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Key parameters for strength control of rammed sand–cement mixtures: Influence of types of portland cement

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HIGHLIGHTS

- Key parameters for dosage of rammed earth–Portland cement walls.
- Unique relationships achieved linking strength of rammed earth–cement blends with porosity/cement ratio and curing periods.
- Normalization allows predicting effect on strength of varying cement content and porosity with given cement and curing time.

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ABSTRACT

The present research aims to quantify the influence of distinct types of Portland cement, amounts of cement, porosity, curing time period and porosity/cement ratio in the assessment of unconfined compressive strength (q_u) of rammed sand–cement mixtures. A program of unconfined compression tests considering distinct types of Portland cement (types I, III and IV), porosities (η), cement contents (C) and curing time periods (t) was carried out in the present study. It was found that a ratio between porosity and cement $[(\eta/C_{iv})^{-1.5}]$ applies to all equations that control the strength of blends (for the curing periods and cement types studied here). The q_u values of the specimens moulded for each cement type and curing period were also normalize (i.e. divided by the q_u attained by a specimen with porosity/cement ratio equals to 20). It was found that a single power function adapts well to the normalized values for all the cement type and curing period studied. From a practical viewpoint, this means that carrying out only one (1) compression test with a specimen moulded with a specific cement time and cured for a given time period, allows the equation that controls the strength for distinct porosity and cement content to be determined.

1. Introduction

Rammed earth-cement wall construction involves compressing a moist mixture of earth that has suitable proportions of soil with an added stabilizer (e.g., Portland cement of several types, lime) into an externally supported frame or mould, creating a solid wall of soil–cement. The major variables that control the properties and characteristics of rammed sand–cement mixtures are the proportion of cement in the mix, the degree of compaction and curing time period. It is possible, simply by varying the cement content and/or porosity of mixture, to produce sand–cement walls whose condition ranges from a basic modification of the compacted sand to fully hardened sand–cement that is strong and durable.

Present study aims at developing the first rational dosage methodology for rammed sand–cement blends to be used in wall construction, as well as quantifying the influence of three distinct types of Portland cement (I, III and IV), the amount of cement, the porosity and curing time period on the unconfined compressive strength of packed sand–cement mixes.

An important contribution of present work is showing the existence of a direct relationship between unconfined compressive strength (q_u) of the rammed sand–cement with porosity/cement ratio (η/C_{iv}) of the blends, defined by the porosity of the compacted mixture divided by the volumetric cement content, for each type of Portland cement studied at all curing time periods.

2. Experimental program

The experimental program has been carried out in two parts. First, the properties of the sand were characterized. Then a number of unconfined compression tests were carried out for three distinct Portland cement types [I, III and IV – ASTM C150 [3]] at three distinct curing time periods (2, 7 and 28 days).

2.1. Materials

The Osorio sand used in the testing was obtained from the region of Porto Alegre, in Southern Brazil, being classified according to *ASTM D 2487* [2] as nonplastic uniform fine sand. Specific gravity of the solids is 2.63. Mineralogical analysis

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Nomenclature

C	cement content (expressed in relation to mass of dry soil)
C_{iv}	volumetric cement content (expressed in relation to the total specimen volume)
D_{50}	mean effective diameter
q_u	unconfined compressive strength
R^2	coefficient of determination
t	curing time period
η	porosity
η/C_{iv}	porosity/cement ratio
γ_d	dry unit weight
ω	moisture content

showed that sand particles are predominantly quartz. The grain size is purely fine sand with a mean effective diameter (D_{50}) of 0.16 mm, having uniformity and curvature coefficients 1.9 and 1.2, respectively. The minimum and maximum porosities are 0.37 and 0.47, respectively.

Portland cement type I—general purpose cement, type III—high early strength and type IV—low heat of hydration were used as the cementing agents. The curing time periods adopted were 2, 7 and 28 days. The specific gravity of the cement grains were 3.12 for type I cement, 3.15 for type III cement and 2.74 for type IV cement.

Tap water was used for moulding specimens for the compression tests.

2.2. Methods

2.2.1. Molding and curing of specimens

For the unconfined compression tests, cylindrical specimens 50 mm in diameter and 100 mm high were used. A target dry unit weight for a given specimen was then established through the dry mass of sand–cement divided by the total volume of the specimen. In order to keep the dry unit weight of the specimens constant with increasing cement content, a small portion of the sand was replaced by cement. As the specific gravities of the cement grains were 3.12 for type I cement, 3.15 for type III cement and 2.74 for type IV cement and the specific gravity of the soil grains was 2.63, for the calculation of porosity, a composite specific gravity based on the sand and cement type and percentages in the specimens were used.

After the sand, cement and water were weighed, the sand and cement were mixed until the mixture acquired a uniform consistency. The water was then added, continuing the mixing process until a homogeneous paste was created. The amount of cement for each mixture was calculated based on the mass of dry sand and the moisture content. The specimen was then statically compacted in three layers inside a cylindrical split mould, which was lubricated, so that each layer reached the specified dry unit weight. 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 measured with accuracies of about 0.01 g and 0.1 mm, respectively. The samples were then placed inside plastic bags to avoid significant variations of moisture content. They were cured in a humid room at 23° ± 2 °C and relative humidity above 95%. The samples were considered suitable for testing if they met the following tolerances: *Dry unit weight* (γ_d): degree of compaction between 99% and 101% (the degree of compaction being defined as the value obtained in the moulding process divided by the target value of γ_d); *Dimensions*: diameter to within ±0.5 mm and height ±1 mm.

2.2.2. 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 stabilization with cement or to access the importance of influencing factors on the strength of cemented sands. One of the reasons for this is the accumulated experience with this kind of test for concrete. The tests usually followed Brazilian standard NBR 5739 [1], which is similar to standard ASTM C39 [4], being simple and fast, while reliable and cheap.

After curing, the specimens were submerged in a water tank for 24 h for saturation to minimize suction. The water temperature was controlled and maintained at 23 ± 2 °C. Immediately before the test, the specimens were removed from the tank and dried superficially with an absorbent cloth. Then, the unconfined compression test was carried out and the maximum load recorded. As acceptance criteria, it was stipulated that the individual strengths of three specimens, moulded with the same characteristics, should not deviate by more than 10% from the mean strength.

The unconfined compression tests constituted the main part of this research. The program was conceived in such a way as to evaluate, separately, the influences of the type of cement, curing time period, cement content, porosity and porosity/cement ratio on the mechanical strength of the artificially cemented sand.

The moulding points were chosen considering porosities varying from high to low values, with the same moisture content (ω = 10%). Portland cement type I—general purpose cement, type III—high early strength and type IV—low heat of hydration were used as the cementing agents. Each point was moulded with four different cement percentages: 3%, 5%, 7% and 9%. These percentages were chosen following Brazilian and international experience with sand–cement [6]. Three distinct curing time periods (2, 7 and 28 days) were used. Because of the typical scatter of data for the unconfined compression tests, a minimum of three specimens were tested for each point.

3. Results

3.1. Effect of the cement content, porosity, cement type and curing time periods on compressive strength

The unconfined compressive strength (q_u) variation with the amount of cement is shown in Fig. 1 for three distinct cement types and 2 days of curing: Portland cement type I—general purpose cement (Fig. 1a), Portland cement type III—high early strength (Fig. 1b) and Portland cement type IV—low heat of hydration (Fig. 1c). Reducing porosity and increasing cement content ends up increasing q_u. A linear function also fits well to the relation q_u–C for the three types of cement studied. Further tests were carried out for 7 and 28 days of curing, resulting in results with similar trends, but with strengths increasing with curing time period.

Fig. 2(a–c) shows how the porosity affects the unconfined compressive strength of the sand–cement for three distinct cement types and 2 days of curing, Portland cement type I—general purpose cement, Portland cement type III—high early strength and Portland cement type IV—low heat of hydration respectively. A linear function also fits well the relation between unconfined compressive strength (q_u) and porosity (η) for three types of cement studied. The unconfined compressive strength reduces with the increase in porosity for all compacted mixtures and curing period studied. This beneficial effect of a decrease in porosity in cemented sands has been reported by several researchers [5]. Further tests were carried out for 7 and 28 days of curing, resulting in similar trends but with strengths increasing with curing time period.

According to previous works on concrete (e.g., [7,8,9,10,11], the effect of porosity and cement content on strength follow qualitatively the same trends as for stabilised rammed earth, which are reducing porosity and increasing cement content ends up increasing the unconfined compressive strength.

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. An average degree of saturation of 89% was obtained for specimens after submersion, irrespective of type of cement, time of curing, initial porosity or cementitious material content.

3.2. Effect of porosity/cement ratio on compressive strength considering three portland cement types (I, III and IV) and three distinct curing time periods

Fig. 3 presents the unconfined compressive strength as a function of the porosity/cement ratio (η/C_{iv}) [expressed as porosity (η) divided by the volumetric cement content (C_{iv}), the latter expressed as a percentage of cement volume regarding total volume],

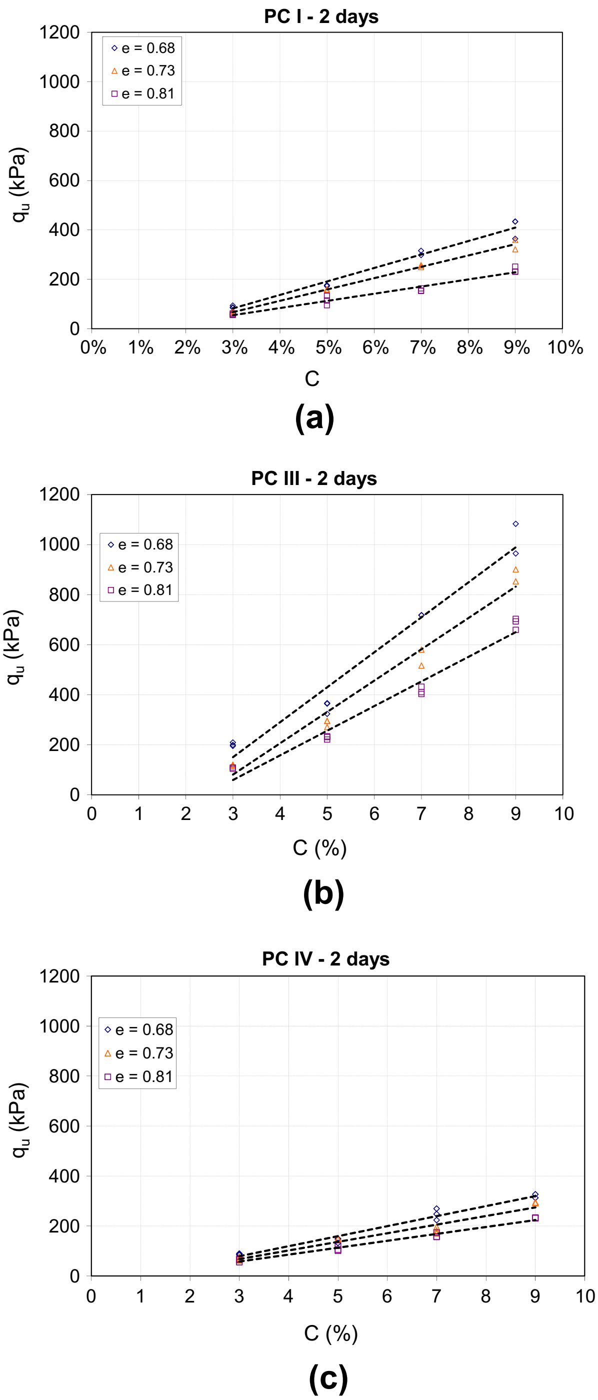

Fig. 1. Unconfined compressive strength (q_u) with cement content for 2 days as curing period: (a) type I—general purpose cement, (b) type III—high early strength and (c) type IV—low heat of hydration.

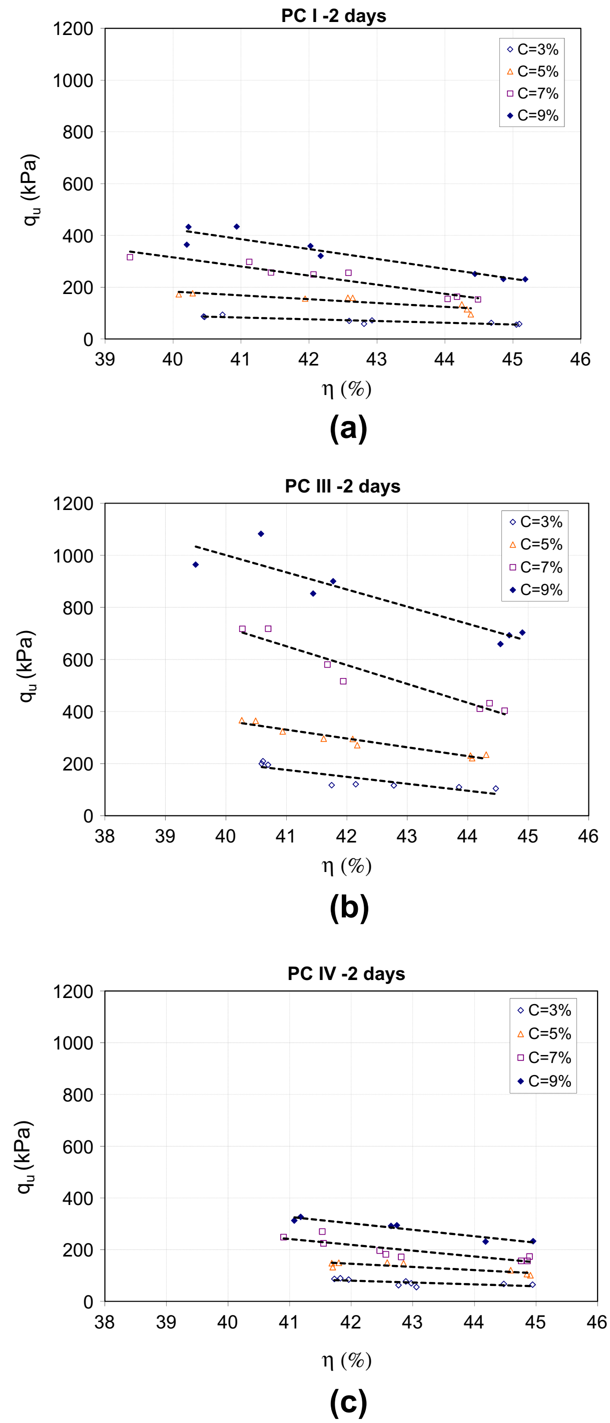

Fig. 2. Variation of unconfined compressive strength (q_u) with porosity (η) and 2 days as curing period: (a) type I—general purpose cement, (b) type III—high early strength and (c) type IV—low heat of hydration.

for Portland cement type I—general purpose cement (Fig. 3) and three curing periods studied (2, 7 and 28 days).

A simple observation of Fig. 3 suggests that the porosity/cement ratio is useful in normalizing results for Portland cement type I. Good correlations ($R^2 = 0.94$, 0.85 and 0.92) can be observed between porosity/cement ratio (η/C_{iv}) and the unconfined compressive strength (q_u) of the sand–cement studied for the three curing periods studied: 2 days of curing (see Eq. (1)), 7 days of curing (see Eq. (2)) and 28 days of curing (see Eq. (3)), respectively.

$$q_u \text{ (kPa)} = 11442.4\left[\frac{\eta}{C_{iv}}\right]^{-1.50} \quad (1)$$

$$q_u \text{ (kPa)} = 32978.2\left[\frac{\eta}{C_{iv}}\right]^{-1.50} \quad (2)$$

$$q_u \text{ (kPa)} = 47716.5\left[\frac{\eta}{C_{iv}}\right]^{-1.50} \quad (3)$$

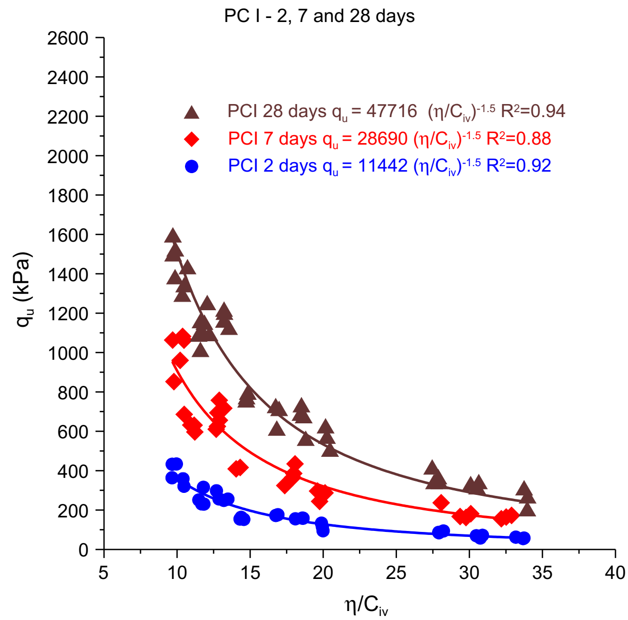

Fig. 3. Variation of unconfined compressive strength (q_u) with porosity/cement ratio for type I—general purpose cement and 3 curing periods (2, 7 and 28 days).

Observing Fig. 4, it could be suggested that the porosity/cement ratio is also useful in normalizing results for Portland cement type III. Good correlations (R^2 = 0.94, 0.97 and 0.88) can be observed between porosity/cement ratio (η/C_{iv}) and the unconfined compressive strength (q_u) of the sand–cement studied for the three curing periods studied: 2 days of curing (see Eq. (4)), 7 days of curing (see Eq. (5)) and 28 days of curing (see Eq. (6)), respectively.

$$q_u \text{ (kPa)} = 27267.2\left[\frac{\eta}{C_{iv}}\right]^{-1.50} \tag{4}$$

$$q_u \text{ (kPa)} = 47782.5\left[\frac{\eta}{C_{iv}}\right]^{-1.50} \tag{5}$$

$$q_u \text{ (kPa)} = 64734.3\left[\frac{\eta}{C_{iv}}\right]^{-1.50} \tag{6}$$

Observing Fig. 5, it could be suggested that the porosity/cement ratio is as well useful in normalizing results for Portland cement type IV. Good correlations (R^2 = 0.95, 0.91 and 0.91) can be observed between porosity/cement ratio (η/C_{iv}) and the unconfined compressive strength (q_u) of the sand–cement studied for the three curing periods studied: 2 days of curing (see Eq. (7)), 7 days of curing (see Eq. (8)) and 28 days of curing (see Eq. (9)), respectively.

$$q_u \text{ (kPa)} = 10086.6\left[\frac{\eta}{C_{iv}}\right]^{-1.50} \tag{7}$$

$$q_u \text{ (kPa)} = 17881.2\left[\frac{\eta}{C_{iv}}\right]^{-1.50} \tag{8}$$

$$q_u \text{ (kPa)} = 40866.2\left[\frac{\eta}{C_{iv}}\right]^{-1.50} \tag{9}$$

So, the use of the porosity of the compacted mixture divided by the volumetric cement content to assess the unconfined compressive strength in the sand–cement mixtures studied herein is valid for all types of cement and curing time periods studied. The results presented in this manuscript therefore suggest that using the porosity/cement ratio as represented by the voids volume of the compacted mixture divided by the cement volume, the engineer can choose the amount of cement and the porosity appropriate (within the studied range) to provide a mixture that meets the strength required by the project at the optimum cost.

For the curing time period interval studied, trends observed in Fig. 6 suggest that cement type IV (low heat of hydration) has an almost linear increase in strength with curing time, whereas cement type I (general purpose cement) starts at a similar strength at 2 days of curing, and have an higher strength rate at reduced curing time period (from 2 to 7 days), reducing such rate at higher curing time period (from 7 to 28 days of curing). Cement type III (early strength cement) has a similar shape that Portland cement I but starts with higher strength that the other two cement types (I and IV) at 2 days of curing. According to Popovics [9] percentage strength gain beyond 28 days for Portland cement types I, III and IV are approximately 9%, 7.5% and 80%, respectively.

Another analysis of the results can be carried by comparing Eqs. (1)–(9), in which q_u has a direct relationship with $\left[\frac{\eta}{C_{iv}}\right]^{-1.50}$ for Portland cement types I, III and IV respectively and all studied curing time periods and only a scalar differs regarding the effects of type of cement and curing time. So, unique relationships can also be achieved linking the q_u with η, C_{iv} and days of curing (t), as presented in Fig. 7 and in Eqs. (10)–(12), respectively for cement types I, III and IV.

$$q_u \text{ (kPa)} = 10,424(t)^{0.46}\left[\frac{\eta}{C_{iv}}\right]^{-1.50} \tag{10}$$

$$q_u \text{ (kPa)} = 24,675(t)^{0.30}\left[\frac{\eta}{C_{iv}}\right]^{-1.50} \tag{11}$$

$$q_u \text{ (kPa)} = 6,261(t)^{0.56}\left[\frac{\eta}{C_{iv}}\right]^{-1.50} \tag{12}$$

Following, a single equation form, for the unconfined compression strength (q_u), can be established for all types of Portland cement employed,

$$q_u \text{ (kPa)} = A(t)^{B}\left[\frac{\eta}{C_{iv}}\right]^{C} \tag{13}$$

where coefficient "A" increases from 6261 (Portland cement type IV) to 10,464 (Portland cement type I) and 24,675 (Portland cement type III), coefficient "B" decreases from 0.56 (Portland cement type IV) to 0.48 (Portland cement type I) and 0.30 (Portland cement type III) and exponent "C" does not change (equal to −1.50) with cement type studied in present research (Portland cement types I, III and IV). So, for the uniform sand, cement types (Portland cement types I, III and IV) and curing time periods (from 2 to 28 days of curing) studied herein, it has been shown that coefficient "A" has to do with initial values of q_u (high early strength cement has largest value) and coefficient "B" has to do with rate increases of q_u with time (low heat of hydration cement has largest value), being exponent "C" independent of cemented type used. Having a unique exponent "C" for all studied cements, it is possible to normalize the data making a graph with all strength results divided by the value of q_u with a porosity/cement ratio of, for example, η/C_{iv} = 20, one will get a distinctive equation (Eq. (14)) and curve (Fig. 8) for all cements and curing time periods studied. This means that carrying out one (1) test with a given cement type and a given curing time (e.g. Portland cement type I at 28 days), one could predict the effect of varying cement content and porosity across a wide range.

$$\frac{q_u}{q_u(\eta/C_{iv} = 20)} = 89.4\left[\frac{\eta}{C_{iv}}\right]^{-1.5} \tag{14}$$

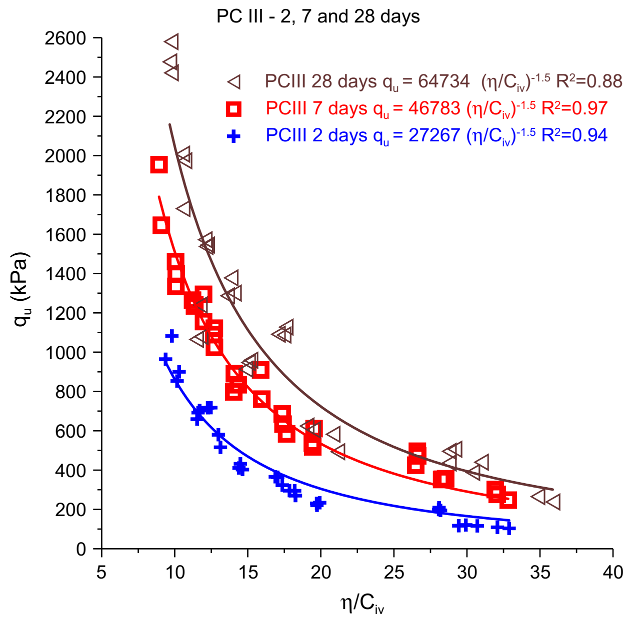

Fig. 4. Variation of unconfined compressive strength (q_u) with porosity/cement ratio for type III—high early strength and 3 curing periods (2, 7 and 28 days).

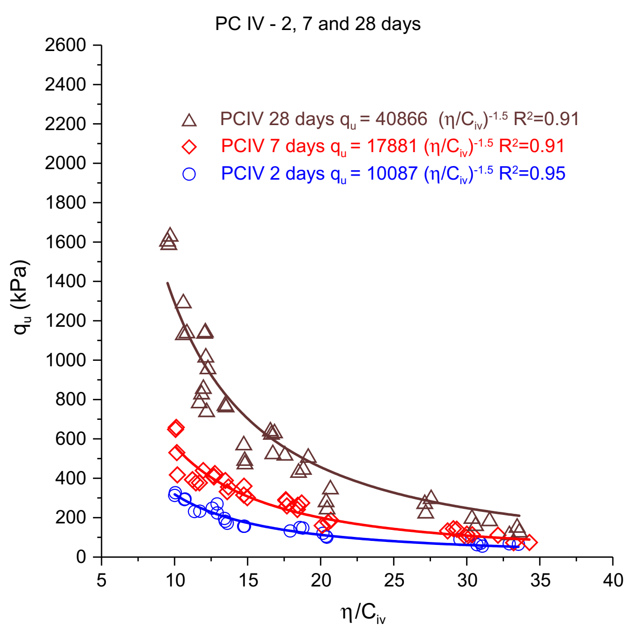

Fig. 5. Variation of unconfined compressive strength (q_u) with porosity/cement ratio for type IV—low heat of hydration and 3 curing periods (2, 7 and 28 days).

Eq. (14) can be used as dosage relationship for Portland cement types I, III and IV and the range of curing time period, cement and porosities studied. For the studied sand–cement mixtures, there are several technical ways of reaching a q_u target value for a given project: choosing a specific type of cement, waiting for the time period needed, porosity and/or cement content variation. The results presented in this manuscript therefore suggest that for a given type of cement, curing time period of interest, the engineer can choose the amount of cement and the porosity appropriate to provide a mixture that meets the strength required by the project at the optimum cost. The best option might change from situation to situation,

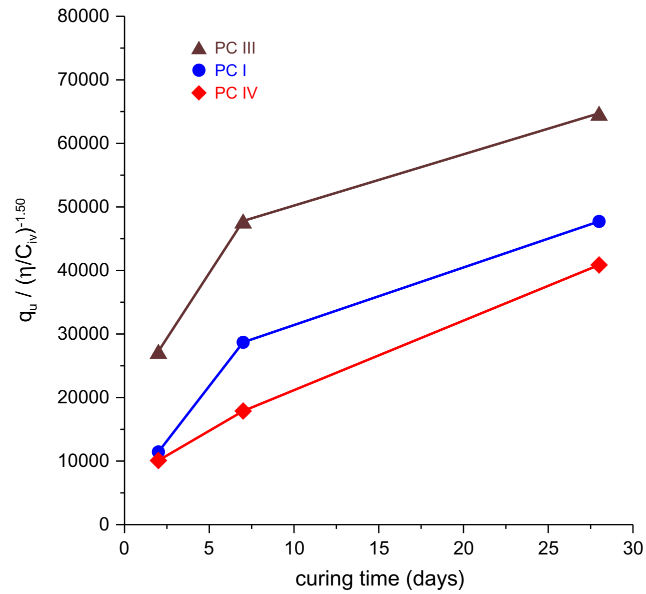

Fig. 6. Trends accounting three distinct types of Portland cement (I, III and IV) for the variation of q_u with η, C_{iv} and curing time.

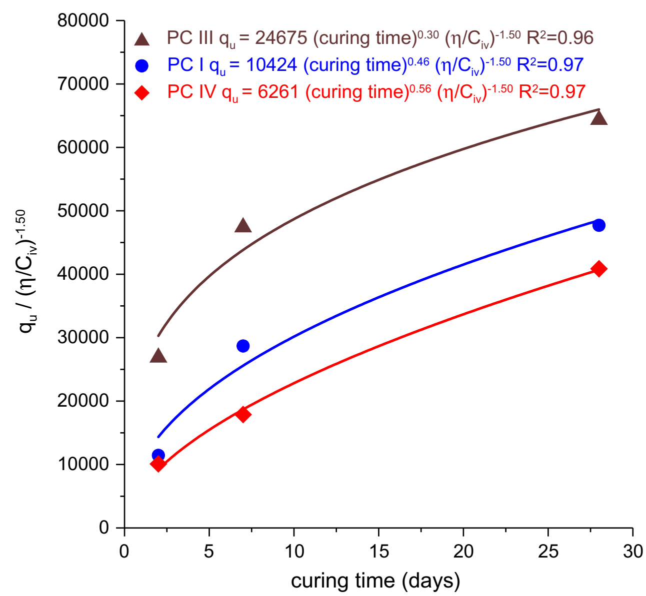

Fig. 7. Relationship accounting three distinct types of Portland cement (I, III and IV) for the variation of q_u with η, C_{iv} and curing time.

depending on time period available, accessibility to equipment to reach a given porosity and cost of cement.

Further studies are required expanding tests to other soils and longer curing time periods in order to check the possibility of generalization of the present findings.

4. Conclusions

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

- The porosity/cement ratio (η/C_{iv}) has been shown to be an appropriate index parameter to assess the unconfined compressive strength (q_u) of rammed sand–cement mixtures studied herein for all types of cement and curing time periods studied.

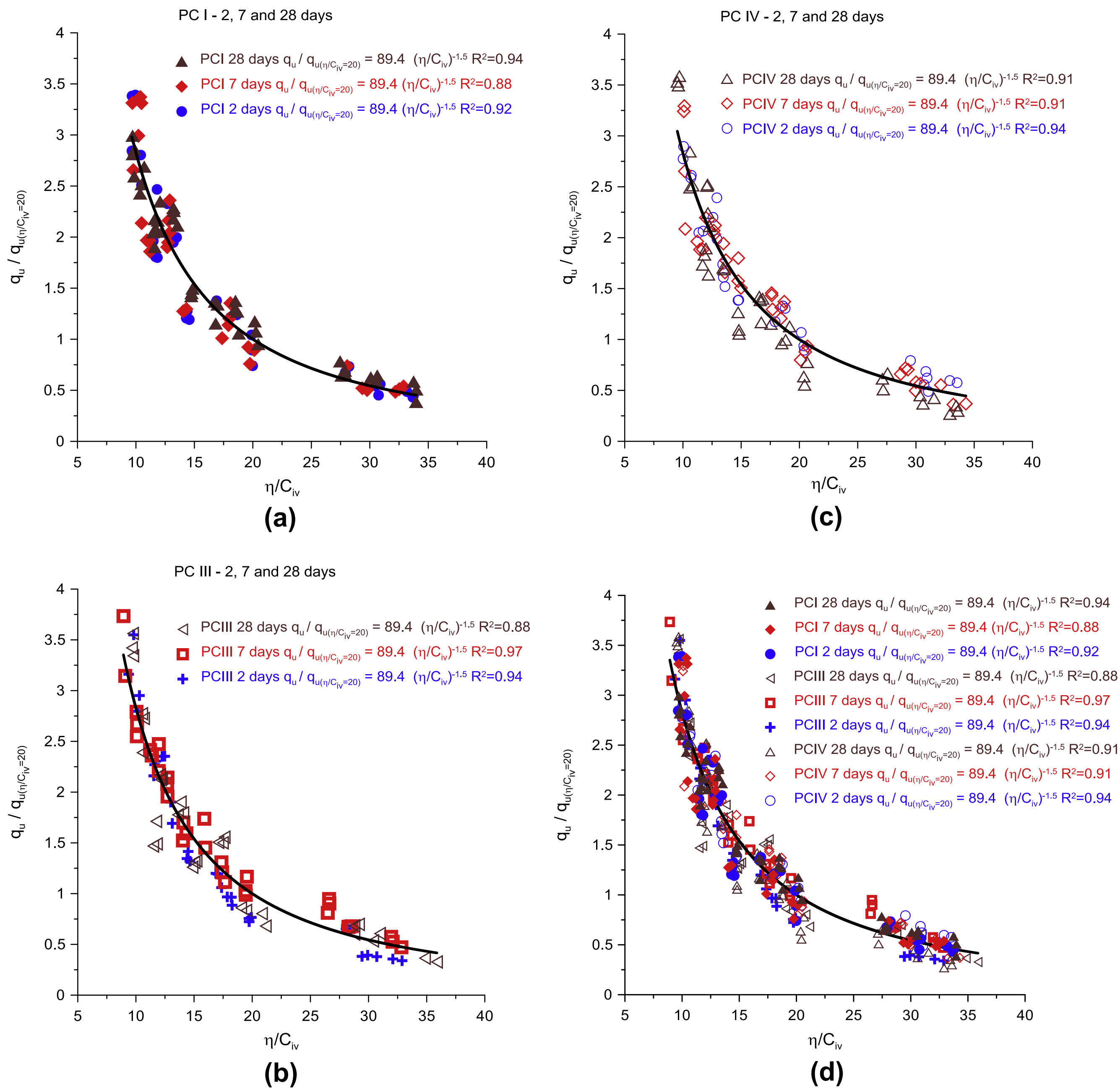

Fig. 8. Normalization of q_u (for the whole range of η/C_{iv}) by dividing for q_u at $\eta/C_{iv} = 20$ considering (a) Portland cement type I, (b) Portland cement type III, (c) Portland cement type IV and (d) all Portland cement types together, and curing times of 2, 7 and 28 days.

- A single equation form, linking porosity/cement ratio (η/C_{iv}), unconfined compression strength (q_u) and curing time, can be used for all types of Portland cement used (see Eq. (13)).
- It was possible to normalize the data by dividing the values of q_u by the value of strength of a given porosity/cement ratio (see Eq. (14)) for all cements and curing time periods studied. This means one could predict the effect of varying cement content and porosity across a wide range carrying out one (1) test with a given cement type and a given curing time.
- Based on the dosage equations established in present research for the studied rammed sand–cement mixtures, there are several technical ways of reaching a q_u target value for a given project and the best solution might change from situation to situation, depending on type of cement, time period available for curing, accessibility to equipment to reach a given porosity and cost of cement.

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