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Effects of the Ratio of Porosity to Volumetric Cement Content on the Unconfined Compressive Strength of Cement Bound Fine Grained Soils

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Abstract: This paper presents an experimental investigation into the effects of porosity, dry density and cement content on the unconfined compressive strength and modulus of elasticity of cement-bound soil mixtures. A clayey sand was used with two different proportions of type IV Portland cement, 10% and 14% of the dry mass of the soil. Specimens were moulded with the same water content but using four different compaction efforts, corresponding to four different dry densities. Unconfined compression testing was conducted at seven days of curing time on unsoaked samples. The results showed that the compressive strength increased with the increase in cement content and with the decrease in porosity. From the experimental data, a unique relationship was found between the unconfined compressive strength and the ratio of porosity to volumetric cement content for all the mixtures and compaction efforts tested. The equation developed demonstrates that it is possible to estimate the amount of cement and the dry density to achieve a certain level of unconfined compressive strength. A normalized general equation was also found to fit other authors' results for similar soils mixed with cement. From this, a cement-bound soil model was proposed for the development of a mixing design procedure for different soils.

Keywords: cement-bound soil; clayey sand; cement-treated soil; porosity; unconfined compressive strength; modulus of elasticity

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1. Introduction

One of the most common soil improvement techniques for fine-grained soils is to compact the in situ soil with cement, as adequate strength can be achieved quickly. Thus, the beneficial effects of cement treatment, or other binding agents, on the engineering properties of a broad range of soils have been widely documented [1–11]. Clayey sands are fine-graded soils that are rich in silt and clay particles, whose physical state is highly affected by the water content and therefore are expected to provide fair to poor subgrade bearing capacity. The addition of a small amount of cement to the soil has proved to be effective in decreasing moisture sensitivity and expansion/shrinkage, which allows better control of workability during compaction and, ultimately, results in significant cost savings compared to removal and replacement of fill material in some projects. Furthermore, the environmental impacts of soil replacement are incompatible with the globally accepted sustainable development goals.

The treatment process begins by mixing the soil with cement while relatively dry and then adding the water specified for compaction. Compaction is needed to make soil particles slip over each other and move into a densely packed state becoming suitable earthwork material [12]. The mechanisms by which the cement improves the fine-graded soil properties are the cation exchange between clay and cement (water sensitivity), the flocculation and agglomeration of particles (workability and compactability) and the cement hydration and pozzolanic reactions that create cement–soil particle bonds (bearing capacity) [13,14]. However, the engineering properties of the soil treated by cement may vary widely because of differences in the microstructure formed, which will depend on the soil properties, the cement and water added and the compaction energy applied [15]. A similar trend has also been identified with different binders [16,17].

In Europe, soils treated by cement are divided in two groups [18]—cement stabilized soil (CSS) and cement-bound soil (CBS)—depending on the amount of cement added to the soil. For CSS, the cement is just enough to improve the engineering properties of fine-graded soils to a level similar to that of good natural soil or untreated aggregate base. In contrast, in CBS, when more cement is added to the soil, the soil–cement mixture attains a level of structural integrity that can be directly measured by the unconfined compressive strength, tensile strength and elastic modulus tests. CBS is a technical solution used to improve the bearing capacity of subgrade of the overlaying structure (embankments, road and railway structures and building foundations). Typical 7-day unconfined compressive strengths (R_c) for CBS range from 0.7 to 2.1 MPa [19].

The placement process of this material usually includes compaction, as in an embankment, and the soil–cement mixture needs to have a water content close to the optimum of a Proctor compaction test for a given energy level. Recent literature indicates that the structural performance of CBS is essentially influenced by the cement type and content, porosity, type of soil, age and degree of compaction [20]. A reliable evaluation of strength and deformation characteristics of a CBS must take into account the characteristics of compaction in order to seek the minimum amount of cement that can guarantee the required mechanical performance. Although cyclic loading/dynamic tests are more suitable for evaluating the mechanical properties of these materials when used in transport infrastructures [20], monotonic tests are most often used in practice [18] and for research purposes [1,15,16].

The water content close to the optimum of CBS mixtures means that these mixtures are cured in a non-saturated condition and the water content does not reflect the amount of voids. Thus, in CBS mixtures, the water/cement ratio (defined as the water mass divided by the cement mass) is inadequate for analysis, whereas in cement concrete, most of voids are filled with water, so the water content reflects more accurately the volume of voids and the concrete stress–strain behavior is related to the initial water content. In addition, in deep soil mixing, with columnar inclusions in soils with a high natural water content, close to the liquid limit, the water/cement ratio plays a fundamental role in the assessment of target strength, like in concrete technology [21]. According to Consoli [22], the porosity affects the strength by modifying the number of contact points between particles, i.e., the soil microstructure.

The influence of the volumetric properties on unconfined compressive strength of soil–cement mixtures was established by Larnach in the 1960s [8]. More recently, in [2], the ratio of porosity to cement volumetric content (n/C_{iv}) has been proposed for evaluation, with n being the porosity and C_{iv} the cement volumetric content (unhydrated cement, immediately after compacting the specimen). Thus, it was reported that a relationship between R_c and n/C_{iv} could be found for the soil–cement mixture. Some studies that investigated other cementitious materials have also found similar relationships, even with different soils [8]. Hence, the relationship R_c-(n/C_{iv}) can play a fundamental role in the determination of the cement content for a CBS design mixture to meet a target unconfined strength.

Cement is an effective chemical stabilizer for improving both the index and strength properties of soils, but the optimum percentage of cement varies from one soil type to another [23]. Therefore, further research must be carried out in order to verify if similar relationships R_c-(n/C_{iv}) can be used with other soils, from different regions, and with variable percentages of cement and porosity values. In this study, a natural clayey sand treated with Portland cement, collected in Almada, Portugal, is investigated. The soil–cement mixtures were fabricated with two different cement contents (10% and 14% of dry mass of the soil) and compacted with four different compaction efforts to evaluate the effect of the cement content and the volumetric properties on compressive strength and stiffness of the CBS mixtures, tested after the specimens had been cured for 7 days at 23 ± 2 °C and relative humidity of 55%. The relationship found between R_c and (n/C_{iv}) enabled the determination of the conditions required in the field to attain a target R_c value for the type of soil studied, and its normalized form was found to be in good agreement with other authors' results. Furthermore, a simple laboratory testing procedure is proposed for CBS with different soils.

2. Materials and Experiments

2.1. Experimental Plan

The experimental plan is summarized in the diagram presented in Figure 1. A fine-graded cohesive soil was selected for this study to investigate the effect of the ratio of porosity to volumetric cement content on the unconfined compressive strength of cement-bound soil mixtures. The soil was first characterized in terms of the most important physical properties, followed by a compaction test with an adequate compaction effort to support the definition of the characteristics of the moulding points of the CBS specimens. The CBS mixtures were fabricated with a single water content and compacted at four different compaction levels to obtain different volumetric properties, as explained in the following sections. Two different cement contents were used. The unconfined compressive testing method was used to evaluate the mechanical properties of different CBS mixtures.

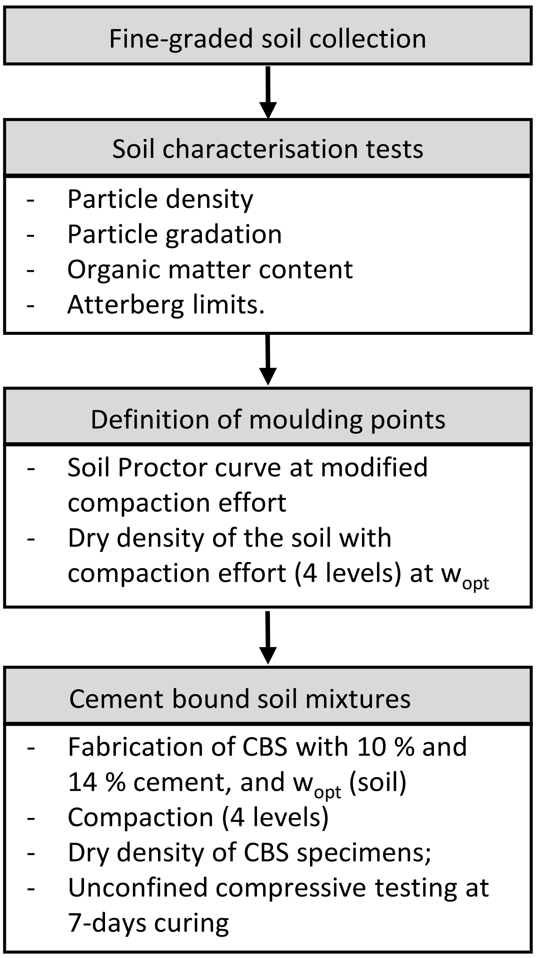

Figure 1. Diagram of the experimental plan.

2.2. Materials

For this study, a sample of a clayey sand was taken from a cut slope running along a local road in Almada, south of Lisbon (see Figure 2). The area comprises an upland on the smooth south-facing slope of the Almada hills, where clayey soils are abundant. In the collection site are "Xabregas blue clays" [24], a geological unit from the Miocene about 15 m thick in the westernmost part of the region [25].

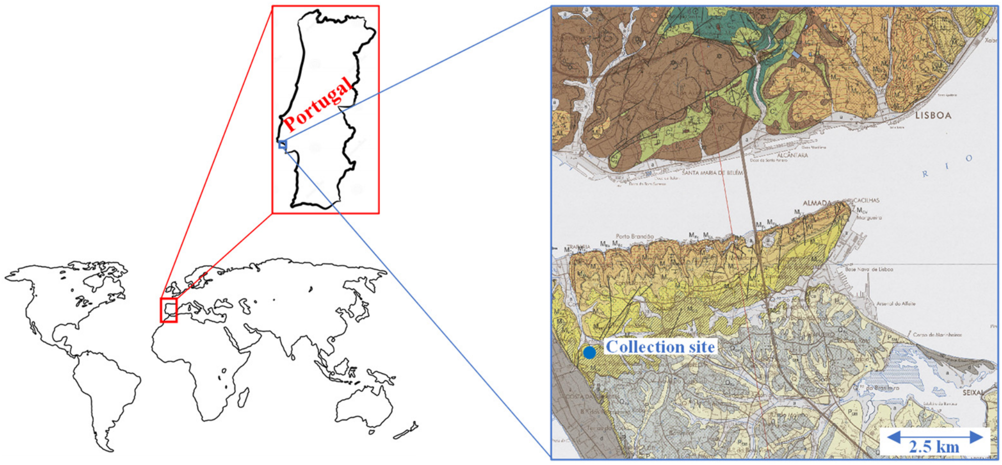

Figure 2. Identification of the collection site on different scales (world; country; local site on an extract of the Geological Map of Portugal, 34-D sheet [24]).

The soil sample was collected in its natural state by digging with a hand tool to carry out all characterization and mechanical strength tests. Once obtained, the sample was stored and transported in suitably sealed plastic boxes. During the collection and transport, all care was taken to avoid any kind of contamination. Although there are no homogenous soils in nature, the soil sample was divided into smaller samples with the quarter technique to ensure homogeneity of the samples tested.

The particle size distribution of the soil was determined by sieving, following the protocol defined in the European standard (EN ISO 17892-4 2016 [26]). The particle size distribution is shown in Figure 3. The Atterberg limits of the soil followed EN ISO 17892-12 2016 [27]. The studied soil contained 40% fine particles (<# 200 sieve).

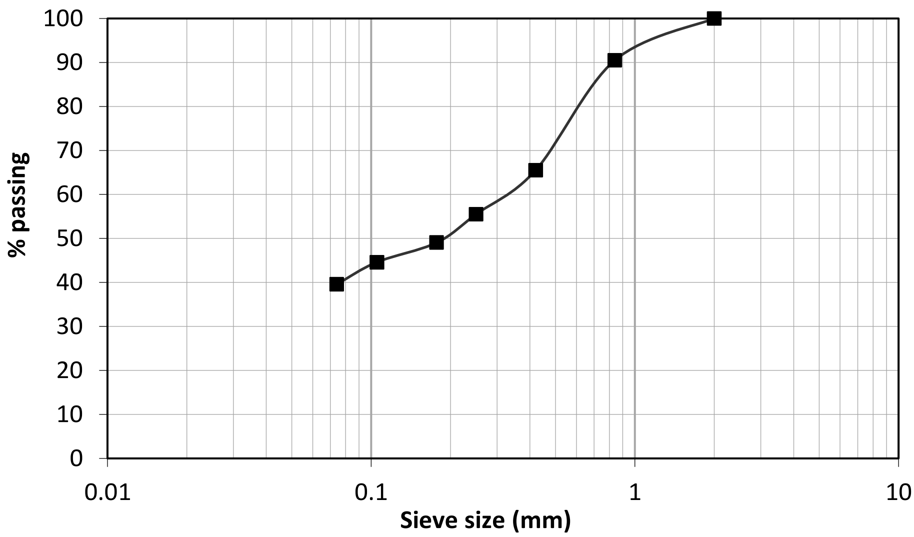

Figure 3. Particle size distribution of soil.

The physical properties of the soil are summarized in Table 1. The soil is classified as a clayey sand (SC) in the unified soil classification system [28], and as an A-6 (14) clayey soil with a group index equal to 14 according to the AASHTO classification system [29]. This soil category comprises granular soils with high contents of clay and silt, and provides fair to poor subgrade conditions for infrastructures. When clayey particles are predominant, the soil is sensitive to expansion and shrinkage with the variation in water content. Mixing cement in this type of soil contributes to the reduction of the plasticity index and the potential for expansion/shrinkage, to attain higher compaction in the field, and increases the bearing capacity [30].

Table 1. Physical properties of the soil.

Properties	Values
Liquid limit (EN ISO 17892-12 2016)	32%
Plastic Limit (EN ISO 17892-12 2016)	21%
Plastic index (EN ISO 17892-12 2016)	11%
Particle density (ρ_{ss}) (EN ISO 17892-3 2016)	2.64 Mg/m^3
Coarse sand (2.0–4.75 mm) (EN ISO 17892-4 2016)	-
Medium sand (0.42–2.0 mm) (EN ISO 17892-4 2016)	34.5%
Fine sand (0.074–0.42 mm) (EN ISO 17892-4 2016)	25.9%
Fines content (<0.074 mm) (EN ISO 17892-4 2016)	39.6%
Mean particle diameter (D_{50}) (EN ISO 17892-4 2016)	0.2 mm
Unified soil classification (ASTM D 2487)	SC
ASHTO soil classification (AASHTO M145-42)	A-6 (14)

In this research, a commercial Portland cement type CEM IV/A(V) 32.5R-SR (SECIL, Outao plant) was used, which, according to [31], is a pozzolanic cement, containing 64–79% clinker (K) and 21–35% fly ash (FA), is greyish (due to the ferrous component) and has high chemical resistance. An equivalent cement type could be also obtained by mixing cement types I and II with additives type II (pozzolana/fly ash). This cement type is suitable for the manufacture of concretes and mortars with specific durability requirements, namely those used on road pavements, soil–cement mixtures and structures located in aggressive environments, such as the marine environment. As opposed to natural soils, Portland cement is an industrial product which is manufactured under strict standards, ensuring uniformity of quality and performance and has advantages that make it economical and easy to use. The cement properties are listed in Table 2. This cement is very fine, with 100% of its particles passing through the 0.074 mm sieve, and has a particle density of 3.15 Mg/m^3.

Table 2. Properties of Portland cement [32].

Properties	Values
Constituents	>69% K >26% FA
Ignition loss	2.3%
Insoluble residue	26.3%
Specific surface area (Blaine) (cm^2/g) (EN 196-6)	4292
Compression strength 28d (MPa) (EN 196-1)	44.3
Setting time (min) (EN 196-3)	>75

In the soil characterization tests, distilled water was used, but in soil–cement mixture specimens, tap water was used.

2.3. Definition of the Moulding Points

The moulding points of the CBS test specimens are established by the water content and compaction effort used in the laboratory. To investigate possible variations in field construction operations, the moulding points used in this study were defined by varying the compaction effort at the parent soil's optimum water content. For this purpose, a soil compaction test was performed.

The soil was compacted in a Proctor stainless steel mould measuring 102 mm in diameter and 117 mm high, using a modified compaction effort with a heavy hammer of 45.4 N, in 5 layers, with 25 blows per layer, from a height of 475 mm. This compaction effort is representative of the compaction process adopted in road construction, and is determined as:

$$E = \frac{B \cdot N \cdot W \cdot h}{V}, \tag{1}$$

where E is the compaction effort (MN.m/m^3); B is the number of blows per layer; N is the number of layers; W is the weight of the hammer (N); h is the height of fall of the hammer (m); V is the volume of the mould (m^3). For the above conditions, E is 2.5 MN.m/m^3. The water content was measured immediately after each compaction test, and determined by the oven drying to constant mass (105 °C for 24 h).

In Figure 4, the effect of the water content (w) on the dry density of soil (ρ_d) is demonstrated with the compaction curve fitted to the plotted compaction results. The optimum water content (w_{opt}) of the parent soil (without cement) is 13%, and the corresponding maximum value of dry density ($\rho_{d,max}$) is 1.74 Mg/m^3.

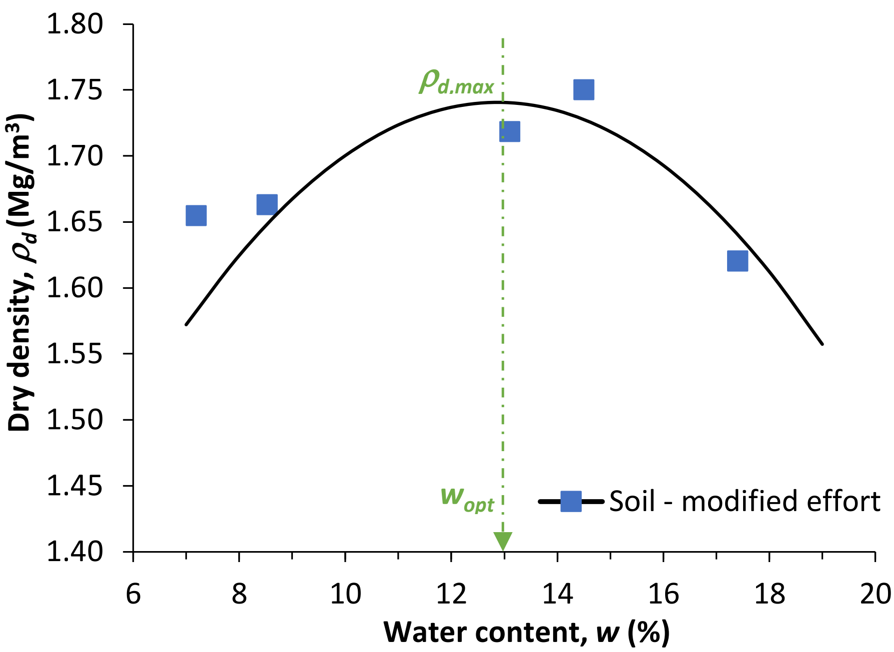

Figure 4. Proctor test results of soil with modified compaction effort.

The moulding points, with less or equal compaction energy than the modified Proctor energy, were chosen at the previously determined optimum water content level of the soil. These moulding points consisted of applying an increasing number of blows per layer: 10 (E1), 15 (E2), 20 (E3) and 25 (E4) blows on CBS mixtures with a water content of 13%, as explained in detail in Section 2.4.

2.4. Moulding the Specimens for the Unconfined Compression Tests

The amount of cement mixed with soil varies with the characteristics of the soil and the modification goal, and can be as low as 2% or as high as 16% of the dry mass of soil [33]. For the soil used in this study, A-6 (14) soil type, 3–6% of cement should be enough to provide long time material modification [30], such as a decrease in shrink/swell potential and an improved/stable bearing capacity, whereas the recommended percentage of cement is between 9% and 15% to obtain cement-bound soil characteristics [33]. In this study, two different cement contents were used, 10% and 14%, to obtain CBS-like characteristics.

Before the addition of water and the following cement hydration reaction, prepared soil–cement mixtures are finer than the initial soils because of the increase in fines induced by the addition of the cement [34]. As mentioned earlier, the cement used in this study has 100% of particles smaller than 0.065 mm, which gives the CBS theoretical gradations of soil cement mixtures presented in Figure 5.

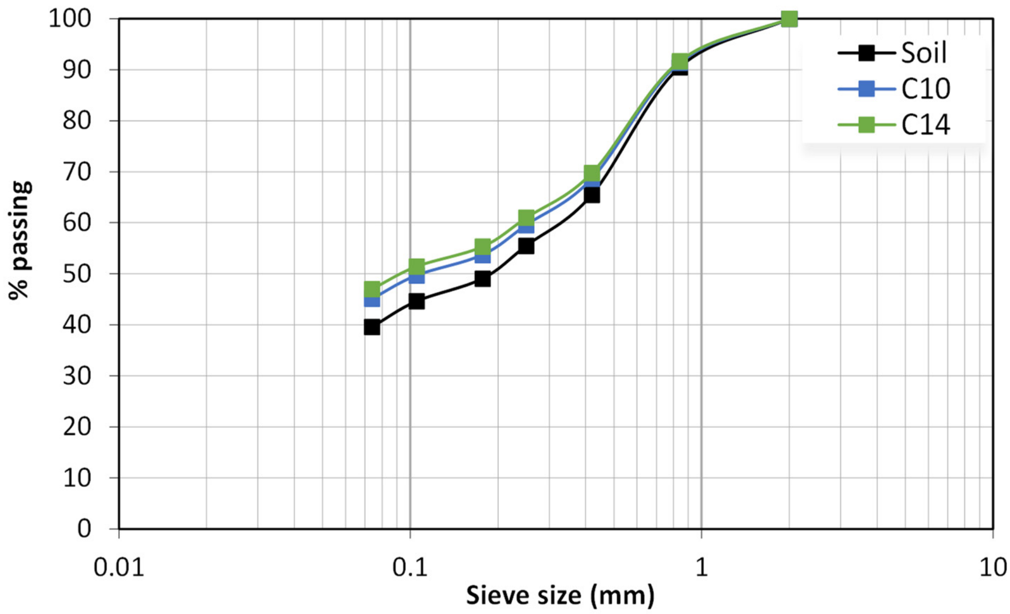

Figure 5. Particle size distribution of CBS mixtures.

The laboratory program was conducted for CBS with the optimum water content of the parent soil determined earlier by the modified Proctor compaction test. This allowed the research of the effect of the compaction effort on the volumetric and mechanical properties of CBS to be carried out under the same moisture content conditions.

To prepare the CBS, the soil was oven-dried and sieved using a 2 mm aperture sieve to eliminate coarser material. Afterwards, the amount of cement, by dry mass of soil, was added to achieve the percentages required: soil with 10% cement (C10), and soil with 14% cement (C14). The dry soil and the cement were mixed and then the water was added to obtain the 13% water content. All components were thoroughly mixed until a homogenous paste was obtained. Then, the mixture was compacted, in the same way as in the soil compaction tests in the Proctor mould, in 5 layers, but varying the number of blows per layer, in order to create the different compaction efforts corresponding to the four moulding points (E1, E2, E3 and E4).

Table 3 summarizes the fabrication conditions of the eight CBS mixtures tested. The CBS are referred to in the paper by their cement content and compaction effort (e.g., "C14-E2" refers to a CBS mixture with 14% cement compacted at E2 (15 blows per layer)).

The time it took to prepare (mixing and compaction) was always less than an hour, which is much shorter that the initial setting time (75 min, see Table 2) of the Portland cement used. After compaction, the specimen was immediately extracted from the mould using a hydraulic device. Then, the specimens were weighed on scales accurate to the nearest 0.01 g and their diameter and height were measured using a 0.1 mm error calliper. Figure 6 shows two specimens after extraction from the mould.

Table 3. Compaction of cement-bound soils.

CBS	C (%)	w_{opt} (%)	Blows Per Layer	E (MN.m/m^3)
C10-E1	10	13	10	0.98
C10-E2			15	1.47
C10-E3			20	1.97
C10-E4			25	2.50
C14-E1	14		10	0.98
C14-E2			15	1.47
C14-E3			20	1.97
C14-E4			25	2.50

Figure 6. Cement-bound soil specimens.

Then, the specimens were wrapped with transparent plastic film and were cured for 7 days in a humidity and temperature control room at 23 $\pm$ 2 °C and relative humidity of 55%. The samples were considered suitable for testing when they met the following tolerances: (1) required optimum water content, w_{opt} (within $\pm$1% of the target value defined for soil only); (2) dimensions: diameter 102 $\pm$ 1 mm and height 117 $\pm$ 1 mm.

The 24 specimens prepared (3 specimens for each mixture) met the specimen preparation and dimensions requirements of [35].

In order to calculate the porosity of specimens, the particle density of each mixture, ρ_{sm}, must be calculated from the particle density of the soil, ρ_{ss}, and the particle density of the cement, ρ_{sc}:

$$\rho_{sm} = \frac{C+1}{\frac{C}{\rho_{sc}} + \frac{1}{\rho_{ss}}}, \tag{2}$$

where C is the cement content of CBS mixtures (0.10 and 0.14 for 10% and 14% cement, respectively). Using Equation (2), the particle density is 2.68 Mg/m^3 and 2.69 Mg/m^3 for the CBS mixtures with 10% and 14% cement, respectively.

The porosity is the ratio of the volume of voids (V_v) to that of the sample (V), where the volume of voids can be calculated as the difference between the total volume of the sample and the volume of soil solids (V_s) and the volume of cement (V_c). From this, the porosity (n) is given by:

$$n = 1 - \frac{\rho_d}{\rho_{sm}}, \tag{3}$$

where ρ_d and ρ_{sm} are the dry density and particle density, respectively, of CBS in (Mg/m^3).

2.5. Unconfined Compression Tests

The unconfined compressive strength R_c is the index used in the European specifications [18] to quantify the improvement given to the soil by the cement in CBS mixtures.

Unconfined compression tests (UCT) were conducted on soil specimens (only E4) and cement-treated specimens in accordance with the procedure defined in [36]. All tests were conducted on unsoaked specimens, which had been cured for 7 days. The tests were carried out on a universal testing machine (Zwick) [37], with a maximum load capacity of 50 kN, and under constant displacement control (load plate speed of 1 mm/min). The vertical deformation of the specimen was monitored with a displacement transducer installed on the top plate. The axial strain (ε) was determined from the vertical deformation and the initial height of the specimen, and the average stress (σ) from the load measured during the test and the average initial cross section of the specimen. Based on the requirements defined in [18], the individual strength of the three specimens, moulded with the same characteristics, should not deviate by more than 20% from the mean strength. These requirements were met with all tested materials.

3. Results

3.1. Physical Properties of CBS Specimens

Table 4 presents the average values and coefficient of variation (CV) of the physical properties of fabricated specimens.

Table 4. Properties of specimens.

Material	w		ρ_d		n
	Mean (%)	**CV (%)**	**Mean (Mg/m^3)**	**CV (%)**	**(%)**
C10-E1	12.2	3.9	1.61	0.5	39.8
C10-E2	12.4	6.5	1.68	0.7	37.4
C10-E3	12.1	2.7	1.72	1.5	35.8
C10-E4	12.6	1.7	1.74	0.1	35.1
C14-E1	11.9	2.2	1.60	0.5	40.7
C14-E2	11.5	3.4	1.67	0.4	38.2
C14-E3	12.4	2.7	1.71	0.7	36.6
C14-E4	12.4	4.1	1.74	0.5	35.3

3.2. Unconfined Compression Tests

Figures 7 and 8 show the stress–strain curves of unconfined compressive tests for the specimens of cement-bound soil with 10% and 14% cement by dry mass of soil.

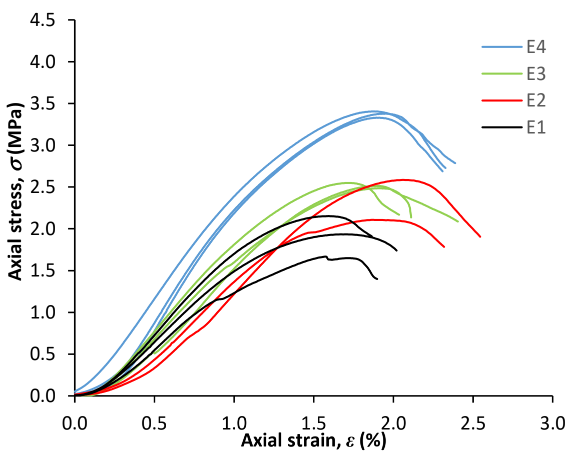

Figure 7. UCT stress–strain curves for CBS specimens with 10% cement.

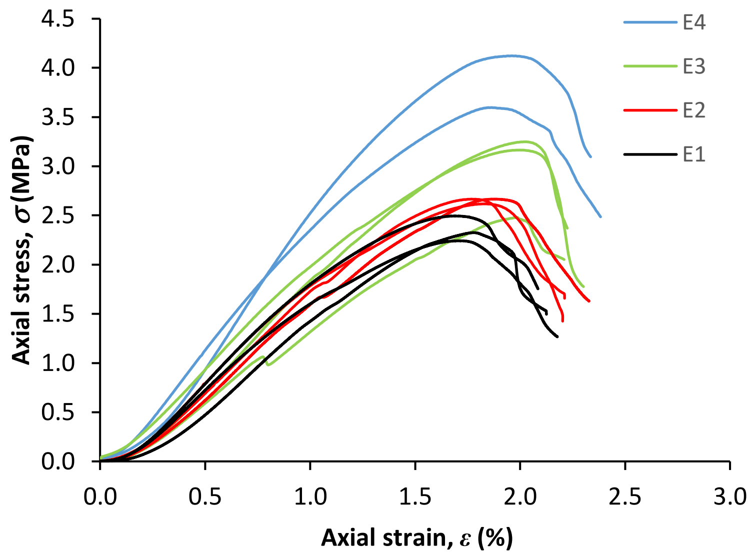

Figure 8. UCT stress–strain curves for CBS specimens with 14% cement.

The modulus of elasticity (E_{30}) was obtained from the stress–strain curves according to [38], with E_{30} being the secant modulus for the stress range from 0% to 30% of R_c. The values of E_{30}, R_c and axial strain at R_c value are summarized in Table 5 for the soil (E4) and the CBS mixtures.

Table 5. Results of unconfined compression tests.

Specimen	R_c		ε at R_c		E_{30}	
	Mean (MPa)	CV (%)	Mean (%)	CV (%)	Mean (MPa)	CV (%)
Soil-E4	0.22	11	1.62	7.7	2	14
C10-E1	1.80	11	1.62	4	111.4	14
C10-E2	2.35	14	1.96	7	102.0	2
C10-E3	2.52	1	1.84	6	137.4	13
C10-E4	3.37	1	1.91	2	196.5	14
C14-E1	2.35	5	1.73	3	136.4	16
C14-E2	2.65	1	1.82	3	147.0	8
C14-E3	3.21	2	2.01	1	172.4	12
C14-E4	3.86	10	1.91	4	215.8	5

4. Discussion

4.1. CBS Specimens

The dry density of specimens, listed in Table 4, increased significantly with the application of a higher compaction energy, and this was more important for the lower levels. For instance, the increase was on average 4.1% from 10 to 15 blows while only 1.7% from 20 to 25 blows. The porosity of compacted specimens varied between approximately 35% and 40%. Good compaction of CBS layers is important to ensure in service higher stiffness and less accumulation of permanent deformation with static and cyclic loadings in the field. Considering the highest dry density (obtained for E4) as the reference, the degree of compaction obtained for E1 was about 92%, which is not sufficient to guarantee adequate in-service behavior. The lowest compaction effort applied in the laboratory to comply with normal field requirements, which is a minimum of 95% maximum dry density [30], is E2 (15 blows per layer).

Preparation and compaction of different CBS mixtures at the soil optimum water content influenced the obtained results. Water is required in CBS to aid in the dispersion of cement particles in the soil and to achieve a high dry density (low porosity), and for the hydration of the cement to create the bonds with natural soil particles. The optimum water content varies with the material (soil or CBS) and the compaction effort applied. It is expected to decrease with increased compaction effort and with decreased cement content [2,39]. In this situation, the water content used was likely lower (dry side) than the optimum value for the CBS mixtures. However, it was significantly higher than required for full hydration of cement [40]. Moreover, the average water content of all fabricated specimens (see Table 4) was below the target of 13% because the water lost to evaporation was higher than initially predicted.

4.2. Unconfined Compressive Strength

From Figures 7 and 8, it can be seen that, as the compaction effort increases, the peak axial stress increases, as expected. The maximum unconfined compressive strength ranges from 1.80 MPa to 3.37 MPa (mean values) for 10% cement, and from 2.35 MPa to 3.86 MPa (mean values) for 14% cement. These values (see Table 5) are much higher than the strength (0.22 MPa) obtained for the natural soil, compacted in E4 conditions. According to the European standard [18], with the exception of C10-E1, the CBS specimens are classified in C1.5/2 (minimum Rc in MPa for cylinders of slenderness ratio 2 and 1, respectively). The class of compressive strength is higher than the typical values suggested in the literature for CBS specimens (0.7 to 2.1 MPa [19]). Hence, this demonstrates the potential of the technique to improve the bearing capacity of subgrades with (poor) fine-graded soils.

The axial strain sustained by the specimen at peak stress was, in general, similar in all CBS specimens despite the different cement contents and being compacted in different conditions. The only exception was for CBS mixtures compacted with E1, which broke at a lower deformation level. Higher porosity in similar specimen sizes means larger pores and a weaker particle structure. Thus, the cement bonds between soil particles should also have been less effective in spreading the load in the bulk specimen. In the literature, similar conclusions have been reported with different soils [3,5,8].

The values of E_{30} summarized in Table 5 show that compaction has the highest impact on specimen stiffness. For C10 specimens, E_{30} rose by 76% when the compaction effort increases from E1 to E4, whereas the effect of adding more cement (from 10% to 14%) varied between 10% and 44%. The increase in compaction effort from E3 to E4 was the most significant.

In addition, Figure 9 demonstrates the importance of both the cement bonding and applied compaction effort to the mechanical properties of CBS, and that R_c and E_{30} provide the same information for assessing these materials. It can be observed that above a certain porosity level (approximately 38%), the mechanical properties of CBS specimens are affected by the cement content but not by the porosity. This demonstrates the importance of applying a high compaction effort to maximize the cement-bonding benefit in CBS mixtures.

4.3. CBS Volumetric Normalisation

To assess the effect of the porosity and cement content on the mechanical properties of CBS mixtures, the analysis of the voids to cement ratio has been proposed, as mentioned earlier. Note that the two quantities have opposite effects on mechanical properties, i.e., the cement–soil mixture is improved (increase in strength) with the decrease in porosity and the increase in cement content. Thus, in [2], the ratio of the porosity to volumetric cement content (n/C_{iv}) was proposed as:

$$\frac{n}{C_{iv}} = \frac{\frac{V_v}{V}}{\frac{V_c}{V}} = \frac{V_v}{V_c}, \tag{4}$$

where V_v is the volume of voids, V_c is the volume of (unhydrated) cement and V is the total volume.

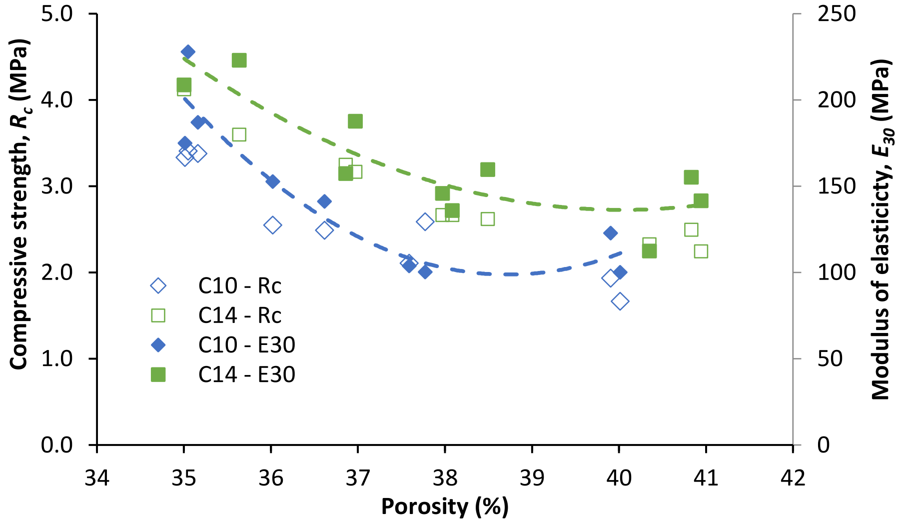

Figure 9. Effect of porosity on unconfined compressive strength and modulus of elasticity.

The influence of the ratio of porosity to volumetric cement content on the unconfined compressive strength is shown in Figure 10. The ratio n/C_{iv} varies between 5.1 and 8.6 for the different CBS specimens, and their strength varies in opposition to the n/C_{iv} value. The relationships between R_c and n/C_{iv} are different for the CBS specimens fabricated with different cement contents but the agreement with the experimental results is good. By dividing the porosity by the volumetric cement content, it was assumed that an increase in porosity could be counteracted by a proportional increase in the volumetric cement content, keeping the unconfined compressive strength unchanged.

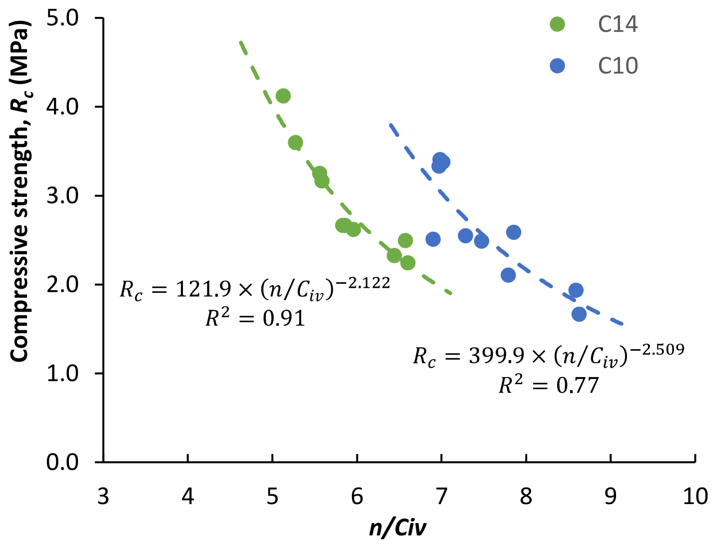

Figure 10. Effect of the ratio of porosity to volumetric cement content on unconfined compressive strength.

In fact, in order to keep the same value of R_c, an exponent might be applied to one of the two variables, n or C_{iv}, to make the effects of their variation on R_c [2] compatible. It was found that by applying a power of 0.2 to the parameter C_{iv}, a good adjustment is reached, as shown in Figure 11.

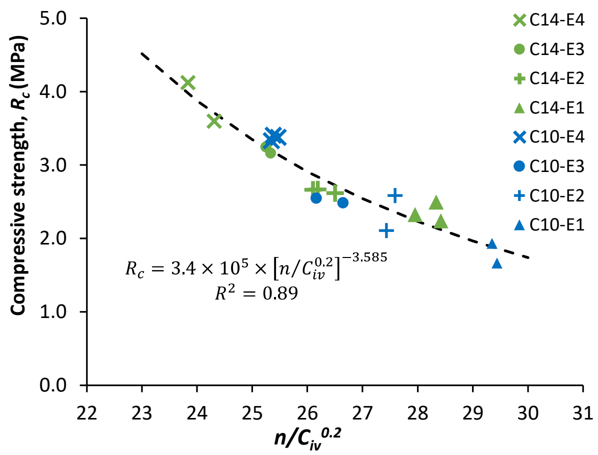

Figure 11. Effect of modified ratio of porosity to volumetric cement content on unconfined compressive strength.

In [2], the authors reported an exponent value of 0.28 for fine-graded soils. The empirical exponent applied to C_{iv} defines the relative contributions of volumetric cement content and porosity to the unconfined compressive strength. In addition, previous research with different soils [41] suggests that this exponent is not greater than one, which means that porosity is more important than cement bonding for the mechanical properties of cement–soil mixtures. Thus, for the soil analyzed in this study, a clayey soil A-6(14), modified with 10% to 14% Portland cement, the unconfined compressive strength after 7 days of cure can be estimated from the porosity and the volumetric cement content as:

$$R_c(\mathrm{MPa}) = 3.4 \times 10^5 \times \left(\frac{n}{C_{iv}^{0.2}}\right)^{-3.585}. \quad (5)$$

In addition, to compare the results of cement–soil mixtures with different native soils and binding agents, in [4], the authors proposed the normalization of the *Rc*-(n/C_{iv}^{α}) as:

$$\frac{R_c}{R_c^{ref}} = \mathrm{A} \times \left(\frac{n}{C_{iv}^{\alpha}}\right)^{-B}, \quad (6)$$

where R_c^{ref} is the R_c value obtained at the reference (n/C_{iv}^{α}) value, and A and B are model fitting constants. Thus, considering the reference (n/C_{iv}^{α}) value of 30 chosen in [3] for silty/clayey soils, the results obtained in this study were compared in Figure 12 with those of fine-graded cohesive soils found in the literature [2,3,8,34], and listed in Table 6. All studies employed unconfined compressive testing of CBS specimens cured for 7 days. The results obtained for different fine grained soils, with different cement contents compacted to different effort levels align in a single curve. An excellent fit of a power law model was obtained for these results. Hence, the normalized equation empirically supports the estimation of the compressive strength of CBS mixtures with different soils with similar geotechnical characteristics (i.e., granulometry, limits of consistency, dry density and geological origin).

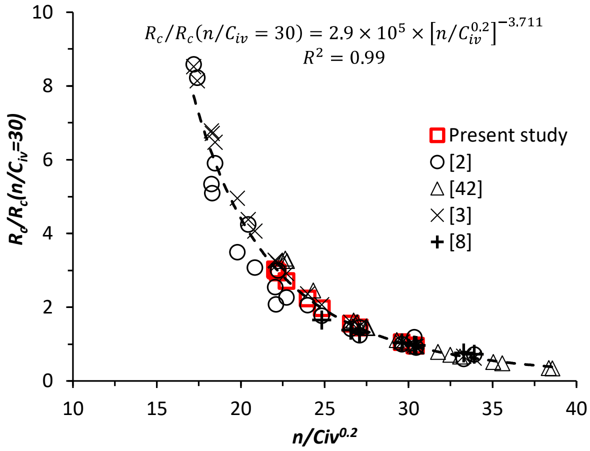

Figure 12. Normalized Rc–$n/C_{iv}^{0.2}$ of different studies.

Table 6. CBS research studies found in the literature.

Type of Soil	Empirical Correlation	$R_c^{ref}(n/C_{iv}^{\alpha})$=30	Reference
Clayey Sand SC	$R_c(\text{MPa}) = 5 \times 10^4 \times \left(\frac{n}{C_{iv}^{0.28}}\right)^{-3.32}$	0.62	[2]
Clayey Sand SC	$R_c(\text{MPa}) = 4 \times 10^6 \times \left(\frac{n}{C_{iv}^{0.21}}\right)^{-4.266}$	2.00	[42]
Paraguay Clay Red Silty Clay Silt	$R_c(\text{MPa}) = 4.29 \times 10^5 \times \left(\frac{n}{C_{iv}^{0.28}}\right)^{-3.85}$ $R_c(\text{MPa}) = 4.86 \times 10^5 \times \left(\frac{n}{C_{iv}^{0.28}}\right)^{-3.85}$ $R_c(\text{MPa}) = 1.47 \times 10^6 \times \left(\frac{n}{C_{iv}^{0.28}}\right)^{-3.85}$	0.80 1.19 3.02	[3]
Silty Soil	$R_c(\text{MPa}) = 9.3 \times 10^3 \times \left(\frac{n}{C_{iv}^{0.4}}\right)^{-2.64}$	1.17	[8]
Cohesive Soil CL	$R_c(\text{MPa}) = 3.4 \times 10^5 \times \left(\frac{n}{C_{iv}^{0.2}}\right)^{-3.585}$	1.74	Present study

5. CBS Design Procedure

5.1. Description

The results obtained in this study support, firstly, the CBS design of the clayey sand soil tested, and furthermore, enable the development of a CBS design method for different soils. From a practical design point of view, the CBS design comprises the definition of the cement content, the water content and the target dry density in the field to ensure a defined mechanical performance, which is often evaluated with unconfined compression testing at seven days of curing. The design mixture procedure relies on the evidence that, as observed in Figure 11, the same value of R_c can be obtained either by using less cement content and increasing the compaction effort, or it can be reached by increasing the cement content and applying less compaction energy. Hence, this means that using Equation (5), or a similar relationship if a different soil is used, the cement content and dry density can be chosen to reach the target compressive strength value for a given project.

Thus, for a different soil to the one investigated in this study, Equation (5) is generalized to [3]:

$$R_c = A \times \left(\frac{n}{C_{iv}^{\alpha}}\right)^{-B}, \tag{7}$$

where A, B and α are the model constants that vary with the soil and cement used.

The method to develop this model with less experimental effort than was used in this study is described in the following section. To establish different combinations that can be used to reach a target compressive strength value, the porosity/cement ratio (n/C_{iv}) must be calculated. Combining Equations (2) and (3), the porosity is:

$$n = 1 - \frac{\rho_d}{(C+1)}\left(\frac{1}{\rho_{ss}} + \frac{C}{\rho_{sc}}\right). \tag{8}$$

For the calculation of C_{iv}, the total dry mass of the CBS specimen (m_{sm}) is the sum of the dry mass of soil (m_{ss}) and dry mass of cement:

$$m_{sm} = m_{ss} + C.m_{ss} = m_{ss}(1+C), \tag{9}$$

and

$$m_{ss} = \frac{m_{sm}}{1+C}, \tag{10}$$

The dry mass of the CBS specimen (m_{sm}) is the product of the dry density of specimen (ρ_{sm}) by the volume (V) of the specimen, so the dry mass of soil becomes:

$$m_{ss} = \frac{\rho_d \cdot V}{1+C} \tag{11}$$

and the volume of cement V_c is:

$$V_c = \frac{m_c}{\rho_{sc}} = \frac{C.V.\rho_d}{\rho_{sc}(C+1)}, \tag{12}$$

Finally, C_{iv} is:

$$C_{iv} = \frac{V_c}{V} = \frac{C.\rho_d}{\rho_{sc}(C+1)}. \tag{13}$$

From Equations (8) and (13), the porosity and volumetric cement content in CBS are a function of the dry density of mixture, of the cement content and of the densities of cement and soil particles. For a certain soil and cement, their particle densities are fixed. Hence, the dry density of the CBS is a function of the cement content for a defined $\frac{n}{C_{iv}^{\alpha}}$. However, due to the exponent α in $\frac{n}{C_{iv}^{\alpha}}$, there is not an explicit solution to $\rho_d = f\left(\frac{n}{C_{iv}^{\alpha}}, C, \rho_{ss}, \rho_{sc}\right)$.

To solve this, it is assumed that ρ_d and C can be modelled with a 2nd order polynomial function:

$$\rho_d = a_1 \cdot C^2 + a_2 \cdot C + a_3 \tag{14}$$

where a_1, a_2 and a_3 are the model constants. Introducing Equation (14) in Equations (8) and (13), the estimated values of the porosity (n^*) and C_{iv} $\left(C_{iv}^*\right)$ are obtained as:

$$n^* = 1 - \frac{a_1 \cdot C^2 + a_2 \cdot C + a_3}{(C+1)}\left(\frac{1}{\rho_{ss}} + \frac{C}{\rho_{sc}}\right), \tag{15}$$

$$C_{iv}^* = \frac{C \cdot \left(a_1 \cdot C^2 + a_2 \cdot C + a_3\right)}{\rho_{sc}(C+1)}. \tag{16}$$

In addition, combining Equation (15) with Equation (6), the porosity can be estimated as:

$$n^{**} = \left(\frac{R_c}{A}\right)^{-\frac{1}{B}} \cdot \left(\frac{C \cdot \left(a_1 \cdot C^2 + a_2 \cdot C + a_3\right)}{\rho_{sc}(C+1)}\right)^{\alpha}. \tag{17}$$

Finally, considering various values of C in a defined range (C_{min}–C_{max}) and the target R_c, the constants a_1, a_2 and a_3 can be determined using the Solver function in Microsoft Excel to minimize the error:

$$error = \sum_{Cmin}^{Cmax} (n^* - n^{**})^2. \tag{18}$$

For the clayey soil investigated, considering the $R_c - \frac{n}{C_{iv}^{\alpha}}$ model described in Equation (5) the constants a_1, a_2 and a_3 are 0.01, -0.35 and 19.09, respectively. Figure 13 shows the ρ_d-C models for various R_c values. From this, project managers and contractors have a range of options to explore. The decision on selected ρ_d and C depends on project requirements and specific conditions, namely the construction time constraints, the availability of adequate equipment to apply the desired compaction energy and the cost of cement.

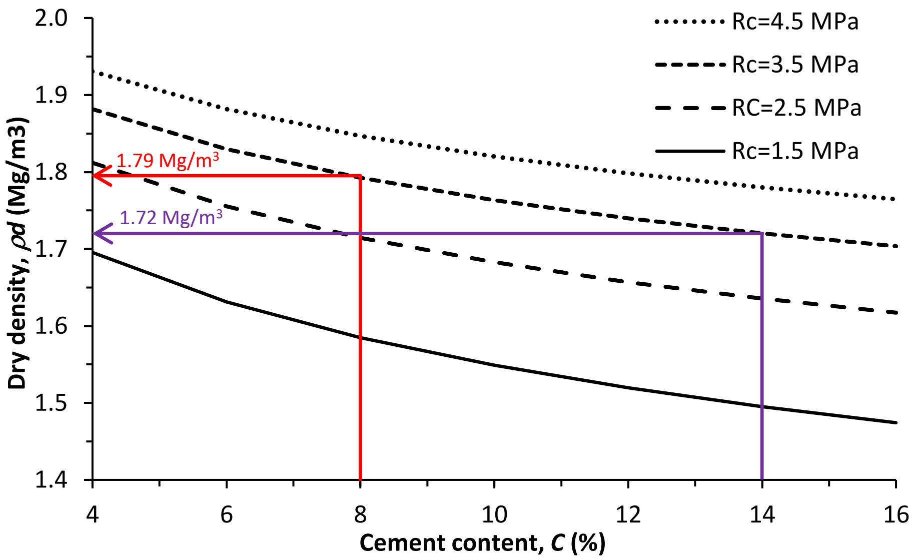

Figure 13. Practical examples of mix design.

Finally, this methodology can also be useful to control compacted cement-bound soil layers in the field. If poor compaction is detected, this can be readily taken into account in the design, identifying through Equation (5) the expected compressive strength, and adopting corrective measures accordingly, such as the reinforcement of the treated layer or the reduction of the maximum vertical stress admitted in the structural design of the overlaying structure [43]. For example, if R_c = 3.5 MPa is required in the project, the minimum dry density is 1.79 Mg/m^3 for 8% cement, and 1.72 Mg/m^3 for 14% cement.

5.2. Determination of CBS Model

The CBS design procedure described considers that a fixed water content is used regardless of the cement content and compaction effort adopted. Thus, in this study, the compaction of CBS materials at the optimum water content determined for the soil was investigated and it was observed that the unconfined compression strength obtained varies with the cement content and compaction effort. The authors acknowledge that by prescribing this water content, the maximum dry density of CBS is hard to achieve because the optimum water content varies slightly with the content of cement. Nevertheless, this method allows considerable savings in the laboratory to design a CBS that meets the project requirements. To build the CBS model, Equation (7), the following procedure is recommended:

1. Build the soil Proctor curve for the determination of the maximum dry density and the optimum water content of the soil;
2. Establish the adequate limits of cement content for the soil type (minimum range 4%), using, for example, recommendations in [33];
3. Establish the limits of laboratory compaction, for example, E4 and E2;
4. Produce CBS specimens with minimum and maximum values of cement content at the soil optimum water content, compacted at E4 and E2;
5. Test CBS specimens cured for 7 days for unconfined compression strength;
6. Determine n and C_{iv};

7. Fit Equation (6) to $\frac{n}{C_{iv}^{\alpha}}$ versus R_c results to obtain A, B and α; in the literature, the best fit model is obtained for an α between 0.18 and 0.4.

6. Conclusions

This paper describes a study investigating the effects of porosity, dry density and cement content on the mechanical properties of fine-graded soils treated with cement. A clayey sand (A-8 class) extracted in the Almada Municipality, Portugal, was mixed with 10% and 14% of Portland cement type IV of the dry mass of the soil, and compacted at the soil optimum water content. To obtain different volumetric properties in cement-bound soil specimens, the compaction effort used in the laboratory varied from 1.0 to 2.5 MN.m/m^3. The mechanical properties were evaluated on unsoaked specimens, cured for 7 days, using unconfined compression testing. From the experiments and discussion of results, and within the limits of test conditions, the following conclusions can be drawn:

- The unconfined compressive stress–strain behavior of CBS is affected by the cement content and compaction effort used in the production of the specimens. Increasing cement content and compaction effort leads to higher peak stress (compression strength, R_c) and less deformation at peak, which results in higher modulus of elasticity, E_{30}, values. For a certain cement content, the R_c and E_{30} had the same variation trend as the specimen porosity.
- The compressive strength is strongly affected by the modified porosity to volumetric cement content ratio ($n/C_{iv}^{0.2}$). The exponent value of 0.2 is in agreement with other studies found in literature for different fine-graded soils. It was also found that by normalizing the compressive strength of CBS to a certain $n/C_{iv}^{0.2}$ value, the results of CBS with different parent soils and cements fit a single model.
- The R_c–$n/C_{iv}^{0.2}$ model allows the determination of the cement content and the dry density required in the field to obtain a certain R_c value.

In addition, supported by these conclusions, a practical CBS design approach was proposed for different soils. This approach allows the CBS conditions to be defined (cement content, target dry density, water content) to obtain a minimum unconfined compressive strength. A protocol was proposed to obtain the R_c–n/C_{iv}^{a} model for the soil with fewer tests than usually required.

Finally, further studies are required (expanding tests to other cement contents and water contents) in order to check the possibility of generalization of the present findings to different soils and binding agents.

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