Porosity/cement index to evaluate geomechanical properties of an artificial cemented soil

Le paramètre porosité/ciment pour l’évaluation des propriétés géomécaniques d’un sol cimenté artificiellement

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ABSTRACT: This paper highlights the importance of the porosity/cement index on the evaluation of the geomechanical properties of soil-cement mixtures as a contribution to analyse these materials. This index is defined as the ratio between porosity and volumetric cement content combining the degree of compaction with the cement content. The relevance of these two parameters is defined by an exponent to the volumetric cement content which changes with the type of soil. This paper results from a broad experimental program with unconfined compression tests, indirect tensile tests, triaxial tests and oedometer tests, which were all analysed by this index adjusted by a specific exponent value. The (tensile and compression) strength, the (elastic and initial tangent) stiffness, as well as the compressional behaviour are conveniently represented by this index and a different behaviour is observed when this index is changed.

KEYWORDS: soil-cement, porosity/cement index, tensile strength, compression strength, compressional behaviour.

1 INTRODUCTION

Soil-cement mixtures are very interesting for the construction of road and railway platforms, especially in the noble layers of subgrade as well as in transition zones between embankment and concrete structures, where good mechanical properties are required. This solution, not only concurs to improve those characteristics, but also leads to a significant reduction in the economic and environmental costs of these works. Despite these advantages this method has not a generalized application in Portugal due to the lack of design methodologies based on mechanical parameters.

There are several factors affecting the behaviour of cemented soils, such as the type of cement and cement content, the curing time and stress, the water content and porosity. Seeking for a ratio that would reflect the influence of some of these parameters Consoli et al. (2007) presented an index property defined as the ratio of porosity to the volumetric cement content, called porosity/cement ratio (n/Civ). Some previous attempts have been made, such as the degree of cementation proposed by Chang and Woods (1992) that concerns the percentage of voids filled with cement, being this parameter developed for sands. Lorenzo and Bergado (2004) have also presented the ratio of the after curing void ratio to the cement content (eC/Ac) proving to be quite interesting for clay mixtures with high values of water and cement content.

Another available parameter is the water/cement ratio used for concrete. However, soil-cement mixtures for road or railway platforms are usually cured in a non saturated condition, which makes the previous ratio inadequate in the analysis of these mixtures behaviour. The main difference between soil-cement mixtures and concrete (besides the cement content) is that during the curing of concrete all voids are completely full of water and therefore concrete stress-strain behaviour is not dependent on the void ratio but on the water content. In opposition, soil-cement mixtures currently executed in embankments and transport platforms have curing water content lower than the saturation water content and so their compressibility will be related to its porosity. Moreover, while concrete has an almost linear behaviour for a wide range of deformations, soil-cement mixtures have a clear non-linear behaviour since very small strains as a result of the progressive degradation of the cemented structure. Therefore, even if the soil-cement mixture is saturated after the maximum strength has been achieved (i.e. after curing) the curing void ratio still has a very important role on the mechanical behaviour of the mixture.

The influence of the porosity/cement ratio on strength and stiffness parameters is described in Consoli et al. (2012) providing the comparison between two different materials mixed with Portland cement: well graded Porto silty sand and uniform Osorio sand. An advance analysis on the compression and shearing behaviour of cemented Porto silty sand through this parameter is described in Rios et al. (2012).

This paper summarizes some geomechanical properties of cemented Porto silty sand through this index in terms of strength (unconfined, tensile and triaxial), stiffness (initial tangent and unload-reload) and one-dimensional compression.

2 MATERIALS AND SPECIMEN PREPARATION

A well graded soil, classified as silty sand (SM) in the unified classification system (ASTM, 1998) was used in this study. The soil is derived from weathered Porto granite which is abundant in Northern Portugal (Viana da Fonseca et al., 2006). Its particle specific gravity is 2.72, and it contains around 30% fines,
although a low plasticity index was obtained (I_p=5%, w_p=34%-
31%/3.5%). From the particle size distribution curve presented in
Figure 1 an average diameter D_50 equal to 0.25 mm was
obtained, as well as uniformity and curvature coefficients of 113
and 2.7 respectively. A high strength Portland cement (CEM I
52.5R) of grain density equal to 3.15 was used as the cementing
agent in order to speed up the laboratory tests.

The experimental program is performed with specimens
made by the mixture of silty sand, Portland cement and tap
water that is compacted statically in three layers in a stainless
steel mould. For each specimen, a quantity of fines equal to the
weight of cement to be introduced was removed from the soil,
in order to have the same grain size distribution curve in the
mixture of soil-cement as in the soil itself. Following this
procedure the dry density of the soil was also constant
throughout the study even though the cement content changed.
The specific gravity of the cement-soil mixture was calculated
as a weighted average of those of the soil (Gs=2.72) and of the
cement (Gs=3.15), and thus it was different for different cement
contents.

The representation of the unconfined compression strength
UCS (kPa) = 4E+09 (n/C_{iv})^{0.21} \times 10^{-4.296}
(1)

This exponent seems to depend on the type of soil as other
authors have found different coefficients when working with
different soils (Consoli et al., 2007, 2011): an exponent of 0.28
was found in a residual soil from sandstone (Botucatu soil),
while a value of 1.0 was found in an uniform sand (Osorio
sand). Based on this parameter, named adjusted porosity/cement
ratio (n/C_{iv}^{0.21}), the results of different tests were analysed.

1.1 Tensile strength

Taking into account the possibility of shrinkage in cemented
materials, the evaluation of the tensile strength is of utmost
importance. In that sense, indirect tensile tests following the
standard EN 13286-42 (CEN, 2003) were performed on similar
specimens whose results were plotted against n/C_{iv}^{0.21} for which
Eq. (2) was obtained,

R_{tb} (kPa) = 2E+09 (n/C_{iv}^{0.21})^{-4.719}
(2)

The results showed that the indirect tensile strength (R_{tb}) was
about 11% of the UCS. In Figure 2 both R_{tb} and UCS are
plotted against n/C_{iv}^{0.21} in different scales for comparison. It is
clear that both trends are very similar (except for the absolute
values) corroborating the convenience of the adjusted
porosity/cement ratio.

In Consoli et al. (2011), where the data from these tests is
plotted together with data from other two soils, it is shown that
for the three soils a decrease in porosity promotes an increase in
the tensile strength as a consequence of the higher number of
contact points between particles which improves the
cementation. Also for the other two soils, a unique correlation
was found between the adjusted porosity/cement ratio and the
indirect tensile strength, the exponent of the ratio depending on
the soil.

\[ UCS = 10^{0.99} \times R_{tb} = 2E+09 (n/C_{iv}^{0.21})^{-4.719} \]

Figure 2. Indirect tensile strength and unconfined compression strength
against the adjusted porosity/cement ratio

3.2 Triaxial tests

Drained triaxial compression tests were performed over soil-
cement specimens, which were moulded to have two different
adjusted porosity/cement ratios (n/C_{iv}^{0.21}=36 and 29) corresponding respectively to UCS of 800 kPa and 2000 kPa.
For these ratios, two moulding conditions were defined
characterized by cement content and dry unit weight while the
water content remains constant and equal to 12%. For the first
ratio (n/C_{iv}^{0.21}=36), 2 and 4% cement contents were considered
which lead to dry unit weights of 16.7 and 15.4 kN/m³,
respectively. For the second ratio (n/C_{iv}^{0.21}=29) higher strength
was needed, so 5 and 7% of cement contents were assumed with
17.0 and 16.4 kN/m³ of dry unit weight. The tests were
performed at three different effective confining pressures (30,
80 and 250 kPa) over specimens moulded in four moulding
points, comprising 12 tests (Table 1).

The stress-strain curves (see Figure 3 as an example) clearly
evidence that the specimens with n/C_{iv}^{0.21}=29 have higher peak
deviator stresses than the specimens with n/C_{iv}^{0.21}=36 independently of the cement content. Adding cement to the sand
had the effect of increasing the shear strength by up to five
times for the adjusted porosity/cement ratio of 36 and tenfold
for the adjusted porosity/cement ratio of 29. All specimens
initially compressed, followed by significant dilation, which
was associated to a peak strength, before strain softening. This
is typical of cemented soils, with the maximum rate of dilation
taking place right after the peak strength (Viana da Fonseca
1998). The peak strength corresponds to the onset of significant
breakage in the cement, while dilation involves particle rearrangement that is only possible after bonding breakage. Assuming only compressive volumetric deformations up to the point of zero dilation, beyond this point yielding exists, which indicates that the onset of cement breakage is progressive starting even before peak. However, being the peak strength not frictional but controlled by the cement yielding, then most destructuration may take place only at peak.

In Figure 4 the stresses acting on the plane are plotted on a \((\sigma', \tau)\) graph for peak conditions from which the correspondent strength parameters were obtained. The points are assigned to each adjusted porosity/cement ratio \((n/C_{iv}^{0.21})\) expressed before. It is interesting to notice that for peak conditions two strength envelopes were obtained depending on the index ratio. The adjusted porosity/cement ratio influences the peak angle of friction and cohesion intercept, being the peak envelope for the index \(n/C_{iv}^{0.21}=29\) higher than that for the index equal to 36. This could have been predicted from moulding characteristics as each ratio corresponds to different UCS.

4 STIFFNESS PARAMETERS

4.1 Initial tangent stiffness

The unconfined compression tests were performed with local measurement of deformation using LDT’s and so the stiffness modulus could be evaluated. An initial tangent modulus \((E_{ti})\) was then calculated based on the linear part of the stress-strain curve. Plotting this modulus against the adjusted porosity/cement ratio for the 16 tests presented above, as Figure 5 shows, it can be concluded that the general adjustment of the data is quite reasonable.

As expected, stiffness parameters are more scattered than strength parameters because strain measurements are always more sensitive to non-homogeneities of the specimen and anchors are introduced in the specimen in single reference points. On the contrary, strength measurements capture more easily an average value of the whole specimen.

4.2 Unload-reload moduli

In the triaxial compression tests reported above, a small static cycle was performed during shearing, between 30% and 15% of the expected peak deviatoric stress. These loads were selected to avoid soil yielding before the cycles so the modulus could be assumed elastic. Figure 6 summarizes the results of the unload-reload modulus \((E_{ur})\) obtained for the two adjusted porosity/cement ratio. The values of \(E_{ur}\) obtained from these triaxial tests are higher than the initial tangent modulus \((E_{ti})\) obtained in the unconfined compression tests presented in Figure 5. This can be considered expected because \(E_{ur}\) is usually assumed to follow an elastic pattern, if performed at low ranges of cyclic stress, while in the initial monotonic loading path some compliance errors of strain gauges may be presented. This graph also evidences a clear and almost discrete increase in the stiffness modulus values for the specimens with \(n/C_{iv}^{0.21}=29\) (5% and 7% cement contents) in comparison with the specimens with distinct ratio \(n/C_{iv}^{0.21}=36\) (2% and 4% cement contents). This could be even clearer if the instrumentation

Table 1. Moulding conditions of the specimens for the triaxial tests

<table>
<thead>
<tr>
<th>Moulding Point</th>
<th>%C</th>
<th>(\gamma_w) (%kN/m²)</th>
<th>(e_0)</th>
<th>w</th>
<th>(n/C_{iv}^{0.21})</th>
<th>UCS (kPa)</th>
<th>(\sigma') (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>16.6</td>
<td>0.61</td>
<td>12</td>
<td>36</td>
<td>800</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>16.5</td>
<td>0.62</td>
<td>12</td>
<td>36</td>
<td>800</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>16.7</td>
<td>0.60</td>
<td>12</td>
<td>36</td>
<td>800</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>15.4</td>
<td>0.74</td>
<td>12</td>
<td>36</td>
<td>800</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>15.7</td>
<td>0.71</td>
<td>12</td>
<td>36</td>
<td>800</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>15.5</td>
<td>0.73</td>
<td>12</td>
<td>36</td>
<td>800</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>16.9</td>
<td>0.59</td>
<td>12</td>
<td>29</td>
<td>2000</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>17.0</td>
<td>0.58</td>
<td>12</td>
<td>29</td>
<td>2000</td>
<td>80</td>
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</tr>
<tr>
<td>5</td>
<td>17.0</td>
<td>0.58</td>
<td>12</td>
<td>29</td>
<td>2000</td>
<td>250</td>
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</tr>
<tr>
<td>4</td>
<td>16.3</td>
<td>0.66</td>
<td>12</td>
<td>29</td>
<td>2000</td>
<td>30</td>
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<tr>
<td>4</td>
<td>16.5</td>
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<td>4</td>
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<td>2000</td>
<td>250</td>
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</tbody>
</table>
would perform in a completely satisfactory way for the highest cemented mixtures (for 5% and 7% of cement content).

5 COMPRESSIBILITY PARAMETERS

One-dimension compression tests in oedometers with constant rate of deformation (CRD) were performed over soil cement specimens in the four moulding conditions presented in Table 1. The preparation of the different mixtures for these tests followed the same procedure of the other tests, as expressed briefly in section 2. Due to the size of the mould, the static cement specimens in the four moulding conditions presented in constant rate of deformation (CRD) were performed over soil - one-dimension compression tests in oedometer cells with compressibility curves do not seem to converge. Different porosity cement ratios, indicating that these two curves provided a relationship between indirect and compressive strength of about 11%.

The strength envelope values of the cemented specimens tested in triaxial compression were obtained through a procedure based on the Mohr’s circles analysis to solve the lack of representativeness of principal stress analysis due to non correspondence of the real localised shear locus. In fact, strain localisation is unavoidable in these very stiff materials, and consequently, the global stress-strain measurements are no longer representative of the conditions throughout the shearing process. Two peak strength envelopes were obtained for each n/C_{iv} (n/C_{iv}=36: \phi' =30° and c'=253 kPa; n/C_{iv}=29: \phi'=39° and c'=589 kPa), showing once again the convenience of this ratio for the analysis of these mixtures behaviour. This ratio also seems to be very useful to reproduce the one dimensional compression behaviour of the mixture, since for each n/C_{iv} a single line was obtained for higher stresses.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

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