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The effect of pH and electrical conductivity of the soaking fluid on the collapse of a silty clay

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Article

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Abstract

Different fluids can permeate the soil collapsing at various levels of severity depending on their physicochemical characteristics. This work evaluated the effect of pH and electrical conductivity (EC_f) of different soaking fluids on the collapsible behavior of a lateritic silty clay. Double and single oedometer tests were performed using four chemically distinct soaking fluids (water, leachate and two laboratory solutions, one alkaline and one acid). The collapse index (I) was evaluated according to two criteria. In addition, physical-chemical analysis of the soil and measurements of pH and EC_f were done. According to the results, the soil is collapsible for the four soaking fluids. No single relationship was found between fluid pH and collapse index, although, the highest values of collapse index were found in the tests soaked with alkaline and acid solutions. Finally, a unique direct relationship was found between the collapse index and the EC_f, that is, the higher this parameter, the higher the collapse index value.

1. Introduction

Leaks in reservoirs and pipes of industrial or domestic effluents can contaminate soils and groundwater. The environmental bias for this context is widely studied. However, the geotechnical implications of these occurrences are sometimes neglected, even though it is known the chemical characteristics of these substances influence the tension versus deformation behavior, due to the interaction between liquid and soil (Mitchell, 1976; Carvalho et al., 1987; Chen et al., 2000; Rodrigues et al., 2010; Futai et al., 2015).

According to Oliveira (2002), who studied the soil of the city of Ilha Solteira, in the state of São Paulo, Brazil, one third of the soil collapse cases occur due to domestic sewage leakage. Réthati (1961) analyzed 57 landfill collapse occurrences in Hungary and identified that the fluids causing such volume reductions were: sewage pipe breakdown (36% of cases), rainwater from the roof (25%), surface water (15%), break in supply line tubes (10%), reflux due to sewage clogging (8%), and processed water (5%).

Soil collapse is the abrupt reduction of volume due to saturation increase, with or without additional load application (Dudley, 1970; Jennings & Knight, 1975; Rezaei et al., 2012). The collapsible soils are characterized by high porosity ($\eta >$ 40%) and low saturation degree ($Sr < 60\%$), resulting in a metastable structure (Feda, 1966; Mariz & Casanova, 1994).

The collapsible condition can occur when the soil has at least one of the following characteristics (Larionov, 1965; Dudley, 1970; Barden et al., 1973):

a) Open, partially saturated and potentially unstable structure, susceptible to volume reductions;

b) High suction value or presence of cementing agents that stabilize the structure;

c) High stress state.

The chemical cementing agents, such as iron or aluminum oxides and carbonates, help to structure the particles. These bonds tend to disappear by chemical attack of certain soaking fluids (Agnelli & Albiero, 1997; Garcia et al., 2004; Gutierrez et al., 2008; Collares & Vilar, 2017).

In general, parameters such as alkaline and acid pH as well as high electrical conductivity, can potentiate the occurrence of the collapse phenomenon, in case the ions present in the solution generate greater structure disaggregation (Reginatto & Ferrero, 1973; Carvalho et al., 1987; Fang, 1997; Olgun & Yildiz, 2010; Motta & Ferreira, 2013; Koupai et al., 2020). Sodium-rich liquids, for example, act as dispersants

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breaking the cementitious bonds, increasing the magnitude of the collapse (Abdullah et al., 1997; Rodrigues & Lollo, 2007; Conciani & Barbosa, 2013; Motta & Ferreira, 2013; Collares & Vilar, 2017).

The Gouy-Chapman Diffuse Double Layer (DDL) theory can also help to explain compressible soil behavior due to percolation of different fluids (Mitchell, 1976; Van Olphen, 1991). According to this theory, the presence of higher valence ions in the soil solution causes greater reductions in DDL thickness, reducing soil compressibility. (Sridharan et al., 1986; Sposito, 2008; Meurer, 2004).

The present work aims to evaluate the collapsible behavior of a laterite silty clay through double and single oedometer tests using different soaking fluids (water, leachate, alkaline solution and acid solution), in order to find a relation between collapse index, pH and electrical conductivity of these liquids.

2. Materials and methods

2.1 Materials

2.1.1 Soil

The study was accomplished using soil from the Experimental Campus of Geotechnical Engineering (ECGE) surface layer of the State University of Londrina, latitude 23º19.6'S, longitude 51º12.1'W, altitude of 585.7 m under subtropical climate. Originated from basalt, it is a highly weathered soil, where the clay fraction is composed of 1:1 silicate minerals, such as kaolinite, hematite and gibbsite, and also amounts of Fe, Al and Mn oxides and hydroxides, belonging to the rocky basement located in the Third Parana Plateau (Gonçalves et al., 2018). The surface soil on the city of Londrina (up to 2 m) is denominated as a Dystrophic Purple Latosol, characterized as lateritic porous silty clay, with void ratio close to 2, solid specific gravity around 30 kN/m^3 and micro aggregation with collapsible potential (Teixeira et al., 2008; Teixeira et al., 2010; Teixeira et al., 2016; Gonçalves et al., 2018). According to the same authors, this high solid specific gravity is due to the intense presence of iron in the soil constitution, originated from basalt rocky basement. In addition, the soil composition carries no sodium content (Melo et al., 2019; Melo et al., 2020).

2.1.2 Soaking fluids

In order to evaluate how soaking fluids influence on soil collapse, four liquids were used: water (pH 7.2), leachate (pH 8.4), alkaline solution (pH 12) and acid solution (pH 2.4). For the two latter, a solution of sodium hexametaphosphate – $(NaPO_3)_6$ (pH = 5.7) – was used as base in the proportion of 45.7 g of salt to 1 liter of distilled water. For the alkaline solution, 10.3 ml of sodium hydroxide (NaOH (6N)) was added in 500 ml of the solution of $(NaPO_3)_6$ until pH = 12 was reached. For the acid solution, 1.8 ml of phosphoric acid (H_3PO_4) was added in 500 ml of solution of $(NaPO_3)_6$ until pH = 2.4 was reached. Alkaline and acid solutions, for instance, are respectively similar to those found in detergents and effluents from food industries.

The leachate came from the former disposing of Londrina urban solid waste, currently deactivated. It is in the methanogenic phase (Felici et al., 2013), with high levels of alkalinity and ammoniacal nitrogen (5,900.2 mg $CaCO_3.L^{-1}$ and 1,048.4 mg $N\text{-}NH_3.L^{-1}$, respectively) and low BOD/COD ratio (0.05).

2.2 Methods

2.2.1 Physical-chemical analysis of soil and soaking fluids

For the soil physical-chemical characterization, deformed samples were collected at 2 m depth in the ECGE, as recommended by NBR 9604-86 standard (ABNT, 1986b) and prepared according to NBR 6457-86 standard (ABNT, 1986a). Two portions of 50 g each were submitted to physical-chemical analysis according to the methodology described in the Manual of Soil Analysis Methods (Teixeira et al., 1997). Phosphorus (P), calcium (Ca), magnesium (Mg), potassium (K) and aluminum (Al) contents, as well as pH (H_2O), pH (KCl), ΔpH and cation exchange capacity (CEC) were determined.

The electrical conductivity for the soaking fluids was determined in accordance with the methodology described by Rice et al. (2005). The equipment was calibrated with the HI 7031 standard (KCl 0.1g.L – 1,413 μS.cm^{-1}). Lastly, the fluid electrical conductivity was taken as the average value of three direct readings.

2.2.2 Oedometer tests

For the soil collapse index evaluation, double and single oedometer tests were performed in undisturbed samples, also collected at ECGE at 2 m depth. The procedure was performed according to the method D2435-11 (ASTM, 2011) with the aid of a unidirectional press. The loading stages, with 24 hours duration each, were taken at 6, 12, 25, 50, 100, 200 and 400 kPa. The readings intervals were 8, 15 and 30 seconds, then, 1, 2, 4, 8, 15 and 30 minutes, and ultimately, 1, 2, 4, 8 and 24 hours. There were three unloading stages (200, 100 and 6 kPa) at the same time intervals for the previous readings, however, lasting 2 hours each. The specimens tested were carved in a metal ring, with diameter of 8 cm and height of 3.2 cm.

In the double oedometer tests two specimens were tested, one in the field natural moisture content, and the other soaked since the very beginning of the test. Therefore, it was possible to predict the collapse index (I) for the intended stress values, i.e., 25, 50 and 100 kPa, as from the difference between the curves through the Equation 1, according to

Jennings & Knight (1957), reformulated by Gutierrez (2005) to adapt the parameters to normalized curves:

$$\boldsymbol{I} = \frac{\Delta \boldsymbol{e_c}}{\left[1 + \left(\dfrac{\boldsymbol{e_{nat}}}{\boldsymbol{e}_{0(\boldsymbol{nat})}}\right) * \boldsymbol{e}_{0(\boldsymbol{aver})}\right]} * 100\% \tag{1}$$

Where:

$$\Delta e_c = \left[\left(\frac{e_{nat}}{e_{0(nat)}}\right) - \left(\frac{e_{soak}}{e_{0(soak)}}\right)\right] * e_{0(aver)} \tag{2}$$

$$e_{0(aver)} = \frac{e_{0(nat)} + e_{0(soak)}}{2} \tag{3}$$

In the single oedometer tests, each specimen was subjected to loading stages up to an interest stress, and maintaining the field moisture content. After stabilization of stress deformations, the chamber was filled with fluid, and a new loading stage was applied only 24 hours after soaking. The stress values of 25, 50 and 100 kPa were adopted for the soaking stages.

The collapse index values for each soaking stress can be found from the curves through the Equation 4, according to Jennings & Knight (1975):

$$\boldsymbol{I} = \frac{\Delta \boldsymbol{e_c}}{1 + \boldsymbol{e_b}} * 100\% \tag{4}$$

Where:

$$\Delta e_c = e_b - e_a \tag{5}$$

From the collapse index values, for both double and single tests, the soil was analyzed taking into account two criteria: one presented by the standard D533-03 (ASTM, 2003) and another showed by Jennings & Knight (1975). Both criteria classifies the soil according to its collapse severity, as it can be seen in Table 1.

3. Results and discussions

3.1 Characterization of soil and soaking fluids

Table 2 presents the soil chemical analysis run before and after the oedometer tests. The pH values obtained for the natural soil through both H_2O and KCl solutions were low, indicating acidity. This condition, when associated with low sodium content, favors the formation of a flocculated structure (Agnelli & Albiero, 1997; Garcia et al., 2004; Rodrigues & Lollo, 2007; Rodrigues et al., 2010), typical of potentially collapsible soils. The observed difference between pH values in water and in potassium chloride indicates the presence of negative charges on the soil surface (Mendonça et al., 2002).

Phosphorus is the main chemical compound used to prepare alkaline and acid solutions, and its content went through a substantial increase after the oedometer tests. According to Sposito (2008), the specific adsorption of phosphorus by the soil tends to decrease positive active sites available on its

Table 1. Classification of the collapse index by its severity (Jennings & Knight, 1975; ASTM, 2003).

Jennings & Knight (1975)		D5333-03 (ASTM, 2003)	
I	Severity of the problem	*I*	Severity of the problem
0 – 1%	None	0%	None
1 – 5%	Moderate	0.1 – 2%	Slight
5 – 10%	Problematic	2.1 – 6%	Moderate
10 – 20%	Serious	6.1 – 10%	Moderately Severe
> 20%	Very Serious	> 10%	Severe

Table 2. Parameters of chemical analysis of the soil.

Parameters	Before the Test	After the Test			
	Natural	Soaked with Water	Soaked with Leachate	Soaked with Alkaline Solution	Soaked with Acid Solution
pH (H_2O)	5.10	4.50	4.40	6.60	6.00
pH (KCl)	4.40	4.50	4.50	4.80	4.40
ΔpH*	-0.70	0.00	0.10	-2.20	-1.60
P (mg/dm^3)	1.85	2.75	2.55	771.85	2327.25
Al^{3+} ($cmol_c/dm^3$)	0.12	0.19	0.07	0.14	1.06
H+Al ($cmol_c/dm^3$)	5.76	5.34	5.34	7.20	10.45
Ca^{2+} ($cmol_c/dm^3$)	0.79	0.57	0.91	0.35	0.25
Mg^{2+} ($cmol_c/dm^3$)	0.18	0.16	0.76	0.20	0.20
K^+ ($cmol_c/dm^3$)	0.12	0.06	2.50	0.10	0.10
CEC ($cmol_c/dm^3$)	6.84	6.13	9.51	7.85	11.00

Note: ΔpH = pH (KCl) – pH (H_2O)

surface, which justifies the pH (H_2O) increase and consequent decrease of ΔpH for soils soaked with such fluids.

The CEC value found for natural soil was characteristic of lateritic soils (less than 17 $cmol_c/dm^3$) (Agnelli & Albiero, 1997; Meurer, 2004). The observed increase on this parameter for the soils soaked with leachate and alkaline and acid solutions, can be partially explained by the addition of ions to the soil solution (Sposito, 2008; Meurer, 2004). In the sample soaked with leachate, exchangeable bases – calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^+) – could be retained more expressively on the soil surface, which explains a substantial increase in CEC, as well as observed by Frempong & Yanful (2006) and Teixeira et al. (2010). In the samples soaked with alkaline and acid solutions, the retention of phosphorus anion (P) was significant, contributing to increase the CEC value.

According to Collares (2002), the reactions between soil particles and soaking fluid occur due to colloidal instability under the influence of some liquid characteristics, such as electrolyte concentration, pH and temperature. Soil pH and CEC vary when exposed to such fluids, interfering on the collapse potential.

As for the soaking fluids characterization, it was observed that the solutions prepared in the laboratory presented the highest values of electrical conductivity, according to Table 3, indicating that these liquids have a higher amount of soluble ions in their composition (Sposito, 2008).

3.2 Oedometer tests

Tables 4 and 5 show the properties and statistical study for the specimens before and after the double and single oedometer tests, respectively.

Table 3. Electrical conductivity of soaking fluids.

Soaking Fluid	EC_f ($\mu S.cm^{-1}$)
Water	0.07642 x 10^3
Leachate	4.910 x 10^3
Alkaline Solution	15.20 x 10^3
Acid Solution	23.10 x 10^3

In general, according to the coefficient of variation values (CV), the specimens were similar to each other. Since undisturbed samples were collected in different days and climatic conditions, high CV values were obtained for the initial moisture content and degree of saturation. The observed variability for the void ratio after the tests can be justified by the different physical-chemical interactions between the different fluids and the soil. Finally, the saturation degree values after the soaked tests were close or equal to 100%, indicating that the specimens reached the maximum saturation.

3.2.1 Double oedometer tests

Figure 1 shows the normalized curves resulting from the double tests for the four soaking fluids.

From Equation 1 and the data displayed in Table 6, it was possible to predict the collapse indexes and to classify them according to the criteria of Jennings & Knight (1975) and ASTM (2003), as shown in Table 7.

The highest collapse index values were noticed in soakings by alkaline and acid solutions. This can be explained through the high sodium content in the composition of these liquids, since the cation of sodium acts as a dispersant in soils with flocculated structure, rearranging the colloidal particles (Abdullah et al., 1997; Agnelli & Albiero, 1997; Garcia et al., 2004; Rodrigues et al., 2010; Futai et al., 2015). Due to these reasons, it is also highlighted the fact that, even for the soaking stress of 25 kPa, below the pre-consolidation stress of this saturated soil, the collapse was quite pronounced when the soil was soaked with these two liquids.

In relation to soakings with leachate and water, it was observed lower collapse indexes when compared to soakings with alkaline and acid solutions, considered as sodium-based dispersants. This behavior corroborates the results obtained by Collares & Vilar (2017). Oztoprak & Pisirici (2011) affirmed that leachate-permeated soil voids can be clogged by suspended solids present in the liquid, decreasing compressibility, which could be observed in this work, once the lowest collapse indexes, in general, were found for soaked samples with such fluid.

Table 4. Specimens properties before and after the double tests.

Condition	Moisture Content (%)		Dry Density (kN/m³)		Void Ratio		Degree of Saturation (%)	
	Before	After	Before	After	Before	After	Before	After
No Soaking	28.3	22.1	9.5	10.8	2.15	1.77	39.6	37.4
Soaked with Water	28.4	42.5	10.1	14.9	1.98	0.99	43.2	100.0
Soaked with Leachate	31.6	38.9	12.5	18.9	2.16	1.19	43.8	97.9
Soaked with Alkaline Solution	20.7	30.9	11.0	17.3	1.73	0.75	35.9	100.0
Soaked with Acid Solution	20.7	28.8	10.0	17.0	2.00	0.86	31.1	100.0
Average	25.3	35.3	10.9	17.0	2.0	0.9	38.5	99.5
Standard Deviation	5.5	6.5	1.2	1.6	0.2	0.2	6.1	1.0
CV (%)	21.9	18.4	10.6	9.7	9.0	20.0	16.0	1.0

Note: Average, Standard Deviation and CV only for the soaked specimens.

Table 5. Specimens properties before and after the single tests.

Condition Before		Moisture Content (%)		Dry Density (kN/m³)		Void Ratio		Degree of Saturation (%)	
		After	Before	After	Before	After	Before	After	
Soaked with Water	Soaked at 25 kPa	35.9	37.2	10.2	13.3	1.95	1.24	55.3	90.2
	Soaked at 50 kPa	31.0	37.1	9.6	13.4	2.13	1.23	43.8	90.1
	Soaked at 100 kPa	31.4	38.6	10.0	14.6	1.99	1.02	47.3	100.0
Soaked with Leachate	Soaked at 25 kPa	30.9	37.6	10.4	14.0	1.88	1.10	49.4	100.0
	Soaked at 50 kPa	29.5	38.9	11.1	14.9	1.69	0.97	52.2	100.0
	Soaked at 100 kPa	32.1	40.5	10.3	14.5	1.92	1.06	50.1	100.0
Soaked with Alkaline Solution	Soaked at 25 kPa	18.1	34.2	10.2	15.5	1.93	0.91	29.2	100.0
	Soaked at 50 kPa	20.2	32.8	10.3	16.6	1.91	0.90	31.7	100.0
	Soaked at 100 kPa	20.8	31.2	10.0	15.7	2.00	0.93	31.3	100.0
Soaked with Acid Solution	Soaked at 25 kPa	21.0	33.8	10.0	18.4	2.00	0.64	31.5	100.0
	Soaked at 50 kPa	20.1	34.6	9.9	16.4	2.03	0.87	29.8	100.0
	Soaked at 100 kPa	32.1	40.5	10.3	14.5	1.92	1.06	50.1	100.0
Average		26.9	36.4	10.2	15.2	1.9	1.0	41.8	98.4
Standard Deviation		6.3	3.0	0.4	1.5	0.1	0.2	10.2	3.8
CV (%)		23.3	8.3	3.6	9.7	5.4	16.6	24.4	3.9

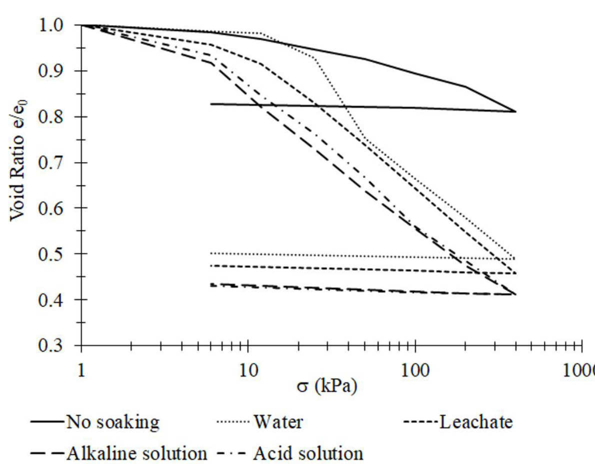

Figure 1. Normalized curves of the double oedometer tests.

3.2.2 Single oedometer tests

Figure 2 below shows the curves obtained from the single oedometer tests for soaking under the stress values of 25, 50 and 100 kPa for the four fluids.

From Equation 4 and the data contained in Table 8, it was possible to obtain the collapse indexes and classify them according to the criteria of Jennings & Knight (1975) and ASTM (2003), as shown in Table 9.

From Figure 2a and Table 9, it is possible to observe for the soaked tests with water that the collapse index was higher at 50 kPa of soaking stress. This is justified by the fact that this specimen has a higher void ratio (e = 2.13) than the test specimen soaked at 100 kPa (e = 1.99).

Vargas (1978) states that high values of void ratios indicate porous soil structure, favoring an increase of collapse magnitude. With the soaking the pore sizes decrease, which generates an abrupt volume reduction.

Regarding the remaining specimens soaked with leached and the alkaline and acid solutions, the observed behavior was the expected, where higher soaking stresses caused higher collapse rates, since the specimens presented similar physical characteristics (Dudley, 1970; Ferreira, 1995).

The highest collapse indexes occurred in the soaking with alkaline and acid solutions, being, in general, more significant in the second condition. The compositions of these liquids were rich in sodium, which contributed to the greater dispersion of the soil, thus, increasing the collapse

Table 6. Void ratios used to calculate the collapse index from double oedometer tests.

Stress of Interest (kPa)	No Soaking		Soaked with Water		Soaked with Leachate		Soaked with Alkaline Solution		Soaked with Acid Solution	
	$e_{0(nat)}$	e_{nat}	$e_{0(soak)}$	e_{soak}	$e_{0(soak)}$	e_{soak}	$e_{0(soak)}$	e_{soak}	$e_{0(soak)}$	e_{soak}
25	2.15	2.03	1.98	1.83	2.16	1.85	1.73	1.26	2.00	1.52
50		1.98		1.49		1.68		1.10		1.33
100		1.92		1.31		1.50		0.96		1.12

Table 7. Evaluation of collapse from double oedometer tests.

Conditions		Collapse Index - I (%)	Classification Criteria	
Soaking Fluid	Stress of Interest (kPa)		Jennings & Knight (1975)	ASTM (2003)
Water	25	1.40	Moderate	Slight
	50	11.98	Serious	Severe
	100	16.80	Serious	Severe
Leachate	25	6.23	Problematic	Moderately Severe
	50	10.34	Serious	Severe
	100	14.63	Serious	Severe
Alkaline Solution	25	14.79	Serious	Severe
	50	19.85	Serious	Severe
	100	24.01	Very Serious	Severe
Acid Solution	25	12.92	Serious	Severe
	50	18.24	Serious	Severe
	100	24.22	Very Serious	Severe

Table 8. Void ratios used to calculate the collapse index from single oedometer tests.

Soaking Stress (kPa)	Soaked with Water		Soaked with Leachate		Soaked with Alkaline Solution		Soaked with Acid Solution	
	e_b	e_a	e_b	e_a	e_b	e_a	e_b	e_a
25	1.90	1.85	1.81	1.72	1.88	1.51	1.96	1.53
50	2.08	1.87	1.58	1.42	1.86	1.42	1.96	1.43
100	1.69	1.57	1.74	1.41	1.91	1.32	1.79	1.25

Table 9. Evaluation of collapse from single oedometer tests.

Conditions		Collapse Index - I (%)	Classification Criteria	
Soaking Fluid	Soaking Stress (kPa)		Jennings & Knight (1975)	ASTM (2003)
Water	25	1.79	Moderate	Slight
	50	6.86	Problematic	Moderately Severe
	100	4.45	Moderate	Moderate
Leachate	25	3.34	Moderate	Moderate
	50	6.24	Problematic	Moderately Severe
	100	11.98	Serious	Severe
Alkaline Solution	25	12.66	Serious	Severe
	50	15.37	Serious	Severe
	100	20.23	Very Serious	Severe
Acid Solution	25	14.45	Serious	Severe
	50	17.77	Serious	Severe
	100	19.54	Serious	Severe

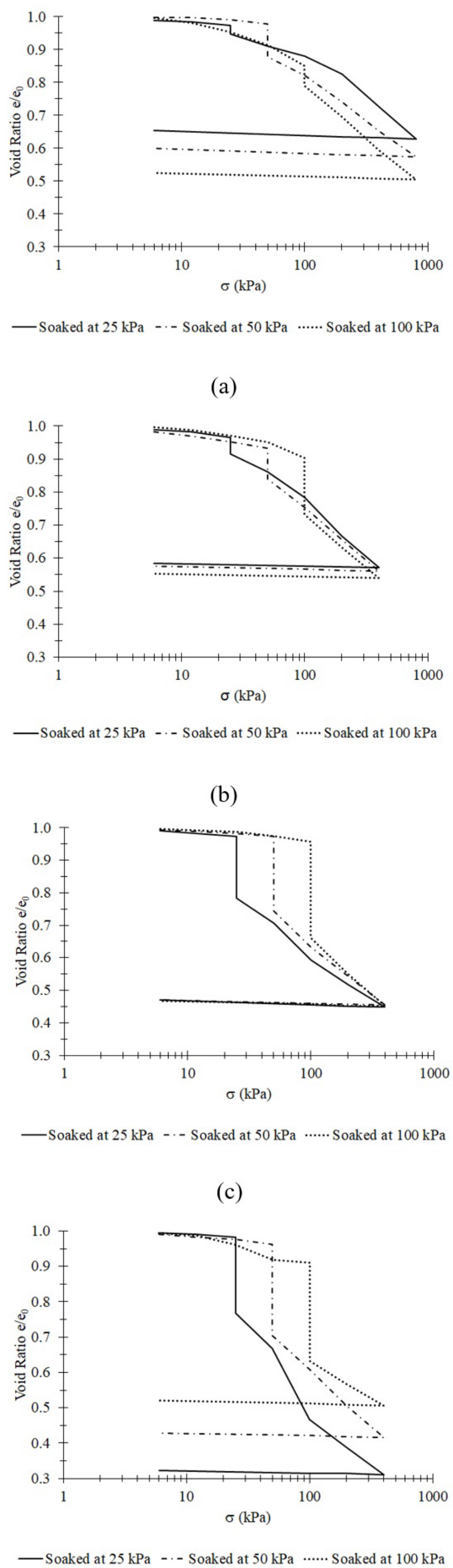

Figure 2. Curves of the single oedometer tests - (a) soaked with water, (b) soaked with leachate, (c) soaked with alkaline solution and (d) soaked with acid solution.

magnitude, even under stresses below that of pre-consolidation saturated, as previously seen in the double test results (Abdullah et al., 1997; Agnelli & Albiero, 1997; Garcia et al., 2004; Rodrigues et al., 2010; Futai et al., 2015).

3.3 Collapse index correlation with pH and electrical conductivity of the soaking fluids

The following Figure 3 shows the variation of (a) total collapse index – I_{total} (%) and (b) partial collapse index – $I_{partial}$ (%) related to pH and EC_f of the soaking fluids at 25, 50 and 100 kPa of soaking stresses (σ_{soak}) for the single oedometer tests. The total collapse index was obtained by the simple difference between the void indexes before and after the soaking for each liquid and soaking stress, according to Equation 4 and shown in Tables 8 and 9. The partial collapse index was obtained by the difference between the normalized final void index after soaking with water and the normalized final void index after soaking with leachate and alkaline and acid solutions, for each soaking stress.

As is already known, matric suction has an important role in the magnitude of soil collapse (Rao & Revanasiddappa, 2000; Jotisankasa et al., 2007; Vilar & Rodrigues, 2011; Benatti & Miguel, 2013; Li and Vanapalli, 2018), and each liquid influences this phenomenon differently. Since the suction analysis was not the focus of this paper, Figure 3b shows the collapse only due to the influence of the composition of the soaking fluid, since the void indexes considered were of the soil already saturated, with matric suction close to zero.

For the Figure 3a and regarding the pH, water and leachate had a proportional relationship, in general – the higher the pH, the higher the collapse index, whereas for the alkaline and acid solutions the relation was inversely proportional – the lower the pH, the higher the collapse index. There were small discrepancies on the collapses at 50 kPa of soaking stress for water and leachate, and at 100 kPa for alkaline and acid solutions. These differences can be explained by the initial void ratio values of the samples (e_0). For the specimen soaked with leachate, the e_0 was smaller (1.69) than that soaked with water (2.13); and for the sample soaked with the alkaline solution, the specimen had a higher value of e_0 (2.00) than the one soaked with the acid solution (1.92). These discrepancies for the alkaline and acid solutions are eliminated when analyzing Figure 3b, where the void indexes were normalized and the influence of the matric suction was almost zero.

This divergence of correlations corroborates the fact that pH alone cannot be an indicative parameter of the collapse behavior, which is, therefore, dependent on other characteristics, such as chemical composition, electrical conductivity and soil structure (Reginatto & Ferrero, 1973; Carvalho et al., 1987; Fang, 1997; Garcia et al., 2004; Olgun & Yildiz, 2010; Collares & Vilar, 2017; Choudhury & Bharat, 2018).

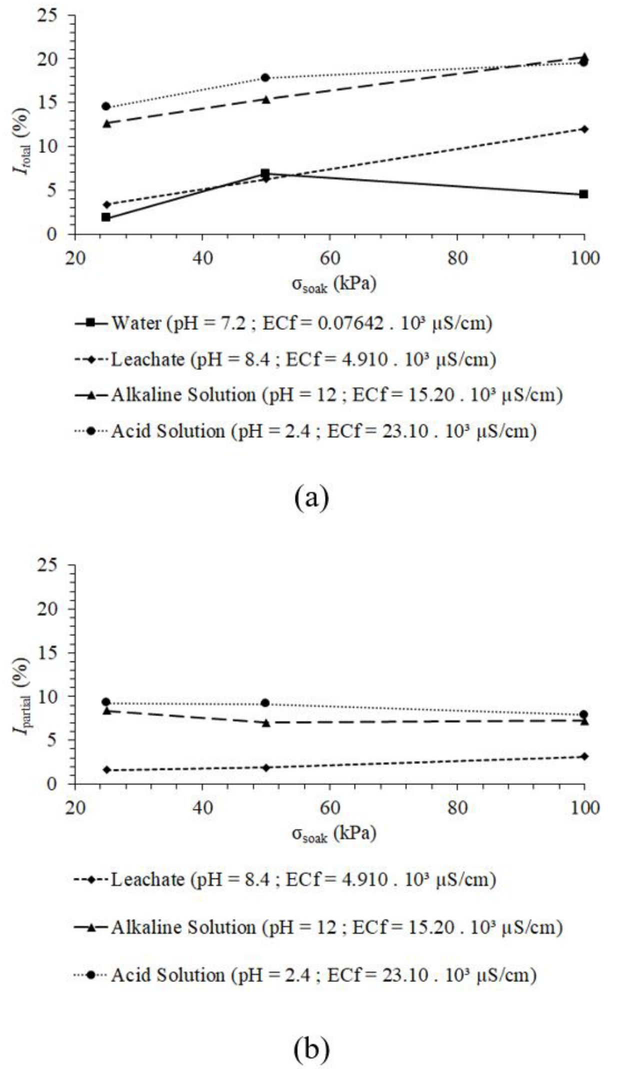

Figure 3. Correlation between (a) the total collapse index and (b) partial collapse index with pH and EC_f of the soaking fluids.

Still considering the trends observed, the soil soaked with the acid solution indicates a higher collapse index compared to the other three fluids, which is in agreement with Imai et al. (2006), Gratchev & Towhata (2011), Gratchev & Towhata (2016), Zhang et al. (2018), Khodabandeh et al. (2020) and Siddiqua et al. (2020), who affirmed that acid fluids could contribute to the dissolution of carbonates, one of those responsible for stabilizing the soil structure. Moreover, Wang & Siu (2006a) and Wang & Siu, (2006b) showed that, in an acidic environment, kaolinite – the main mineral of this soil – tends to form more open arrangements that might result in greater soil compressibility.

Sunil et al. (2006), Motta & Ferreira (2013) and Siddiqua et al. (2020) pointed out that alkaline solutions also tend to cause significant values of collapse index (I), a behavior verified in this study when comparing the alkaline solution with the water and the leachate, with lower pH. This shows that alkaline and acid solutions tend to cause higher collapse indexes when compared to liquids with pH close to neutrality.

In this study it was also observed a direct relationship between collapse index (I) and electrical conductivity (EC_f) that is, the higher the electrical conductivity, the higher the collapse index. According to Motta & Ferreira (2011) and Khan et al. (2017), liquids with higher electrical conductivities tend to cause greater collapses, since the higher this parameter, the greater the ions mobility induced in the soil.

In addition, the soaking with acid solution, whose EC_f value is the highest, presented the highest collapse index. According to Sridharan et al. (1986) and Van Olphen (1991), in acidic environments, H^+ ions tend to change positions with higher valence cations from the diffuse double layer of soil particles, leading to an increase in DDL thickness and, consequently, a higher soil compressibility.

Similar to the correlation with pH, the correlation with EC_f and I_{total} also indicated some divergences: for water at 50 kPa of soaking stress, and for acid solutions at 100 kPa. These differences can again be explained by the initial void ratio or matric suction values of the samples. However, when analyzing the $I_{partial}$ at Figure 3b, where the influence of the matric suction was practically canceled and the void indexes were normalized, it is noted that the divergences were eliminated, confirming the trend mentioned above: the higher the EC_f, the greater the collapse index of the soil.

4. Conclusions

It is concluded from this study that the evaluated soil presents collapsible behavior when soaked with the four fluids. The characteristics of such fluids interfere with the collapse magnitude. Sodium-rich liquids tend to be dispersive to soils, destroying the bonds between the particles and generating greater deformations.

In general, the higher the soaking stresses, the higher the collapse indexes (I). However, it is worth mentioning that this behavior depends on the porosity of the soil structure and the moisture and matric suction before the soaking.

It was not found a unique relationship between pH and collapse index, therefore, this characteristic is insufficient for a more accurate evaluation of the soil collapsible behavior. However, a tendency of alkaline and acid liquids to cause higher collapse indexes was found when compared to liquids with pH closer to neutrality.

Finally, the electrical conductivity of the fluid presented a unique and direct relationship with the collapse index. Hence, the greater the electrical conductivity of the fluid, the greater the collapse magnitude generated by the soaking.

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Declaration of interest

The authors guarantee that there are no conflicts of interest in this research.

Authors' contributions

Renan Zanin: data curation, formal analysis, investigation, visualization, writing – original draft, writing – review & editing. Ana Padilha: conceptualization, data curation, investigation. Flávia Pelaquim: data curation, formal analysis, writing – review & editing. Nelcí Gutierrez: data curation, writing – original draft. Raquel Teixeira: conceptualization, data curation, supervision, writing – original draft.

List of symbols

BOD	biological oxygen demand
COD	chemical oxygen demand
CV	coefficient of variation
EC_f	electrical conductivity of the soaking fluid
e_{nat}	final void index for applied stress of the double test without soaking
e_{soak}	final void index for applied stress of the double test with soaking
Δe_c	variation of the void index due to soaking
$e_{0(nat)}$	initial void index of the double test without soaking
$e_{0(soak)}$	initial void index of the double test with soaking
$e_{0(aver)}$	average initial void index of the double test with and without soaking
e_0	initial void index of the single test sample
e_b	void index before soaking of the single test
e_a	void index after soaking of the single test
I	collapse index
NBR	Brazilian Standard
Sr	degree of saturation
w	moisture content
η	porosity
σ	stress
σ_{soak}	soaking stress

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