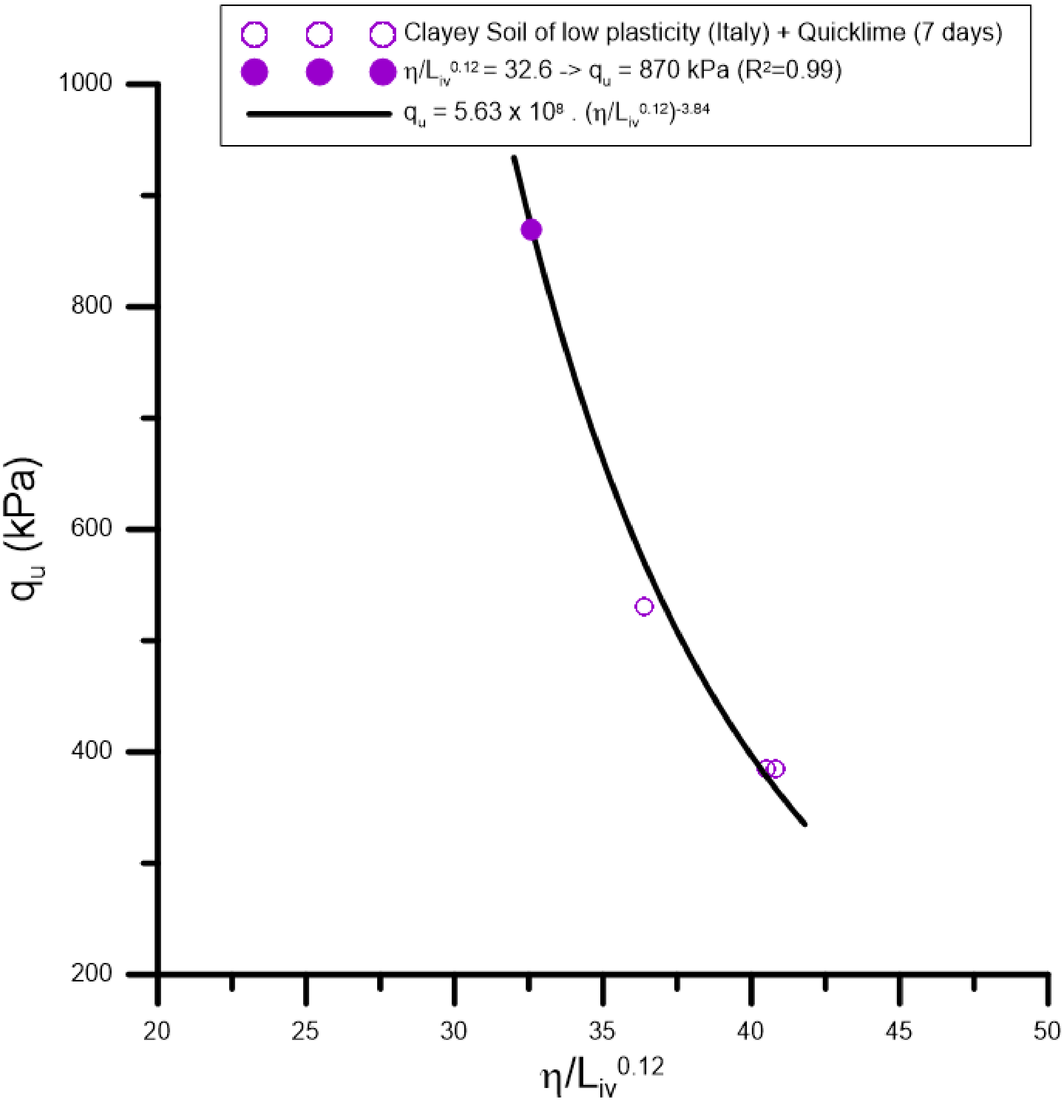

FIGURE 4: Curve obtained using Eq. (6) and lab-testing data from Consoli *et al.* (2015) for clayey soil of low plasticity from Italy - quicklime mixtures under curing period of 7 days.

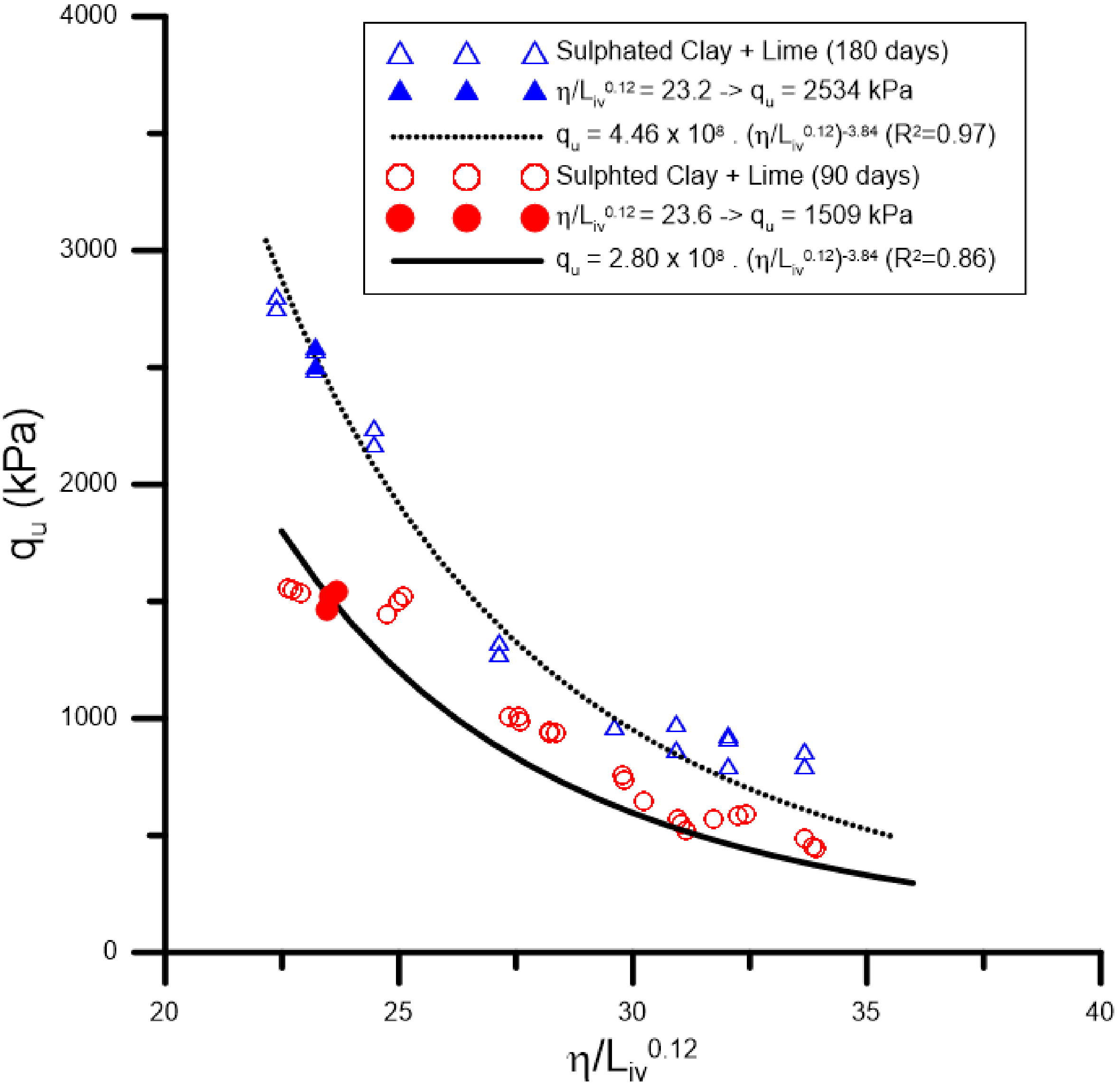

FIGURE 5: Curve obtained using Eq. (6) and lab-testing data after Bittar (2017) for sulphated clay – hydrated lime mixtures for curing periods of 90 and 180 days.