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The strength of soil–industrial by-products–lime blends

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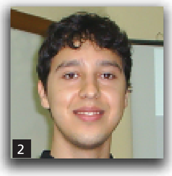

The aim of this study is to assess the strength controlling parameters of a sandy soil (Botucatu residual soil (BRS)) treated with industrial by-products (basaltic powdered rock (PR) or coal fly ash (FA)) and lime, as well as to show that the porosity/volumetric lime content (η/L_v) plays a fundamental role in the assessment of the target strength. The controlling parameters evaluated were addition of industrial wastes, quantity of lime, porosity and η/L_v. The unconfined compressive strength (q_u) increased non-linearly with the amount of lime and decreased with porosity for all studied mixtures. Similar equations were found relating q_u to $\eta/(L_v)^{0 \cdot 12}$ for BRS–lime, BRS-PR–lime and BRS-FA–lime mixtures. Tests of potential reactivity of siliceous materials with alkalis on the materials studied indicated that the higher amount of dissolved silica in the alkaline environment of the FA, when compared with the BRS and the PR, was responsible for increasing the number of reactions with the lime and consequently increasing the strength for BRS (25% FA)–lime mixtures, when compared to BRS–lime and BRS (25% PR)–lime blends.

Notation

D_{50}	mean effective diameter (mm)
L	lime content (mass of lime in relation to mass of dry soil) (%)
L_v	volumetric lime content
q_u	unconfined compressive strength (kPa)
R^2	coefficient of determination
γ_d	dry unit weight (kN/m^3)
η	porosity
η/L_v	ratio of porosity/volumetric lime content

1. Introduction

Engineered fills, canal lining and subgrades for pavements are some of the geotechnical engineering applications in which combining industrial wastes with lime for soil stabilisation find application. The development of alternatives for reusing industrial by-products (e.g. powdered rock, fly ash, bottom ash) mostly brings environmental, economical and technical benefits. Materials such as basaltic powdered rock and coal fly ash, by-products of crushing rock and coal combustion in thermal power plants, respectively, are abundantly produced in southern Brazil (180 000 tons/year of powdered rock (Lopes Jr, 2007) and 1 500 000 tons/year of coal ash (Consoli *et al.*, 2007a)). Even though these materials are used for engineering purposes (as additive to cement), the majority are sent to storage or disposal sites. Several methodologies have been established in recent years (e.g. Rogers *et al.*, 1997) to determine the quantity of lime required for modification of soil characteristics. Such methodologies establish a threshold value intended to chemically satisfy the soil's demand for lime, which has been often suggested as the starting content to adopt for practical construction purposes. In spite of the numerous applications, there are no dosage methodologies for the assessment of a target soil–industrial by-product–lime blend strength, based on rational criteria, as in the case of soil–cement technology, where the voids/cement ratio plays a fundamental role (Consoli *et al.*, 2007b). The need for a dosage methodology results from the fact that the soil–industrial by-product–lime blend shows a complex behaviour that is affected by many factors, for example the particle mineralogy of the soil and of the industrial by-products, as well as the specimen's porosity and the amount of lime (e.g. Consoli *et al.*, 2001, 2008; Mitchell, 1981).

The aim of the present study is therefore to assess the strength controlling parameters of a sandy soil treated with industrial by-products (basaltic powdered rock or coal fly ash) and lime, as well as to show that the ratio of porosity/volumetric lime content

(η/L_v) plays a fundamental role in determining the target strength. The controlling parameters evaluated were addition of the industrial by-product (powdered rock or fly ash), quantity of lime, porosity and η/L_v. The physical–chemical mechanisms of both the short- and long-term reactions involved in lime stabilisation of soil mixtures have been extensively described in the literature during the last few decades (e.g. Ingles and Metcalf, 1972; TRB, 1987). The focus here was therefore on the long-term effects (90 days of curing) of the lime addition on the unconfined compressive strength of the soil–industrial by-products mixtures.

2. Experimental programme

The experimental programme was carried out in three parts. First, the geotechnical properties of the sandy soil, basaltic powdered rock, coal fly ash and lime were characterised. Next, the minimum amount of lime required for full stabilisation, based on the modified initial consumption of lime (ICL) method (Rogers *et al.*, 1997) was established. Then a number of unconfined compression tests and measurements of matric suction were carried out as discussed below.

2.1 Materials

The Botucatu residual soil (BRS) used in the present study was derived from weathered Botucatu sandstone and was obtained from the region of Porto Alegre, in southern Brazil. The results of the soil characterisation tests are shown in Table 1 and the grain size curve is shown in Figure 1. The soil was classified as clayey sand (SC) according to the Unified Soil Classification System. A chemical analysis showed that the studied soil was 62·5% silica (SiO_2), 29·9% alumina (Al_2O_3), 5·6% iron (III) oxide (Fe_2O_3) and 0·7% potassium oxide (K_2O). X-ray diffraction showed that the fine portion was predominantly kaolinite. The soil pH was 5·2. Following ASTM standard C 289-07 (ASTM, 2010) to determine the BRS potential reactivity of siliceous aggregates (SiO_2) with alkalis, it was found that the amount of dissolved silica was approximately 16 mmol/l.

A basalt rock crusher plant situated in close proximity to Porto Alegre has as by-product a fine, powdered rock (PR) that was selected for the present study. The grain size distribution curve is presented in Figure 1 and physical properties of the sample collected for the experimental programme are presented in Table 1. PR is classified as lean clay (CL) according to the Unified Soil Classification System. Chemical analysis showed that the powdered rock was 54·1% silica (SiO_2), 12·0% alumina (Al_2O_3), 15·7% iron (III) oxide (Fe_2O_3), 10·0% calcium oxide (CaO), 4·9 % magnesium oxide (MgO), 2·3% sodium oxide (Na_2O) and 1·0% potassium oxide (K_2O). X-ray diffraction showed that the fine portion was predominantly albite (plagioclase feldspar mineral). The PR pH was approximately 9·6. Regarding PR potential reactivity of siliceous aggregates with alkalis, the amount of dissolved silica was approximately 247 mmol/l.

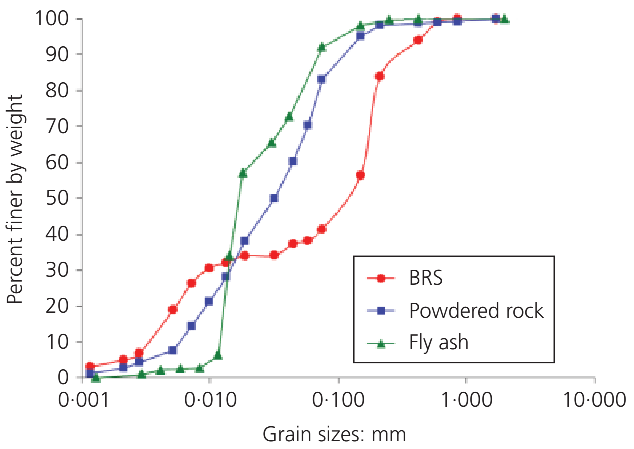

Figure 1. Grain size distribution of BRS, powdered rock and fly ash

The fly ash (FA) selected (type F according to ASTM C 618-98 (ASTM, 1998)) was a residue of burning coal in a thermal power station, located close to Porto Alegre. The results of the FA characterisation tests are presented in Table 1 and the grain size curve is shown in Figure 1. The material is non-plastic. The FA is

Properties	BRS	Powdered rock (PR)	Fly ash (FA)
Liquid limit	25%	28%	—
Plastic limit	17%	20%	—
Plastic index	8%	8%	Non-plastic
Specific gravity	2·64	3·33	2·28
Medium sand (0·2 mm < diameter < 0·6 mm)	16·2%	1·9%	1·0%
Fine sand (0·06 mm < diameter < 0·2 mm)	45·4%	38·4%	13·6%
Silt (0·002 mm < diameter < 0·06 mm)	33·4%	57·5%	84·9%
Clay (diameter < 0·002 mm)	5·0%	2·2%	0·5%
Effective diameter (D_{50})	0·12 mm	0·03 mm	0·018 mm
Uniformity coefficient	45·7	9·0	1·7

Table 1. Physical properties of soil sample

classified as silt (ML) according to the Unified Soil Classification System. A chemical analysis showed that the fly ash was 65·2% silica (SiO_2), 23·3% alumina (Al_2O_3), 6·1% iron (III) oxide (Fe_2O_3), 0·8% calcium oxide (CaO) and 0·1% sulfate (SO_3). X-ray diffraction showed that the material was composed of predominantly amorphous minerals. The fly ash pH was approximately 8·3. Regarding FA potential reactivity of siliceous aggregates with alkalis, the amount of dissolved silica was 611 mmol/l.

Dry hydrated lime ($Ca(OH)_2$) was used as the cementing agent. Its slow gain of strength required the adoption of 90 days as the curing time. The specific gravity of the lime grains was 2·49.

For the characterisation tests, distilled water was used, but for moulding specimens for the compression tests tap water was used.

2.2 Methods

The minimum percentage of lime (in terms of dry unit weight of soil) adopted in this work was established using the modified initial consumption of lime (ICL) method (Rogers *et al.*, 1997). It was based on the interpretation of pH tests carried out on mixtures of soil with lime added and water (proportions of 1:3, i.e. one part (soil plus lime) to three parts (water)). Figure 2(a) shows results of BRS pH variation with lime addition. It can be observed that a minimum amount of lime of 3% was necessary to reach a pH similar to the standard (lime–water mixture) solution. Figure 2(b) shows results of BRS + 25% PR mixture pH variation with lime addition. It can be seen that for this mixture as well, 3% lime was the required percentage to reach a pH similar to the standard solution. Finally, Figure 2(c) shows results of BRS + 25% FA mixture pH variation with lime addition. Again, for this mixture 3% lime was the required percentage to reach a pH similar to the standard solution. So, based on these results, 3% of lime is the minimum amount of lime chosen for all of the mixtures studied (BRS, BRS (25% PR) and BRS (25% FA)), as well as 5%, 7%, 9% and 11%, which were chosen considering international experience with combined soil–fly ash–lime (Consoli *et al.*, 2001, 2008; Mitchell, 1981).

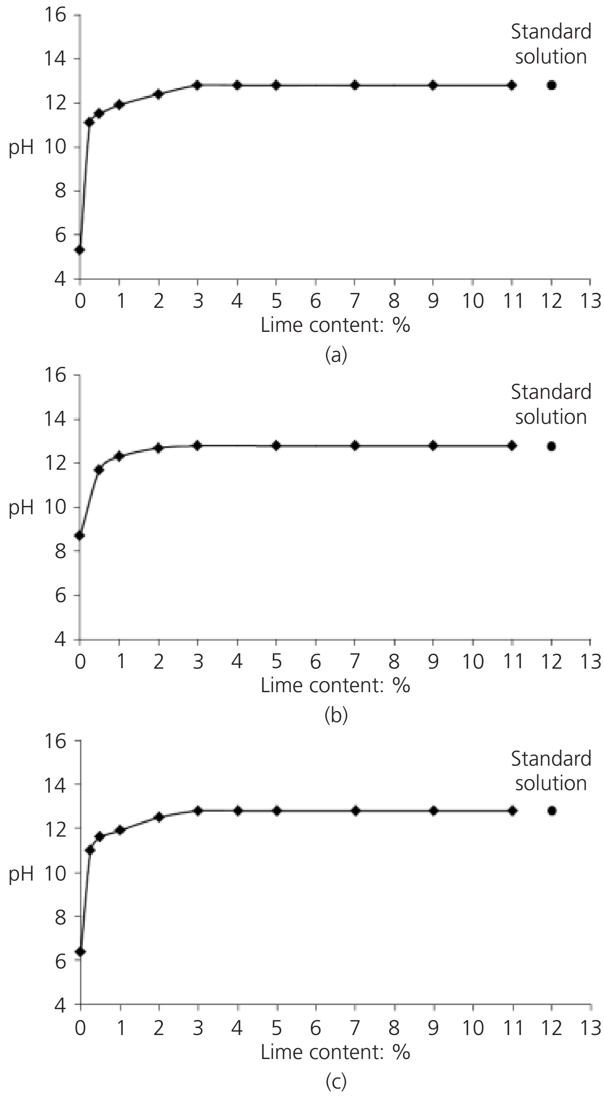

Figure 2. Results of ICL tests for (a) BRS; (b) BRS (25% PR); (c) BRS (25% FA)

2.3 Moulding and curing of specimens

For the unconfined compression tests cylindrical specimens, 50 mm in diameter and 100 mm high, were used. After the soil, powdered rock (when applicable), fly ash (when applicable), lime and water had been weighed, the soil (mixed with powdered rock or fly ash, as appropriate) and the lime were mixed until the mixture acquired a uniform consistency. Water was then added, continuing the mixture process until a homogeneous paste was created. The amount of lime for each mixture was calculated based on the mass of dry soil plus fly ash and the target moisture content. After mixing sufficient material for one specimen, the mixture was stored in a covered container to avoid moisture losses before subsequent compaction. The time used to prepare, mix and compact was always less than 1 h. Two small portions of the mixture were also taken for moisture content determination. Next, following the undercompaction method proposed by Ladd (1978), each mixture was compacted in three layers into a 50 mm diameter cylindrical split-mould, to a target dry density. The top of each layer was slightly scarified. After the moulding process, the specimen was immediately extracted from the split mould, and its weight, diameter and height were measured to within an accuracy of 0·01 g and 0·1 mm. The samples were then placed within plastic bags to avoid significant variations of moisture content. These were cured in a humid room at 23°C ± 2°C and relative humidity above 95% for 89 days. The samples were considered suitable for testing if they met the following tolerances: dry density within ±1% of the target value; moisture content within ±0·5% of the target value; diameter within ±0·5 mm and height within ±1 mm.

It is important to point out that the dry density of the specimens was calculated as the dry mass of the soil, powdered rock or fly ash (when applicable) and lime divided by the total volume of the sample. As the specific gravity of the lime is 2·49, of the powdered rock is 3·33, of the fly ash is 2·28 and of the soil is 2·64, for the calculation of void ratio and porosity, a composite specific gravity based on the soil, powdered rock or fly ash (when applicable) and lime percentages in the specimen was used.

2.4 Unconfined compression tests

An automatic loading machine, with maximum capacity of 50 kN and proving rings with capacities of 10 and 50 kN and resolutions of 0·005 and 0·023 kN, respectively, were used for the unconfined compression tests. The displacement rate adopted was 1·14 mm/min. After curing in a humid room for 89 days, the specimens were submerged in a water tank for 24 h for saturation and to minimise suction, bringing the total curing time to 90 days. The water temperature was maintained at 23°C ± 2°C. Immediately before the test, the specimens were taken out of the tank and dried superficially with an absorbent cloth. Then, the unconfined compression test was carried out and the maximum load reached by the specimen recorded. As acceptance criteria, it was stipulated (Consoli *et al.*, 2010) that the individual strengths of three specimens, moulded with the same characteristics, should not deviate by more than 10% from the mean strength.

2.5 Matric suction measurement

At their moulding moisture contents all the specimens tested were in an unsaturated state and a certain level of suction may have been present; the aim of the suction measurements was to verify its magnitude and examine if there was significant variation between specimens of different porosities and cement contents. The measured suction was matric suction arising from capillary forces inside the sample. It was measured using the filter paper technique (Marinho, 1995). The filter paper used was Whatman no. 42. Its initial moisture content, in the air-dried state, is approximately 6%, which allows measurements of suction from zero to 29 MPa. The calibration equations for this filter paper are those presented by Chandler *et al.* (1992). The matric suction measurements were performed on samples after failure in unconfined compression tests.

2.6 Unconfined compression tests programme

The unconfined compression tests programme was elaborated in such a way as to evaluate, separately, the influences of the powdered rock (PR) or fly ash (FA) quantity, the lime content, the porosity and the voids/lime ratio on the mechanical strength of the BRS–lime, BRS (25% PR)–lime and BRS (25% FA)–lime mixtures. The moulding points were chosen considering dry densities of 14, 15, 16 and 17 kN/m^3, for BRS and BRS (25% FA) mixtures and 16, 17, 18 and 18·8 kN/m^3, for BRS (25% PR) mixture, all with the same moisture content of 14% ± 0·5%. The amounts of powdered rock and fly ash used in this work (25%) fall into the interval suggested by TRB (1987) for fly ash and were defined according to regional practice, following compaction difficulties found using higher amounts of fly ash. Each moulding point was moulded with different lime percentages: 3, 5, 7, 9 and 11%. Because of the typical scatter of data for unconfined compression tests, for each point three specimens were tested.

3. Results

3.1 Effect of the powdered rock/fly ash inclusion, lime content and porosity

Results of unconfined compression tests for BRS–lime, BRS (25% PR)–lime and BRS (25% FA)–lime are presented in Figures 3(a), 3(b) and 3(c) respectively. Each figure presents results considering dry densities in the range 14–18·8 kN/m^3 and lime contents from 3% to 11%. The inclusion of 25% PR increased the unconfined compressive strength (q_u) for any given density and lime content. However, the inclusion of 25% FA dramatically increased the q_u values. Non-linear relationships between q_u and lime content can be observed for the BRS–lime, BRS (25% PR)–lime and BRS (25% FA)–lime mixtures.

To explain differences in the results when using lime on BRS, BRS (25% PR) and BRS (25% FA), it is important to point out that the fine portion of BRS consists predominantly of kaolinite minerals, while PR has albite minerals and FA was mainly composed of amorphous minerals. Chemically the three are mainly siliceous. After 90 days of curing, pozzolanic reactions between lime and the fine particles will have occurred (not necessarily to completion). Such reactions occur because silica within the soil/powdered rock/fly ash structure reacts with water and lime to form calcium silicate hydrate gel, which subsequently precipitates to bind the structure together. The potential reactivity of siliceous materials with alkalis was found to be lowest for BRS (amount of dissolved silica 16 mmol/l) resulting in small strengths for the BRS–lime mixtures, average for PR (amount of dissolved silica 247 mmol/l) resulting in average strengths for BRS (25% PR)–lime mixtures and high for FA (amount of dissolved silica 611 mmol/l) resulting in quite high strengths for BRS (25% FA)–lime mixtures.

Figures 4(a), 4(b) and 4(c) show how porosity affects the unconfined compressive strength of the BRS–lime, BRS (25% PR)–lime and BRS (25% FA)–lime mixtures, respectively. The unconfined compressive strength increases non-linearly with the reduction in porosity of all compacted mixtures studied. This beneficial effect of a decrease in porosity has been reported by several researchers (e.g. Consoli *et al.*, 2006, 2007b, 2009). The mechanism by which the reduction in porosity influences the mixture strength is related to the existence of a larger number of contacts between particles.

The process of submerging the specimens for 24 h before the unconfined compression tests was found to be satisfactory to ensure a high and repeatable degree of saturation. For the three studied blends, an average degree of saturation of 89% was

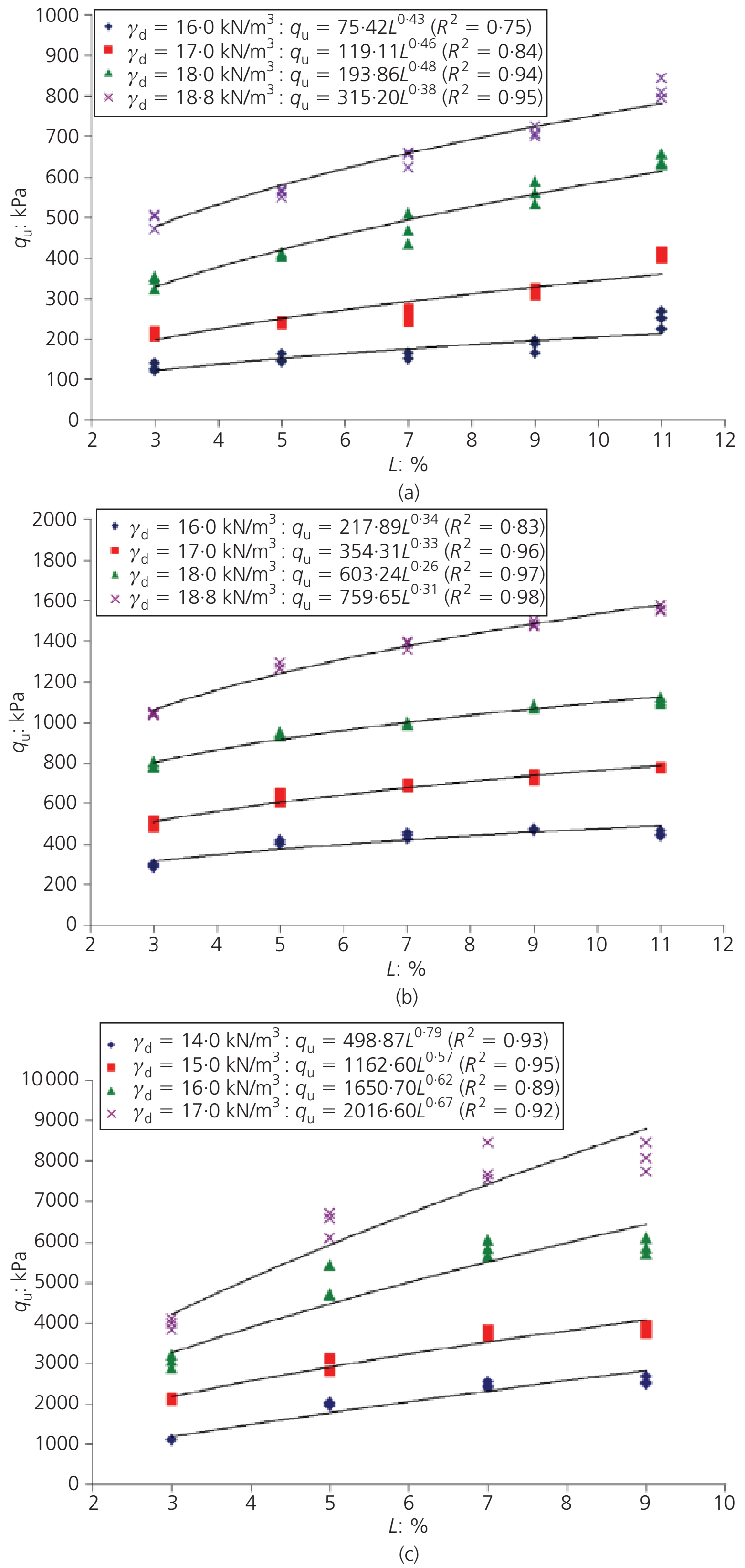

Figure 3. Variation of unconfined compressive strength with lime content: (a) BRS–lime specimens; (b) BRS (25% PR)–lime specimens; (c) BRS (25% FA)–lime specimens

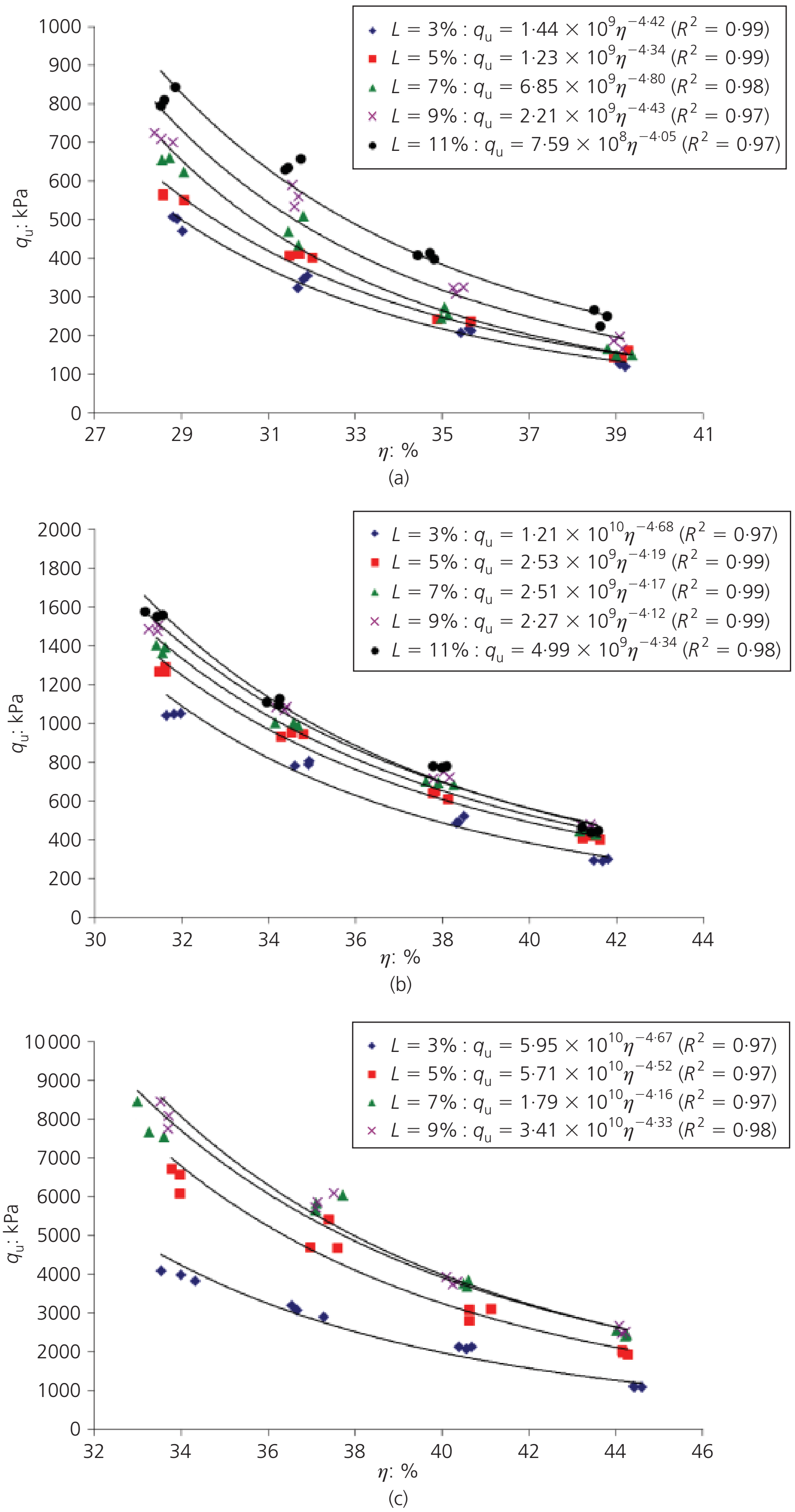

Figure 4. Variation of unconfined compressive strength with porosity: (a) BRS–lime specimens; (b) BRS (25% PR)–lime specimens; (c) BRS (25% FA)–lime specimens

obtained for specimens after submersion, irrespective of the initial porosity or cementitious material content. The values of suction measured were low, with values ranging from about 1% up to 5% of the unconfined compressive strength. These measurements were made on the samples after failure in the unconfined compression tests and are therefore likely to overestimate the real value, because there may have been a slight drying of the sample during the few minutes from the start of the test until the measurement was made. Since only small values of suction were measured relative to the respective unconfined compressive strength, suction was not taken into account in this analysis.

3.2 Effect of porosity/volumetric lime content ratio

Figure 5 shows the relation between unconfined compressive strength (q_u) and the porosity/volumetric lime content (η/L_v), defined by Equation 1

$$\frac{\eta}{L_v} = \frac{\text{Porosity}}{\text{Volumetric lime content}} \tag{1}$$

Figures 5(a), 5(b) and 5(c) present how η/L_v affects the q_u of the BRS–lime, BRS (25% PR)–lime and BRS (25% FA)–lime, respectively. For the three blends studied, specimens have different lime content and porosities. It can be seen that in all cases there is no unique relation between q_u and the η/L_v ratio.

In dividing the porosity by the volumetric lime content, it has been assumed that an increase in the porosity of the mixture could be counteracted by a proportional increase in the volumetric lime content, keeping the unconfined compressive strength unchanged. Actually, in order to keep the same q_u, a power needed to be applied to one of the variables (η, L_v) to make compatible the effects of its variation on q_u. It was found that by applying a power of 0·12 on the parameter L_v for all mixtures studied, a good agreement to the unconfined compressive strength data was found, as presented in Figures 6(a)–6(c). A good agreement between q_u and $\eta/(L_v)^{0{\cdot}12}$ was found using a power relationship (Equations 2–4)

$$q_u\ (\text{kPa}) = 2{\cdot}17 \times 10^8 \left[\frac{\eta}{(L_v)^{0{\cdot}12}}\right]^{-4{\cdot}00}$$

2. for BRS–lime mixtures $(R^2 = 0{\cdot}96)$

$$q_u\ (\text{kPa}) = 6{\cdot}41 \times 10^8 \left[\frac{\eta}{(L_v)^{0{\cdot}12}}\right]^{-4{\cdot}00}$$

3. for BRS (25% PR)–lime mixtures $(R^2 = 0{\cdot}94)$

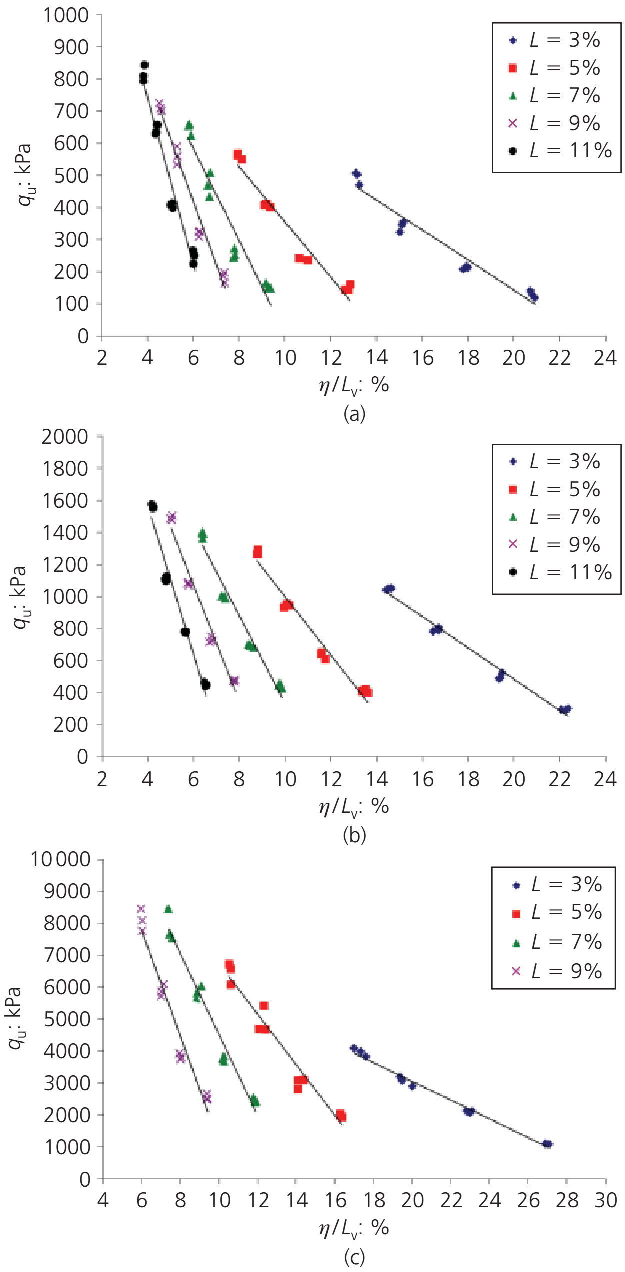

Figure 5. Variation of unconfined compressive strength with porosity/volumetric content of lime: (a) BRS–lime specimens; (b) BRS (25% PR)–lime specimens; (c) BRS (25% FA)–lime specimens

$$q_u\ (\text{kPa}) = 47{\cdot}80 \times 10^8 \left[\frac{\eta}{(L_v)^{0{\cdot}12}}\right]^{-4{\cdot}00}$$

4. for BRS (25% FA)–lime mixtures $(R^2 = 0{\cdot}94)$

4. Discussion

The results presented above indicate the existence of unique and distinct relationships for the compacted BRS–lime, BRS (25%

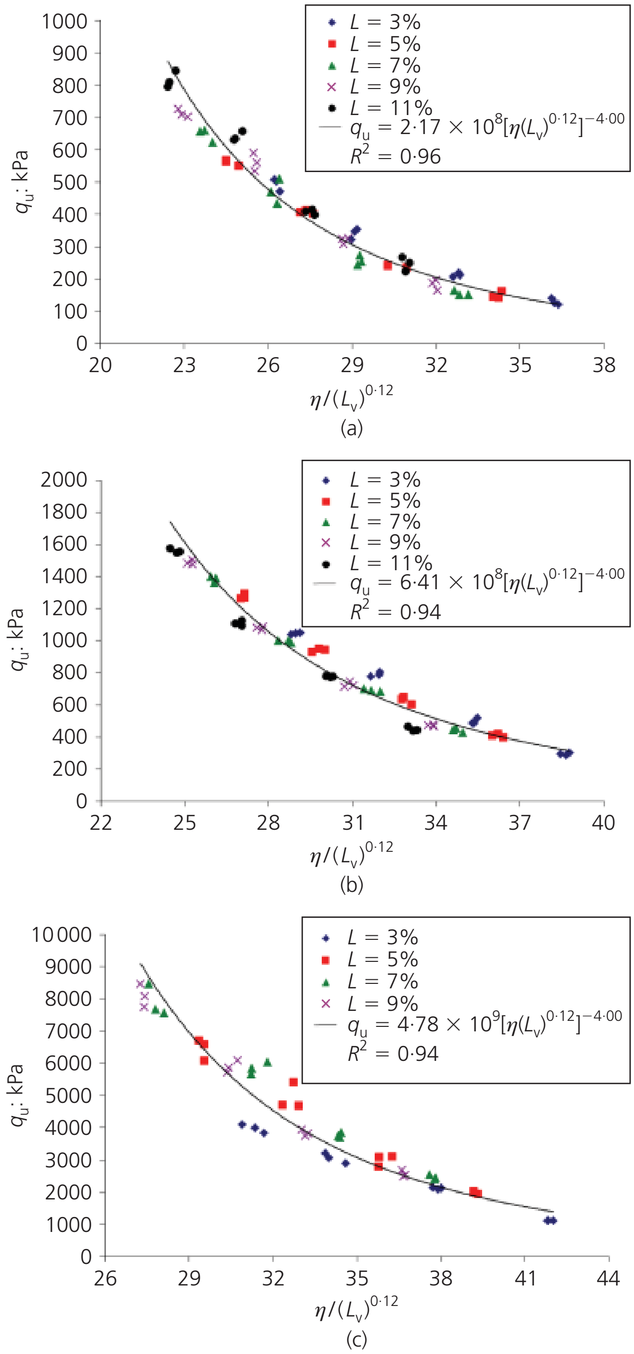

Figure 6. Variation of unconfined compressive strength with adjusted porosity/volumetric content of lime: (a) BRS–lime specimens; (b) BRS (25% PR)–lime specimens; (c) BRS (25% FA)–lime specimens

PR)–lime and BRS (25% FA)–lime mixtures studied in the current research (see Figure 7). Comparing Equations 2, 3 and 4, it can be seen that q_u has a linear relationship with $[\eta/(L_v)^{0.12}]^{-4.00}$ for the three blends (BRS–lime, BRS (25% PR)–lime and BRS (25% FA)–lime) and the inclusion of PR or FA has only the effect of changing the gradient.

So, for the mixtures studied in the present research, it can be concluded that the minerals contained in the basaltic powdered rock and in coal fly ash, when compared to the minerals in the BRS, have more effective reactions with lime, consequently increasing strength. Basaltic powdered rock has a smaller amount of dissolved silica in the alkaline environment than the coal fly ash, but more than the sandy soil. Consequently, soil specimens treated with powdered rock and lime form more calcium silicate hydrate gel (which subsequently crystallises to bind the structure together) than soil–lime and less than soil–coal fly ash–lime blends, resulting in relatively high strengths for BRS (25% FA)–lime mixtures, average strengths for BRS (25% PR)–lime mixtures and lower strengths for BRS–lime mixtures. Equations 2, 3 and 4 show a consistent relationship between unconfined compressive strength and the porosity/volumetric lime content ratio; the difference being a single constant that probably depends on the effectiveness of the mixture's reaction with lime. Further studies are required, expanding the testing programme to other curing periods, residues, soils and limes, in order to check the possibility of generalisation of the present findings. This may enable prediction of unconfined compressive strength of a soil–industrial by-product–lime blend based on porosity, volumetric lime content and amount of dissolved silica.

Equations 2, 3 and 4 can be used as dosage relationships. For any one of the mixtures studied, there are several technical ways of reaching a q_u target value for a given project: porosity adjustment and/or lime content change, always using larger amounts than the minimum required following the ICL modified method. The results presented in this paper therefore suggest that the engineer can choose (using BRS with or without inclusion of PR or FA, depending on the availability of a given industrial by-product nearby) the amount of lime and the compaction effort appropriate to provide a combination that meets the strength required by the project at the optimum cost. The best option might change from situation to situation, depending on availability of equipment to transfer high compaction energy, costs of lime and availability of PR or FA nearby.

Although this work may appear specific to materials found in the region of Porto Alegre, what has been presented is a methodology and an empirical framework that may be used to derive equations of similar form for any project. Once a suite of simple experiments has defined the governing equations, unconfined compressive strengths may be predicted for any value of lime content or porosity, aiding in the design and field control of soil–industrial by-product–lime layers. If poor compaction of a layer has been recognised, it can be readily taken into account in the design, identifying through Equations 2, 3 or 4, depending on the blending used, the q_u value that will be achieved, and adopting corrective measures accordingly.

5. Conclusion

An extensive laboratory testing programme was used to evaluate the strength controlling parameters of a sandy soil mixed with

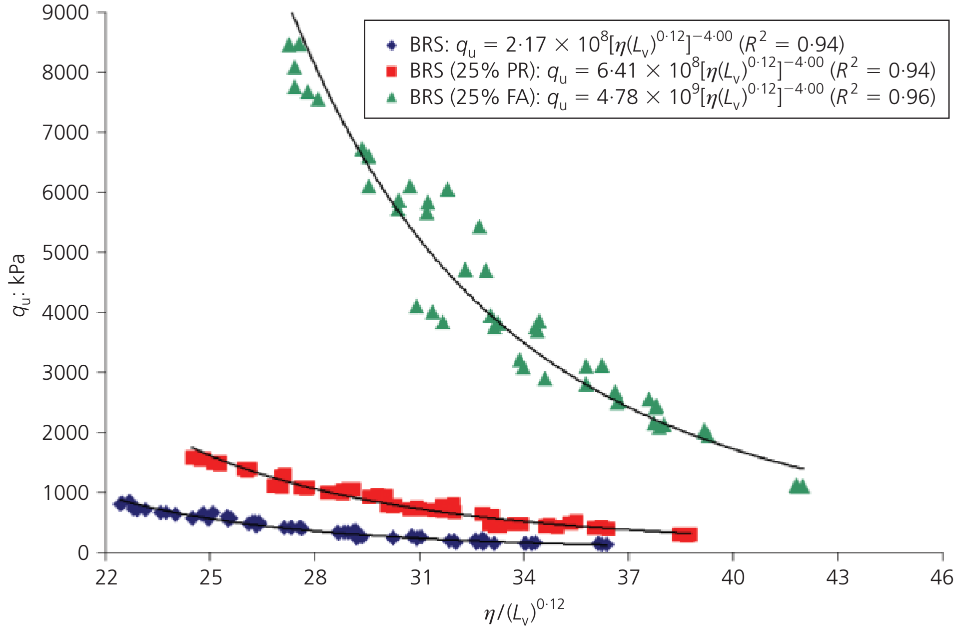

Figure 7. Variation of unconfined compressive strength with adjusted porosity/volumetric content of lime (curves adjusted for BRS–lime specimens, BRS (25% PR)–lime specimens and BRS (25% FA)–lime specimens)

industrial by-products (basaltic powdered rock or coal fly ash) and lime, as well as to show that the porosity/volumetric lime content (η/L_v) plays a fundamental role in the assessment of the target strength. The observations and conclusions can be summarised as follows.

- The potential reactivity of siliceous aggregates (SiO_2) with alkali, measured by the amount of dissolved silica in an alkaline environment, was found to be lowest for the BRS, average for PR and relatively high for FA. Consequently, soil specimens mixed with fly ash and lime (BRS (25% FA)–lime) form more calcium silicate hydrate gel (which subsequently crystallises to bind the structure together) than BRS (25% PR)–lime, which in its turn forms more calcium silicate hydrate gel than BRS–lime blends. This resulted in the BRS (25% FA)–lime blends having higher strengths than BRS (25% PR)–lime, which in its turn had higher strengths than BRS–lime mixtures.
- The unconfined compressive strength increases non-linearly with the increase of lime content and the reduction of the porosity for all studied mixtures.
- Unique and distinct relationships between q_u and $[\eta/(L_v)^{0{\cdot}12}]^{-4{\cdot}00}$ were found for the compacted BRS–lime, BRS (25% PR)–lime and BRS (25% FA)–lime mixtures. Even using the composition of three distinct materials (sandy soil, powdered rock and fly ash – BRS, BRS (25% PR) and BRS (25% FA)), the exponents 0·12 and 4·00 in the equations relating q_u to η/L_v were unique. Such uniqueness suggests that the exponents might even be a function of the lime characteristics, but definitely are not a function of the soil–industrial by-product matrix (at least for the soil, powdered rock and fly ash used in the present work). Adding 25% PR or 25% FA to BRS has only the effect of changing the gradient of the linear relationship between q_u and $[\eta/(L_v)^{0{\cdot}12}]^{-4{\cdot}00}$, with the effectiveness of the reactions with lime being the controlling factor.

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