Laboratory characterization and model calibration of a cemented aggregate for application in transportation infrastructures

Caractérisation en laboratoire et calibration d'un modèle d'agrégat cimenté pour une utilisation dans les infrastructures de transport

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ABSTRACT: Research on increasingly stiffer and more resistant artificially stabilized geomaterials, such as soil-cement mixtures has frequently revealed interesting properties. The knowledge of such materials behaviour is as important as they are increasingly used in several layers of transportation infrastructures, as well as in transition zones between embankments and rigid structures. Most of these last situations involve zones close to sensitive prefabricated structures, where compaction of soils or aggregates demand for moderate energies, being necessary to increase the content of the hydraulic binders to increase their stiffness and strength. The present work reports some of the most notorious results obtained in some laboratory studies aiming to characterize different mixtures of cement and limestone aggregate. Seismic wave measurements, indirect tensile strength tests and triaxial compression tests were performed. The results indicated some relevant differences on dynamic and static stiffness properties and shear strength Mohr-Coulomb parameters, directly associated to the variation of porosity/cement ratio. Based on the triaxial test results, a calibration of the geo-mechanical parameters of the Hardening Soil Model available on commercial software was made.

RÉSUMÉ: La recherche sur des géomatériaux de plus en plus rigides et plus résistants artificiellement stabilisés, comme les mélanges sol-ciment, a souvent révélée des propriétés intéressantes. La connaissance du comportement de ces matériaux est importante car ils sont de plus en plus utilisés en plusieurs couches dans les infrastructures de transport, ainsi que dans les zones de transition entre remblais et structures rigides. Dans la plupart de ces dernières situations, on trouve des zones sensibles proches de structures préfabriquées, où le compactage des sols ou d'agrégats doit être réalisé à énergie modérée. En conséquence, il est nécessaire d'augmenter la teneur en liants hydrauliques pour augmenter leur rigidité et résistance. Ce travail présente des résultats remarquables obtenus dans certaines études en laboratoire visant caractériser différents mélanges de ciment et de granulats calcaires. Des mesures d'ondes sismiques, des essais de résistance à la traction indirecte et des essais de compression triaxiale ont été réalisés. Les résultats ont montré des différences intéressantes sur les propriétés de rigidité statique et dynamique aussi bien que sur les paramètres de résistance au cisaillement de Mohr-Coulomb, directement liées à la variation du ratio porosité/ciment. Sur la base des résultats d'essais triaxiaux, une calibration des paramètres géo-mécaniques du Hardening Soil Model, disponible sur logiciels commerciaux, a été réalisée.

KEYWORDS: Aggregate-cement mixtures, Hardening Soil Model, Parametric calibration, Porosity cement ratio.

1 INTRODUCTION

The research on increasingly stiffer and more resistant artificially stabilized geomaterials, such as aggregate-cement mixtures, has frequently revealed interesting properties. The knowledge of such materials behaviour is as important as they are regularly used in several layers of transportation infrastructures, as well as in transition zones between embankments and rigid structures. Most of these last situations involve zones close to sensitive prefabricated structures, where compaction of soils or aggregates demand for moderate energies, being necessary to increase the content of the hydraulic binders to increase their stiffness and strength.

Despite the widespread use of Portland cement in the improvement of soils and aggregates, there seems to be no dosage methodologies based on rational criteria.

However, the relationship between the porosity of the mixture (n) and the volumetric cement content (ie, the ratio between the cement volume and the total volume - C_{iv}) adjusted by an exponent x, (x Є [0, 1]) has become a good parameter to evaluate the strength and stiffness of artificially cemented soils.

This parameter, designated as adjusted porosity/cement ratio (n/C_{iv}^x) has been related with the compressive strength determined in uniaxial compression tests (Consoli et al., 2007) and with the parameters of strength and deformability obtained in triaxial compression tests (Consoli et al., 2009). More recently, the ratio was applied to the stress–dilatancy relation of an artificially cemented sand (Rios et al., 2012) and even more recently in stress–strain and strength-dilatancy relationships on a cemented aggregate (Viana da Fonseca et al. 2012).

The present paper reports some of the most notorious results obtained with the scope of optimization of mixtures of aggregates and Portland cement. A laboratory program was developed to define the geomechanical characteristics of those mixtures, which includes indirect tensile strength tests, seismic wave measurements and triaxial compression tests. Based on the results obtained, the relationships between the mechanical properties and the n/C_{iv}^x parameter were evaluated. A constitutive law was calibrated, taking into account the behaviour of these mixtures - in laboratory tests, and then evaluated in numerical modelling of triaxial compression tests.

2 LABORATORY TESTS

2.1 *Tested materials*

The aggregate tested is a well graded material which grain size is shown in Figure 1. This material has a plasticity index of 10% and a liquid limit of 22%. The Los Angeles Abrasion Index is 30%. The maximum dry unit weight obtained by the Modified Proctor test is 21.4 kN/m^3 and the corresponding optimum water content is 6.6%. This aggregate was mixed with different percentages of cement, namely 2%, 3%, 4% and 5%. Portland cement of very high initial strength (CEM I 52.5 R) was used as binder. The maximum dry unit weight determined by the Modified Proctor test ranged between 21.3 and 21.8 kN/m^3 and the optimum water content ranged between 6.8 and 7.2%, for the four mixtures.

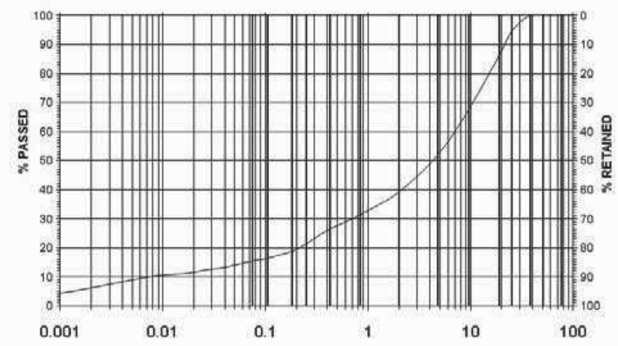


Figure 1. Grain size distribution curve of the aggregate without cement.

This study sought to evaluate the mechanical characteristics of mixtures with low and medium compaction. This kind of materials is usually placed in difficult compaction zones such in the borders of concrete structures (e.g. underpasses).

2.2 *Indirect tensile tests*

Usually the characterization of the tensile strength of aggregate concrete mixtures is made using indirect tensile tests. In this case the standards EN 13286-42 (CEN, 2003) were used. Test specimens were compacted with 150 mm diameter and 145 mm high, with low compaction (LC) and medium compaction (MC), using the Modified Proctor test. The degree of compaction (DC) of the MC specimens ranged between 91% and 93% and the one of the LC specimens varied between 81% and 85% of maximum dry unit weight from Modified Proctor test. According to CEN (2003), the tensile strength, q_t, is computed by:

$$q_t = \frac{2}{\pi}\,\frac{Q}{\Phi\,H} \tag{1}$$

where Q is the maximum applied force during diametrical compression and Φ and H are the specimens diameter and height. In the performed tests the tensile strength varied significantly with the degree of compaction and the cement content, the values ranging between 35 kPa for samples with 2% cement content with low compaction and 440 kPa for samples with 5% cement content and medium compaction. Figure 2 shows the values of the tensile strength, obtained in these tests, depending on the adjusted porosity/cement ratio (n/C_{iv}^x). The relation shows a relatively high determination coefficient (R^2=0.92) with an exponent of 0.27.

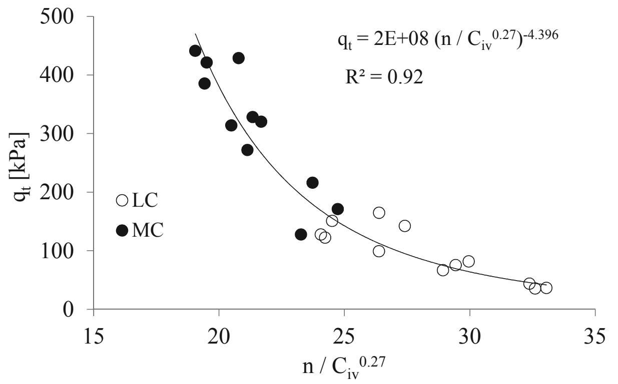


Figure 2. Relationship between indirect tensile strength and n/C_{iv}^x.

2.3 *Seismic wave tests*

Seismic wave tests are an easy and economic technique to measure dynamic properties (Amaral et al. 2012). Aiming at determining materials elastic properties, seismic wave tests were performed on several specimens: five specimens with degree of compaction ranging from 95% to 98% (MC-medium compaction); seven specimens with degree of compaction from 83% to 86% (LC-low compaction). The wave velocity propagation was determined with ultrasonic piezoelectric transducers, namely compression transducers and shear transducers (Figure 3).

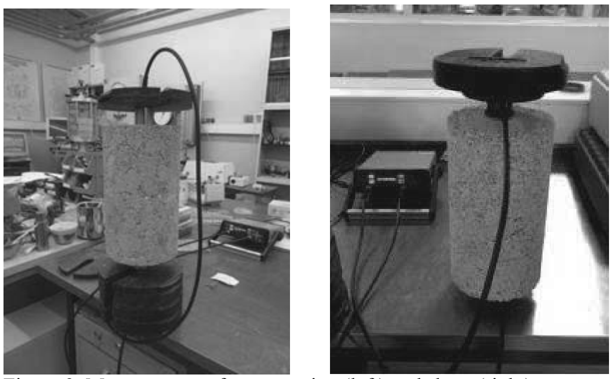


Figure 3. Measurement of compression (left) and shear (right) waves.

The dynamic parameters of the mixtures were computed taking into account the following relations:

$$E_0 = V_L^2\,\rho \tag{2}$$

$$G_0 = V_S^2\,\rho \tag{3}$$

$$\upsilon_0 = \frac{E_0}{2\,G_0} - 1 \tag{4}$$

where:

E_0 - dynamic deformability modulus	V_S - shear wave velocity
V_L - longitudinal wave velocity	ρ - density
G_0 - dynamic shear modulus	υ_0 – Poisson ratio

The dynamic shear modulus values range from about 2 GPa to 7 GPa. There was a significant increase in the dynamic modulus with increasing cement content and compaction effort. In general, the values of Poisson's ratio (ν) decreased with increasing cement content, assuming values of 0.25, 0.23, 0.21 and 0.20, for cement content of 2%, 3%, 4% and 5%, respectively. The Figure 4 shows the values of the dynamic shear modulus as a function of n/C_{iv}^x. The relation has a high determination coefficient (R^2=0.96) having an empirical exponent with a value of 1.0, which shows the possibility of estimating G_0 of the material based on that parameter.

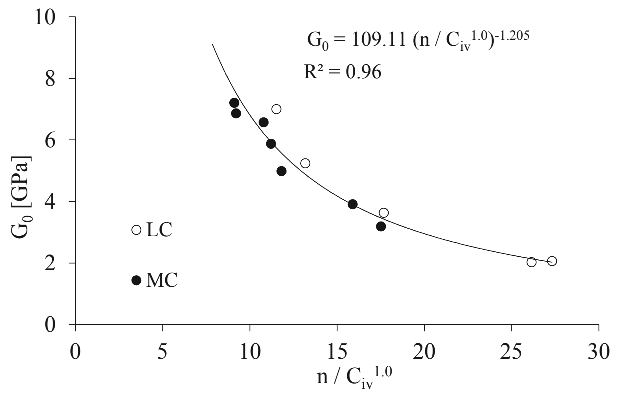
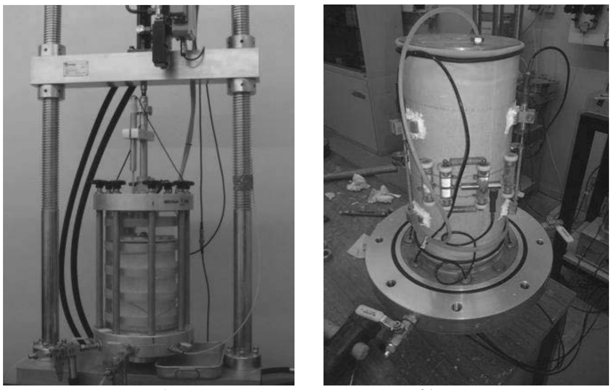


Figure 4. Relationship between dynamic shear modulus and n/C_{iv}^x.

2.4 *Triaxial compression tests*

Monotonic triaxial tests were performed on specimens with 150 mm diameter and 280 mm height. These specimens were prepared with a cement content of 2%, 3%, 4% and 5% and a degree of compaction from 83% to 86% (LC-low compaction), and with a cement content of 2% and 3% and a degree of compaction from 95% to 98% (MC-medium compaction). All of these specimens have been previously tested with seismic waves (see 1.3). For each cement content value three constant confining pressures (30, 50 and 100 kPa) were applied, leading to 18 tests. The triaxial tests were performed according to CEN ISO/TS 17892-9 (2004) standard, with saturation, consolidation and triaxial compression.

To measure the axial strain three linear variable differential transformers (LVDT) were fixed in the specimen, while for radial deformation, a system was developed for measuring the variation of the perimeter using one LVDT which is mounted between the ends of a wire that surrounds the specimen. The wire is kept under tension by two helical springs (Figure 5).



a) b)

Figure 5. Triaxial test equipment: a) cell and load frame apparatus; b) axial and radial deformation transducers installed on the specimen.

During shear compression, at 0.0016 mm/second, the specimens were submitted to two unload/reload cycles in order to define the quasi-elastic behaviour. Some of the stress-strain curves obtained in the tests are presented in Section 3 of this paper, when discussing the numerical modelling of the tests.

Figure 6 shows the relationship between the adjusted porosity/cement ratio and deformability modulus computed at 50% of ultimate shear strength for specimens with confining pressure of 100 kPa (E_{50}^{ref}). The mixtures are referenced by the percentage of cement and the type of compaction (for example, 2_LC means a mixture with 2% of cement content and low compaction). In this analyses, the best correlation is also found to an exponent of 1.0, but it is associated with a lower coefficient of determination (R^2=0.76) than those presented above.

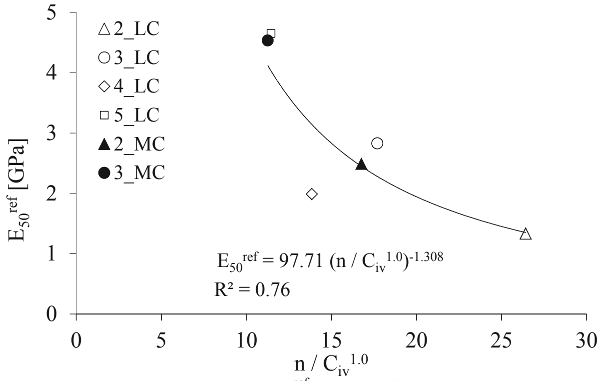


Figure 6. Relationship between E_{50}^{ref} and n/C_{iv}^{x}.

It is important to point out that, with exception of 4_LC specimen, there was a significant increase in the deformability modulus with increasing cement content. Furthermore, it is also interesting to note the significant increase in deformability modulus with degree of compaction, when comparing mixtures having the same cement content.

Strength parameters, such as the angle of shearing resistance (ϕ') and the cohesion intercept (c'), were computed using the results of three specimens of each type of mixture, with similar compaction and the same cement content, for different isotropic consolidation pressures.

With regard to the angle of shearing resistance, there is a slight increase from 40° to 42° when the cement content increases from 2% to 5% in the samples with low compaction. In the samples with medium compaction it was computed a angle of shearing resistance of 58°, regardless of the cement content, which shows the great importance of the compaction on the mechanical characteristics of the mixtures.

The values of c' ranged from 250 kPa to 830 kPa, reflecting a significant increase in this parameter with the increase of the cement content. For specimens with low compaction, the increase from 2% to 5% in the cement content causes an increase of c' from 255 kPa to 835 kPa. Figure 7 shows the relationship between the cohesion intercept and the porosity/cement ratio. The best correlation is also achieved for an exponent of 1.0, with a coefficient of determination R^2=0.88.

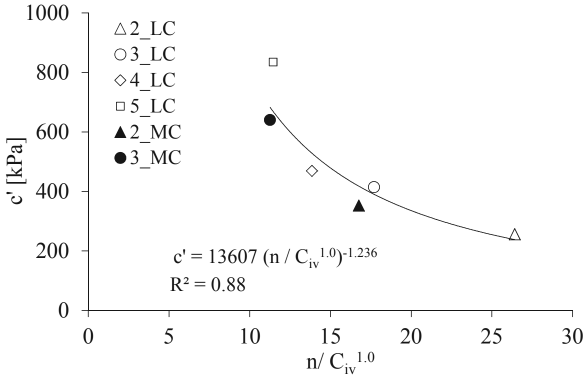


Figure 7. Relationship between cohesion intercept and n/C_{iv}^{x}.

Considering the presented results, it could be concluded that it is possible to assume the value 1.0 for the exponent x, when one intend to relate the adjusted porosity/cement ratio with mechanical properties of these aggregates, with exception of the tensile strength.

3 MODELLING OF TRIAXIAL TESTS

Based on the triaxial test results, a calibration of the geo-mechanical parameters for the Hardening Soil Model available on the commercial software Plaxis® was made. The model parameters that were considered for each aggregate-cement mixture are shown in Table 1.

This paper presents only the tests results and the modelling curves (mod) for the specimens with 2% of cement content, with low compaction (Figure 8) and with medium compaction (Figure 9). As previously mentioned, three different values of confining pressure were applied (30, 50 and 100 kPa). Further details can be seen in Viana da Fonseca et al. (2012).

The analysis of Figures 8 and 9 shows that: a) the curves that relate the deviatoric stress with the axial deformation are fairly well approximated by the modelling curves, in particular for mixtures with low compaction; b) it is rather difficult to model the curves that relate the volumetric deformation with the axial deformation, particularly for the higher values of the confining pressure. For the tests performed on other aggregate-cement mixtures similar trends were found.

Table 1. Hardening Soil Model parameters

Parameters		Materials					
		2_LC	3_LC	4_LC	5_LC	2_MC	3_MC
Failure parameters as in Mohr-Coulomb model	c' [kPa]	256	414	469	835	352	640
	ϕ' [º]	39.7	41.0	41.6	41.8	58.0	58.1
	ψ [º]	35.8	41.0	41.6	41.8	42.1	46.9
Basic parameters for soil stiffness	E_{50}^{ref} [GPa]	1.33	2.83	1.99	4.65	2.49	4.53
	E_{ur}^{ref} [MPa]	4.0	8.48	5.96	13.95	7.46	13.60
	E_{oed}^{ref} [kPa]	1.33	2.83	1.99	4.65	2.49	4.53
	m	0.60	0.40	0.16	0	0.50	0.30
Advanced parameters	ν_{ur} [-]	0.2	0.2	0.2	0.2	0.2	0.2
	p^{ref} [kPa]	100	100	100	100	100	100
	K_0^{nc} [-]	1.0	1.0	1.0	1.0	1.0	1.0
	R_f [-]	1.0	1.0	1.0	1.0	1.0	1.0

c' - Cohesion intercept
ϕ' - Angle of shearing resistance
ψ - Angle of dilatancy
E_{50}^{ref} – Secant stiffness in standard drained triaxial test
E_{ur}^{ref} – Unloading / reloading stiffness (default $E_{ur}^{ref} = 3\ E_{50}^{ref}$)
E_{oed}^{ref} – Tangent stiffness for primary oedometer loading (default $E_{oed}^{ref} = E_{50}^{ref}$)
m – Power for stress-level dependency of stiffness
ν_{ur} – Poisson's ratio for unloading-reloading (default $\nu_{ur} = 0.2$)
p^{ref} – Reference stress for stiffnesses (default $p^{ref} = 100$ kPa)
K_0^{nc} – K_0-value for normal consolidation (default $K_0^{nc} = 1$)
R_f – Failure ratio q_f / q_a (default $R_f = 1.0$)

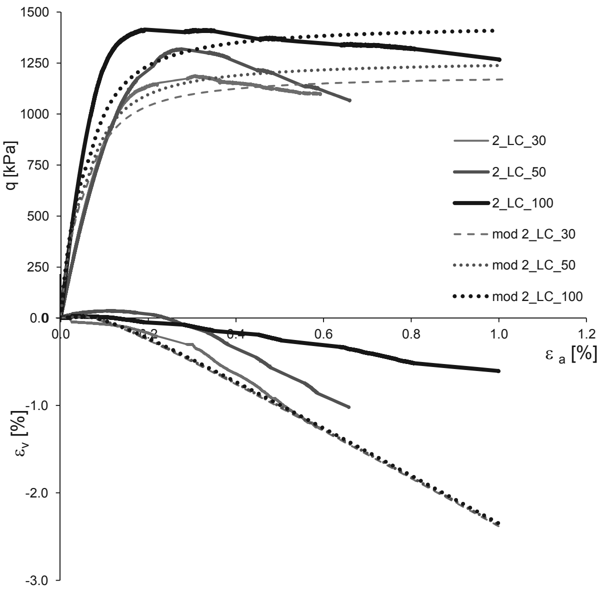


Figure 8. Test results and modelling of low compaction mixtures with a cement content of 2%.

4 FINAL REMARKS

The results obtained in a laboratory experimental program over an aggregate mixed with high strength Portland cement were presented. The tensile strength, elastic stiffness parameters, and Mohr-Coulomb shear strength values were analysed by the porosity/cement ratio adjusted by an exponent x (n/C_{iv}^{x}). Most parameters revealed that the best correlation was obtained with an exponent of 1.0, although a significant growth in stiffness and strength was obtained with increasing cement content and degree of compaction. The Hardening Soil Model parameters calibrated from the triaxial tests results allowed a good adjustment of the stress-strain curve. The volumetric behaviour as well as the post-peak strain softening cannot be reproduced satisfactory due to model limitations.

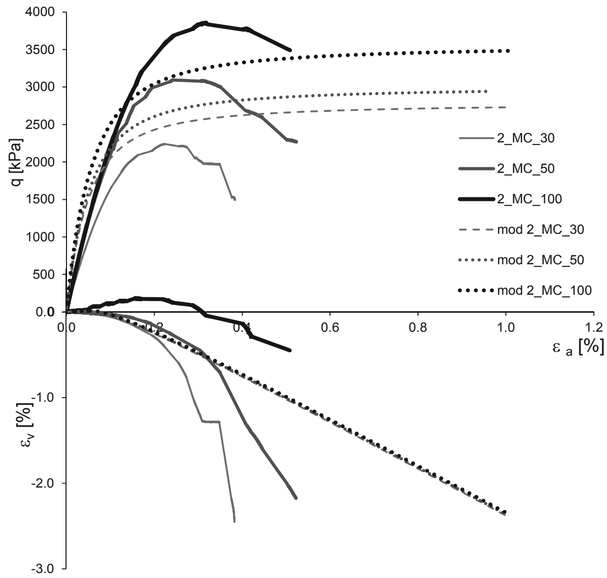


Figure 9. Test results and modelling of medium compaction mixtures with a cement content of 2%.

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