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Predictive models for the shear strength of municipal solid waste

Modelos de previsão da resistência ao cisalhamento de resíduos sólidos urbanos

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Abstract: The stability of landfill slopes is often compromised by inaccurate estimations of the shear strength parameters of Municipal Solid Waste (MSW), a material characterized by its heterogeneity and dynamic nature. This study aims to develop statistical models capable of predicting the geomechanical parameters (shear stress, cohesion intercept, and friction angle) of MSW with varying ages, moisture contents, and unit weights, under saturated and unsaturated conditions. The experimental program was conducted at the Campina Grande Landfill in Paraíba, Brazil. The methodology employed direct shear tests based on the Mohr-Coulomb failure criterion, utilizing a central composite design with controlled variables. The resulting models exhibited high statistical accuracy and proved to be effective tools for estimating the strength parameters of MSW, offering support for safer and more economically viable landfill designs and operations.

Keywords: Shear Strength; Municipal Solid Waste; Constitutive Model.

Resumo: A estabilidade de taludes em aterros sanitários frequentemente é comprometida por estimativas imprecisas dos parâmetros de resistência ao cisalhamento de resíduos sólidos urbanos (RSU), os quais são heterogêneos e dinâmicos. Neste contexto, o presente estudo objetiva desenvolver modelos estatísticos capazes de predizer parâmetros geomecânicos (tensão cisalhante, coesão interceptada e ângulo de atrito) de RSU com diferentes idades, teores de umidade e pesos específicos, em condições saturadas e não saturadas. O campo experimental foi o Aterro Sanitário de Campina Grande-PB. A metodologia baseou-se em ensaios de cisalhamento direto, seguindo o critério de ruptura de Mohr-Coulomb, com delineamento composto central e variáveis controladas. Os modelos obtidos demonstraram elevada acurácia estatística e se revelaram instrumentos eficazes na estimativa dos parâmetros de resistência dos RSU, podendo subsidiar projetos e operações mais seguros e economicamente viáveis em aterros sanitários.

Keywords: Resistência ao Cisalhamento; Resíduos Sólidos Urbanos; Modelo Constitutivo.

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1. Introduction

The shear strength of Municipal Solid Waste (MSW) is a critical parameter in the analysis of landfill slope stability. However, accurately determining this parameter remains challenging due to the complex nature of MSW, which is influenced by factors such as material composition, biodegradation processes, and operational practices. As noted by Norberto et al. (2020), MSW is composed of heterogeneous materials, each exhibiting distinct mechanical behavior and undergoing progressive transformation over time.

Throughout the development of the field, various models have been developed to predict the shear strength of MSW. Researchers such as Stoll (1971), Dixon and Jones (2005), Remédio (2014), Norberto et al. (2020), Sheng et al. (2021), and Wang et al. (2024) have contributed to this field, primarily focusing on the geomechanical aspects of landfill stability while neglecting the influence of waste transformation processes. A more comprehensive investigation is therefore required to better characterize the variability of key parameters influencing MSW shear strength, including age, unit weight, and moisture content.

The stability of landfills is significantly influenced by waste biodegradation processes, as demonstrated by Landva and Clark (1986), Faria (2002), Loureiro (2005), and Khaleghi et al. (2024). To mitigate the risk of landfill failure, it is essential to consider the temporal evolution of shear strength parameters as the waste undergoes aging.

The shear strength and service life of a landfill are directly influenced by the unit weight of MSW (Hanson et al., 2010; Karimpour-Fard et al., 2021) and the moisture content within the landfill. The presence of liquids can reduce the effective stress, consequently leading to lower shear strength values (Martins, 2006).

The unit weight of MSW serves not only as a key parameter for quantitative waste characterization (Ayuba et al., 2013) but also facilitates the determination of other essential physical properties, such as void ratio, porosity, and degree of saturation. Moreover, it constitutes a fundamental variable in landfill slope stability analyses (Hettiarachchi et al., 2007; Reddy et al., 2011; Bareither et al., 2012; Karimpour-Fard et al., 2021). It is important to note that the unit weight of landfilled waste varies over time, directly influencing the shear strength behavior of the material.

According to Boscov (2008) and Andrades (2018), the moisture content of MSW is a challenging parameter to quantify, as its diverse components possess varying water contents. Assessing the moisture content of waste within the waste body allows for the evaluation of whether environmental conditions are conducive to biodegradation. Richard et al. (2019) noted that materials with 30% moisture content tend to inhibit microbial activity, while environments with moisture levels above 65% promote slow decomposition.

Numerous studies have investigated the shear strength characteristics of solid waste, including works by Zekkos et al. (2010), Bareither et al. (2012), Shariatmadari et al. (2017), Alidoust et al. (2018, 2021), Pulat and Yukselen-Aksoy (2019), Dehdari (2022), Xie et al. (2022), Fei (2023), Norberto et al. (2024), and Chen et al. (2024). These studies highlight significant challenges in developing a comprehensive understanding of the shear behavior of MSW, which exhibits substantial spatial variability. Furthermore, laboratory characterization of MSW properties remains complex and time-consuming. In this context, predictive modeling emerges as a practical alternative, offering more efficient and economical estimation of MSW properties while accommodating diverse scenarios compared to conventional experimental approaches.

Accurately determining the shear strength parameters of MSW remains a significant challenge, particularly due to the limitations associated with conventional field and laboratory testing methods. These constraints highlight the need to explore alternative approaches for the estimation of these parameters. Reliable characterization is essential, as the application of inappropriate shear strength parameters is fundamentally compromised when waste properties are poorly defined. Therefore, the proper selection of shear strength parameters is critical for the design and operation of landfills, which must adhere to stringent technical standards. Inadequate parameterization can result in operational failures with severe socio-environmental consequences (Gulnihal et al., 2021; Osra et al., 2021; Morita et al., 2021; Hussein et al., 2021; Singh et al., 2021; Chetri and Reddy, 2021; Lindamulla et al., 2022; Vaverková et al., 2022; Bahia et al., 2024).

A significant research gap exists in the application of artificial intelligence techniques to characterize the dynamic properties of MSW. The development of reliable predictive methods for waste shear strength parameters represents a novel contribution that could substantially enhance landfill design practices. This study aims to develop statistical models for predicting shear strength parameters of MSW in landfills, accounting for temporal variations in waste properties.

2. Methodology

2.1 Experimental setup and waste collection

The study was conducted at the Campina Grande Landfill (ASCG), situated approximately 10 km from the urban center of Campina Grande in the district of Catolé de Boa Vista, Paraíba, Brazil.

Recently landfilled waste was collected from the most recent disposal cell, containing waste deposited within the preceding eight days. Six representative samples were obtained from this area, capturing waste accumulated over one week from all municipalities served by the ASCG.

Subsequently, MSW samples with one and two years of landfilling were collected based on the documented disposal history of the landfill cells. Sampling locations were selected according to operational records indicating the disposal periods for each landfill sector. The age of the samples was verified through landfill records and corroborated by the manufacturing or expiration dates found on product packaging retrieved from the sampling points. Figure 1 presents the spatial distribution of the sampling locations, and Figure 2 illustrates the ASCG site layout with georeferenced details.

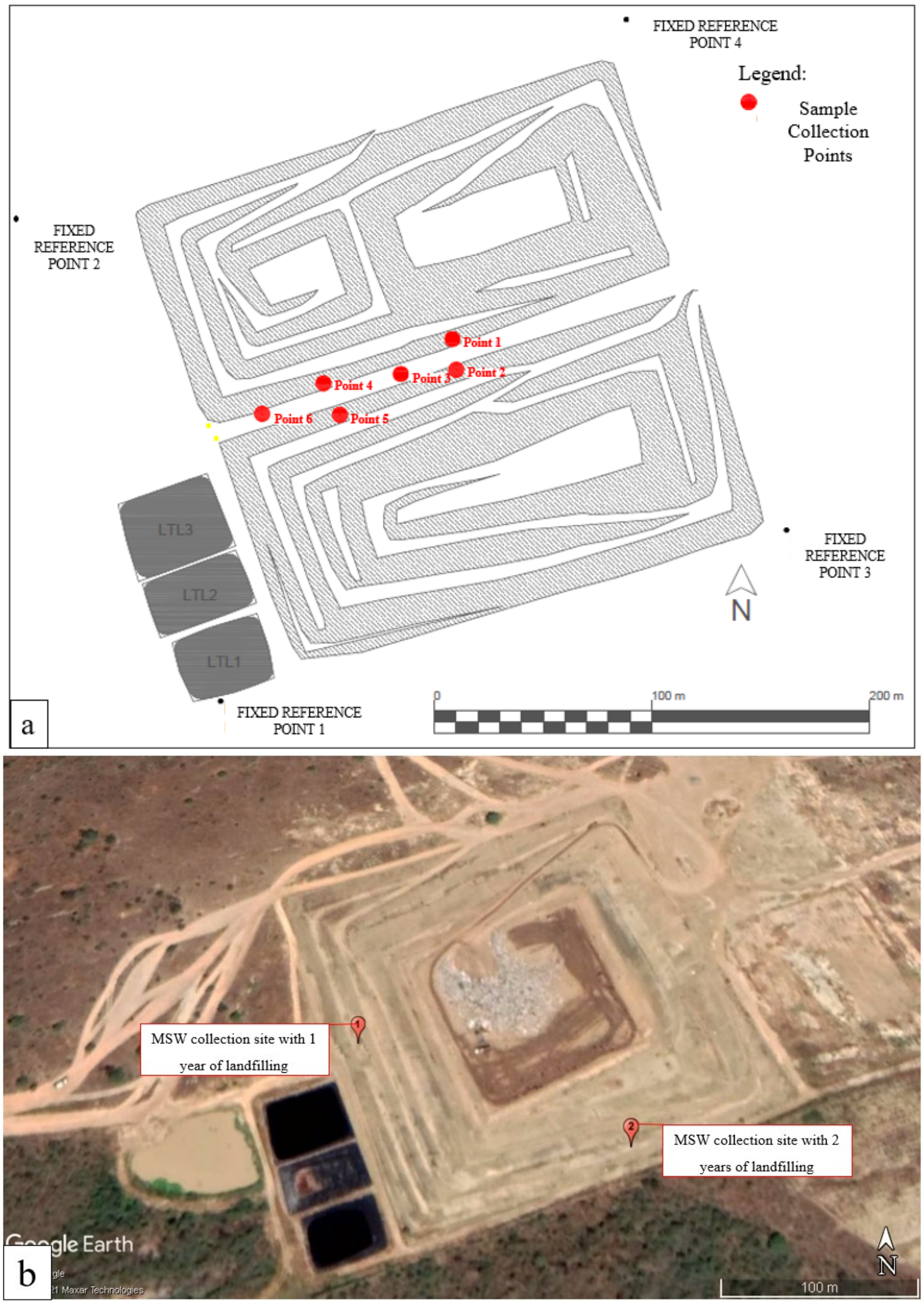

Figure 1 – Locations of waste collection: (a) recently landfilled waste; (b) waste with 1 and 2 years of landfilling.
Source: Authors (2022).

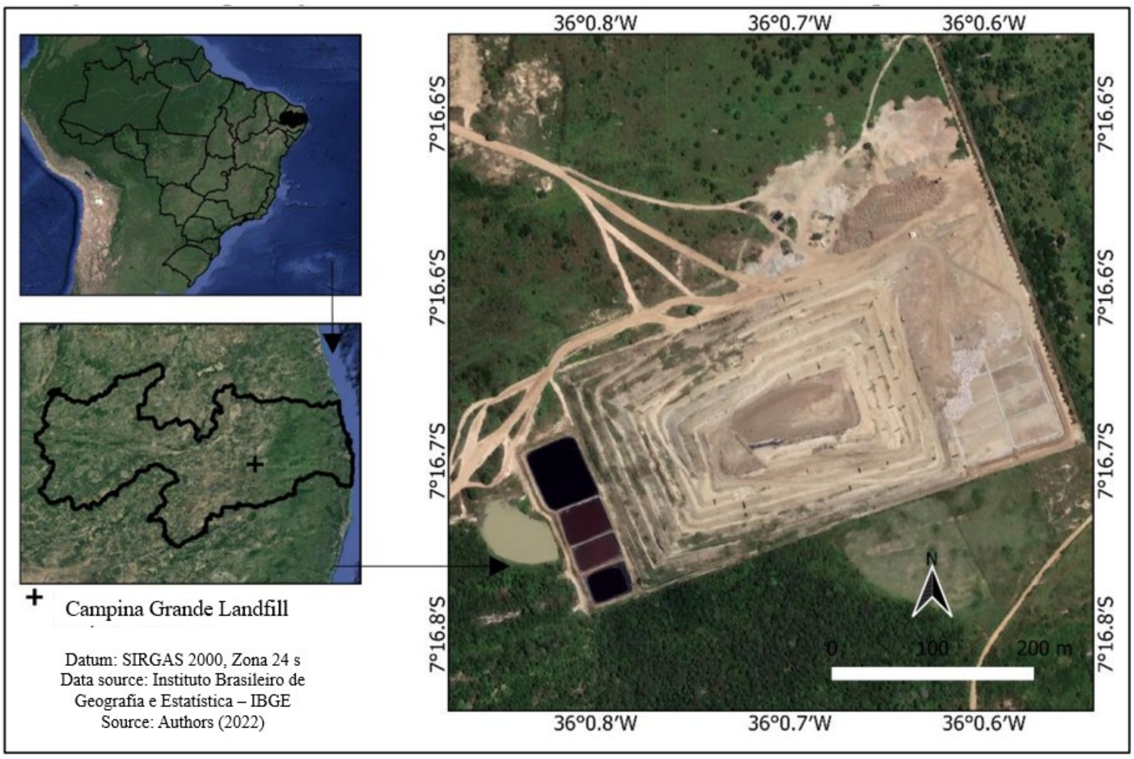

Figure 2 – Georeferenced map of the Campina Grande Landfill (ASCG).
Source: Bezerra (2023).

2.2 Shear strength of waste

Shear strength characterization of waste was performed through direct shear testing under both saturated and unsaturated conditions. The investigation focused on quantifying variations in strength parameters (cohesion intercept and internal friction angle) with respect to waste age, moisture content, unit weight, and applied normal stress. In the absence of standardized protocols for MSW shear testing, established soil mechanics procedures were implemented following the Mohr-Coulomb failure criterion and ASTM D3080 (ASTM, 2011). This methodological approach aligns with previous work by Gabr and Valero (1995), Abreu and Vilar (2017), Pulat and Yukselen-Aksoy (2017), Singh and Uchimura (2023), and Norberto et al. (2024) in MSW shear behavior analysis.

The experimental program employed a two-level factorial design incorporating three factors with three central point replicates. This configuration enabled a comprehensive evaluation of different scenarios to which the waste may be subjected in the landfill. The testing matrix was consistently applied to three waste age categories: recently disposed, 1-year-old, and 2-year-old MSW.

Table 1 details the independent variables in the experimental design, with shear stress serving as the response variable. The analysis accounted for interdependent variations in unit weight, moisture content, and normal stress across different waste ages.

Table 1 – Factorial design matrix for analyzing the shear strength of municipal solid waste landfilled at different ages.

Variables	**Level**		
	-1	**0**	**+1**
Unit weight (kN/m^3)	10	12.5	15
Moisture content (%)	34	49.5	65
Normal stress (kPa)	50	175	300

Source: Authors (2022).

The unit weight levels adopted in this study were established based on typical values reported in the literature. According to the bibliographic survey conducted by Ramaiah et al. (2017), although unit weight exhibits variability, it generally ranges between 10 and 15 kN/m³. Consequently, this range (10-15 kN/m³) was selected as the experimental domain for unit weight evaluation. Normal stress application spanned 50 to 300 kPa, representing overburden pressures equivalent to waste depths of approximately 5 m to 30 m (assuming γ = 10 kN/m³). These values align with those reported by Zekkos et al. (2006) and Boscov (2008) as average values of unit weight for surface-collected MSW.

Moisture content levels were determined according to Ribeiro (2012), who investigated an experimental MSW landfill in Campina Grande, reporting seasonal variations from 34% (dry season) to 65% (rainy season). The experimental range was accordingly set at -1 (34%) to +1 (65%) to account for regional climatic variations, particularly relevant as Campina Grande constitutes the primary waste source for the studied landfill.

The experimental program employed a Central Composite Design (CCD) with two levels, three factors, and three central point replicates. Direct shear testing was conducted under both saturated and unsaturated conditions using identical factor levels (Table 2). The comprehensive testing regime comprised 66 total tests: 22 tests per waste age category (0, 1, and 2 years), with each age group including 11 saturated and 11 unsaturated condition tests.

Table 2 – Factorial design matrix for analyzing the shear strength of municipal solid waste landfilled at different ages.

Experiments	Unit weight (kN/m³)	Moisture content (%)	Normal stress (kPa)
1	10	34	50
2	15	34	50
3	10	65	50
4	15	65	50
5	10	34	300
6	15	34	300
7	10	65	300
8	15	65	300
9 (C*)	12.5	49.5	175
10 (C*)	12.5	49.5	175
11 (C*)	12.5	49.5	175

C: central point.*
Source: Authors (2022).

2.3 Statistical modeling of shear strength parameters of waste

A multiple linear regression model (Equation 1) was implemented to quantify the relationship between the experimental variables and shear stress response. This analytical approach facilitated both shear stress estimation and subsequent derivation of shear strength parameters for municipal solid waste across different landfill ages.

$$\tau = \mathrm{a} + b_1x_1 + b_2x_2 + b_3x_3 + \cdots + b_kx_k \qquad (1)$$

Where:
τ = shear stress;
a = slope parameter for the i-th predictor variable;
S = number of independent variables;
b1 = regression coefiecient for the predictor x_1;
b2 = regression coefiecient for the predictor x_2;
b3 = regression coefiecient for the predictor x_3;
b_k = regression coefiecient for the predictor x_k.

The statistical significance of the developed models and the relative influence of individual factors were evaluated through Pareto analysis and Analysis of Variance (ANOVA). Statistically significant factors affecting shear stress were subsequently incorporated into adjusted models, which were visualized using response surface and/or contour plot representations. Model performance was quantified using the coefficient of determination (R^2) and further validated through residual analysis.

The validity and significance of the multiple linear regression coefficients were evaluated through comprehensive regression analysis. Model adequacy was assessed by verifying compliance with the fundamental assumptions of residual normality and homoscedasticity. Diagnostic evaluation employed normal probability plots and residual-versus-predicted value plots, complemented by observed-versus-predicted value plots to examine model linearity. Nonlinear patterns in these diagnostic plots would indicate potential inadequacy of the linear regression approach, necessitating consideration of alternative modeling strategies such as nonlinear regression or variable transformations.

3. Results and discussion

Table 3 summarizes the descriptive statistics of shear stress measurements obtained through factorial design experimentation for landfilled waste.

Table 3 – Descriptive statistics of shear strenth measurements for landfilled waste.

Age of waste	**Recently landfilled**		**1 year**		**2 years**	
Saturation condition	UNSAT	SAT	UNSAT	SAT	UNSAT	SAT
Sample size (kPa)	11	11	11	11	11	11
Mean (kPa)	108	78	133	123	116	96
Median (kPa)	112	79	137	127	106	101
Standard deviation (kPa)	65.3	49	71	65	68	56
Coefficient of variation	60%	62%	53%	52%	59%	58%
Maximum value (kPa)	219	175	251	205	226	191
Minimum value (kPa)	18	29	34	27	12	21
Amplitude (kPa)	201	146	217	178	214	170

UNSAT: Unsaturated; SAT: Saturated
Source: Authors (2022).

According to Table 3, the shear stress values ranged from 146 to 217 kPa. For all tested conditions, the coefficients of variation exceeded 50%, highlighting the significant variability in the shear stress behavior of confined MSW. The experimental results demonstrate significant shear stress variability in confined waste materials, even among samples with identical composition and age. Despite similar composition and age among the MSW samples, variations in their three-dimensional molecular structure may occur. These structural variations can evolve temporally through physicochemical and biological processes, directly influencing shear stress behavior and potentially explaining the observed value discrepancies.

Additional variables including normal stress, unit weight, and molding moisture content significantly contribute to MSW shear stress variability. These findings suggest that central tendency measures may be inadequate when waste properties are poorly characterized. Kavazanjian (2001), Reddy et al. (2009), and Reddy et al. (2011) have similarly reported wide variations in shear strength parameters. These results underscore the need to identify key factors influencing MSW shear behavior and develop more accurate predictive models.

Table 4 summarizes the analysis of variance (ANOVA) results for the factorial design experiments, presenting the determination coefficients (R^2) of the developed models at a 5% significance level. The analysis encompasses all investigated waste ages under both saturated and unsaturated conditions.

Table 4 – R^2 values for the generated residual models.

Age of waste	**R^2**	
	UNSAT	SAT
Recently landfilled waste	0.997	0.908
1 year of landfilling	0.997	0.995
2 years of landfilling	0.988	0.983

Source: Authors (2025).

As shown in Table 4, the generated models explain more than 90% of the process variability, regardless of MSW age or saturation state. This indicates that the models provide a strong fit and are capable of adequately capturing the behavior of the waste under the conditions investigated.

The failure envelopes were derived from Equations (2) through (7), which represent the models developed from the factorial design for each tested scenario.

$$\tau = -154.28 + 0.47 * \sigma + 16.59 * \gamma + 2.12 * w + 0.01 * \sigma * \gamma - 0.24 * \gamma * w \quad (2)$$

$$\tau = -80.80 + 0.45 * \sigma + 5.97 * \gamma + 1.93 * w + 0.018 * \sigma * \gamma - 0.006 * \sigma * w - 0.13 * \gamma * w \quad (3)$$

$$\tau = -90.13 + 0.59 * \sigma + 7.95 * \gamma + 0.67 * w + 0.017 * \sigma * \gamma - 0.0042 * \sigma * w - 0.021 * \gamma * w \quad (4)$$

$$\tau = -73.66 + 0.86 * \sigma + 8.98 * \gamma + 0.49 * w + 0.023 * \sigma * \gamma - 0.0002 * \sigma * w - 0.017 * \gamma * w \quad (5)$$

$$\tau = -239.12 + 0.73 * \sigma + 19.70 * \gamma + 3.13 * w - 0.003 * \sigma * w - 0.24 * \gamma * w \quad (6)$$

$$\tau = 46.42 + 0.33 * \sigma - 0.96 * \gamma + 1.39 * w + 0.025 * \sigma * \gamma - 0.0041 * \sigma * w - 0.086 * \gamma * w \quad (7)$$

Where:
τ = shear stress (kPa);
σ = normal force (kPa);
γ = unit weight (kN/m³);
w = molding moisture content (%).
Table 5 summarizes the scenarios corresponding to each equation.

Table 5 – Rupture envelope equations.

Equation	Scenario
Equation (2)	Recently landfilled waste under unsaturated condition
Equation (3)	Recently landfilled waste under saturated condition
Equation (4)	1-year-old waste under unsaturated condition
Equation (5)	1-year-old waste under saturated condition
Equation (6)	2-year-old waste under unsaturated condition
Equation (7)	2-year-old waste under saturated condition

Source: Authors (2022).

Residual analysis was performed using normal probability plots (Figure 3). The residuals adhere closely to a normal distribution, exhibiting minimal deviation from the reference line, thereby satisfying the normality assumption. Thus, no evidence of non-normality was detected in the residual distribution.

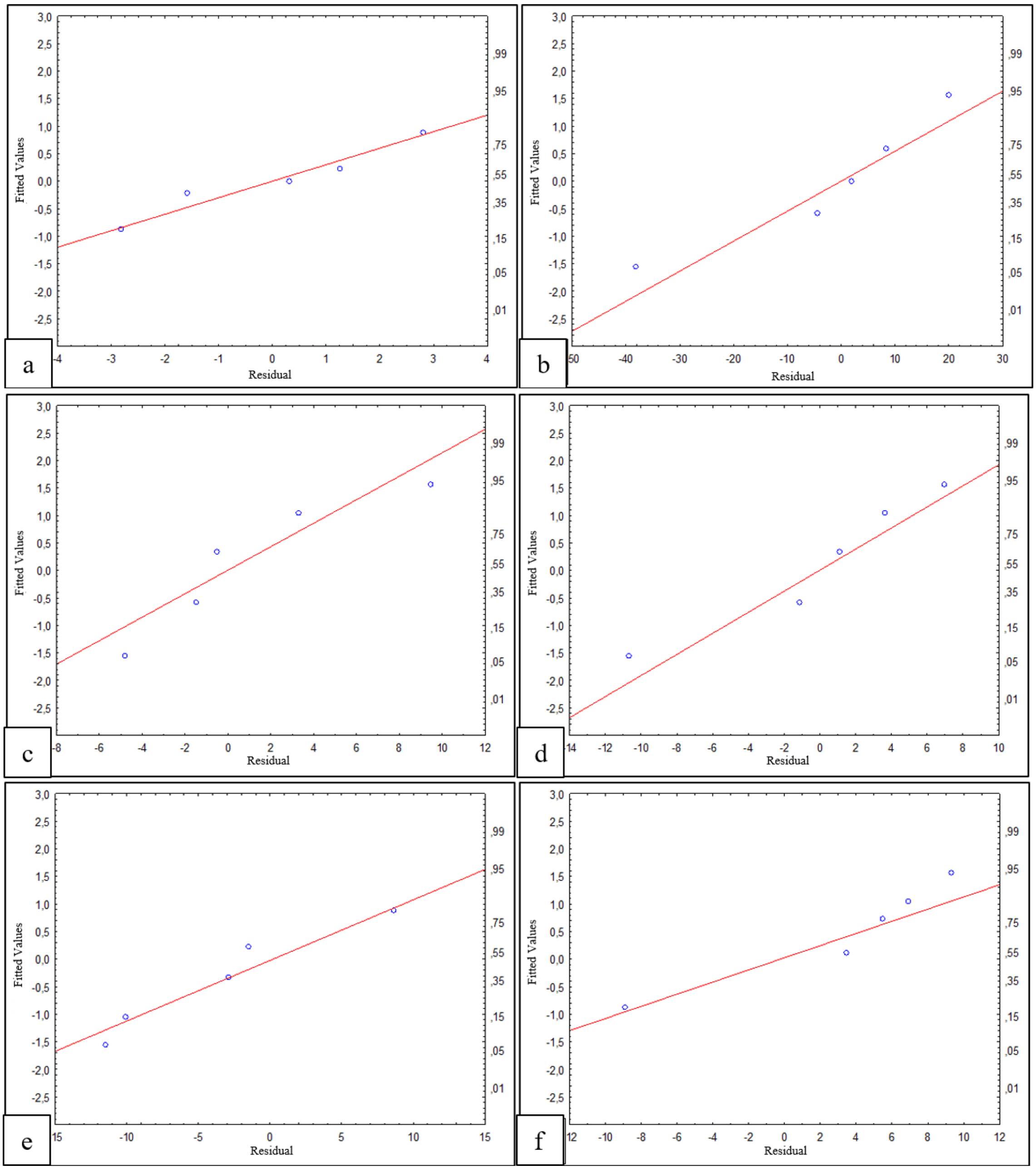

Figure 3 – Normal probability plots of the residuals from the models predicting shear stress in unsaturated conditions for MSW aged 0 (a), 1 (c), and 2 (e) years, and in saturated conditions for MSW aged 0 (b), 1 (d), and 2 (f) years.
Source: Authors (2022).

Figure 4 compares experimentally measured and model-predicted shear stress values for MSW. The close agreement between observed and predicted values aligns with the variance analysis results, confirming good model performance. All developed models demonstrate satisfactory predictive capability for determining MSW shear stress.

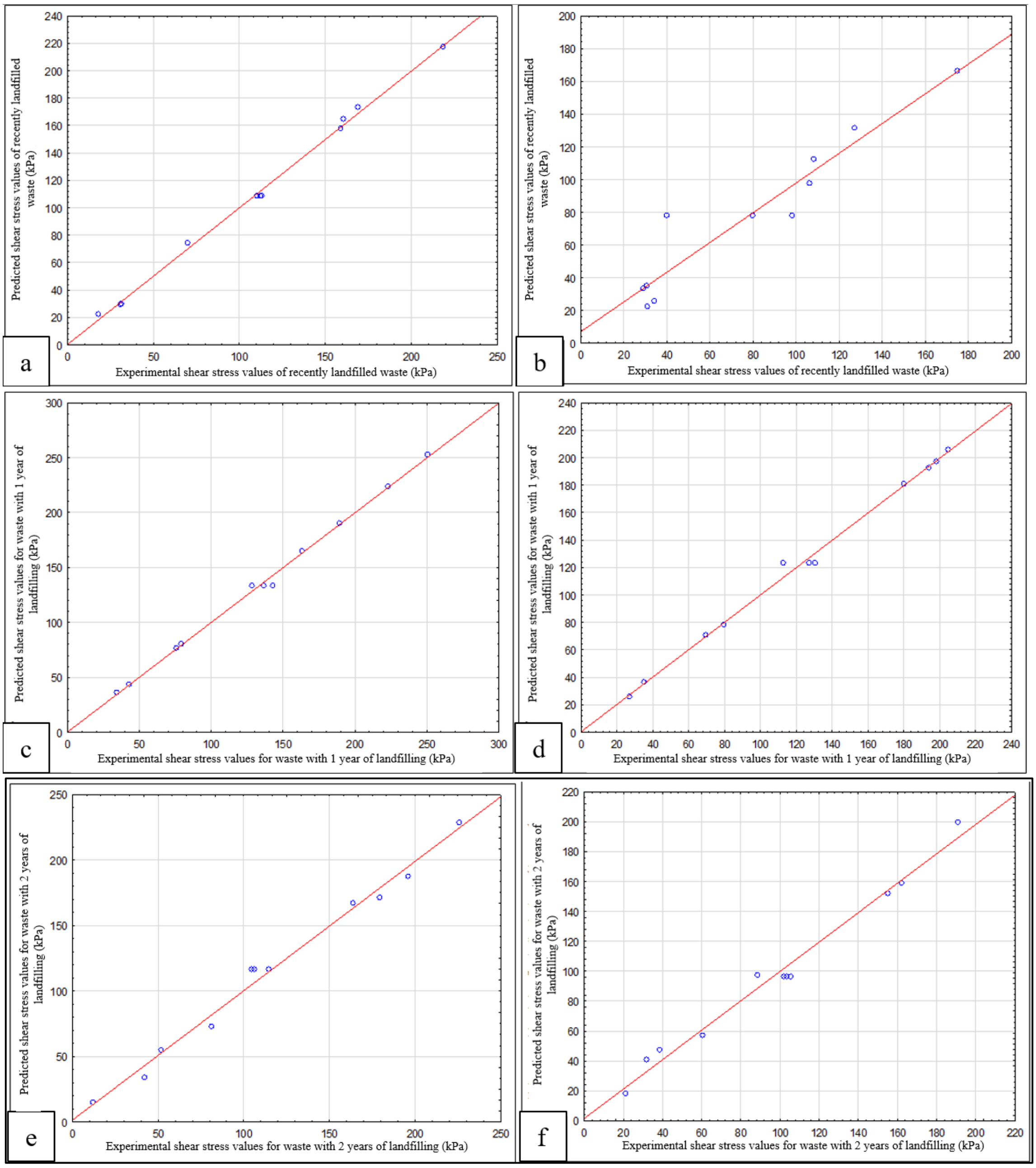

Figure 4 – Experimental versus predicted values from the shear stress prediction models under unsaturated conditions for MSW aged 0 (a), 1 (c), and 2 (e) years, and under saturated conditions for MSW aged 0 (b), 1 (d), and 2 (f) years.
Source: Authors (2022).

Thus, the MSW shear stresses were calculated using Equations (2) - (7), which enabled the determination of cohesion intercepts and friction angles. These equations yielded failure envelopes (shear stress vs. normal stress) for waste at 0, 1, and 2 years of landfilling, covering the boundary conditions specified in the factorial design under both saturated and unsaturated states (Figure 5).

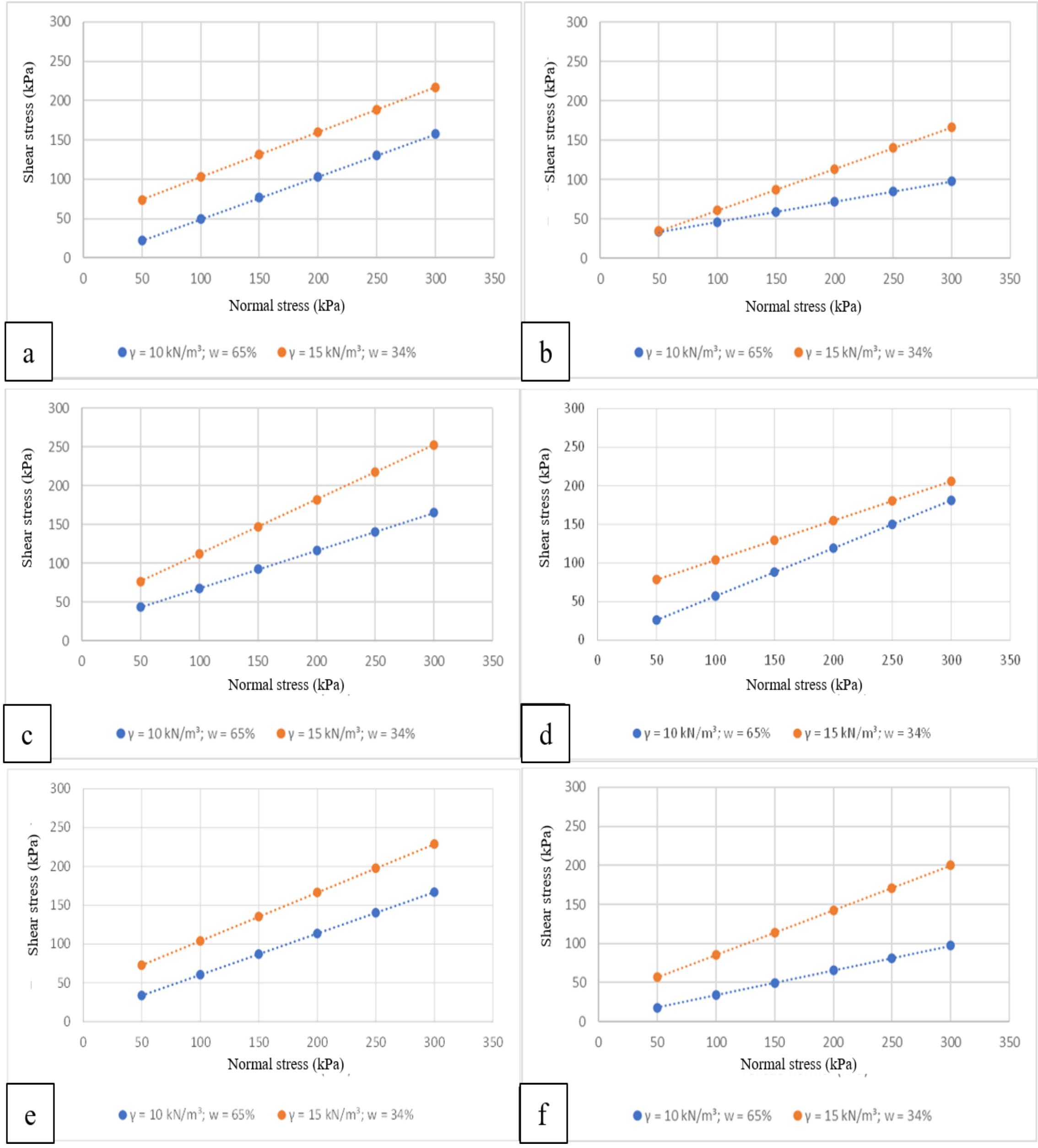

Figure 5 – Shear strength envelopes for municipal solid waste (MSW) with 0 (a), 1 (c), and 2 (e) years of age under unsaturated conditions, and with 0 (b), 1 (d), and 2 (f) years of age under saturated conditions. Source: Authors (2022).

Figure 5 demonstrates that specimen saturation reduces waste shear stresses and diminishes the influence of unit weight on shear strength. Under saturated conditions, MSW experiences decreased particle proximity and organic particle softening, which collectively affect both unit weight and its effectiveness as a strength parameter.

Unit weight governs the mobilization of internal friction and apparent cohesion in MSW, particularly where waste microstructure plays a critical role (Bareither et al., 2012; Gulnihal et al., 2021). Denser specimens develop enhanced shear resistance through increased fiber entanglement, overlapping plastic layers, and greater interparticle contact density (Alemayehu et al., 2024).

The influence of water content on shear strength is more complex. Under unsaturated conditions, water adsorbed within the pores induces capillary suction, which can enhance apparent cohesion. However, as water content approaches saturation, this cohesive effect diminishes, and the pore water begins to act as a lubricant, reducing internal friction and promoting structural rearrangement, ultimately leading to a decrease in shear strength (Chen et al., 2023).

Table 6 presents the characteristic shear strength parameters for the failure envelopes displayed in Figure 5.

Table 6 – Strength parameters.

Test condition	Age of waste (year)	Unit weight (kN/m³)	Water content (%)	Friction angle - φ (°)	Cohesion - c (kPa)
Unsaturated	0	10	65	28.4	0
		15	34	29.7	45.4
	1	10	65	25.9	19.1
		15	34	35.2	41
	2	10	65	28.0	7.0
		15	34	31.9	41.6
Saturated	0	10	65	14.4	20.6
		15	34	27.7	8.6
	1	10	65	31.8	0
		15	34	27.0	52.9
	2	10	65	17.6	2.0
		15	34	29.7	28.4

Source: Authors (2022).

The friction angle exhibited little to no variation for MSW with lower unit weight (10 kN/m³) and higher water content (65%) across all three landfilling ages (0, 1, and 2 years) under unsaturated conditions. In these specimens, cohesion increased from 0 kPa to 19.1 kPa between 0 and 1 year of backfilling, and from 0 kPa to 7 kPa between 0 and 2 years. Conversely, specimens with higher unit weight and lower moisture content exhibited increasing friction angles with decreasing cohesion under unsaturated conditions. Saturated specimens demonstrated progressive increases in both friction angle and cohesion with waste aging.

The lowest shear strength values were observed in samples under saturated conditions. This reduction can be attributed to the loss of matric suction and the consequent increase in pore water pressures, which diminish shear resistance. The influence of suction in MSW remains a complex topic, with no definitive characterization of its behavior currently established (Araujo, 2024; Silva, 2024). Existing interpretations of MSW behavior are largely based on investigations originally developed for soils. However, the role of matric suction in unsaturated conditions is still not fully defined, even for conventional soil materials. Given that MSW typically exhibits more complex properties than soils, the effect of suction in this material remains a subject of ongoing investigations. Nonetheless, an analysis of MSW behavior in the presence of liquids confirms that the saturated condition is the most critical, yielding the lowest shear strength values.

The analysis of waste aging effects reveals a consistent increase in MSW shear strength with landfilling time. The measured friction angles and cohesion values align with established literature under comparable testing conditions (Gabr & Valero, 1995; Reddy et al., 2009, 2011, 2015; Shariatmadari et al., 2014; Pulat & Yukselen Aksoy, 2017). Although these findings suggest discernible behavioral trends, the two-year evaluation period constitutes a relatively short timeframe. A more comprehensive understanding of the aging effects on MSW would require analysis over extended landfilling durations.

In the Brazilian literature, a wide range of cohesion and friction angle values has been reported for municipal solid waste (Abreu and Vilar, 2017; Jucá et al., 2021; Bahia et al., 2024; Norberto et al., 2024). This variability is likely influenced by multiple factors, including differences in moisture content, climatic conditions, and landfill operational practices (Bareither et al., 2020; Akbari et al., 2022; Dehdari et al., 2022). Furthermore, the distinct gravimetric compositions of waste across different landfills significantly contribute to the observed variability in shear strength parameters (Bahia et al., 2024).

4. Final considerations

- The factorial design-derived models effectively predicted MSW shear stress across the investigated ranges of waste age, moisture content, and normal stress for saturated and unsaturated conditions, demonstrating robust statistical fit and reliable estimation capability.
- The shear strength of MSW samples increases with normal stress, primarily due to enhanced interparticle contact within the waste matrix.
- MSW shear strength increases with aging, as the degradation of organic components and the rising proportion of fibrous content enhance interparticle interaction, resulting in greater shear resistance.
- Water saturation of waste reduces shear strength, while water content variations up to 64% maintain shear resistance.
- The developed models support geotechnical analyses and landfill design by enabling predictions of slope stability and assessments of structural failure risks, particularly in scenarios where direct testing methods (laboratory and field tests) are economically unfeasible.
- The evaluated timeframe (0 to 2 years of landfilling) constrains the extrapolation of these findings to more advanced stages of decomposition. Future research should investigate MSW from broader geographic regions and over longer timeframes to strengthen the empirical basis.

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