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Effects of wetting and drying cycles on the swelling pressure and free swelling of expansive soil

Larissa da Silva Oliveira[1#], Erinaldo Hilário Cavalcante[1]

Article

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Expansive soil
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Free swelling

Abstract

The aim of the current study is to investigate the influence of consecutive wetting and drying cycles on the free swelling and swelling pressure properties of a potentially expansive soil. The investigated sample consisting of high-plasticity inorganic clay with high consistency-limit values and extremely high swelling potential. The adopted methodology comprised free swelling and swelling pressure tests – based on the post-swelling loading method, under 0.5 kPa overload. Both tests were conducted in a cyclic manner by implementing eight wetting and drying cycles. Results have shown that the wetting and drying cycles acted as agents influencing the swelling pressure and free swelling properties of the expansive soil. It was found that the expansive soil sample, when moistened and then dried to its initial moisture content, time and again, showed higher values of swelling pressure and free swelling at the first moistening cycle. It was also observed that the expansive soil sample decreases its expansive behavior as the number of wetting and drying cycles increases.

1. Introduction

Expansive soils are unsaturated soils with high volumetric instability. Their terminology is associated with their high ability to swell when they have free access to water, as well as to shrink when they lose moisture. Expansive soils present high fine particle and high plasticity. According to Ferreira (2007), their mineralogical composition comprises 2:1 clay minerals, such as montmorillonite and vermiculite. Soil swelling and shrinking process accounts for several pathologies observed in construction works performed on expansive soils, such as pillars out of plumb, cracks in walls, and breaks in slopes and road sidewalks (Cavalcante et al., 2006). Therefore, these features made them known as problematic soils, worldwide.

Expansive soils derive from igneous rocks (basalts, diabases and gabbros) presenting feldspar and pyroxene decomposition and montmorillonite formation, as well as from sedimentary rocks (shale and limestone) whose composition presents the clay mineral known as montmorillonite. Expansive soil layer depths can exceed six meters. These soils are often found in arid and semi-arid regions, where water evaporation rates exceed rainfall rates. Moreover, they swell and shrink in regular cycles in places with well-defined and alternate wet and dry seasons (Ferreira, 2007; Murthy, 2010).

Seasonal rainfall and temperature variations are the main factors for constant shrinking-swelling alternations observed in expansive soils, mainly in arid and semi-arid regions. High temperatures and lack of rainfall in summer can increase soil suction values and make it shrink. Expansive soils with high suction value tend to show high swelling values when they have contact with water, whether due to the rainy season or to anthropic factors.

According to Tripathy et al. (2002), wetting and drying cycles can reduce, or even increase, expansive soils' free swelling property by a factor of two, in comparison to the first swelling-shrinking cycle. Therefore, assessing soils' expansive behavior without taking into consideration cyclical seasonal fluctuations may lead to underestimated soil swelling potential and, consequently, to damage in structures built on these soil types.

According to Al-Taie et al. (2020), expansive soil samples recorded higher free swelling and swelling pressure values after the second wetting and drying cycle - their swelling degree has changed from "moderate" to "very high". Studies conducted by Tripathy & Rao (2009), Tripathy et al. (2002) and de Basma et al. (1996) also recorded similar results for expansive soil samples subjected to total swelling and shrinking cycles. On the other hand, Rao & Rao (2010) and Al-Homoud et al. (1995) have indicated that the investigated soil samples suffered fatigue at each cycle and this process resulted in lower free swelling and swelling pressure values.

Results recorded by Wei & Dong (2020) for swelling curves under different wetting and drying cycles have shown that the sample's vertical swelling displacement increased by 20% after the first wetting and drying cycle, as well as that it reduced as the number of cycles increased. The nuclear magnetic resonance-based analysis conducted by the

[#]Corresponding author. E-mail address: loliveira.engenharia@gmail.com
[1]Universidade Federal de Sergipe, Departamento de Engenharia Civil, São Cristóvão, SE, Brasil.

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aforementioned authors at microscale level has shown that micropores were converted into macropores due to loss of both fine and water-soluble cementing particles. Soil's free swelling decreased as the number of macrospores increased.

Thus, there are indications that constant wetting and drying cycles are directly accountable for changes in the free swelling and swelling pressure properties of expansive soils. Therefore, the aim of the current study was to investigate the effects of local seasonal temperature and humidity variations on the free swelling and swelling pressure properties of an expansive soil in Aracaju metropolitan region - SE.

2. Materials and methods

2.1 Geotechnical properties of the soil sample

The herein investigated soil was collected in Nossa Senhora do Socorro City, Aracaju metropolitan region, Sergipe State, Brazil. According to Embrapa (1975), red-yellow podzolic soil - which derives from Barreiras formation sediments - is the prevalent soil type in the investigated site. Climate in this region is tropical, hot and humid; it presents three-month dry period in summer, which is followed by the rainy season, from March to August. The temperature and humidity range observed in the locality is 22 °C to 35 °C and 3% to 97% respectively, with an average annual precipitation of approximately 1689 mm. These features make this region conducive to the incidence of expansive soils. The geographic coordinates of the collection point are 10°53'26.7" S and 37°07'01.5" W. Collected samples were of the deformed and non-deformed types; they were collected at approximately one meter down the ground.

The collected soil consisted of clay, presenting variegated color, i.e., without a predominant color. Its consistency was hard and had high plasticity. Its granulometry comprised 45.39% clay, 41.01% silt, 12.50% sand and 0.10% gravel. Soil sample properties are shown in Table 1. High values recorded for liquidity limits and plasticity index have classified the investigated soil as having very high swelling potential [Chen (1965), Seed et al. (1962) and Dakshanamurthy & Raman (1973) criteria].

The chemical characteristics of the soil sample are presented in Table 2.

The quantitative composition of the oxides present in the soil sample, obtained by X-ray fluorescence (XRF) assay, is presented in Table 3.

The soil sample studied has a mineralogical composition composed of clay minerals of 2:1 structure. The X-ray diffraction test diffractograms (XRD), Figure 1, indicate the presence of the clay minerals mica, smectite, montmorillonite and kaolinite.

2.2 Preparing the specimens

Specimens used in the free swelling and swelling pressure tests were molded into metallic rings, based on using non-deformed samples. Rings measuring 50 mm in diameter and 20 mm in height were used for the free swelling test. Rings measuring 70 mm in diameter and 20 mm in height were used for the swelling pressure test.

The used sample presented low moisture content and high rigidity, and it impaired specimens' preparation. Manual molding was not possible; thus, electric saws were used for molding purposes, as shown in Figure 2. A marble saw was initially used to cut the sample. Next, a grinder was used to reduce the sample to the size of the ring. Then, the final ring setting, finishing and surface smoothing process was carried out with the aid of knives and saw blades.

Table 1. Properties of soil.

Properties	Value	Unit	Norm
Specific gravity	2.679	-	DNER-ME 093/1994 (DNER, 1994b)
Moisture content	5.26	(%)	ABNT NBR 7181/2016 (ABNT, 2016c)
Clay (< 0.002 mm)	45.39	(%)	ABNT NBR 7181/2016 (ABNT, 2016c)
Silt (0.002 mm to 0.06 mm)	41.01	(%)	ABNT NBR 7181/2016 (ABNT, 2016c)
Sand (0.06 mm to 2 mm)	12.50	(%)	ABNT NBR 7181/2016 (ABNT, 2016c)
Gravel (> 2 mm)	0.10	(%)	ABNT NBR 7181/2016 (ABNT, 2016c)
Liquid limit	72	(%)	ABNT NBR 6459/2016 (ABNT, 2016a)
Plastic limit	26	(%)	ABNT NBR 7180/2016 (ABNT, 2016b)
Shrinkage limit	14	(%)	DNER-ME 087/1994 (DNER, 1994a)
Plasticity index	46	(%)	ABNT NBR 7180/2016 (ABNT, 2016b)
Consistency index	1.45	-	-
Skempton index	1.00	-	Skempton (1953)
Maximum dry density[a]	1.696	(Mg/m^3)	ABNT NBR 7182/2016 (ABNT, 2016d)
Optimum moisture content[a]	18.1	(%)	ABNT NBR 7182/2016 (ABNT, 2016d)
USCS[b] Classification	CH[c]	-	-

[a]Normal Proctor Energy. [b] Unified Soil Classification System. [c]Inorganic clays of high compressibility.

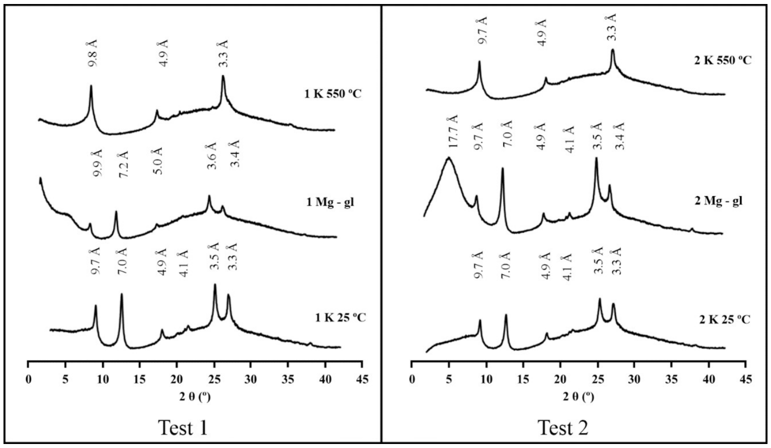

Figure 1. X-ray diffractograms.

Table 2. Chemical properties of soil.

Properties	Value	Unit	Norm
pH in water	6.72	-	Embrapa (2009)
pH in KCL*	5.42	-	Embrapa (2009)
pH em SMP**	7.20	-	Embrapa (2009)
OM***	3.56	g/dm^3	Embrapa (2009)
Ca^{2+}	11.50	cmolc/dm^3	Embrapa (2009), KCL
Mg^{2+}	11.80	cmolc/dm^3	Embrapa (2009), KCL
Na^{+}	9.78	cmolc/dm^3	Embrapa (2009), Mehlich-1
K^{+}	0.57	cmolc/dm^3	Embrapa (2009), Mehlich-1
Al^{3+}	< 0.08	cmolc/dm^3	Embrapa (2009), KCL
$H^{+} + Al^{3+}$	0.857	cmolc/dm^3	Embrapa (2009)
CEC****	34.6	cmolc/dm^3	Embrapa (2009)

*Potassium chloride. **Shoe-Maker, Mclean and Patt buffer solution. ***Organic matter contente. ****Total cation-exchange capacity.

Table 3. Percent of oxide present in the soil.

Oxide	(%)
SiO_2	63.45
Al_2O_3	20.25
Fe_2O_3	5.45
F.L*	4.98
K_2O	2.18
MgO	1.26
TiO_2	0.93
Na_2O	0.55
CaO	0.39
Cl	0.19
SO_3	0.13

*Fire lost.

2.3 Cyclic free swelling test

The cyclic free swelling test aimed to measuring the vertical swelling rates shown by the analyzed sample in successive wetting and drying cycles. ASTM D4546 (ASTM, 2014), method B, was the standard adopted to run this test. The specimen was placed in a metallic capsule, on a filter paper disc and a porous stone. A filter paper disk and a header coupled to a porous stone - which transferred a 0.5 kPa overload to the sample - were placed at the top of the specimen. A deflectometer was positioned on the header in order to measure height variations in the specimen during the test. Due to time limitations, only one specimen was tested. The schematic diagram of the experimental set is shown in Figure 3.

Deflectometer was adjusted to initial reading of 1.00 mm; the specimen was saturated with distilled water and its height variation readings were taken at time intervals of ¼ min, ½ min, 1 min, 2 min, 4 min, 8 min, 15 min, 30 min, 1 h, 2 h, 4 h, 8 h and 24 h. A new reading was performed, at each 24 h time interval, whenever necessary, until secondary swelling stabilization was observed. This stage lasted approximately nine days.

The distilled water was removed from the metallic capsule at the end of the secondary swelling and the specimen was left to dry in drying chamber, at 35 °C, which is the maximum temperature recorded in the sample collection region during the dry season. A 37-liter expanded polystyrene thermal box (dimensions equivalent to 40.0 cm x 30.5 cm x 33.0 cm) coupled to two 70 W halogen incandescent lamps was used for such a purpose. The internal temperature of the drying chamber was controlled based on using digital thermostat and thermo-hygrometer.

The drying stage lasted 14 days, on average; it was carried out until the specimen recovered its initial test density, which enabled inferring that the soil sample returned to its initial moisture content. After the drying stage was over, which featured the conclusion of a full wetting and drying cycle, the specimen was saturated again and a new wetting and drying cycle started. Soil density control during the test was performed based on using a 0.01 g-precision digital scale. In total, eight cycles were performed on the same specimen.

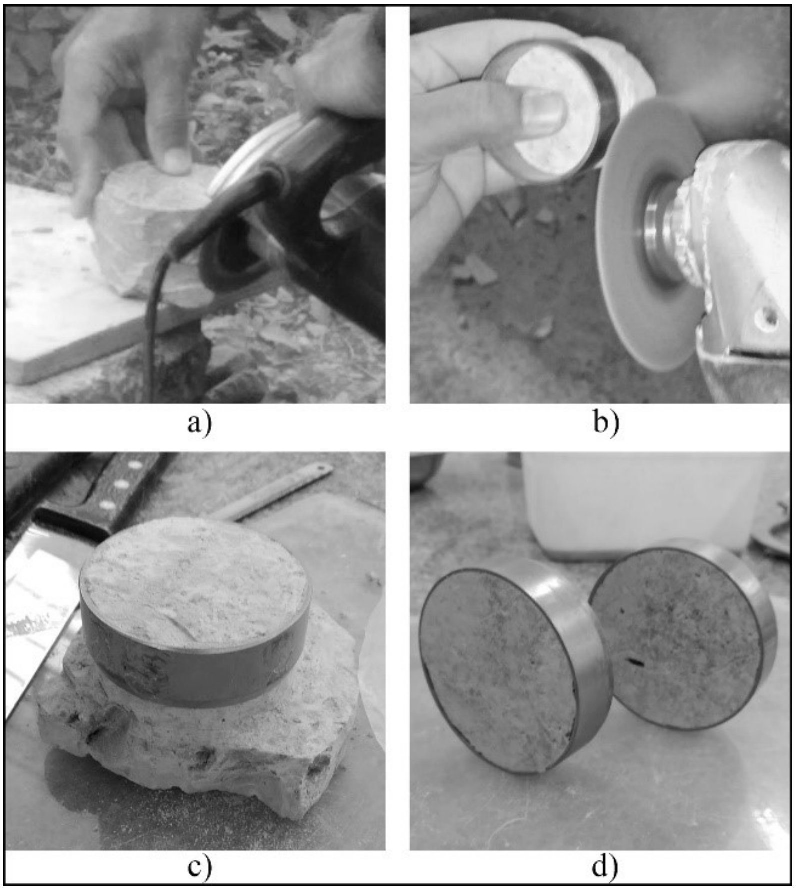

Figure 2. Confection of specimens: a) cutting with marble saw; b) diameter reduction with grinder; c) surface finishing with knives and saw blades; d) finished specimens.

2.4 Cyclic swelling-stress test

The cyclic swelling-stress test was based on the post-swelling loading method, under 0.5 kPa overload, in compliance with ASTM D4546 (ASTM, 2014), method B. Conventional consolidation press was the device used for the load application system. The specimen coupled to the density cell had its density measured right before the test began. It was saturated with distilled water, after the cell was duly positioned in the consolidation press, under 0.5 kPa overload (deriving from the load application header). Deflectometer readings of specimen's height variations were performed at the following time intervals: ¼ min, ½ min, 1 min, 2 min, 4 min, 8 min, 15 min, 30 min, 1 h, 2 h, 4 h, 8 h and 24 h. After this time interval, a new reading was performed every 24 hours, until the end of primary swelling was observed. This stage lasted six days, on average.

At the end of primary swelling, the specimen was subjected to increasing vertical stress values (25, 50, 100, 200, 400 and 800 kPa), which were applied at successive stages. Variations in specimen's height were read at ¼ min, ½ min, 1 min, 2 min, 4 min, 8 min and 15 min intervals, after the application of each stress value. Next, a new stress

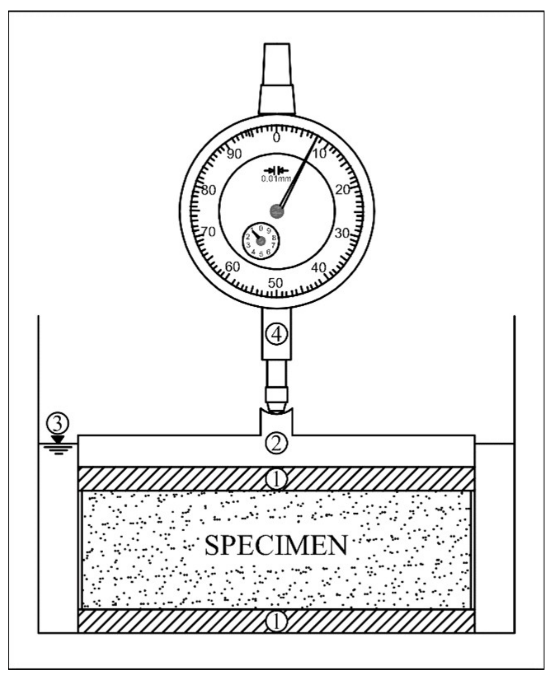

Figure 3. Schematic diagram of the experimental set-up. Legend: 1) porous stone; 2) header; 3) water level; 4) deflectometer.

increase was applied to the specimen and new readings were taken until the specimen returned to its initial height. Thus, soil swelling pressure is the sum of loads applied to the specimen until it returns to its initial height, divided by the cross-sectional area of the specimen.

The consolidation cell was removed from the consolidation press and left to dry (closed) in greenhouse, at 35 °C, after the test was over. The drying specimen remained in the greenhouse until the initial density of the set (consolidation cell + specimen) was reached. It was done to guarantee that the specimen could go back to its initial moisture content. Similar to free swelling tests, the drying stage lasted approximately 14 days. The density of the set was checked on a daily basis, with the aid of 0.01 g-precision digital scale. Once the initial density was reached, the consolidation cell was placed back in the consolidation press and a new wetting and drying cycle was implemented. In total, eight full wetting and drying cycles were performed.

3. Results and discussions

The initial physical indices observed for specimens used in the free swelling and swelling pressure tests are shown in Table 4. Moisture content was measured based on using shavings of the non-deformed sample used to prepare the specimens, whereas the other indices were calculated based on correlations among soil density, volume, moisture content and moisture-correction factor.

There are at least two important points to be discussed about the initial physical indices of the specimens. The first one concerns the initial moisture content, whereas the second one refers to specific dry density. Specimens' initial moisture content was quite close to the soil hygroscopic moisture content and approximately 57% below the shrinkage limit. In other words, the soil sample was extremely dry. On the other hand, the herein calculated specific dry density was higher than the maximum specific dry density resulting from the optimal compaction condition, by factor of 1.24.

This finding enabled inferring that the analyzed sample had high suction value, and it explains its high rigidity. In other words, its low moisture content accounted for increasing the suction value of the soil, which shrank during the drying process and brought its particles closer to each other. Another factor playing key role in this outcome lies on the fact that it was necessary increasing the soil sample moisture from 5.26% to 18.1% in the compaction test in order to reach maximum specific dry-bulk density. Since the herein investigated sample was a highly expansive soil, this moisture variation triggered soil swelling and, consequently, its particles moved away from each other throughout the compaction test. Thus, the non-deformed sample has shown better structure consolidation than the deformed sample, after the compaction process, at Normal Proctor energy.

Table 4. Initial physical indexes of the specimens.

Parameter	Value
Moisture content (%)	5.76 – 6.00
Natural density (Mg/cm^3)	2.185 – 2.236
Dry density (Mg/cm^3)	2.066 – 2.110
Void ratio	0.270 – 0.297
Degree of saturation (%)	52.00 – 59.50

3.1 Free swelling curves

Figure 4 presents the swelling vs. time curves generated for each wetting and drying cycle. It is possible seeing that the swelling curves grew fast as time interval increased; then, their growth rate decreased until they stabilized. That is, when the primary expansion ends and the swelling versus time curve becomes horizontal. Negative swelling values were observed in the first 110 minutes of cycles 7 and 8. This event was consistent with specimen's height decrease due to particle disintegration resulting from the high cracking degree observed after several shrinking events.

Figure 5 shows the state of the specimen after completion of the cyclic free swelling test. It is possible to note the partial fragmentation of the specimen, which may indicate that the soil, in addition to being expansive, may also be dispersive.

3.2 Variations in free swelling based on number of cycles

Figure 6 shows the free swelling and swelling reduction rates observed for each wetting and drying cycle. Based on the graphs in the Figure 6, the highest free swelling value (approximately 47.8%) was recorded for cycle 1, whereas cycle 2 showed decrease by more than 20% in the free swelling rate. All cycles have shown significantly reduced free swelling values in comparison to cycle 1; the biggest difference was observed in the last cycle, which recorded free

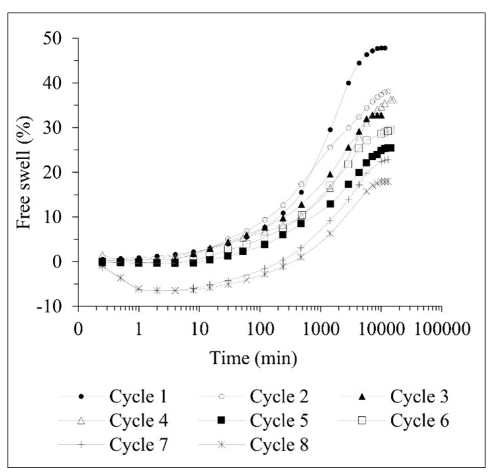

Figure 4. Free swelling curves.

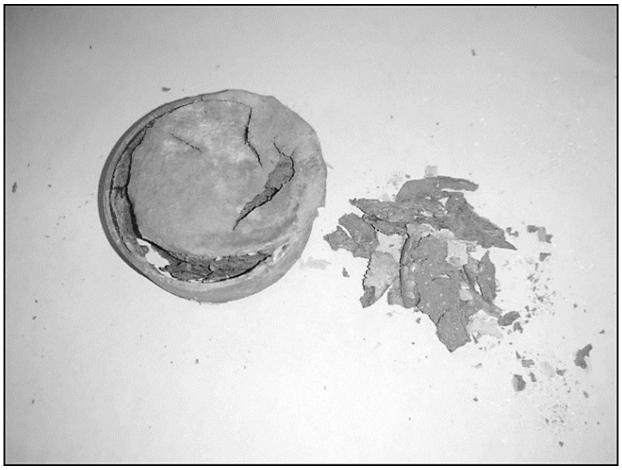

Figure 5. Specimen after completion of the cyclic free expansion test.

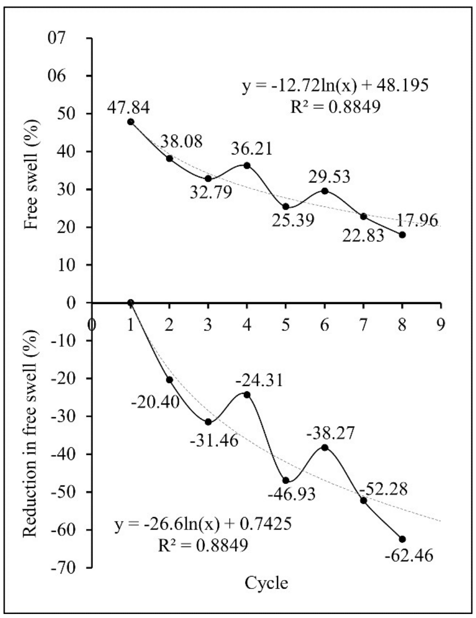

Figure 6. Free swell and percent reduction in free swell.

swelling reduction by approximately 62%; this outcome has evidenced the influence of repeated effects of drying-wetting alternations on the expansive properties of this soil type.

Logarithmic trendline is the value prediction model that best fits this behavior, as shown in Figure 6. This model shows determination coefficient equal to 0.88 and it predicts further reductions in free swelling values for consecutive cycles. However, such a prediction is conditioned to the assumption that the moistened sample and is desiccated to its initial moisture content. Nevertheless, if the sample is desiccated to moisture contents lower than the initial one and, consequently, induced to suction values higher than it already had, the soil free swelling rate is expected to increase as new wetting and drying cycles takes place.

Findings similar to the ones reported in the current research were recorded by Al-Homoud et al. (1995), Basma et al. (1996), Tripathy et al. (2002), Rao & Rao (2010) and Al-Omari et al. (2010), who reported the highest free swelling rate in cycle 1, as well as gradual reduction in free swelling values as the number of wetting and drying cycles increased. The highest free swelling reduction rate was observed from the first to the second cycle.

Basma et al. (1996) have correlated the gradual free swelling decrease behavior to the adopted shrinking type (partial shrinking); they observed the opposite outcome when full shrinking was applied. However, tests conducted by the aforementioned authors used specimens molded at mean humidity of 21% (above the shrinking limit) and overload of approximately 10 kPa. However, according to Tripathy et al. (2002), progressive decrease in free swelling values was only observed at overload values equal to, or higher than, 50 kPa. These authors worked with molded specimens at optimum moisture content and with different overloads.

Tripathy & Rao (2009), Al-Taie et al. (2016) and Wei & Dong (2020) reported results different from the ones observed in the current research; the aforementioned authors observed significantly increased free swelling rates in cycle 2, which gradually decreased as the number of swelling and shrinking cycles increased. It is worth emphasizing that, according to Tripathy & Rao (2009) and Wei & Dong (2020), the free swelling values recorded for the last cycle were lower than the ones recorded in cycle 1. Moreover, according to Al-Taie et al. (2016), the free expansion value of the last cycle remained considerably higher than the one observed in cycle 1, despite its gradual decrease. Tripathy & Rao (2009), Al-Taie et al. (2016) and Wei & Dong (2020) have used specimens molded under optimal compaction condition and adopted overloads of 50 kPa, 25 kPa and 0 kPa, respectively.

3.3 Free swelling development over time

Figure 7 shows the analysis applied to free swelling evolution at predefined time stages. It is possible seeing in the first 480 min that the sample has shown 15.5% free swelling in the first cycle and 17.4%, in the second cycle. Thus, this time interval enabled considerable increase in free swelling development from cycle 1 to cycle 2. However, the other cycles did not show such increase in this parameter in this same time interval (480 min); on the contrary, there was gradual reduction in it.

The justification for this outcome lies on the fact that, during the first drying stage, the specimen was susceptible to develop shrinkage cracks, which, in their turn, enabled water percolation and sample saturation at the second wetting stage. Consequently, the clay minerals had faster access to water and it resulted in faster initial variation in specimen's height in the first minutes of cycle 2. On the other hand, the addition of new wetting and drying cycles also led to

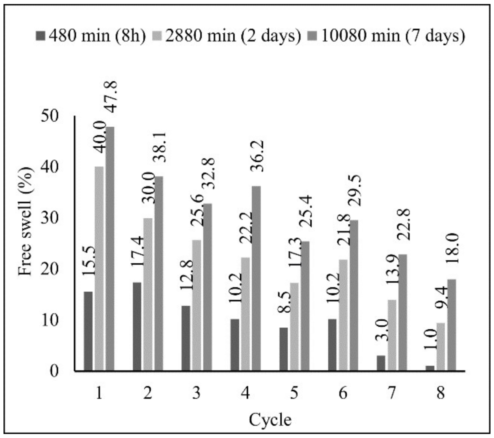

Figure 7. Development of the free swell in time.

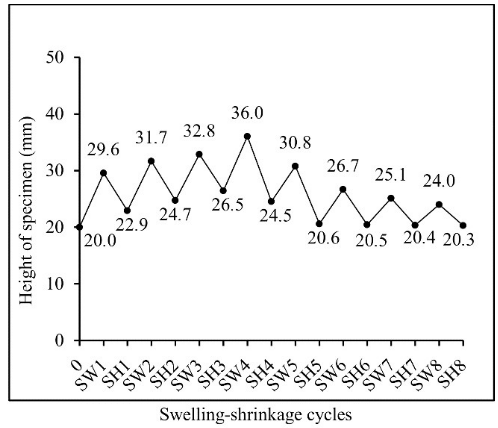

Figure 8. Variation of specimen height.

loss of fine particles and cementing agents in the sample, a fact that led to specimen degradation and, consequently, to expansive–potential loss. Because the cementing agent is composed of the finest fraction of the soil, and it is where the clay minerals responsible for the expansion mechanism are. Thus, it is reasonable to believe that with the decrease of the cementing agent occurs a reduction in the expansive effects of the soil.

Thus, it was possible seeing that cycle 1 recorded higher free swelling rates at the subsequent time intervals. Cycle 8, for example, recorded high particle losses when the sample was flooded; it resulted in negative height variations and in only 5.8% free swelling at the end of the first 480min. Lack of guiding ring to restrict vertical sample swelling has also contributed to material loss and to swelling decrease, since swelling at the ends of the specimen took place in a volumetric manner.

It is important emphasizing that the specimen reached 84% total free swelling within 2 days, as well as 100% of it at the end of 7 days, during cycle 1. On the other hand, the specimen took longer to reach these rates in the other cycles. This outcome shows that the wetting and drying cycles did not only change soil free swelling property, but also its association with time.

3.4 Variation in specimen's height

Figure 8 shows the variation in specimen's height observed for each cycle. It evidences continuous increase in specimen's height from cycle 1 to cycle 4, as well as swellings exceeding shrinking's. During the tests, it was visually observed that the sample recorded radial shrinking values higher than the vertical ones, during the drying process. It may have happened because the specimen's radius was greater than its height. Thus, it was possible seeing that the specimen's height always remained above 20 mm and that its diameter remained smaller than 50 mm, at the drying stages. Wei & Dong (2020) have also reported this very same outcome when they used specimens measuring 20 mm in height and 61.8 mm in diameter. The steady state equilibrium, where, according to Tripathy et al. (2002), vertical deformations remain constant, was not found in the current research. However, it was possible seeing that specimen's height returned to a value a very close to it, in the last four cycles. This finding also corroborates the study by Al-Omari et al. (2010), according to whom, values recorded for the same swelling cycle were considerably higher than the shrinking values; moreover, the sample did not shrink back to the initial test height, or to a value lower than that, in any cycle.

3.5 Variation in swelling pressure based on number of cycles

Figure 9 shows swelling pressure values and swelling pressure reduction rates observed for each of the herein conducted eight wetting and drying cycles. The highest swelling pressure value observed in the current study was recorded in cycle 1, similar to what was observed for the free swelling test; these findings corroborate what was reported by Al-Homoud et al. (1995) and Basma et al. (1996). The swelling pressure reduction rate observed in cycle 2 reached 72%. With respect to cycle 1, all cycles recorded reduced swelling pressure reduction by approximately 73%, on average. In other words, cycle 1 required higher swelling pressure than the subsequent cycles to remove water from soil voids and to enable the specimen to recover its initial height. After the swelling pressure reduction observed in cycle 2, the specimen maintained the swelling pressure values observed in the other cycles ranging from 100 kPa to 138.33 kPa; this value was still quite high and conducive to cause pathologies in light structures. In light of the foregoing, and based on results observed in the free swelling test, it is evident that the wetting and drying cycles have remarkable influence on the swelling properties of the investigated soil type.

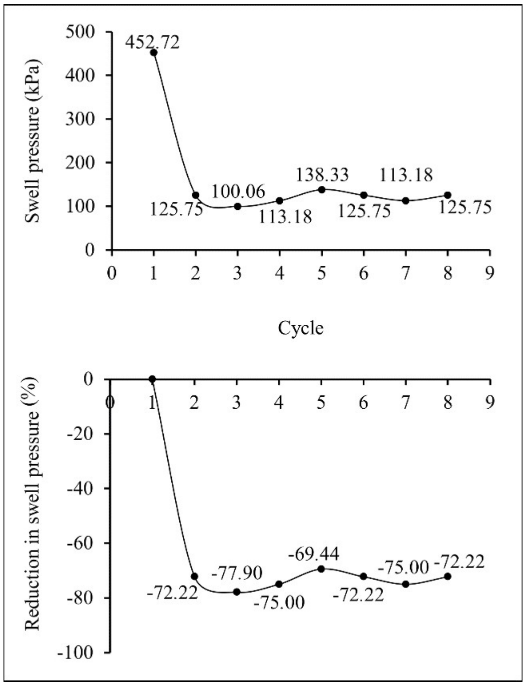

Figure 9. Swell pressure and percent reduction in swell pressure.

3.6 Swelling fatigue

The cyclical wetting and drying process can significantly change soil structure. The saturation stage increases specimen's volume and void ratio, whereas water is adsorbed between the crystalline layers of clay minerals, which, in the current case, were of the 2:1 type. Soil pores shrink during the drying stage and non-recoverable deformation is observed, since free swelling and swelling pressure values get lower after cycle 1. Soil pores' shrinking increases the number of macropores and enables the emergence of vertical cracks that favor sample disaggregation. The addition of new wetting and drying cycles led to accumulation of non-recoverable deformations that, in their turn, accounted for gradual decrease in soil swelling capacity. Al-Omari et al. (2010) and Al-Homoud et al. (1995) call this phenomenon swelling fatigue and correlate it to the remaining irreversible deformations deriving from each swelling cycle.

4. Conclusions

Based on the analysis of the current findings, it is possible concluding that the herein investigated expansive soil sample presented high swelling potential, as well as initial free swelling and swelling pressure values equal to 47.84% and 472.52 kPa, respectively. The sample has virtually doubled its initial volume in the first cycle of the free swelling test. Yet, lack of guiding ring and the consequent volumetric expansion of the sample at the ends of the ring may have minimized this swelling value. The swelling pressure in the same cycle also presented great magnitude, and it made the soil unfeasible to lay foundations, mainly for light structures.

The highest free swelling and swelling pressure values observed in the wetting and drying cycles were recorded in cycle 1. Soil expansive behavior has decreased as the number of wetting and drying cycles increased. The highest reduction value recorded for free swelling and swelling pressure was observed from cycle 1 to 2. The addition of new cycles implied further reductions in these parameters, so that free swelling decreased by 63% between the first and eighth cycle, whereas swelling pressure decreased by approximately 72%, on average, in this same interval. It is worth emphasizing that the herein perceived reductions were associated with sample drying back to its initial moisture content. Thus, the same behavior was not expected to be evidenced in samples dried to lower moisture contents and to suction values higher than the initial test values. Thus, in light of the foregoing, it is possible proving that wetting and drying cycles account for influencing swelling pressure and free swelling parameters in expansive soils.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Larissa da Silva Oliveira: conceptualization, data curation, methodology, writing. Erinaldo Hilário Cavalcante: supervision, validation, writing – review & editing, formal analysis.

Data availability

The datasets generated and analyzed in the course of this paper are available from the corresponding author upon request via e-mail.

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