Ground Improvement
Volume 166 Issue GI4

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ice | proceedings

Proceedings of the Institution of Civil Engineers
Ground Improvement 166 November 2013 Issue GI4
Pages 221–232 http://dx.doi.org/10.1680/grim.12.00004
Paper 1200004
Received 16/01/2012 Accepted 29/11/2012
Published online 03/05/2013
Keywords: materials technology/strength and testing of materials

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Institution of Civil Engineers
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Variables controlling strength of fibre-reinforced cemented soils

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This study aimed to quantify the influence of the amount of cement, the porosity and the porosity/cement ratio in the assessment on tensile strength (q_t) and compressive strength (q_u) of fibre-reinforced and non-reinforced artificially cemented sand, as well as in the changes of q_t/q_u relationships and particular increases in q_t and q_u due to fibre insertion. The controlling parameters evaluated were the fibre content (*F*), the cement content (*C*), the porosity (η) and the porosity/cement ratio (η/C_{iv}). A number of splitting tensile and unconfined compression tests were carried out in fibre-reinforced and non-reinforced artificially cemented sand specimens. The results showed that fibre insertion in the cemented soil, for the whole range of cement studied, caused an increase in both q_t and q_u. Both q_t and q_u increased linearly with the amount of cement (*C*) and a power function fitted well as the relation between splitting tensile strength (q_t) and porosity (η) and unconfined compressive strength (q_u) and porosity (η) for both the fibre-reinforced and non-reinforced specimens. It was also shown that the porosity/cement ratio, in which volumetric cementitious material content is adjusted by an exponent (0·28 for all the fibre-reinforced and non-reinforced cemented soil mixtures of this study) to end in unique correlations for each mixture, is a good parameter in the evaluation of the splitting tensile strength and unconfined compressive strength of the fibre-reinforced and non-reinforced cemented soil studied. Finally, the unique q_t/q_u relationships equal to 0·14 (fibre-reinforced sand cement specimens) and 0·10 (non-reinforced sand–cement specimens) were found, being independent of the porosity/cement ratio, q_t increased 86% due to fibre insertion and q_u increased just 34·5% due to fibre addition.

Notation

C	cement content (expressed in relation to mass of dry soil)
C_{iv}	volumetric cement content (expressed in relation to the total specimen volume)
C_u	uniformity coefficient
D_{50}	mean effective diameter of soil grains
q_t	splitting tensile strength
q_u	unconfined compressive strength
γ_d	dry unit weight
η	porosity
η/C_{iv}	porosity/cement ratio
ω	moisture content

1. Introduction

The strength of artificially cemented soils has been studied in the past by several investigators (Clough *et al.*, 1981; Consoli *et al.*, 2007a, 2009a, 2009b, 2009c, 2009d, 2010, 2011, 2012a, 2012b, 2012c; Huang and Airey, 1998; Thomé *et al.*, 2005). In addition, studies on reinforcing sand by the inclusion of fibre have also been reported (Ahmed, 2012; Casagrande *et al.*, 2006; Consoli *et al.*, 2007b, 2007c, 2009e, 2009f, 2012d; Ibraim *et al.*, 2010; Maher and Gray, 1990; Santos *et al.*, 2010a, 2010b). Few studies have been carried out on the influence of fibre inclusion on the mechanical behaviour of cemented soil (Ahmed *et al.*, 2011; Consoli *et al.*, 1998, 2002, 2004; Maher and Ho, 1993; Santos *et al.*, 2010b; Tang *et al.*, 2007). Usually the fibre-reinforced cemented soil strength is assessed by numerous laboratory tests (e.g., unconfined compression, splitting tensile and triaxial tests) that aim to find the minimum amount of cement that meet the target property. This approach probably results from the fact that fibre-reinforced cemented soils show a complex behaviour that is affected by many factors such as the fibre characteristics, the amount of cement and the porosity.

The soil–cement–fibre technique has been used successfully in pavement base layers and as an improved layer to shallow foundations. Some examples of application in the field are given in the following paragraphs.

Crockford *et al.* (1993) demonstrated that the inclusion of polypropylene fibres to lime stabilised clayey soil layers increased the life of such layers when submitted to cyclic loading.

The compressive load–settlement response from two plate load tests carried out on a layered system formed by two different top layers, sand–cement and sand–cement–fibre, overlaying the residual soil stratum was discussed by Consoli *et al.* (2003). The utilisation of a cemented top layer increased bearing capacity, reduced displacement at failure and changed soil behaviour to a noticeable brittle behaviour. After maximum load, the bearing capacity dropped towards approximately the same value found for a plate test carried out directly on the residual soil. The addition of fibre to the cemented top layer maintained roughly the same bearing capacity but changed the post-failure behaviour to a ductile behaviour. A punching failure mechanism was observed in the field for the load test bearing on the sand–cement top layer, with tension cracks being formed from the bottom to the top of the layer. A completely distinct mechanism was observed in the case of the sand–cement–fibre top layer, the failure occurring through the formation of a thick shear band around the border of the plate, which allowed the stresses to spread through a larger area over the residual soil stratum.

Consoli *et al.* (2012e) observed experimentally that the uplift capacity of plates embedded in cement-stabilised backfill layers improved after the insertion of 0·5% polypropylene fibres on the backfilled material. The addition of fibres to the cement-stabilised backfill led to an increase in uplift capacity of about 50% for an H/D ratio of 1·0, where H is the thickness of the treated layer and D is the diameter of the plates.

The present study aimed to quantify the influence of the amount of cement and the porosity on the tensile and compressive strength of fibre-reinforced and non-reinforced artificially cemented sandy soil, as well as to evaluate the use of a porosity/cement ratio to assess their splitting tensile strength and unconfined compressive strength. Finally, the influence of fibre insertion on q_t and q_u of the cemented soil, as well as the influence of fibre-reinforcement on q_t/q_u relationships, will be investigated.

2. Experimental programme

The experimental programme was carried out in two parts. The geotechnical properties of the studied soil were characterised and then a series of splitting tensile and unconfined compression tests for both the fibre-reinforced and non-reinforced cemented specimens were carried out.

2.1 Programme of splitting tensile and unconfined compression tests

The splitting tensile and unconfined compression tests constituted the main part of this research. The programme was conceived in such a way as to evaluate, separately, the influences of the cement content, porosity and porosity/cement ratio on the mechanical strength of the fibre-reinforced cemented soil.

The moulding points were chosen considering dry densities of 17·3, 18·0, 19·0 and 19·7 kN/m^3, with the same moistures content (about 10%). Each condition was moulded with five different cement percentages, namely 1, 2, 3, 5 and 7%. The cement percentages were chosen following Brazilian and international experience with soil–cement (Consoli *et al.*, 2007c, 2009e, 2009f, 2010; Mitchell, 1981). Because of the typical scatter of data for both splitting tensile and unconfined compression tests, a minimum of six specimens moulded with the same characteristics were tested (three under compression and three under tensile conditions).

2.2 Materials

The soil used in this study was derived from a weathered sandstone and was obtained from a borrow pit in the region of Porto Alegre, southern Brazil. The sample was collected in a disturbed state, by manual excavation, in sufficient quantity to complete all the tests.

The results of the characterisation tests are shown in Table 1. This soil is classified as non-plastic clayey sand (SC) according to the Unified Soil Classification System.

Portland cement of high early strength (Type III according to ASTM C150-07 (ASTM, 2007)) was used as the cementing agent. Its fast gain of strength allowed the adoption of 7 days as the curing time. The specific gravity of the cement grains is 3·15.

Monofilament polypropylene fibres were used throughout this investigation to reinforce (when necessary) the cemented soil. The fibres were 24 mm in length and 0·023 mm ($d_{tex} = 3{\cdot}3$, where d_{tex} is a unit of measure for the linear mass density of fibres (mass in grams per 10 000 m)) in diameter (consequent aspect ratio of 1043), with a specific gravity of 0·91, tensile strength of 120 MPa, elastic modulus of 3 GPa and linear strain at failure of 80% (a picture of the polypropylene fibres employed in present research, zoomed ninety times, is shown in Figure 1). The fibre contents used in the experiments were zero and 0·50% by weight of the sum of dry soil and cement. The selection of fibre type, percentage and dimensions followed studies by Consoli *et al.* (2004, 2007b).

Distilled water was used both for moulding specimens for the tensile and compression tests, as well as for the characterisation tests.

2.3 Methods

2.3.1 Moulding and curing of specimens

For the unconfined compression and splitting tensile tests, cylindrical specimens, 50 mm in diameter and 100 mm high,

Properties	Value
Liquid limit	23%
Plastic limit	13%
Plasticity index	10%
Specific gravity	2·64
Medium sand (0·2 < diameter < 0·6 mm)	16·2%
Fine sand (0·06 < diameter < 0·2 mm)	45·4%
Silt (0·002 < diameter < 0·06 mm)	33·4%
Clay (diameter < 0·002 mm)	5·0%
Mean effective diameter (D_{50})	0·12 mm
Coefficient of uniformity (C_u)	50
Maximum dry unit weight for modified Proctor compaction effort	20·1 kN/m^3
Optimum moisture content for modified proctor compaction effort	10%

Table 1. Physical properties of the soil sample

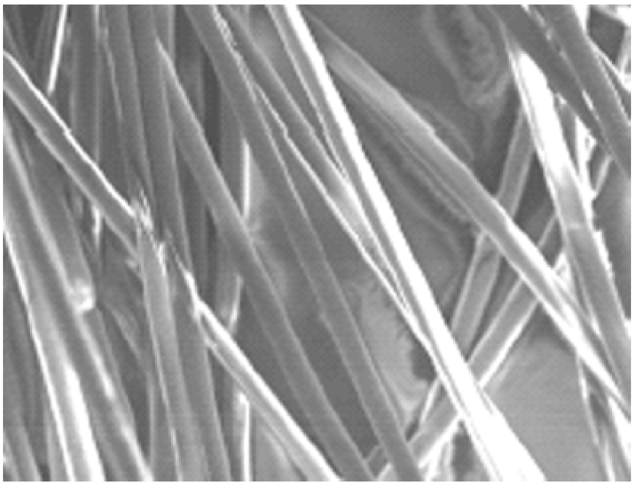

Figure 1. Picture of polypropylene fibres employed in present research

were used. The fibre-reinforced and unreinforced compacted soil specimens used in the tests were prepared by hand-mixing dry soil, cement, water and polypropylene fibres (when appropriate). During the mixing process, it was found to be important to add the water prior to adding the fibres, to prevent floating of the fibres. The amount of fibres for each mixture was calculated based on the mass of dry soil plus the mass of cement. Visual and optical microscope examination of exhumed specimens showed the mixtures to be satisfactorily uniform.

After mixing sufficient material for one specimen, the mixture was stored in a covered container to avoid moisture losses before subsequent compaction. Two small portions of the mixture were also taken for moisture content determination.

The specimen was then statically compacted (using a hydraulic jack) in three layers inside a cylindrical split mould, which was lubricated, so that each layer reached the specified dry density. The top of the first and the second layers was slightly scarified. After the moulding process, the specimen was immediately extracted from the split mould, and its weight, diameter and height were measured with accuracies of about 0·01 g and 0·1 mm. The samples were then placed within plastic bags to avoid significant variations of moisture content before testing. They were cured in a humid room at 23° ± 2°C and relative humidity above 95% for 6 days.

The samples were considered suitable for testing if they met the following tolerances: dry density (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); moisture content (ω): within ± 0·5% of the target value and dimensions: diameter to within ± 0·5 mm and height ± 1 mm.

2.3.2 Splitting tensile tests

Splitting tensile tests followed Brazilian standard NBR 7222 (ABNT, 1983). An automatic loading machine, with maximum capacity of 50 kN and proving rings with capacity of 10 kN and resolution of 0·005 kN was used for the splitting tensile tests. After curing, the specimens were submerged in a water tank for 24 h for saturation to minimise suction. The water temperature was controlled and maintained at 23 ± 3°C. Immediately before the test, the specimens were removed from the tank and dried superficially with an absorbent cloth. Then a cylindrical specimen was placed horizontally between the platens of the compression testing machine. The specimen was compressed by loading it along two opposite generatrices, leading to failure in tension along the diameter contained in the plane formed by these two generatrices (the maximum load was recorded). The split tensile test was originally developed by Carneiro and Barcellos (1953) as a tension test for brittle materials. As an acceptance criterion, 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.

2.3.3 Unconfined compression tests

Unconfined compression tests have been systematically used in most experimental programmes reported in the literature in order to verify the effectiveness of the stabilisation with cement or to access the importance of influencing factors on the strength of cemented soils. 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 (ABNT, 1980), being simple and fast, while reliable and cheap.

The automatic loading machine was the same as that used for the splitting tensile tests, and the proving rings with capacities of 10 and 50 kN and resolutions of 0·005 and 0·023 kN were used for the unconfined compression tests. Curing of specimens and acceptance criteria were exactly the same as for splitting tensile tests.

2.3.4 Matric suction measurements

At their moulding moisture contents, all specimens were in an unsaturated state exhibiting a certain level of suction. Suction measurements aimed to verify its magnitude and examine if there was significant variation between specimens of different porosities and cement contents.

The matric suction, namely that arising from the capillary forces inside the sample, 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 was approximately 6%, which allowed measurements of suction from zero to 29 MPa. The calibration equations for this filter paper are those presented by Chandler *et al.* (1992).

3. Results

3.1 Effect of the cement content and porosity on compressive and tensile strength

Figure 2 shows the raw data and the fitted lines for the splitting tensile strength (q_t) (Figure 2(a) for non-reinforced cemented specimens and Figure 2(b) for fibre-reinforced cemented specimens) and unconfined compressive strength (q_u) (Figure 2(c) for non-reinforced cemented specimens and Figure 2(d) for fibre-reinforced cemented specimens) as a function of the cement content (C). It can be observed that the cement content has a great effect on the tensile and compressive strength of non-reinforced and fibre-reinforced soil–cement. A small addition of cement is enough to generate a significant gain in tensile and compressive strength. It can be seen that for the fibre-reinforced and non-reinforced materials the tensile and compressive strengths increase approximately linearly with the increase in the cement content. Figures 2(a) and (b) for tensile strength and Figures 2(c) and (d) for compressive strength show the increase in the rate of tensile and compressive strength gain with cement content (for both non-reinforced and fibre-reinforced specimens), represented by the gradient of the fitted line, with the increase of the dry density. At high dry densities (more compacted mixtures) there are many more contacts between the products of the cement hydration and the particles of the soil, as well as more contacts between the soil matrix and the reinforcement inclusions, and so the effectiveness of the cement and the fibres (when applicable) is greater.

Graphs of the tensile strength (q_t) plotted against cement content (C) results, at a dry density of 19·0 kN/m^3, considering non-reinforced and fibre-reinforced specimens, are presented in Figure 3(a). It can be observed that fibre insertion in the cemented soil (for the whole range of cement studied) cause an increase in tensile strength. Figure 3(b) presents graphs of q_u plotted against C, also at a dry density of 19·0 kN/m^3, and considering non-reinforced and fibre-reinforced specimens. The fibre reinforcement also causes an increase in compressive strength, but it appears to be of smaller intensity when compared with the tensile strength increase. The insertion of fibres to the soil–cement blend allowed the development of friction between soil particles and plastic strips and a number of such fibres will intercept the failure shear plane formed during unconfined compression and splitting tensile tests, increasing compressive and tensile strengths.

Figure 4 shows how the porosity (η) affects the splitting tensile strength (q_t) (Figure 4(a) for non-reinforced cemented specimens and Figure 4(b) for fibre-reinforced cemented specimens) and unconfined compressive strength (q_u) (Figure 4(c) for non-reinforced cemented specimens and Figure 4(d) for fibre-reinforced cemented specimens). A power function fits the relation between q_t and η of non-reinforced and fibre-reinforced cemented soil specimens well, as well as the relation between q_u and η of non-reinforced and fibre-reinforced cemented soil specimens. Both the tensile and the compressive strengths decrease with the increase in porosity for the non-reinforced and fibre-reinforced cemented mixtures studied. The mechanism by which the reduction in porosity influences the soil–cement and soil–cement–fibre strength is again related to the existence of a larger number of contacts. It is important to recall that porosity is directly related to the dry unit weight of the blends: the greater the dry unit weight, the smaller the porosity.

Graphs of q_t plotted against η, at a cement content of 2%, considering non-reinforced and fibre-reinforced cemented soil specimens are presented in Figure 5(a). It can be observed that the fibre insertion in the cemented soil causes an increase in tensile strength for all porosities studied. Strength increase trends also can be observed when analysing the graphs of q_u plotted against η presented in Figure 5(b), at a cement content of 2%, considering both non-reinforced and fibre-reinforced cemented

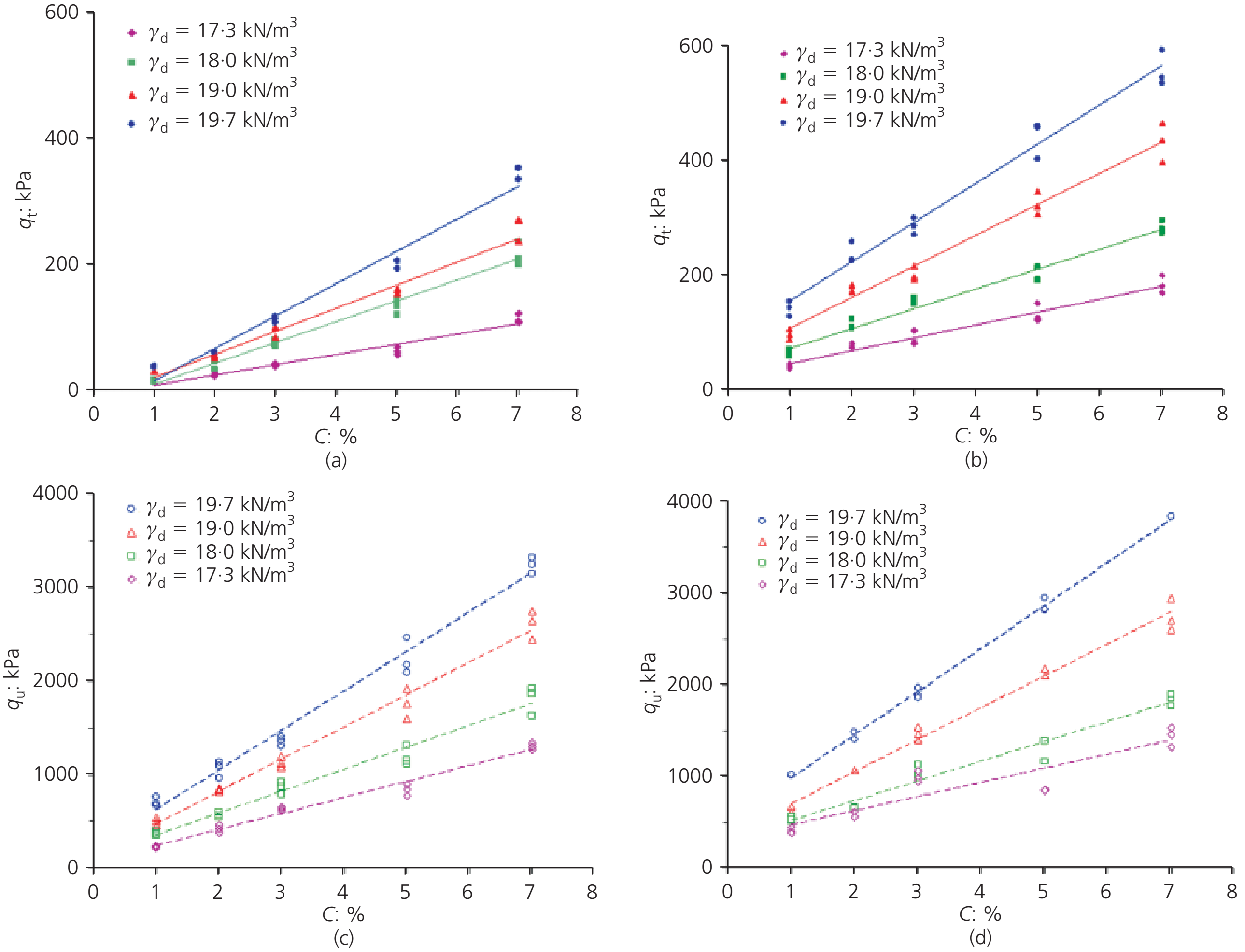

Figure 2. Variation of splitting tensile strength with cement content for (a) non-reinforced specimens and (b) fibre-reinforced specimens; and unconfined compression strength with cement content for (c) non-reinforced specimens and (d) fibre-reinforced specimens

mixtures. However, the increase in compressive strength due to fibre-reinforcement appears to be proportionally smaller that the effect of fibres under tensile loading.

The process of submerging the specimens for 24 h before the splitting tensile and 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 the initial porosity or cementitious material content. The values of suction measured were low with values ranging from about 1 to 10% of the tensile strength. These measurements were made on the specimens after failure in the tests and are therefore likely to overestimate the real value, because a slight drying of the sample may have occurred during the few minutes from the start of the test until the measurement was made. Given the small values of matric suction measured in these specimens, the small effects arising from the unsaturated nature were disregarded.

3.2 Effect of porosity/cement ratio

As seen in the results presented above (Figures 2 to 5), for non-reinforced and fibre-reinforced specimens, both tensile strength and compressive strength were dependent on the porosity and the cement content of the mixture. Increasing values of porosity cause reduction of q_t and q_u whereas increasing values of cement content yield larger values of q_t and q_u. It is proposed that a specific explicit relation exists betweem q_t and the porosity/cement ratio (η/C_{iv}) and between q_u and the porosity/cement ratio

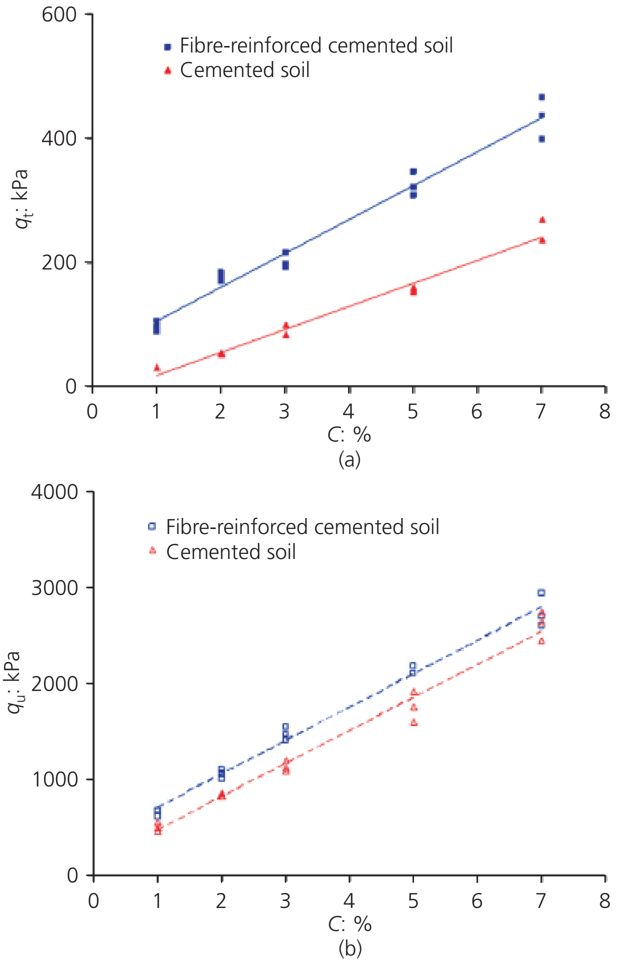

Figure 3. Variation of (a) splitting tensile strength with cement content for fibre-reinforced and non-reinforced specimens considering $\gamma_d = 19{\cdot}0$ kN/m^3 and (b) unconfined compressive strength with cement content for fibre-reinforced and non-reinforced specimens considering $\gamma_d = 19{\cdot}0$ kN/m^3

(η/C_{iv}), namely C_{iv} the volumetric cement content, for both non-reinforced and fibre-reinforced cemented specimens.

The relations between q_t and η/C_{iv} and between q_u and η/C_{iv}, for both non-reinforced and fibre-reinforced cemented specimens, suggest that η/C_{iv} joins the distinct effects of both variables (η and C_{iv}) in a unique factor controlling q_t and q_u. It means that η and $1/C_{iv}$ affect q_t and q_u separately and that the effect on q_t and q_u of increasing values of porosities can be counteracted by increasing values of volumetric cement contents, leading to η/C_{iv} governing q_t and q_u.

Figure 6 shows the raw data and the fitted lines for the splitting tensile strength (q_t) (Figure 6(a) for non-reinforced cemented specimens and Figure 6(b) for fibre-reinforced cemented specimens) and unconfined compressive strength (q_u) (Figure 6(c) for non-reinforced cemented specimens and Figure 6(d) for fibre-reinforced cemented specimens) as a function of the porosity/cement ratio (η/C_{iv}), highlighting the distinct cement contents used.

Best-fit curves for the splitting tensile strength plotted against porosity/cement ratio present fair correlations (coefficient of determination: $R^2 = 0{\cdot}83$ and $0{\cdot}78$, respectively, for non-reinforced cemented specimens (Equation 1), and for fibre-reinforced cemented specimens (Equation 2)) and best-fit curves for unconfined compressive strength plotted against porosity/cement ratio also present fair correlations (coefficient of determination: $R^2 = 0{\cdot}87$ and $0{\cdot}77$, respectively, for non-reinforced cemented specimens (Equation 3), and for fibre-reinforced cemented specimens (Equation (4)). Some scatter of data around the best-fit curves can be seen for all mixtures and fibre contents studied

1. $$q_t\ (\text{kPa}) = 7{\cdot}38 \times 10^3 \left[\frac{\eta}{C_{iv}}\right]^{-1{\cdot}61}$$

2. $$q_t\ (\text{kPa}) = 3{\cdot}23 \times 10^3 \left[\frac{\eta}{C_{iv}}\right]^{-1{\cdot}00}$$

3. $$q_u\ (\text{kPa}) = 24{\cdot}20 \times 10^3 \left[\frac{\eta}{C_{iv}}\right]^{-1{\cdot}13}$$

4. $$q_u\ (\text{kPa}) = 16{\cdot}50 \times 10^3 \left[\frac{\eta}{C_{iv}}\right]^{-0{\cdot}88}$$

Figure 6 distinguishes (for each one of the fibre contents studied) the plotted points by their cement contents. The observation of points with similar η/C_{iv}, but obtained by different combinations of cement content and density, showing distinct strengths for each cement content are supposed to be due to substantial differences in rates of change of unconfined compressive strength and splitting tensile strength with porosity (η) and with the inverse of the volumetric cement content ($1/C_{iv}$). A way to make the variation rates of η and $1/C_{iv}$ compatible is through the application of a power to one of them (in the present work the application of a power is suggested to be on C_{iv} – the optimum fit (obtained after a search for the highest coefficient of determination) was found to be applying a power equal to 0·28 to the non-reinforced and fibre-reinforced tensile strength (Figures 7(a) and (b)) and compressive strength (Figures 7(c) and (d)) results studied herein). Curves for the splitting tensile strength plotted against porosity/cement ratio present better correlations (coefficient of determination: $R^2 = 0{\cdot}85$ and $0{\cdot}95$, respectively, for non-reinforced cemented specimens (Equation 5), and for fibre-reinforced cemented speci-

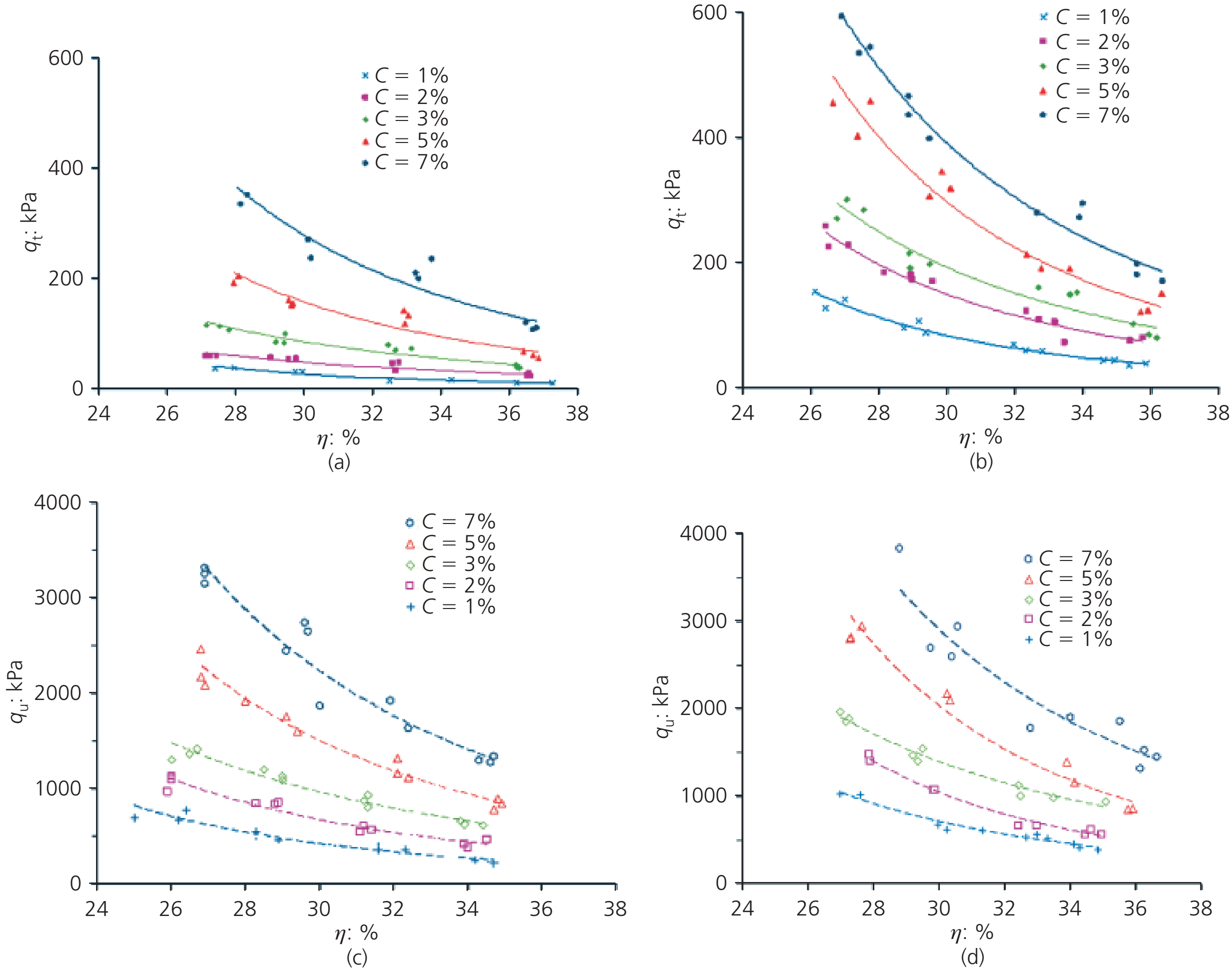

Figure 4. Variation of splitting tensile strength with porosity for (a) non-reinforced specimens and (b) fibre-reinforced specimens and unconfined compression strength with cement content for (c) non-reinforced specimens and (d) fibre-reinforced specimens

mens (Equation 6)) and best-fit curves for unconfined compressive strength plotted against porosity/cement ratio also present excellent correlations (coefficient of determination: $R^2 = 0{\cdot}95$ and 0·97, respectively, for non-reinforced cemented specimens (Equation 7), and for fibre-reinforced cemented specimens (Equation 8))

5. $$q_t\ (\text{kPa}) = 1{\cdot}37 \times 10^6 \left[\frac{\eta}{(C_{iv})^{0{\cdot}28}}\right]^{-2{\cdot}90}$$

6. $$q_t\ (\text{kPa}) = 2{\cdot}55 \times 10^6 \left[\frac{\eta}{(C_{iv})^{0{\cdot}28}}\right]^{-2{\cdot}90}$$

7. $$q_u\ (\text{kPa}) = 13{\cdot}35 \times 10^6 \left[\frac{\eta}{(C_{iv})^{0{\cdot}28}}\right]^{-2{\cdot}90}$$

8. $$q_u\ (\text{kPa}) = 17{\cdot}96 \times 10^6 \left[\frac{\eta}{(C_{iv})^{0{\cdot}28}}\right]^{-2{\cdot}90}$$

The results presented above indicate the existence of unique and distinct relationships for the non-reinforced and fibre-reinforced compacted clayey sand–cement tensile and compressive strengths with $[\eta/(C_{iv})^{0{\cdot}28}]^{-2{\cdot}90}$. Therefore, for the mixtures studied in the present research, q_t/q_u is a scalar and has values of 0·10 for non-reinforced sand–cement specimens and 0·14 for fibre-reinforced sand–cement specimens (independently of the porosity, the ce-

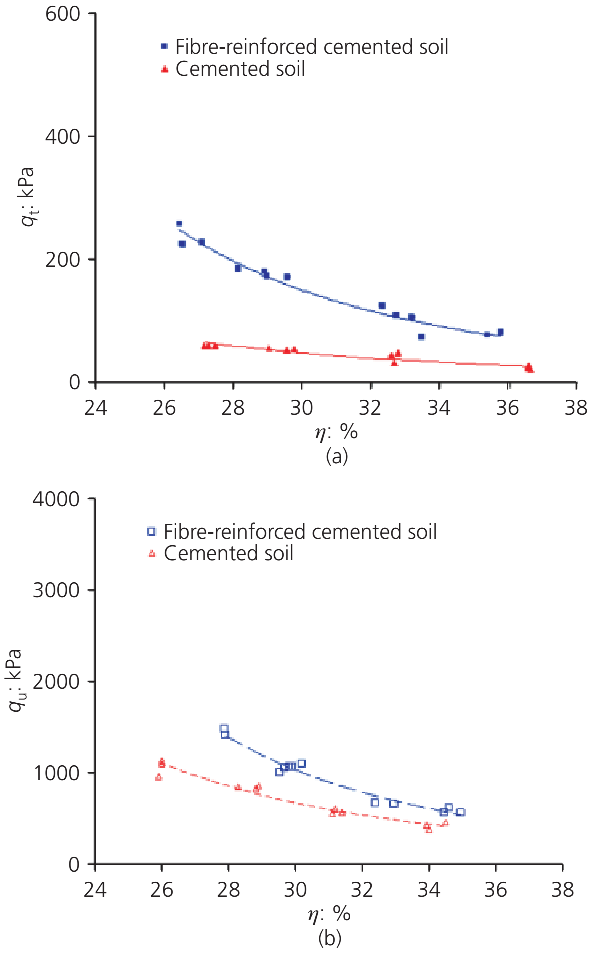

Figure 5. Variation of splitting tensile strength with porosity (a) for fibre-reinforced and non-reinforced specimens considering $C = 2\%$ and (b) unconfined compressive strength with porosity for fibre-reinforced and non-reinforced specimens considering $C = 2\%$

ment content or the porosity/cement ratio), showing that fibre-reinforcement looks to be much more efficient for tensile strength than for compressive strength. Splitting tensile strength (q_t) increased 86% due to fibre insertion whereas unconfined compressive strength (q_u) increased just 34·5% due to fibre addition. The distinct effectiveness of fibre introduction regarding compressive and tensile strength of a soil–cement mix might be explained as the improvement of soil–cement blends under compression after insertion of fibres is attributed to the large contact area (enhancing friction) between fibres and soil–cement particles, whereas the performance of soil–cement blends under tension, after insertion of fibres, improves once fibres act under tension with a random orientation and several fibres will position in the favourable tensile strain directions.

Thus there is a straight proportionality between tensile and compressive strengths of the fibre-reinforced mixtures, as well as of the non-reinforced mixtures, which is valid for the whole range of voids ratio and cement content studied in the present research programme. It is therefore possible to conclude that any rational dosage methodology for fibre-reinforced and non-reinforced cemented sand, considering the effect of different variables (porosity, cement content or porosity/cement ratio), can be centred on tensile or compression tests on either reinforced or non-reinforced samples, once they are intimately related through unique proportionalities. Additionally, the existence of such unique and distinct relationships enables the assessment of the compressive strength and the tensile strength of the reinforced mixtures through the results of the non-reinforced mixtures, and vice-versa. For example, with the studied materials, for a given $\eta/(C_{iv})^{0{\cdot}28}$, if the q_u of the non-reinforced mixture is 1000 kPa, the q_t of the non-reinforced mixture will be about 100 kPa and the q_t of the reinforced mixture will be around 186 kPa. The validity of present study is limited to the soil type, fibre type, dimensions and percentages used in present research, type and amounts of cement and porosity range studied, and curing time, curing conditions, water content and period of submersion of sample in water established herein. Further studies are under way (expanding tests to other fibres (considering a range of dimensions and percentages), soils and cementitious agents) in order to check the possibility of generalisation of the present findings.

Finally, the results presented herein suggest that the porosity/cement ratio can be an extremely useful index for practitioners from which an engineer can choose the amount of cement appropriate to provide a mixture that meets the strength required by the project at the optimum cost. The porosity/cement ratio can also be useful in the field control of fibre-reinforced soil–cement layers. Once a poor compaction has been identified, it can be readily taken into account in the design being adopted through the curves of q_t or q_u plotted against η/C_{iv}, with corrective measures applied accordingly such as the reinforcement of the treated layer.

4. Conclusions

From the data presented herein the following conclusions can be drawn.

(*a*) A straight line adjusts well to both q_t–C and q_u–C clayey sand–fibre content–cement mixtures relations.

(*b*) The reduction in porosity of the compacted mixtures improves both the tensile and compressive strengths of the clayey sand–fibre content–cement mixtures greatly.

(*c*) The porosity/cement ratio, adjusted by a unique exponent (in this case 0·28), was shown to be a good parameter in the evaluation of both tensile and compressive strength of the clayey sand–fibre content–cement studied. Such uniqueness suggests that the adjustment exponent might even be a function of the characteristics of the soil and cementitious agent (further studies using other soils and cement agents are in progress), but does not appear to be a function of the fibre insertion.

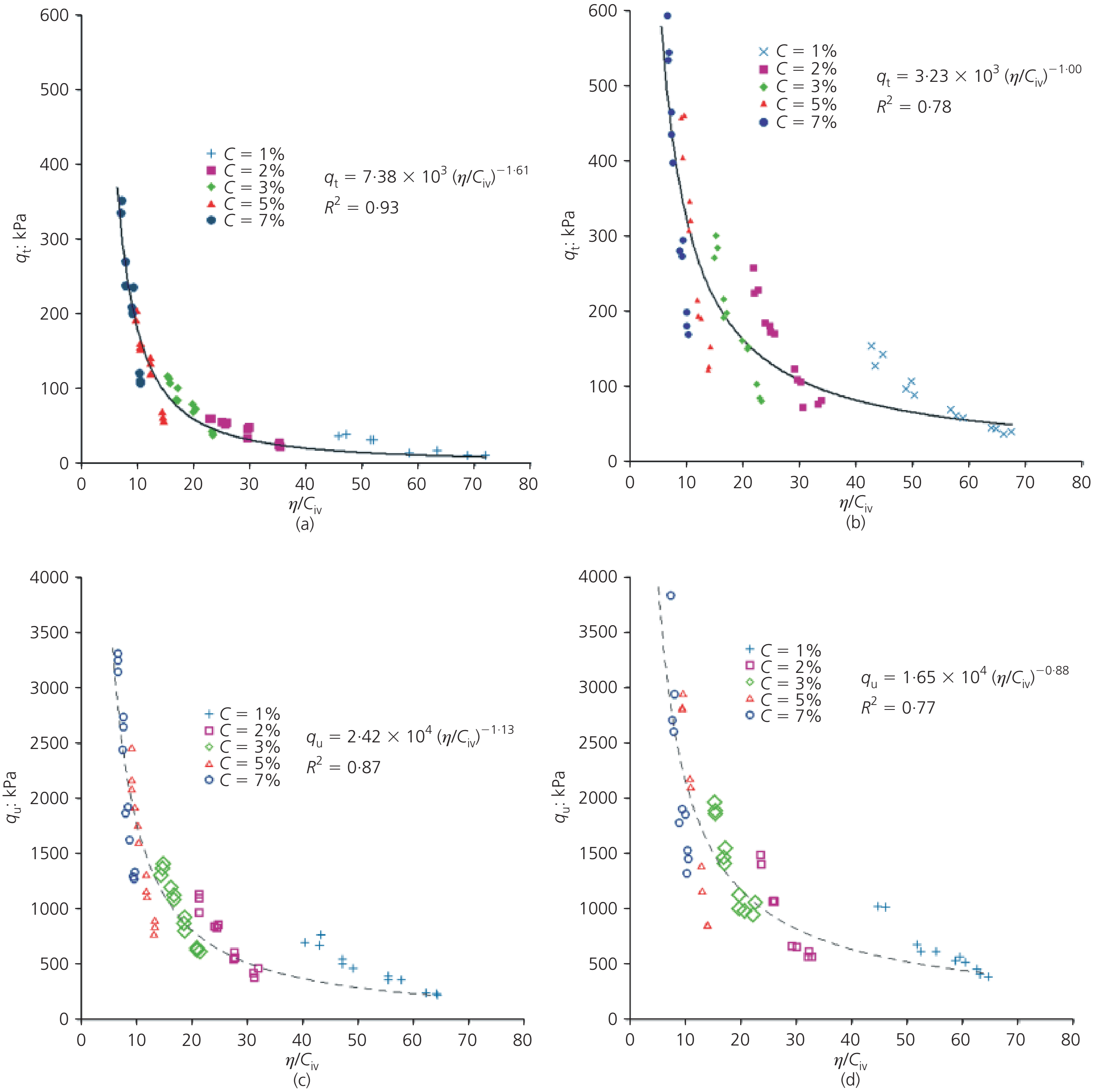

Figure 6. Variation of splitting tensile strength with η/C_{iv} for (a) non-reinforced specimens and (b) fibre-reinforced specimens and unconfined compression strength with η/C_{iv} for (c) non-reinforced specimens and (d) fibre-reinforced specimens

(*d*) There is a straight proportionality between tensile and compressive strengths of the fibre-reinforced mixtures, as well as of the non-reinforced mixtures evaluated in the present study, being independent of porosity/cement ratio. As a consequence, rational dosage methodologies can be centred on tensile or compression tests on either reinforced or non-reinforced samples, once they are interdependent.

(*e*) Fibre-reinforcement looks to be much more efficient for tensile strength than for compressive strength.

Acknowledgement

The authors wish to express their gratitude to the Brazilian Research Council (CNPq) for the financial support to the research

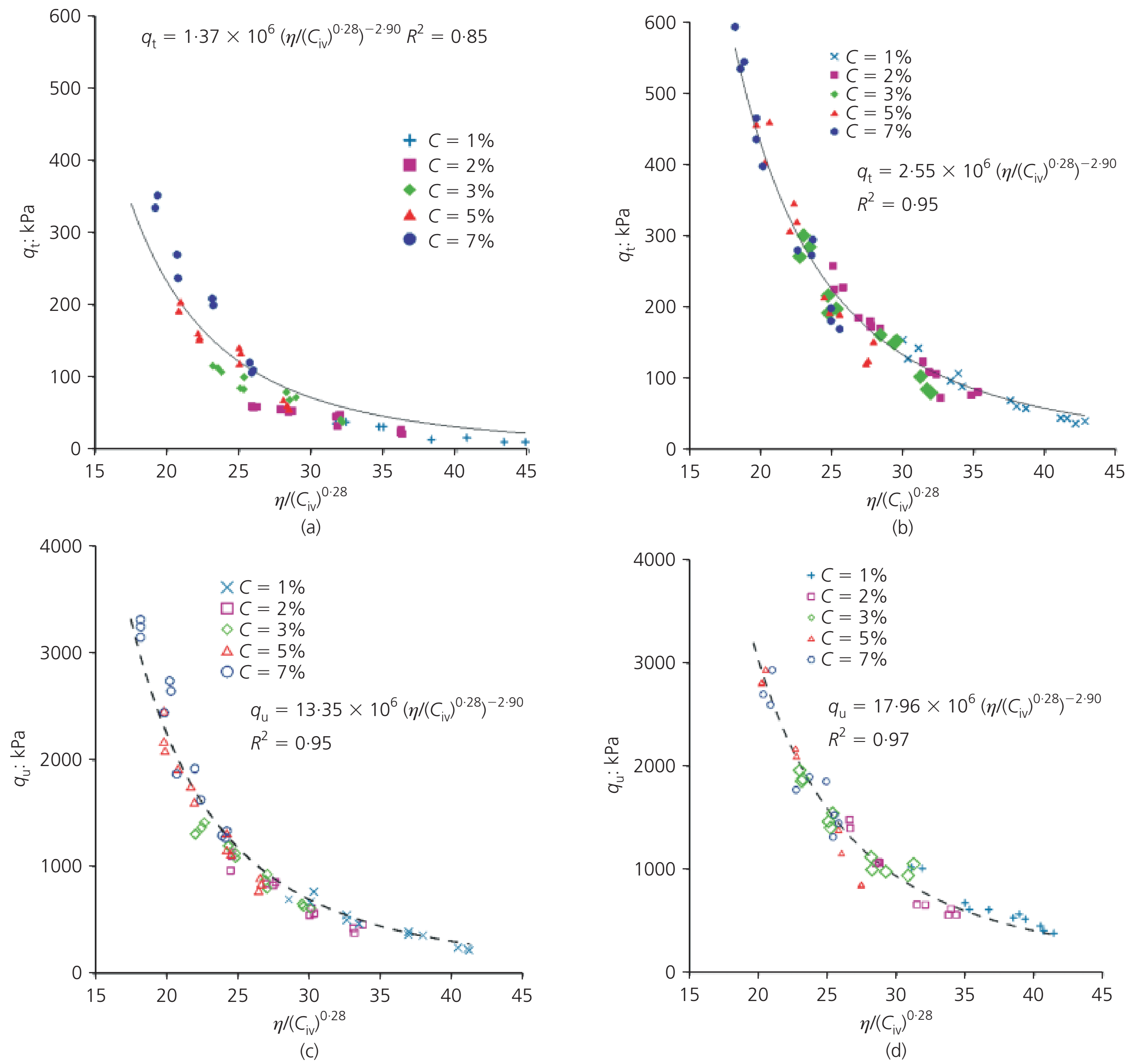

Figure 7. Variation of splitting tensile strength with adjusted η/C_{iv} for (a) non-reinforced specimens and (b) fibre-reinforced specimens and unconfined compression strength with adjusted η/C_{iv} for (c) non-reinforced specimens and (d) fibre-reinforced specimens

group (Projects PNPD, INCT-REAGEO, Edital Universal and Produtividade em Pesquisa).

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