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Improvement of an expansive soil with construction and demolition waste

Melhoramento de um solo expansivo com resíduo de construção e demolição

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Abstract: Expansive soils increase in volume when subjected to increased moisture and contract when they lose moisture. Construction on expansive soils can exhibit various pathological manifestations. This article presents a study on the improvement of an expansive soil located in Santa Maria da Boa Vista–PE, mixed with 10%, 20%, and 30% construction and demolition waste (CDW), relative to the mass of the dry sample. Physical and mechanical characterization tests were carried out on the soil and mixtures, chemical and microstructural tests were performed on the soil, and physical and chemical characterization was conducted on the CDW. The soil showed 8.58% free expansion, classifying it as a highly expansive soil with the potential to cause serious damage due to its swelling pressure (81.25 kPa by the Constant Volume Method). The mixture with 30% CDW reduced the swelling pressure to 20 kPa and the free expansion to 0.90%. Therefore, the addition of CDW to the soil proved effective in stabilizing expansion..

Keywords: Problematic soils; Soil stabilization; Aggregates.

Resumo: Solos expansivos aumentam de volume quando submetidos ao acréscimo de umidade e sofrem contração quando perdem umidade. Construções executadas sobre solos expansivos podem apresentar várias manifestações patológicas. Este artigo apresenta um estudo sobre melhoramento de um solo expansivo localizado em Santa Maria da Boa Vista-PE, misturado com 10%, 20% e 30% de resíduo de construção e demolição (RCD), em relação à massa da amostra seca. Foram realizados ensaios de caracterização física e mecânica no solo e nas misturas, ensaios químicos e microestrutural no solo, e caracterização física e química no RCD. O solo apresentou 8,58% de expansão "livre", tratando-se, de um solo com alto grau de expansividade, e com a possibilidade de danos graves, devido à sua tensão de expansão (81,25 kPa pelo Método do Volume Constante). A mistura com 30% de RCD reduziu a tensão de expansão para 20 kPa e a expansão "livre" para 0,90%. Com isso, a adição de RCD ao solo mostrou-se eficiente na estabilização da expansão.

Palavras-chave: Solos problemáticos; Estabilização de solos; Agregados.

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1. Introduction

Soils are of great importance in Civil Construction, since it is on them that buildings are supported. Some soils can present problems, among them, there are expansive soils, which increase in volume when subjected to the increase of moisture and suffer contraction when they lose moisture. This phenomenon tends to be repeated cyclically due to seasonal variations in soil moisture or suction (FERREIRA; VILAR, 2023).

The volumetric variation of expansive soils is influenced by the presence of interstratified montmorillonite with chlorite, illite and vermiculite. Montmorillonite, from dry condition to complete saturation, has a potential for volume variation 50 times greater than kaolinite. The distribution of clay particles, porosity, mineralogical orientation, cementation, stratigraphic profile, soil thickness, discontinuity, tension state are other factors that influence the process of soil expansion (CHEN, 1988; FERREIRA; FERREIRA, 2009; MARQUES *et al*., 2014).

In rainy periods, expansive soils have a soft consistency, stickiness, microrelief, densification caused by the trampling of machines and animals during grazing and agricultural practices and in small buildings fissures, cracks and cracks in buildings, in addition to the surface impermeabilization of the soil caused by the impact of rain (COLLARES *et al*., 2008, FLEUREAU *et al*., 2015). In dry periods, expansive soils have a hard consistency, high resistance, forming internal agglomerates, fissures and superficial cracks (Al-RAWAS *et al.,* 2006; YUAN *et al*., 2016). When soil is used for engineering structures, such as irrigation canals and agrovillages, special attention is required in the implementation of the structures due to the inevitable modification of the interaction between water and soil in the field (AL-RAWAS *et al*., 2006, FERREIRA; VILAR, 2023).

Expansive soils are found worldwide and are particularly common in semi-arid regions with tropical and temperate climates, where evapotranspiration exceeds precipitation (CHEN, 1988; FLEUREAU *et al*., 2015). In Pernambuco, expansive soils were found in Carnaíba, Afrânio, Petrolina, Cabrobó, Salgueiro, Serra Talhada, Petrolândia, Ibimirim, Pesqueira, Nova Cruz, Paulista, Cabo, Olinda, Recife, Cedro, Inajá, São Francisco, Suape, Itaparica, Agrestina, Brejo da Madre de Deus, Bonito and Santa Maria da Boa Vista (CONSTANTINO, 2018).

The identification of expansive soils is carried out using direct and indirect methods (SCHREINER, 1987; FERREIRA, 1995). Indirect methods use mineralogical identification, physical indices, consistency limits, or parameters related to the texture, composition, and behavior of soils, while direct methods are based on measuring the expansion induced in the soil (free expansion) or the stress required to prevent it (swelling pressure). "Free" Expansion Tests use small overloads before flooding. Seed et al. (1962) and Vijayvergiya and Ghazzaly (1973) consider overloads of 7 kPa an 10 kPa, respectivelly. In Table 1 presents the degree of soil expansiveness based on “free” expansion according to the proposals of the aforementioned authors, while Table 2 indicates the potential damage to structures classified according to the swelling pressure values proposed by Jimenez Salas (1980).

Table 1 – Classification of the degree of soil expansiveness.

Criterion de Seed *et al.* (1962)	**Vijayvergiya and Ghazzaly's criterion (1973)**		**Degree of Expansiveness**
“Free” Expansion (%) for Overload Stress 7 kPa	**“Free” Expansion (%) for Overload Stress 10 kPa**	**Swelling Pressure (kPa)**	
0-1	<1	<30	Low
1-5	1-4	<30-120	Average
5-25	4-10	120-300	Loud
>25	>10	>300	Very high

Source: Authors (2025).

Constructions built on expansive soils may present various problems to civil engineering, such as cracks or fissures in the soil (during dry periods), diagonal cracks beneath windows and doors, pavement failures, etc. (FERREIRA, 1995). One of the techniques used to reduce the expansiveness of such soils is the partial replacement with granular soils, modifying their granulometry. Constantino et al. (2018) added sand in proportions of 10%, 20%, 30%, and 50% to the expansive soil from Paulista–PE, and Stive (2017) added sand in proportions of 10%, 20%, 30%, 40%, 50%, and 75% to the expansive soil from Ipojuca–PE to reduce its expansiveness.

Another issue faced by the civil construction sector concerns the generation of its waste, commonly known as construction and demolition waste (CDW). According to Abrelpe (2021), approximately 47 million tons of CDW were collected by municipalities in 2020, with 9,046,890 tons per year collected in the Northeast region.

Table 2 – Possible damages by the Jimenez Salas Criterion (1980).

Swelling pressure	Possible Damage
>200	Demolition
Between 100 and 200	Serious Damage
Between 50 and 100	Important fissures
Between 20 and 50	Small fissures
<20	No Damage

Source: Jimenez Salas (1980).

This article presents an analysis of the behavior of volume variation due to moisture change in an expansive soil in the municipality of Santa Maria da Boa Vista, Pernambuco, with and without the addition of CDW in order to reduce soil expansion and CDW reuse.

2. Materials e Methods

The expansive soil sample was collected from the municipality of Santa Maria da Boa Vista–PE, located at 8°48'28" S latitude and 39°49'32" W longitude, in the region of São Francisco and Pontal River basins. This municipality is characterized by a semi-arid climate, exhibiting hot and humid summers, warm and dry winters, and very hot and dry springs (Figure 1). This soil was identified by Marinho (2018), approximately 40 m away from a collapsible soil, as shown in Figure 2. In 1987, collapsible soil had already been found on a plot of land where 1856 housing units were built, being identified by Ferreira (1988), Ferreira and Teixeira (1989), Vargas et al., (1989) and Ferreira (1990).

Figure 1 – Location of the municipality of Santa Maria da Boa Vista.
Source: Cunha et al. (2012).

The experimental program initially consisted of the collection of soil samples, and physical characterization of CDW, soil and soil-CDW mixtures. Near the F4 probing holes, 30 kg of deformed and undefined soil samples were collected (Figure 2). In a recycling plant located in Recife city, it was collected approximately 75 kg of CDW.

In the soil and CDW samples, granulometry (NBR 7181/2016) and real grain density (NBR 6508/1984) tests were performed. Solid particles of the CDW retained in sieve No. 100 were added to the espansive soil (ES) in the weight proportions of 10%, 20% and 30%, thus constituting the mixtures 90%ES10%CDW, 80%ES20%CDW, 70%ES30%CDW. In all samples and mixtures, the Liquidity Limit (NBR 6459/2016), Plasticity Limit (NBR 7180/2016), Contraction Limit (NBR 7183/1982), "Free" Expansion with 10 kPa overload and Swelling Pressure tests were performed. Scanning Electron Microscopy (SEM) were performed only soil and chemical tests were pwefoed in soil and in CDW.

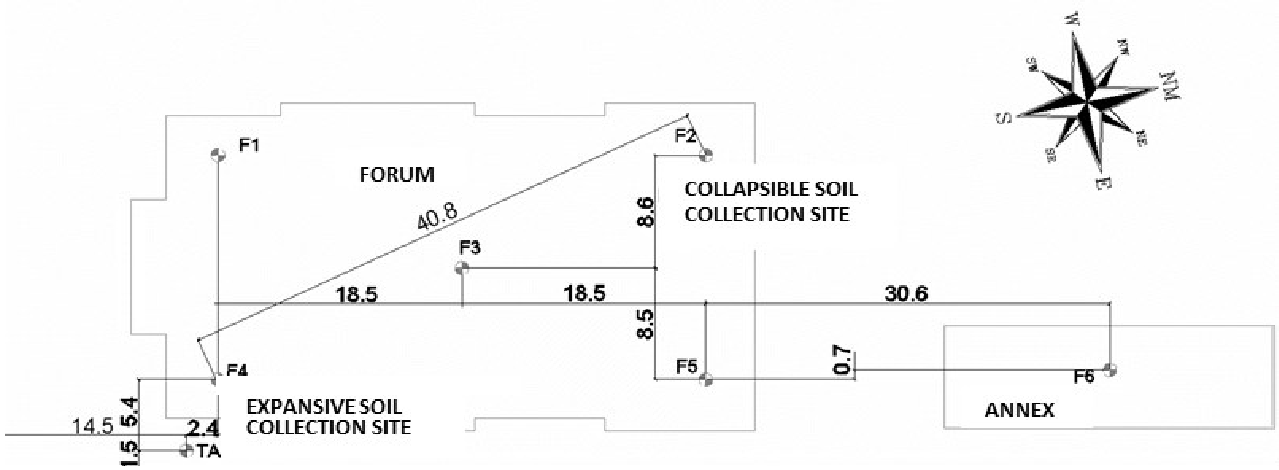


Figure 2 – Location of the boreholes and the soil collection.
Source: Adapted from Oliveira Júnior (2016).

Compaction tests were conducted using standard Proctor energy to determine the optimum moisture content and maximum dry unit weight of the soil and soil-CDW mixtures. These results were employed to prepare the specimens for mechanical and chemical testing, following the guidelines of ABNT technical standards.

Chemical tests were conducted at the Chemical Analysis Laboratory of the Catholic University of Pernambuco (UNICAP), following the methodology outlined in the Embrapa Manual of Analysis Methods (TEIXEIRA *et al*., 2017). The determination of soil oxides was performed through X-ray fluorescence spectrometry (XRF) at the Federal University of Pernambuco (UFPE).

Microstructural characterization tests were carried out at the Laboratory of Devices and Nanostructures (LDN) at UFPE, and the soil microstructures were analyzed by scanning electron microscopy (SEM).

The expansibility of the soil and the mixtures with CDW was evaluated by means of “free” Expansion and Swelling pressure tests on undisturbed soil samples and on compacted soil samples with CDW added in proportions of 10%, 20%, and 30%. Two specimens were used at the optimum moisture content and maximum dry unit weight of the mixtures.

In the “Free” Expansion tests, undisturbed samples of expansive soil and compacted samples of expansive soil mixed with CDW were molded into stainless steel rings with a height of 20.00 mm and an area of 40 cm², and subjected to a stress of 10 kPa. The expansion of soil was monitored until its stabilization.

The swelling pressure of the soil was determined through 6 (six) different methods, included: Loading after expansion with different vertical consolidation stresses (8 specimens); Expansion and Collapse under Stress (6 specimens); Constant Volume (1 specimen); Double Oedometer (2 specimens); Rao *et al.* (1988) Method (1 specimen); and Justo *et al*. (1984) Method (7 specimens). For the soil-CDW mixtures, swelling pressurees were determined only by the Constant Volume Method (1 specimen for each mixture).

3. Results and discussion

3.1 Physical characterization

Figure 3a presents the grain size distribution curves of the soil and CDW. It can be observed that the soil consists of 39% clay, 11% silt, 45% sand, and 5% gravel, classified as CL (low plasticity clays) and A-6 (clayey soils) according to the Unified Soil Classification System (USCS) and the Transportation Research Board (TRB), respectively. The two taxonomies SUCS and TRB classified the soil as clayey, but considering only the distribution of grains, 50% are coarse-grained (sand and gravel) and 50% are fine-grained (fine sand, silt and clay). CDW is composed of 12% clay, 10% silt, 77% sand and 1% gravel, being classified as SM (silty sand) and A-2-4 (gravel or silty or clayey sand) accord the SUCS and TRB classifications, respectively. The mixtures 90%ES10%CDW, 80%ES20%CDW and 70%ES30%CDW were classified as SC (clay sands) and A-2-4 (silty or clayey boulders or sands), by the SUCS and TRB classifications, respectively (Figure 3b).

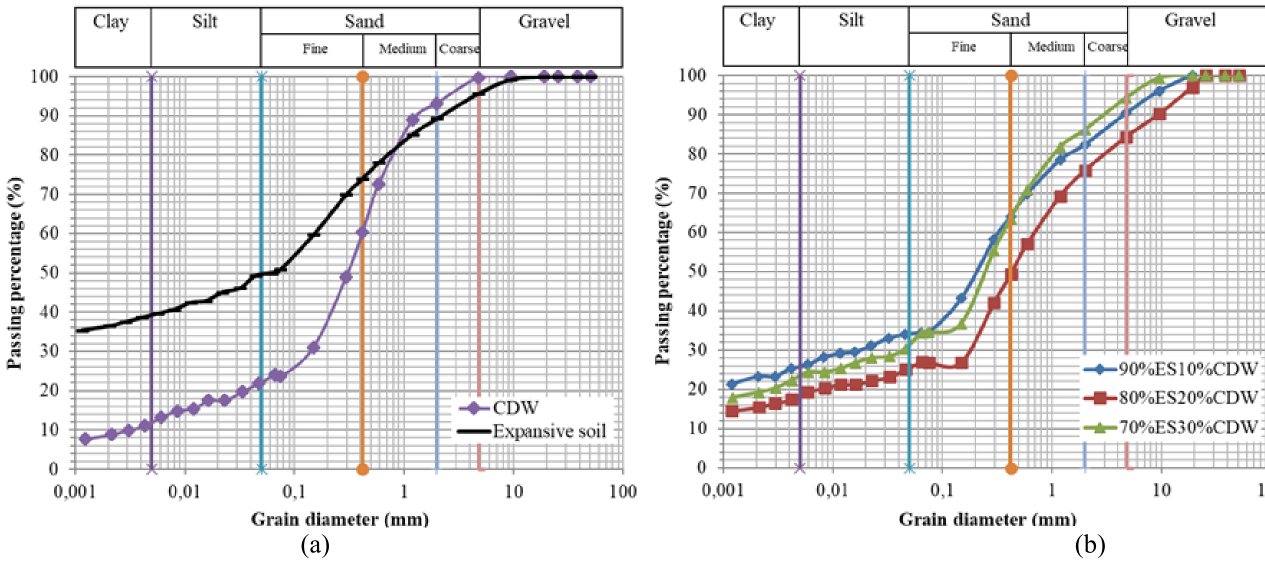


Figure 3 – Particle size curves: (a) soil and CDW; (b) soil-CDW mixtures.
Source: Authors (2025).

The results of the consistency tests performed in the soil, in the CDW and in the soil-CDW mixtures are shown in Table 3. The addition of CDW to the soil modifies the physical characterization of the soil, as there is a decrease in the percentages of clay and silt and an increase in the percentages of sand and gravel. The Liquidity Limits and Plasticity Index have decreased, this is due to the decrease in clay percentages as CDW is added.

Table 3 – Results of the Consistency Limits tests.

Tests (%)	Soil	CDW	Mixtures soil - CDW		
			90%ES-10%CDW	80%SE-20% CDW	70%SE-30% CDW
LL	28	NL*	23	22	22
LP	16	NP**	14	15	16
IP	12	-	9	7	6
CC	17	NC***	14	14	14

NL = Non-Liquid; NP = Non-Plastic; NC*** = Did not contract.*
Source: Authors (2025).

The compaction curves of the soil and the soil-CDW mixtures are shown in Figure 4a. For the soil, the optimum moisture content and maximum apparent dry unit weigh were 12.50% and 19.25 kN/m³, respectively. These values are more typical in granular soils, because the material contains nearly equal proportions of fine and coarse particles (50% each). For the CDW, the corresponding values were 13.69% and 19.00 kN/m³. In the soil-CDW mixtures, a slight reduction in maximum dry unit weight and an increase in optimum moisture content were observed. The most pronounced change occurred in the 90%SE–10%CDW mixture, which reached an optimum moisture content of 13.70% and a maximum dry unit weight of 18.40 kN/m³ (Figure 4b).

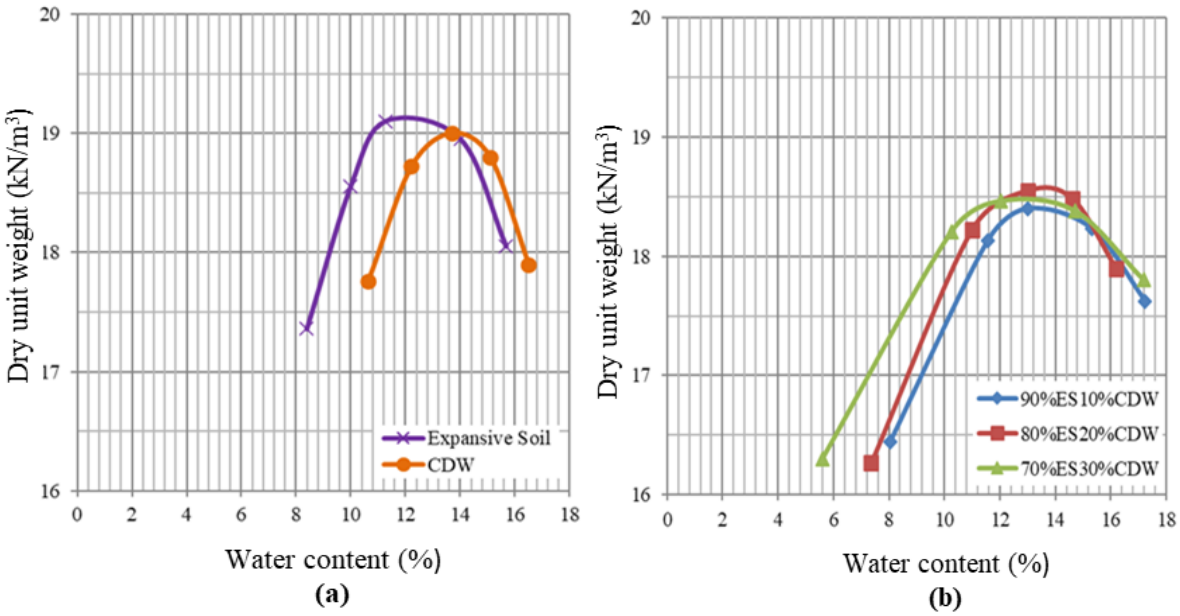


Figure 4 – Compaction curves: (a) soil and CDW; (b) soil-CDW mixtures.
Source: Authors (2025).

3.2 Chemical Characterization

The pH and ΔpH values obtained for the soil and for the CDW, as well as the classification of the samples, are presented in Table 4. The variation between pH in water and pH in KCl (ΔpH = pH (KCl) – pH (water)) is related to the presence of clay minerals in the weathering process and the presence of exchangeable aluminum (H+, Al3+), responsible for the flocculation of the clay mineral (PAIVA, 2016). For all the samples tested, a negative ΔpH is verified, indicating that the soils have a predominance of silicate clays, according to the classification of Kiehl (1979) apud Morais (2017). The soil has a cation exchange capacity of 29.54 cmolc/kg and the RCD of 22.67 cmolc/kg. Teixeira et al. (2017) uses 27 cmolc/kg as a reference to distinguish high CEC values from low values. Based on the values found in the samples, the soil has high CEC values and the RCD has low cation exchange capacity.

Table 4 – pH and ΔpH values for expansive soil and CDW.

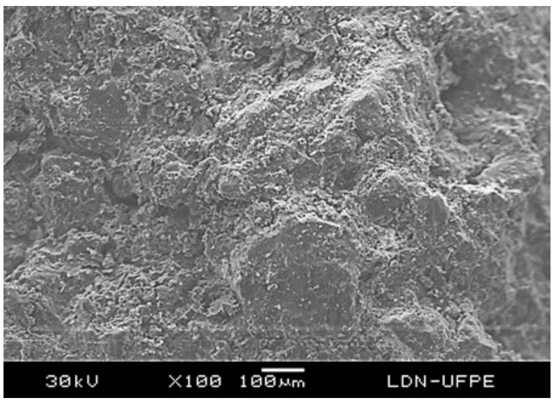
Determinations	Samples		pH Classification (GUIMARÃES, 2002)	
	Soil	CDW	Soil	CDW
pH in water	5,87	7,45	Moderately acidic	Alkaline
pH in KCl	3,62	5,52	Extremely acidic	Moderately acidic
pH in $CaCl_2$	4,70	4,99	Acid	Acid
ΔpH	-2,25	-1,93	Expansive soil	CDW

Source: Authors (2025).

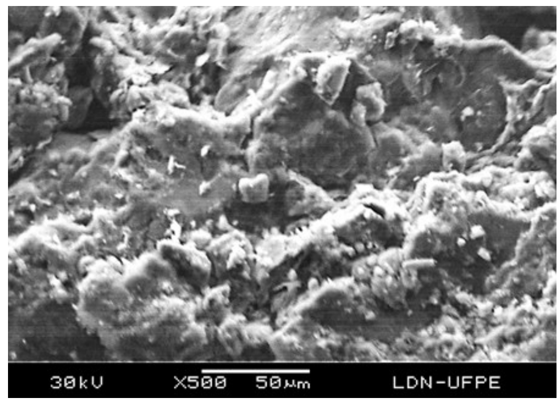
All soil samples have CEC values above 20 cmolc/kg, which means that they must have high levels of montmorillonite, according to Buol et al. (1997). The organic matter value was less than 5%, therefore, no sample is rich in organic matter, according to Teixeira et al. (2017). The soil and CDW samples have a percentage of saturation and base (V) higher than 50%, which characterizes them as eutrophic soils. Sodium saturation values (n) are less than 15%, so they have low sodium saturation. The electrical conductivity of the saturation extract is low in expansive soil and RCD (577.4, 196.0 and 1318.0 μS/cm/25°C).

3.3 Microstructural Characterization

Soil electromicrographs were obtained by scanning electron microscopy (SEM) (Figure 5). The matrix of the undeformed soil has a fine, compact texture, preponderant of silicate clays. The quartz grains are permeated by silt and clay fractions (Figure 5a). The presence of montmorillonite and a large amount of flattened pores are observed, as a result of the expansion and contraction typical of expansive clays (Figure 5b). The "Vugh" cavity also occurs, being predominantly of the interconnected type.



(a)



(b)

Figure 5 – Electromicrographs of compacted expansive soil in the undisturbed condition: a) Fine, compact texture, preponderant of silicate clays and flattened pores. b) Quartz grains permeated by silt and clay fractions, presence of montmorillonite and predominant interconnected cavity.
Source: Authors (2025).

3.4 Characterization of Expansiveness

The values of the "free" expansions (El = 100Δh/h0), under consolidation stress of 10 kPa, and of the Swelling pressure by the Constant Volume Method of both the soil and the soil-CDW mixtures, are shown in Table 5. The soil showed 8.58% of "free" expansion, which according to the criterion of Vijayvergiya and Ghazzaly (1973), is a high degree of expansion. By adding CDW to the soil, the degree of expansivity becomes low for the three mixtures.

Table 5 – Values of the "Free" Expansion with 10 kPa overload and the Swelling pressure by the Constant Volume Method in soil samples and soil-CDW mixtures.

Samples	"Free" Expansion - 10 kPa (%)	Swelling Pressure (kPa)
Soil	8,58	81,25
90%ES10%CDW	0,90	26,25
80%ES20%CDW	0,63	23,75
70%ES30%CDW	0,62	20,00

Source: Authors (2025).

The values of the swelling pressurees determined by various methods in the compacted clay collected from the LaPaz de Arahal Barrier in Serilla (DELGADO, 1986) and in undisturbed soils of Pesqueira-PE (SILVA; FERREIRA, 2007), Petrolândia-PE (FERREIRA; FERREIRA, 2009), Cabrobó-PE (BARBOSA, 2013), Paulista-PE (ARAÚJO *et al*., 2020) and the expansive soil of Santa Maria da Boa Vista-PE obtained in this article are presented in Table 6. The differences in the values of the expansion voltage are associated with the voltage trajectory followed in its determination before and after the flood. The order in which the soil is loaded and flooded or flooded and loaded or even flooded and charged simultaneously to prevent expansion significantly influences the value of the swelling pressure in addition to the very heterogeneity of the soil formation process. The values of the mean, standard deviation and coefficient of variation of the swelling pressure are strongly influenced by the stress trajectory and soil formation.

Table 6 – Swelling pressure values obtained in different soils and methods.

		Swelling pressure (kPa)					
	Swelling Pressure Method	**Servilha – Spain Delgado (1986)**	**Pesqueira-PE (Silva; Ferreira, 2007)**	**Petrolândia-PE, Ferreira e Ferreira (2009)**	**Cabrobó-PE Barbosa (2013)**	**Paulista-PE Ferreira *et al.* (2020)**	**Santa Maria da Boa Vista-PE Authors (2025)**
1	Loading after expansion with different overloads	260	168	333	90	145	242
2	Expansion and collapse under stress	150	365	239	100	213	105
3	Constant volume	193	110	242	87	169	81
4	Double Edometer	290	180	308	-	-	320
5	Rao *et al.* (1988)	--	140	330	120	-	120
6	Justo *et al.* (1984)	200	310	277	80	-	220
-	Average	218	212	271	95	176	181
-	Standard deviation	56	101	42	15	34	94
-	Coefficient of Variation %	27	46	19	7	16	43

Source: Authors (2025).

Figures 6b, 6c, 6d, 6e and 6f show the results of the methods used to determine swelling pressure. Expansion deformations decrease over time as the vertical flood stresses increase (10, 20, 80, 160, and 320 kPa), with collapse occurring at 640 kPa (Figure 6a). In fact, during the deformation process caused by flooding over time, what is evaluated is the resultant of the deformation processes. After the stabilization of expansion deformations, the soil is compressed during the stress stage until it returns to zero deformation (Figure 6b).

The mean values of the swelling pressure obtained in method 1 (Loading after expansion with different overloads), in method 2 (Expansion and collapse under stress), in method 3 (Constant volume), in method 4 (Double edometric) were 242 kPa, 105 kPa, 81 kPa and 320 kPa, respectively (Figures 6b, 6c, 6d e 6e). In the method 5 (Rao et al., 1988) and in method 6 (Justo et al., 1984), the mean values of the swelling pressure were 320 kPa (Figure 6e) and 220 kPa, respectively. Its determination depends on both the flood curve under strees and the loading curve at constant moisture (Figure 6f). The initial stress state of the soil (void index, applied vertical stress and suction) influences the volume variation when flooded. Similar behavior was reported by Delgado (1986), Schreiner (1987), and Ferreira; Vilar (2023).

According to criterion of Jimenez Salas (1980), the undeformed soil is classified as having possible serious damage to buildings, considering the average value of the swelling pressure (181.38 kPa). In compacted soil at optimum moisture and maximum dry specific weight, the value of the Swelling pressure by the Constant Volume Method is 81.25 kPa, being classified by the same criterion with possible damage from important cracks. After the addition of CDW to the soil, there was a reduction in the values of the Swelling pressurees, and the soil-CDW mixtures are classified with possible damage from small cracks.

The addition of CDW to the expansive soil of Santa Maria da Boa Vista-PEand the addition of sand to the expansive soils of Ipojuca-PE (STIVES, 2017) and Paulista-PE (CONSTANTINO, 2018) decreased the "Free" Expansion (Figure 7a) and the Swelling pressure, (Figure 7b). Although the expansive soils mentioned are from different locations, with different values of "Free" Expansion and Swelling pressurees when compacted and with different materials added, it is pertinent to make some comparisons of the effect of adding granular materials to expansive soils. Considering only the addition of 30% of sand, it is observed that there is a reduction of 31% (Figure 7c) and 55% (Figure 7d) in the values of the "Free" Expansion and the Swelling pressure of the soil of Ipojuca-PE, respectively; there is a reduction of 18% (Figure 7c) and 67% (Figure 7d) in the values of "Free" Expansion and Swelling pressure of the soil of Paulista-PE, respectively.

Considering the same percentage of 30% of CDW to the expansive soil of Santa Maria da Boa Vista-PE, there is a reduction of 93% (Figure 7c) and 75% (Figure 7d) in the values of "Free" Expansion and Swelling Pressure, respectively.

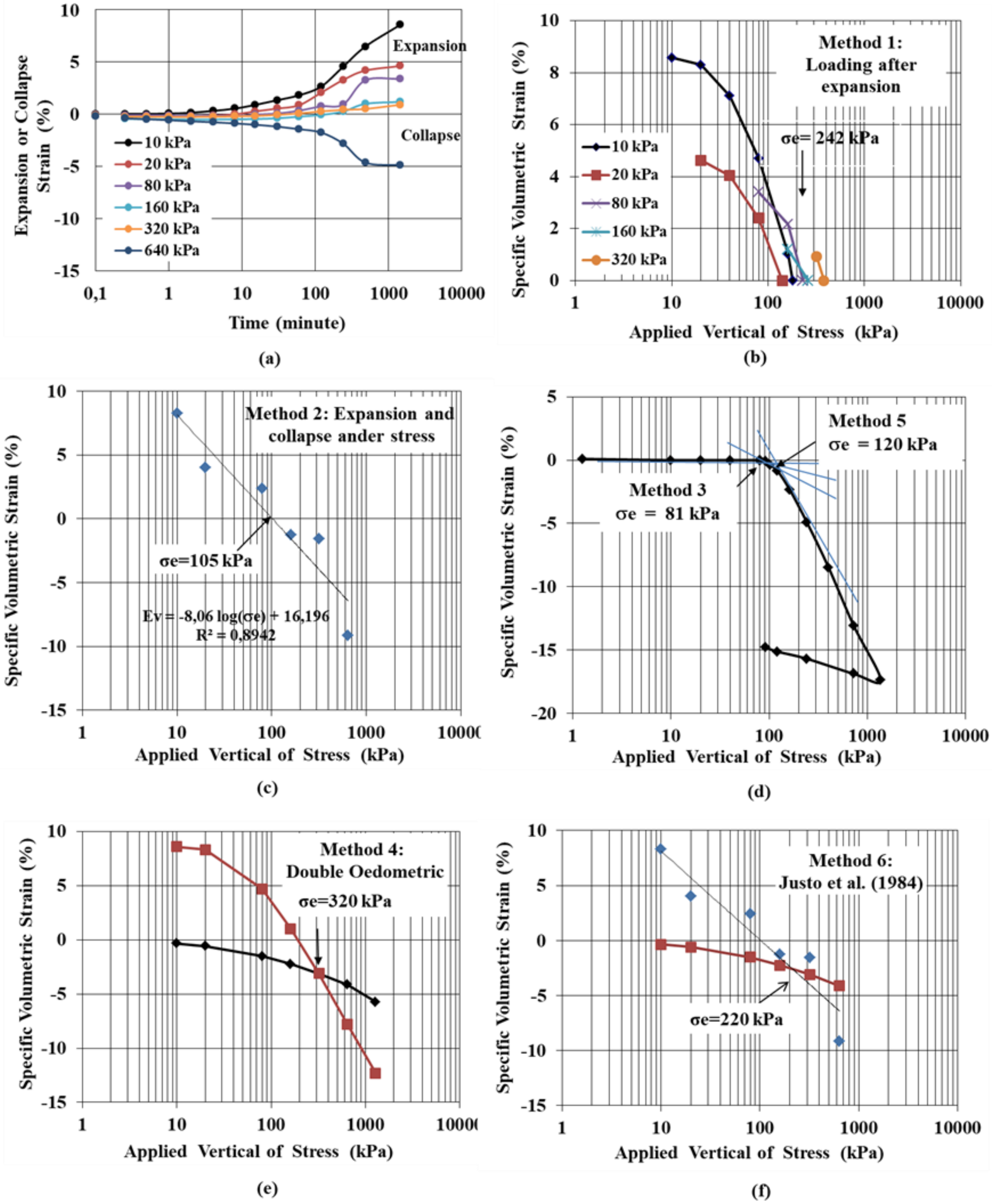


Figure 6 – Methods for determining swelling pressure: (a) Expansion and collapse tests under stress; (b) Method of Loading after expansion; (c) Method of Expansion and Collapse under Stress; (d) Constant volume Method and Rao et al method (1988); e) Double Edometric Method; (f) Justo et al (1984) Method.
Source: Authors (2025).

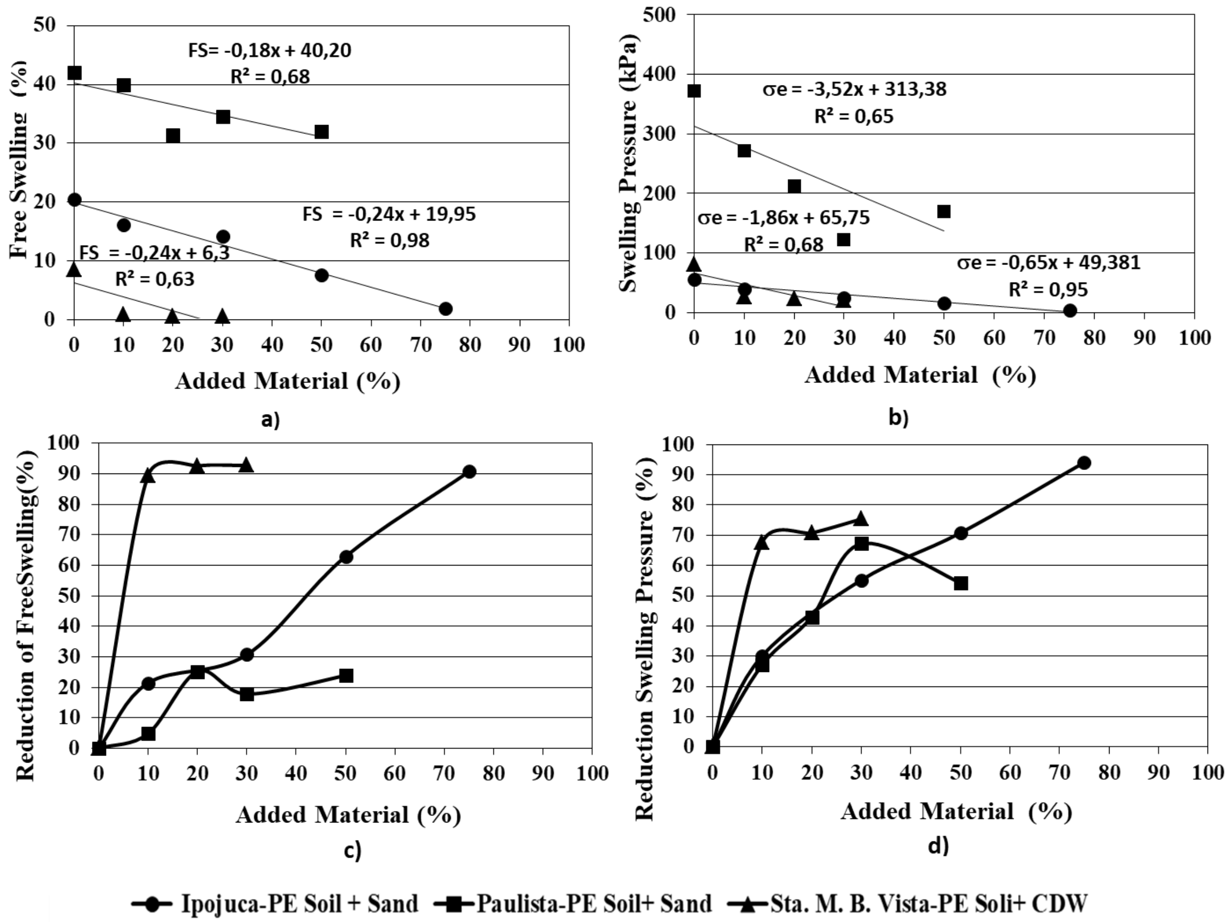


Figure 7 – Values of "Free" Expansion (a), Swelling Pressure (b), Reduction of "Free" Expansion (c) and Reduction of Swelling Pressure in expansive soils and in mixtures of these soils with CDW and sand.
Source: Authors (2025).

The comparison performed does not imply that, in general, the addition of CDW to expansive soils promotes a greater reduction in "Free" Expansion and Expansion Pressure than the addition of sand for the same percentage incorporated. Several factors influence this behavior, including the origin and formation of the soil, mineralogy, clay mineral content, stress state, among others, which affect both the mixing process and the interaction with the added granular material. The results indicate a high potential for CDW addition to reduce the volumetric variation of expansive soils, in addition to contributing to the mitigation of environmental liabilities through its application in soil improvement. It is important to emphasize that adding inert granular material to an expansive soil does not alter the mineralogical composition of the clay minerals. The reduction in expansion is associated with the decrease in the proportion of clay minerals in the mixture for the same compacted volume and under the same compaction energy.

4. Final considerations

The soil was classified as CL (Inorganic clays of low and medium plasticity) and A-6 (clay soils), by the SUCS and TRB classifications, respectively.

The "free" expansion of the pure soil was 8.58%, which, according to the criterion of Vijayvergiya and Ghazzaly (1973), is a high degree of expansiveness. By adding CDW to the soil, the degree of expansiveness became low for the three mixtures. The greatest reduction in the "free" expansion value occurs when adding 30% of RCD to the expansive soil, presenting a value of 0.62%, resulting in a 93% reduction in the "free" expansion value of the soil.

According to the criterion of Jimenez Salas (1980), the soil was classified with possible serious damage considering the average value of its swelling pressure (181.38 kPa) and considering only the value of the swelling pressure by the Constant Volume Method (81.25 kPa) it was classified with possible damage of important cracks. After the addition of CDW to the soil, there was a reduction in the values of the swelling pressurees, classifying the soil-CDW mixtures with possible damage from small cracks. The mixture with 30% RCD reduced the expansion voltage to 20 kPa, representing a reduction of 75.38% in the value of the expansion voltage by the Constant Volume Method. With this, it is possible to verify the efficiency in the improvement of the expansive soil through compaction and replacement by CDW in the proportion of 30%.

The evaluation of the expansiveness of a soil is of great importance, especially in semi-arid regions such as Santa Maria da Boa Vista-PE, because the constructions executed on these soils can present several problems in the structures and foundations, which can be avoided by improving the soil.

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