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Soil-cement formation factor: methodological approach and relationship with unconfined compression strength

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Article

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Archie's Law
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Electrical conductivity

Abstract

This study investigated the use of the Formation Factor of the material as an alternative way to estimate soil-cement strength involving no destructive tests. This factor is obtained from Archie's Law and consists of the ratio of pore water electrical conductivity to saturated porous material electrical conductivity, being related to porosity by constant terms. In this study, the electrical conductivity of the pore solution was obtained from a soil-cement leaching test after curing, and the conductivity of the monolithic soil-cement, by applying continuous voltage between 12-35 V onto electrodes of 1 mm thick copper plates. The influence of cement content and dry density on the electrical properties and water absorption was studied and discussed for curing times of 7 and 28 days. The samples molded with higher dry densities and cement contents presented higher Formation Factor for Soil Cement and higher unconfined compression strength. The Formation Factor and the unconfined compression strength are linearly related. Due to the methodology adopted, the Formation Factor was predominantly influenced by the conductivity of the pore solution and was related to the open porosity by means of a power function. Therefore, the Archie's Law can be applied to soil-cement. In this case, the cementation coefficient varies until 28 days of curing, tending to stabilize around 8 from that age onwards. The volumetric coefficient can be adopted as a constant with a value of 10^{12}.

1. Introduction

Soil stabilization with the use of cement is used on a large scale in the production of earth bricks and in geotechnical works, such as pavement layers in roads and also in embankments (Bahar, et al., 2004; Cardoso & Maranha das Neves, 2012). Performance standards prescribe minimum values for unconfined compression strength and water absorption. These parameters are largely affected by the cement dosage and compaction dry density, which may vary during construction, and for this it is important to develop non-destructive monitoring tools during construction for quality control.

In this context, there are studies involving the relationship between the physical properties of soil-cement and electrical conductivity or resistivity (e.g., Khalil & Santos, 2011; Kibria & Hossain, 2012; Zhang et al., 2012; Hammad, 2013; Fallah-Safari et al., 2013; Bai et al., 2013; Vincent et al., 2017). The methods used to obtain electrical measurements are easy and quick to apply, in addition to being non-destructive and non-invasive, which justifies their increasingly frequent use in research.

The electrical conductivity of the monolithic material, when associated with the conductivity of the pore solution, provides a parameter known as the Formation Factor (Archie, 1942). This factor, originally conceived for rocks, has been largely used in soil studies mainly for geophysical prospection (Rinaldi & Cuestas, 2002; Lorenzo & Bergado, 2004; Shah & Singh, 2005; Song et al., 2008; Kahraman & Yeken, 2010). This factor (*FF*) is defined using Archie's equation (Equation 1), representing the relation between the electrical conductivity of the pore water and the saturated solid material (respectively K_w and K_0), being function of porosity ϕ and calibration constants *A* (volumetric coefficient) and *m* (cementation coefficient).

$$FF = \frac{K_w}{K_0} = A.\phi^{-m} \tag{1}$$

The electrical conductivity depends on soil structure and minerals, and chemical composition of the pore fluid. In fact, electrical current flows through the conductive liquid phase existing in soil voids and eventually through the surface of conductive minerals, being dependent on pore geometry, or tortuosity. This explains the fact that molding dry density and water content affect the electrical conductivity (Vaillant,

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2013; Vaillant & Cardoso, 2016). For the case of soil-cement mixtures, a combination of the porous net and the cement content of the mixture will contribute to introduce more tortuosity. This combination is also primarily responsible for the mechanical strength of the material. In addition, soluble elements from cement will affect the electrical conductivity of the pore solution. For this reason, it is important to evaluate the electrical conductivity of the pore fluid as it will change with cement dosage and curing time.

The relationship between the Formation Factor of the material and its mechanical strength has not been properly addressed in soil-cement research yet. This fact may be due to a difficulty in obtaining the measurement of the electrical conductivity of the pore solution or a scarcity of studies correlating the conductivity of the solid material with its compression strength. Only a few studies can be cited, especially Song et al. (2008), Zhang et al. (2012), Fallah-Safari et al. (2013) and Vincent et al. (2017).

Song et al. (2008) established relationships between the resistivity of a stabilized soil and its cement content, degree of saturation, moisture content, curing time and unconfined compression strength, as well as relationships with the soil SPT. They found a directly proportional linear function in the relation between resistivity (ρ) and resistance (q_u), as shown in Equation 2.

$$q_u = 286.\rho - 334 \tag{2}$$

A similar relationship between compression strength and resistivity can be found in the study by Kahraman & Yeken (2010) carried out on rocks. This study particularly highlights a model obtained from multiple regressions, relating the compression strength (σ_c, in MPa) with the electrical resistivity (ρ, in Ω.m), the apparent density (γ, in g/cm^3), and porosity (n, in %), according to Equation 3.

$$\sigma_c = -296 \cdot 16 + 0 \cdot 071\rho + 6.33n + 135 \cdot 8\gamma \quad r = 0 \cdot 97 \tag{3}$$

Zhang et al. (2012) studied the influence of cement content, porosity and curing time on the electrical resistivity and compression strength of soil-cement, before and after wet curing. In that study, the authors established relations of resistivity (ρ) and unconfined compression strength (UCS) with a synthetic parameter, combining total porosity (n_t), curing time (T) and cement content (a_w). It was suggested that this relationship is similar to Archie's Law and, therefore, this law can be applied to soil-cement. The relationships mentioned above have a linear correlation coefficient of 0.98 and are represented in Equations 4 and 5, respectively for electrical resistivity (ρ) and compression strength (UCS).

$$\rho = 33.65\left(\frac{n_t}{a_w.T}\right)^{-0,71} \tag{4}$$

$$UCS = 9.857.\left(\frac{n_t}{a_w.T}\right)^{-1,11} \tag{5}$$

Fallah-Safari et al. (2013) used different samples of compacted clay (without reuse) at different apparent molding densities, to observe the relation between UCS and electrical resistivity. They observed a non-linear relation between the variables - an increase in electrical resistivity for increases in apparent density. The results, on average, were not consistent, since the highest correlation coefficient (R^2) obtained was 0.829 for a bentonite sample, and for four other samples the obtained coefficient was lower than 0.7.

Vincent et al. (2017) studied four different samples of a soil stabilized with cement. They performed a multiple regression analysis between the unconfined compression strength and the electrical resistivity of the material before curing (fresh state), in the periods of 1 and 7 days of curing. The results are consistent with those obtained in other studies, observing increases in resistivity for proportional increases in cement content and curing time. This study presented only the equations for the initial stage of the mixture (before curing) and after a period of 1 day of curing, as it sought to obtain the UCS prediction at 7 days, that is, before hardening, to avoid losses. The type of curing adopted in this research was not mentioned.

In this context, this study proposes an easy-to-apply methodology to evaluate the compression strength of soil-cement composites based on relations with an Apparent Formation Factor of the soil-cement (henceforth called FF_{sc}). Using the Archie's Law, this Formation Factor was determined both from measurements of electrical conductivity in the solid material after determined curing times (K_f) and from measurements of the leached solution, named K_{sp} (Equation 6). Electrical conductivity is the physical parameter that rules FF_{sc}, which, in turn, is influenced by the material design parameters (dry volumetric weight or dry density at compaction, and cement content) and curing time.

$$FF_{sc} = \frac{K_{sp}}{K_f} = A.Abs^{-m} \tag{6}$$

In this work the soil-cement porosity was replaced by the water absorption (*Abs)* (or open porosity), found using the saturation process described in the methodology section of ABNT NBR 8492 (ABNT, 2012b). The water absorption is a parameter of quality control of soil-cement bricks at 7 days of age, whose value is limited to 20% (ABNT, 2012a).

The experimental conditions to measure the electrical conductivity of the solution, for which Archie's Law was postulated, were not obeyed in this study. This is because conductive clay minerals are dispersed in pore solution (Shale effect), and pore solution may be diluted. However, Archie's Law for this soil-cement is simple to use and allows obtaining a representative value of the "cementation" of the material. This law is being used as concept, because the formation factor depends on porosity, which comes from the connected porous network derived from dosing, molding, and curing conditions. Being associated with the presence of hydrated cement minerals, it will be latter possible to observe a relation between this factor and UCS.

Finally, this Apparent Formation Factor (FF_{sc}) for soil-cement was related with UCS to define relationships which may be useful as a non-destructive method for quality control. The relations were established to consider dry density and cement dosage, in addition to the curing time.

2. Materials and methods

2.1 Materials and sample preparation

The soil samples used were fragments of marl from the Portuguese region of Abadia, which were passed through a #4 sieve. The fines content passed through sieve #200 with diameter <0.075 mm was of 17%. The minerals present were carbonates (16-23% calcite and dolomite), quartz (5-10%), other non-clayey minerals (8-17%), clays (1 5% chlorite, 17-30% kaolinite, 21-35% illite, 0-1% smectite and 30-60% mixed layer clays) and a very small percentage of organic matter (0-2%) (Maranha das Neves & Cardoso, 2006). Liquid limit was 40% and plasticity index was 28% (classification CL) - values found using the fine fraction of the marl. The unit weight of solid particles was 27.5 kN/m^3. The Portland cement type II-32 with unit weight of solid particles of 31.0 kN/m^3 was used.

The specimens, molded in rectangular metallic forms with section of 4 × 4 cm^2 and length of 16 cm (CEN, 2007), as shown in Figure 1a, were manually compacted in four layers, one-centimeter thick each. The compaction moisture adopted was approximately 2% above the optimum moisture obtained in Proctor Normal test. A pilot test was carried out to find the maximum possible dry density to be achieved in manual compaction. Thus, four levels of dry volumetric weights were defined up to the maximum limit achieved in the test: 14, 15, 16 and 17 kN/m^3, respectively G1, G2, G3 and G4. Four cement dosages were mixed with each dry unit weight of marl: 5% (D1), 10% (D2), 15% (D3) and 20% (D4). The choice of these cement percentages was based on the most used content in the literature consulted. To individually identify each of the 16 combinations of density (G) and cement content (D), variable C was created. It represents the dosage of cement per volume or the cement content per m^3 of mixture which values are shown in Table 1.

The samples were immediately extracted from the mold after compaction, weighted and their initial electrical conductivity was recorded. Then, curing was carried out in a humid chamber with a relative humidity greater than or equal to 95%. Curing times were established to be 7 days (ABNT, 2012a) and 28 days, being different specimens prepared for each period. The 28-day curing was included to observe the hydration process and its influence on electrical measurements. Considering the reference samples (without cement), a total of 108 specimens were manipulated for study.

After curing, the specimens were prepared for compression and leaching/absorption tests, which were performed after a

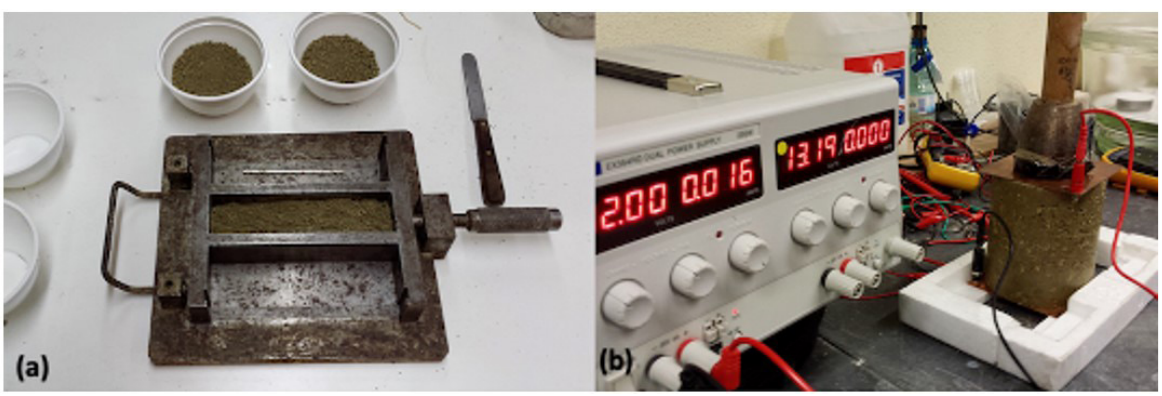

Figure 1. (a) specimen molding; (b) electric current reading procedures.

Table 1. Cement content (C) per m^3 of soil-cement (kg/m^3).

(C) cement content (kg/m^3)					
		(G) dry density (kg/m^3)			
		G1 (1400)	G2 (1500)	G3 (1600)	G4 (1700)
(D) cement dosage (%)	D1 (5)	72.15	77.30	82.46	90.63
	D2 (10)	152.27	163.16	174.06	191.29
	D3 (15)	241.84	259.14	276.45	303.79
	D4 (20)	342.62	367.11	391.64	430.39

new measurement of the electrical conductivity. This is the electrical conductivity of the saturated soil-cement (K_0, or K_f if measured for different curing times). Each specimen of 4 cm × 4 cm × 16 cm was cut into three parts, being the cubic central part (4 × 4 cm^2) reserved for the leaching and water absorption tests, and the two extremes (6 × 4 cm^2) reserved for the simple compression tests (load applied along the larger dimension). The specimens reserved for the compression tests were wrapped in plastic wrap to prevent edge breaks.

2.2 Electrical conductivity of the treated compacted marls

The procedure adopted to measure the electrical conductivity of the treated compacted marls is presented in Figure 1b. A source of continuous tension between 12-35 V and one-millimeter-thick copper plate electrodes (10 × 10 cm^2) was used to measure the electrical conductivity in the solid samples.

Electrical conductivity was computed using the well-known Ohm's law. The electric current was measured using the voltage source in the central part of the sample, applied perpendicularly to bedding layers formed in the compaction. The contact between the electrodes and the soil was ensured using a small weight, and a standard time for current stabilization of 15 seconds was adopted to consider capacitive effect of the material. Capacitive properties were not explored further. The soil-cement conductivity was taken in the saturated material with dry surface, i.e., superficially dried (ABNT, 2012b).

2.3 Leaching, electrical conductivity and water adsorption joint tests

The central part of each sample was wrapped in filter paper to avoid possible loss of solid material (Figure 2a) after measuring the electrical conductivity. Then the sample was totally submerged in distilled water whose volume was defined to be 7.5 times the volume of the sample. It remained submerged (Figure 2b) until full saturation. Saturation was determined by controlling the sample weight along the leaching test.

The experimental conditions to measure the electrical conductivity of the pore solution were not postulated as in Archie's Law. They were adapted in this study from the sample leaching. Two factors, then, probably affected the electrical conductivity measures obtained: the dispersion of clay minerals in pore solution, and the dilution of pore solution. However, the expectation is to validate Archie's Law for soil-cement under simplified experimental conditions and to obtain a representative value of the "cementation" of the material, that is, of the connected porous network derived from dosing, molding, and curing conditions

The electrical conductivity of the leached solution was measured using a CRISON conductivity meter (Figure 2c) (reading range of 0.2 μS/cm). The electrical conductivity of the pore solution of the samples (K_{sp}) was obtained from the relation between the accumulated conductivity and the leaching period, according to Vaillant (2013). The correlation curve presents a linear zone that is representative of the conductivity of the pore solution. Thus, the K_{sp} value was calculated from the slope of that line.

At the end of the leaching test the open porosity was determined after curing, at 7 and 28 days, by measuring the difference between total masses measured after saturation and after oven drying.

2.4 Unconfined compression tests

The unconfined compression tests were done following CEN EN 1015-11 (CEN, 2007). The load was applied adopting a constant rate of 0.5 mm/min for axial deformation. The precision of the equipment is 0.01 kN. The specimens tested were cut from the ends of the main sample (6 cm × 4 cm) and were subjected to saturation for four hours before the compression test. Figure 3 shows the steps followed for samples preparation.

2.5 Electron scanning microscope images and mercury intrusion porosimetry tests

Complementary mercury intrusion porosimetry (MIP) tests were performed in 1 × 1 × 1 cm^3 cubic portions extracted from some samples after 28 days curing to evaluate changes

Figure 2. (a) sample packaging; (b) submersion for leaching test; (c) measurement of the leachate electrical conductivity.

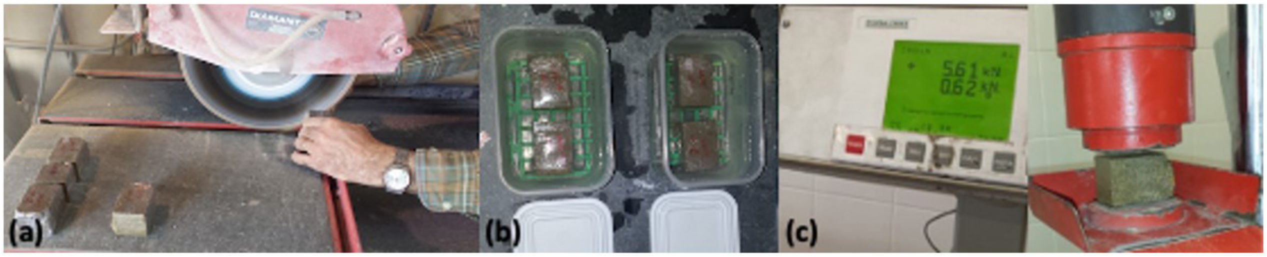

Figure 3. Sample preparation for the UCS tests: (a) cutting; (b) saturation; (c) compression.

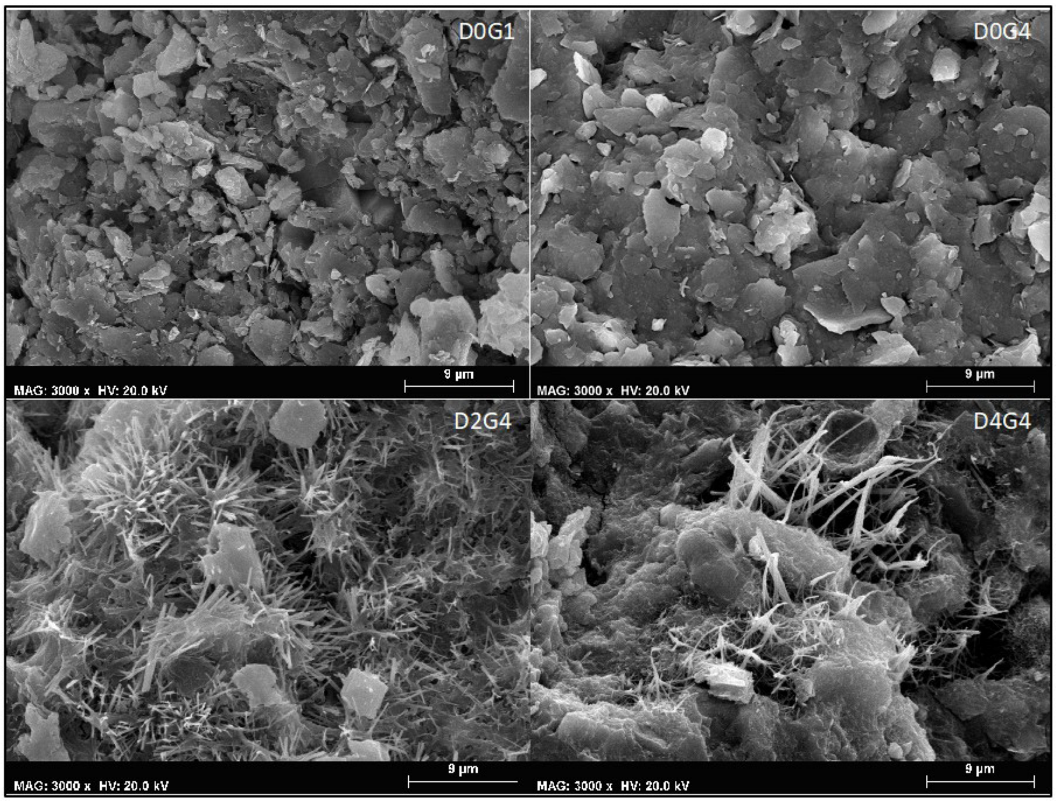

Figure 4. Microscopy of treated (bottom images) and untreated (top images) marls at different cement contents and molding density.

in pore sizes due to compaction and cement dosage. Electron scanning microscope images allowed to visualize the hydrated cement minerals formed for the different dosages adopted.

3. Results and discussion

3.1 Electron scanning microscope images

Figure 4 presents some electron scanning microscope images of the soil-cement structures modified by the compaction density (top photos) and stabilization with cement for 28 days of curing (bottom photos). The presence of the hydrated cement minerals is obvious in both samples, being more disperse and less thick in sample D2G4 than in sample D4G4. Their presence confirms pore clogging of the compacted material, interfering with electrical conductivity of the material because electrical current flows mainly through the liquid phase, i.e., by the pore fluid.

3.2 Influence of cement content on the conductivity of solid material (K_f)

Figure 5 presents the relation between cement content and saturated material electrical conductivity for 7 and 28 days of curing. In general, the electrical conductivity for a given curing period (K_f) tends to decrease with the increase of both cement content (C) and dry density (G) at compaction. This same behavior can be observed in other studies (e.g. Khalil & Santos, 2011; Kibria & Hossain, 2012; Zhang et al., 2012; Hammad, 2013; Fallah-Safari et al., 2013; Bai et al., 2013; Vincent et al., 2017).

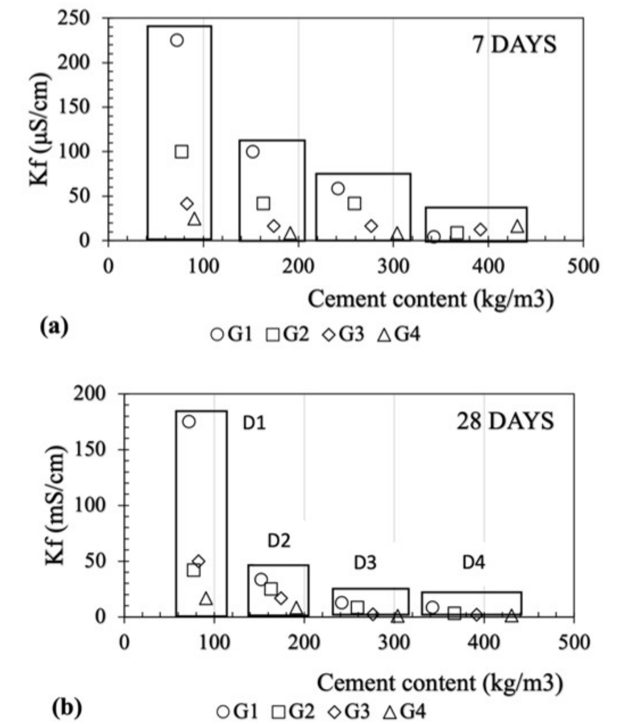

Figure 5. Influence of cement content on the conductivity of the solid material for (a) 7 days and (b) 28 days of curing.

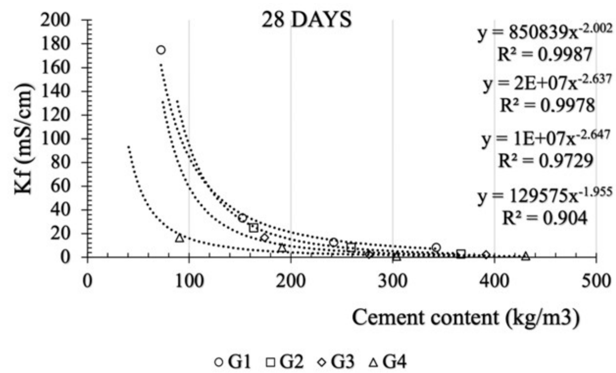

Figure 6. Influence of cement content on the conductivity of the solid material.

This behavior was expected, because the hydrated cement paste creates a new porous network in the material, with less quantity of pores and also disconnecting them (see the bottom images in Figure 4). This structural change has a direct impact on the material conductivity because the electrical current flows through the liquid phase and the path followed depends on the geometry of the connected pores. In addition, the amount of liquid present in the porous material is reduced by decreasing porosity and, for this reason, the conductivity decreases with the increase of dry density.

This reduction in conductivity is more marked for 28 days of curing, when the hydrated cement minerals are expected to be completely formed and therefore the quantity of ions dissolved in the pore water is reduced. Indeed, assuming the same amount of cement minerals for the same dosage (D), a consistent trend of behavior can be observed, indicating a power function whose exponent is close to 2.0 (Figure 6). This also seems to be the behavior trend observed in the work by Zhang et al. (2012), for three samples studied at six different curing times.

There was a great dispersion for samples with seven days of curing, mainly for the highest cement dosages, which may be due to hydration reactions still in progress, with a greater amount of hydrated calcium compounds present in the system. This fact can also be observed and explained in other studies already mentioned (Liu et al., 2008; Chen et al., 2011; Zhang et al., 2012; Vincent et al. (2017). For this reason, the regressions for the seven-day-curing samples were not presented.

3.3 Influence of cement content on the conductivity of the pore solution (K_{sp})

The presence of cement contributes to increase the conductivity of the pore solution (K_{sp}) due to dissolved ions. This conductivity is different from that of distilled water even for the untreated material due to the presence of dissolved clay minerals. The contribution of the cement is evident in the values of K_{sp} measured for the lowest curing age (7 days), when there is intense chemical activity (cement hydration reactions) impairing the diffuse ion transport. This can be seen in Figure 6, in which the relations were more dispersed at this early age than after 28 days of curing. It is assumed that, in the latter, the pore water system is chemically more stable and, therefore, there is a well-defined trend between the variables. For 28 days the values of K_{sp} are linearly related to the cement content (slope close to 0.4, in Figure 7b).

By keeping cement dosage (D) constant there is an increase in K_{sp} for increasing dry density (G). The increase in dry density imposes an increase in cement content to adjust to the required percentual dosage. For this reason, there will be a greater concentration of ions in the pore solution which, in turn, will have their volume reduced because of the reduction of large pores produced by the higher density. It seems that this may have accelerated the ion transport mechanism, increasing its concentration in the leached solution and, consequently, increasing its conductivity.

3.4 Influence of cement content on the soil-cement Formation Factor (FF_{sc})

The FF_{sc} represents the structural arrangement of the material at its "formation". For soil-cement, therefore, this factor will influence dosage parameters (cement content and compaction density), type and curing time. The mathematical relations between the FF_{sc} and cement content (C), defined in kg/m^3, are presented in Figure 8. The regressions were performed as a function of the samples dry density, which, in this case, also represents an increase in the cement content,

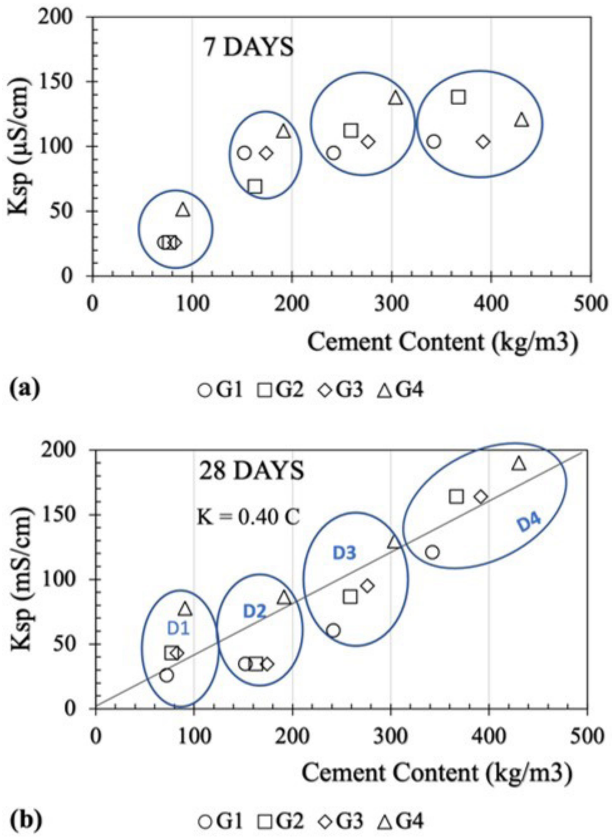

Figure 7. Influence of cement content on the conductivity of the pore solution for (a) 7 days and (b) 28 days of curing.

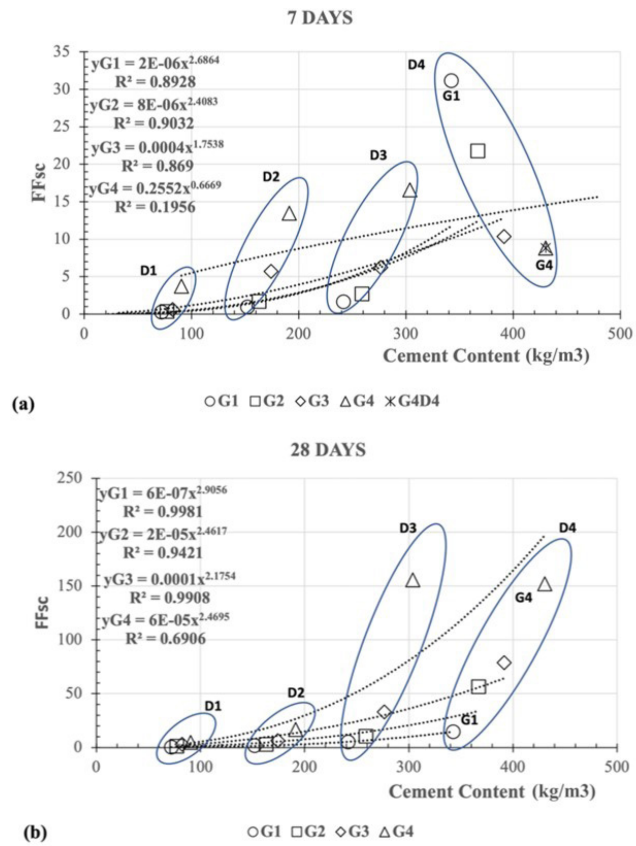

Figure 8. Influence of cement content on the soil-cement Formation Factor for (a) 7 days and (b) 28 days of curing.

as indicated by the deviations of the points to the right. The groups of samples for the different cement dosages (D) were highlighted with circles in the graphs.

Similar trends relating the two variables can be seen, except for sample D4 for 7 days of curing. The differences found for this sample are possibly due to the presence of larger amounts of non-hydrated cement particles. In other words, the sample with 20% of cement (D4) seems to indicate a disproportionate hydration process, suggesting that the relationship between water and cement was not ideal, with not enough water to hydrate the existing amount of cement particles. This caused a kind of "delay effect" in the hydration process at this age, which interfered with the conductivity readings, reversing the trend presented for the other groups of samples, with lower cement contents. At 28 days of curing, however, there was greater stability in the formation of the porous network, and the slope of the curve tended to be constant for any dosage, as indicated by the equations in Figure 8b. This suggests that, for cement contents above 15%, it would be prudent to have a curing time longer than 7 days to ensure that the measurements of the treated materials will no longer be affected by this hydration delay.

No study was found in the literature on the application of the electrical conductivity of soil-cement for a content of 20%. There were also no studies of this material associated with Archie's Law, involving electrical conductivity reading of the pore solution. There are many studies on the application of Archie's Law to concretes and mortars, associated with porosity, permeability, setting time and ion diffusion, as reported in Vaillant (2013). These differences in porosity can be observed in the mercury intrusion porosimetry (MIP) tests, which indicated a minor difference in the porous network for samples D2 e D4. The curves presented in Figure 9, for samples D0G4, D2G4 and D4G4, indicate the expected overall reduction of the pore size with increasing density, being more visible for the smallest pores because the peak displaced from dimensions around 120 nm to 80 nm and to 50 nm, for increasing dosages D0, D2 and D4, respectively.

Finally, as observed in Figure 8, samples with a higher cement content showed a higher FF_{sc}, represented by the points shifting up and to the right. Those samples with a higher density had a higher FF_{sc}, represented by the upward shift of samples G1-G4 (except for group D4, as already discussed). Curing time concurs to reduce electrical conductivity of the solid sample (K_f) and, therefore, the higher it is, the greater is the FF_{sc}.

3.5 Influence of K_f and K_{sp} on the FF_{sc}

Figure 10 presents the relations between the conductivities of the solid material and the pore solution, K_f and K_{sp}, and the

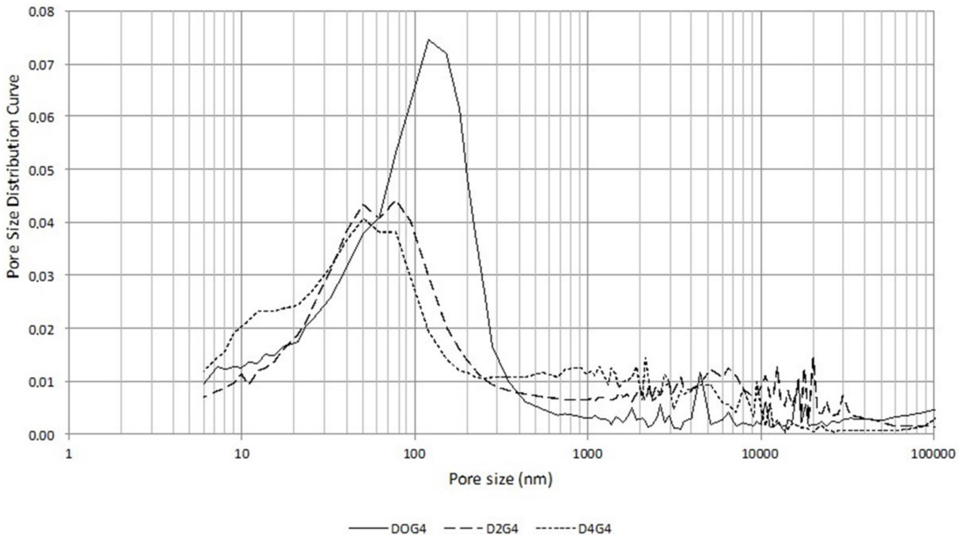

Figure 9. Mercury intrusion porosimetry for the samples with dry density G4 with different cement dosage.

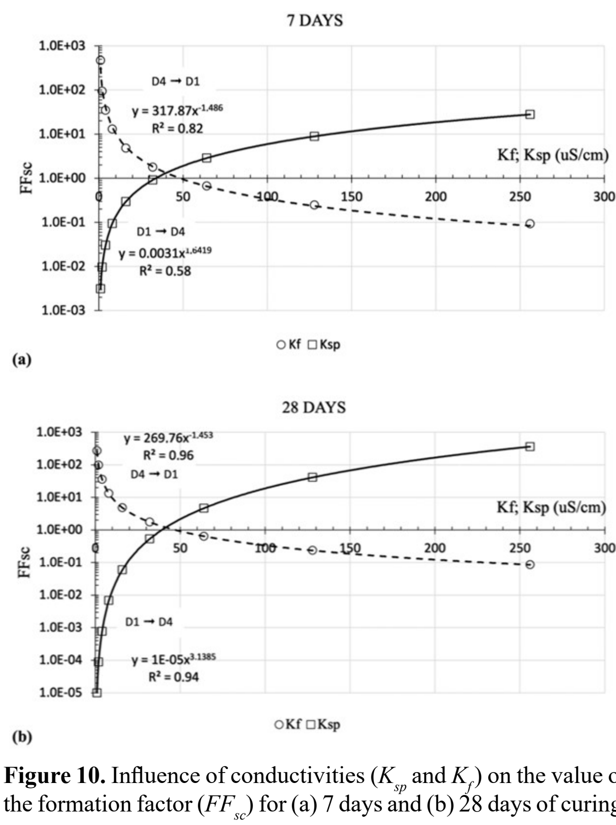

Figure 10. Influence of conductivities (K_{sp} and K_f) on the value of the formation factor (FF_{sc}) for (a) 7 days and (b) 28 days of curing.

FF_{sc} value. The conductivity of the solid sample is lower for higher cement contents and higher for low contents (D4→D1). Thus, the FF_{sc} increases when the conductivity of the solid decreases. On the other hand, the conductivity of the pore solution is lower for lower cement contents and higher for high cement contents (D1→D4). Therefore, the FF_{sc} increases when the conductivity of the pore solution is increased.

However, FF_{sc} is more sensitive to K_{sp} than to K_f: when K_f increases by a ratio of two (2), FF_{sc} decreases by a ratio close to three (3) times or 37%; when K_{sp} increases in the same proportion, the FF_{sc} increases in the rate of ten (10) times on average, or 1000%. This fact is certainly related to the lower resistance of the liquid medium to the passage of electric current, and also to the method used to obtain K_{sp} from the leaching test, as discussed above. The FF_{sc} will be unitary when the conductivities of the solution and the solid are equal. For the studied soil, this occurred for the value of 45 µS/cm, as can be seen in Figure 10.

3.6 Influence of open porosity on the FF_{sc}

FF_{sc} is inversely proportional to the open porosity (Figure 11), represented here by the absorption of water, in compliance with Archie's Law. The only exception was observed in sample D4 at 7 days.

The results show small variations in open porosity for increases in cement content. These variations are more consistent when the mold density is increased, except for the D4 sample. Considering only samples with 28 days of curing, the minimum open porosity achieved for the soil-cement in this study was close to 20% (D2G4), and the maximum close to 32% (D1G1). The FF_{sc} is close to 5 for samples D1G4, 17 for D2G4 e reaches 150 in samples D4G4, indicating the influence of cement content on this factor.

It seems that the cementation coefficients (m) tend to stabilize for cement contents above 10%. This occurred with the samples with 7 and 28 days, demonstrating an independence of curing time from that dose onwards. The cement content influences the FF_{sc} due to the hydration products, and its value varies if there are hydration reactions taking place, as indicated by the results (Figure 8). However, the increase

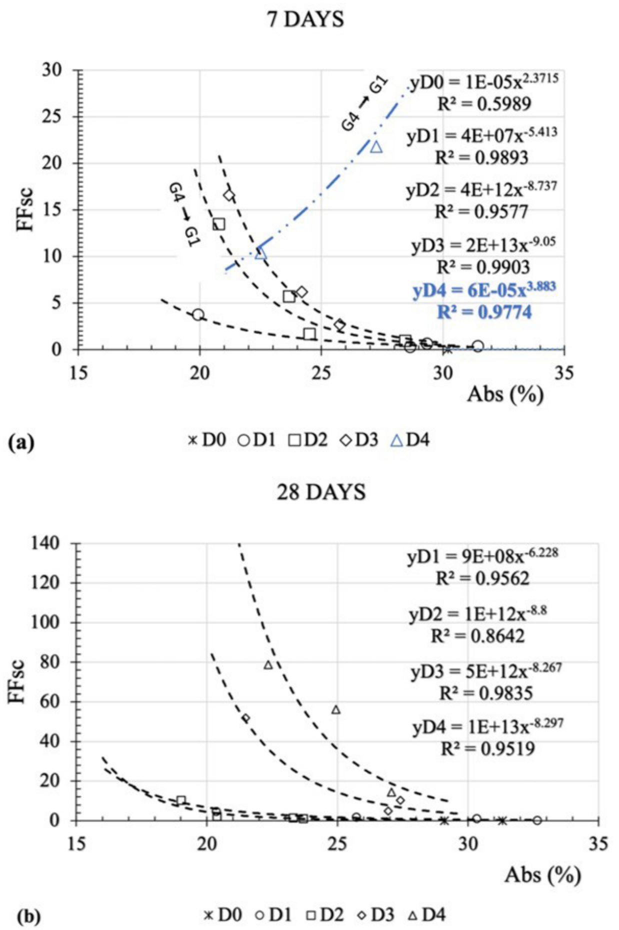

Figure 11. Influence of open porosity (*Abs*) on the soil-cement FF_{sc} for (a) 7 days and (b) 28 days of curing.

in cement content does not represent a reduction in open porosity, in general. This will also depend on the mold density, as exemplified in Table 2.

The value of the cementation coefficient was close to 8 for the samples D3 and D4, being close to 9 and 6 for samples D2 and D1, respectively. These values for *m* constant are similar to those found for soil-cement mixtures (Backe et al., 2001) and hardened mortars (Garboczi, 1990; Christensen et al., 1994; Backe et al., 2001) and sand-cement mixtures (Cardoso, 2016), higher than the values found for soils and rocks (between 1 and 3, if Archie´s law is used). An acceptable explanation given by Christensen et al. (1994) for such high value is that the pore structure of cement slurries is much more tortuous and less porous than that of rocks. Similar explanation was given by Bryant & Pallatt (1996) in the interpretation of the results found for very low-porosity rocks.

The other constant in Archie's equation (*A*) represents a volumetric factor and its value has an extensive range of variations attributed to a series of intervening factors (Worthington, 1993). For the soil-cement samples in this study, this coefficient did not show significant variations for samples above 10%. The values

Table 2. Variation of open porosity (*Abs*) with cement content for the samples G3 and G4.

	Abs (%)	
	7 days	28 days
D1G3	29.4	25.7
D2G3	23.7	20.4
D3G3	24.2	21.0
D4G3	22.5	21.5
D1G4	19.9	20.4
D2G4	20.8	19.0
D3G4	21.2	21.5
D4G4	20.8	21.0

were very high, in the order of magnitude of 10^{12}, indicating that the FF_{sc} tends to infinity when porosity tends to zero. On the other hand, experimental data reveal the tendency of the curve to tangent the porosity axis. It means that when it reaches its maximum value, the FF_{sc} value reaches zero, theoretically.

4. *FFsc* and UCS

4.1 Influence of the soil-cement formation factor on UCS

The relation between the UCS of the soil-cement mixtures and the Formation Factor is presented in Figure 12. The samples dosed with 20% of cement (D4) were excluded from the analysis, due to the deviations presented by the FF_{sc} in the samples with 7 days of curing. Although this dispersion was minimized in the 28-day samples, as previously mentioned. UCS increases linearly with FF_{sc}, which in turn increases with cement content (D1→D4) and molding density (G1→G4), as shown in Figure 12.

The logarithmic scale was adopted to favor the visualization of the trend curves, with indicate good linear relations between the variables. A good fitting is also found if all samples are considered in a unique relationship (Figures 12b and 12d), with angular and linear coefficients with values of 0.08 and 0.11 for curing of 7 days, and 0.02 and 0.53 for curing of 28 days.

Considering that the FF_{sc} is lower for the largest porosities (Figure 11), then the UCS will be higher for higher values of FF_{sc}, as expected due to this mechanical property of the material. Note that there is also a progression of strength in relation to the cement dosage, which can be verified on the right part of the plot (Figures 12a and 12c).

The FF_{sc} is a parameter obtained after curing the soil-cement in saturation condition and should not vary for periods over 28 days. So, it can be an alternative to control this material strength after its production, in addition to the usual way that relates strength to the design parameters (GC). Nevertheless, it is best to consider each dosage to minimize error, as discussed next.

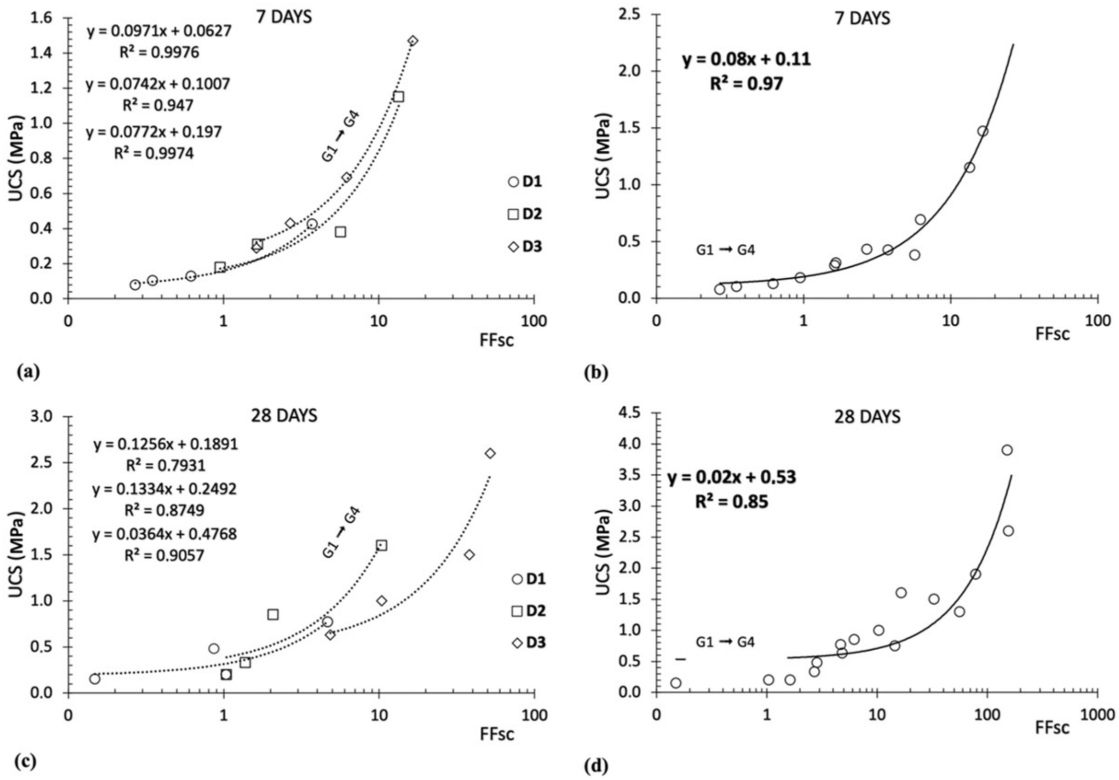

Figure 12. Relation between FF_{sc} and UCS for: (a) 7 days for each cement content; (b) 7 days for any content; (c) 28 days for each cement content; (d) 28 days for any content.

Considering the soil characteristics and the manual molding conditions adopted in this study, the unconfined compression strength reached minimum values (2 MPa) only at the curing time of 28 days, for samples molded close to dry density of 1.7 (G4) and cement content equal to or above 15% (D3 and D4).

The equation in Figure 12b indicates that to obtain a minimum value of UCS = 2 MPa at 7 days, the FF_{sc} should be close to 24 or greater. Thus, by the graph of Figure 10, it is possible to know which value of electrical conductivity of the solid and of the solution must be obtained in the measurements. Applying the equation, the values found are, respectively, 5 µS/cm and 113 µS/cm, approximately.

4.2 Influence of design parameters on soil-cement UCS

The values of soil-cement UCS can be mathematically related with the cement contents, as it is usually done for mortars and concrete. This is presented in Figure 13. In this figure it is also shown that there is a direct relationship between the soil-cement UCS and its molding density.

The slope of the regression line corresponds to an increase in the UCS when dry density and cement content increase. Regarding the constant cement content (C), the UCS grows vertically with the dry mold density. The small slope of the correlation line is due to the cement content that was increased with the density. On the other hand, for constant molding density (G), the UCS values also increase vertically with dosage. Relationships such as these are useful to quantify UCS using this non-destructive technique.

From the plots in Figure 13, the UCS is obtained for any combination of cement consumption (C) and mold density (G) for the cement-stabilized soil. Table 3 presents the calculations obtained for a UCS = 2 MPa, including the control parameters, confirming that high dry densities are required in molding for low cement contents. It seems relevant to remember that more unfavorable conditions were adopted in this study, such as manual compaction, immediate demolding and curing in a wet chamber.

The calculations show the possible combinations in dosing parameters to achieve the desired strength, both at 7 and 28 days. In some cases, it is still necessary to meet a water absorption requirement at 7 days of curing, which is 20% on average. Thus, the most economical dosage in this context would be for a cement consumption of 337.3 kg/m^3 and molding density of 2059.2 kg/m^3. However, this density would not be obtained manually.

The calculations also indicate the variation of FF_{sc} as a function of curing time. This factor was calculated based on the good general relations shown in Figure 12. Therefore, it is constant for all combinations. The volumetric constant

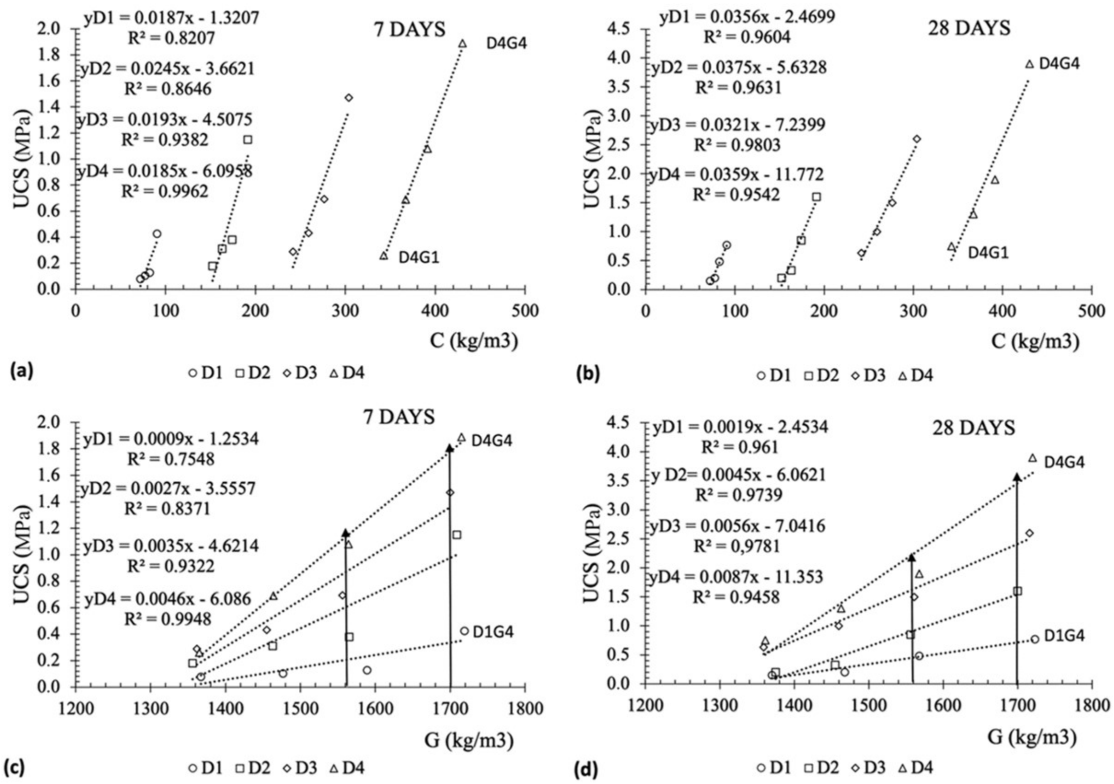

Figure 13. Influence of cement content on soil-cement UCS for: (a) 7 days and (b) 28 days. Influence of the dry density on soil-cement UCS for: (c) 7 days and (d) 28 days.

Table 3. Results of dosing and control parameters for UCS = 2 MPa.

D (kg/m³)	G (kg/m³)	*Abs* (%)	K_{sp} (µS/cm)	K_f (µS/cm)	FF_{sc} (min)	*A*	*m*
7 days							
177.5	3611.0	13.8					9.3
231.0	2059.2	19.0	210	6	24	1E+12	8.3
337.3	1891.4	20.5					8.0
437.8	1758.7	28.0					7.3
28 days							
125.6	2342.1	16.8					8.7
203.5	1791.1	16.6	102	6	20	1E+12	8.7
163.2	1614.3	23.9					7.8
383.6	1534.8	25.3					7.7

(*A*) of Archie's Law was also considered constant for all sample combinations because it is "volumetric factor" with a value of a high order of magnitude. Small variations in the "cementation coefficient" (*m*) can be observed for each variation in dosage. Also, this coefficient tends to stabilize at the end of the "formation" of the definitive structure of the material at 28 days of curing.

The K_f values were obtained from the equations in Figure 10 and they presented a constant value along curing time. The K_{sp} value was calculated from this conductivity and the FF_{sc}. Thus, minimum values were obtained for this variable and equations with poor correlation coefficients were avoided, as seen in Figure 10a.

5. Conclusions

A methodology is proposed to evaluate the UCS of compacted soil-cement mixtures by using a non-destructive technique, in which the electrical conductivity of the material and that of the fluid from a leaching test are measured to compute the parameter FF_{sc}. This Formation Factor of the soil-cement varies for each combination of dosage/dry density. These parameters contribute to the variations in the electrical conductivity of the material (K_f) and of the pore solution (K_{sp}). This last measure increases with increasing cement content, and the second decreases. However, FF_{sc} is more sensitive to K_{sp} than to K_f, in a proportion 5 times greater. Curing time concurs to reduce electrical conductivity of the solid sample (K_f) and, therefore, the higher it is, the greater is the FF_{sc}. The cement content influences the FF_{sc} from the porous network formed with the hydration products, and its value varies as long as there are hydration reactions taking place. However, the increase in cement content does not represent a reduction in open porosity in general. This will also depend on the mold density.

The cementation coefficient is not constant for the material up to 7 days of curing, but it seems to stabilize at 28 days. At this age, the value of the cementation coefficient was close to 8 for the samples D3 and D4, and close to 9 and 6 for the samples D2 and D1, respectively. The same occurred to the volumetric factor (A), whose values were very high, in the order of magnitude of 10^{12} on average. Therefore, the higher the FF_{sc} of the soil-cement, the higher its UCS. It was seen that UCS increases with both mold density and cement content.

Therefore, it is possible to design the material quality control parameters of the soil-cement and, consequently, the dosage parameters to obtain a specific UCS using the methodological conditions proposed by this study.

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Declaration of interest

The authors have no conflicts of interests that could inappropriately bias this work. There is no financial interest to report.

Authors´ contributions

João Marcos Vaillant: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, visualization, writing. Rafaela Cardoso: resources, supervision, validation, writing.

List of symbols

m	cementation coefficient of the Archie's Law
A	volumetric coefficient of the Archie's Law
Abs	water absorption or open porosity
C	cement content in kg/m^3
CL	clay low
D	cement content in percentage
FF	Archie's Formation Factor for conductivity
FF_{sc}	Apparent Factor Formation for soil-cement
G	molding dry volumetric weight (kN/m^3)
K_0	electrical conductivity of saturated material
K_f	electrical conductivity of soil-cement saturated after curing
K_{sp}	electrical conductivity of soil-cement pore solution
K_w	electrical conductivity of material pore solution
UCS	unconfined compression strength of the soil
ϕ	porosity of the material

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