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Shear strength of municipal solid waste rejected from material recovery facilities in the city of São Paulo, Brazil

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Case Study

Keywords
Municipal solid waste
Sorting
Shredding
Compaction
Friction angle
Cohesion

Abstract

The mechanical behavior of municipal solid waste (MSW) is a critical issue in environmental geotechnics, given the pollution and public health risks associated with slope failures. In Brazil, waste composition is expected to change due to the hierarchy of sustainable practices established by the National Solid Waste Policy, which aims to improve the recovery of organic and recyclable materials. Not much progress has been made since the implementation of this law; thus, its effects on the design and operation of landfills are not fully clear. This study presents and discusses compaction and shear strength parameters of dry MSW after mechanical sorting of medium and large recyclable items and shredding. The maximum dry unit weight for the standard Proctor compaction test ranged from 6.6 to 10.0 kN/m^3 and the optimum moisture content ranged from 20% to 42%. Stress-displacement curves of direct shear tests showed strain hardening and shear strength parameters of Mohr-Coulomb envelopes were displacement-dependent. The friction angle ranged from 3.2° to 42.9° and the cohesion intercept ranged from 1.3 to 31.3 kPa, at a displacement of 9 mm (15% of the specimen length). These results are in line with the literature, since a high content of waste materials that proved to affect geotechnical properties, such as plastic, paper, cardboard, textile, and glass, remained after pre-treatment.

1. Introduction

Due to the increasing generation of municipal solid waste (MSW) worldwide and the impact of improper disposal sites on the environment and public health, the circular economy model has gained attention (Kaza et al., 2018). The National Solid Waste Policy was implemented in Brazil by Federal Law No. 12,305/2010, providing for the following targets: non-generation reduction, reuse, recycling, treatment, and environmentally adequate final disposal (Brasil, 2010). Despite its introduction over the past decade, the transition from a conventional waste management system to an integrated system has been slow, unevenly taking place across the country. Waste materials are usually source-separated into dry (recyclable and non-recyclable) and wet (organic) streams in cities with a selective collection program (Lima et al., 2018). Less than 3% of dry materials are estimated to be recycled, and an even lower percentage of organic waste is treated (Brasil, 2022).

Many authors have assessed the environmental, economic, and social effects of different reverse logistics scenarios, including material recovery facilities (MRFs), waste pickers cooperatives, mechanical-biological treatment (MBT), and thermal treatment of MSW (Leme et al., 2014; Maier & Oliveira, 2014; Ferri et al., 2015; Lima et al., 2018; Fuss et al., 2020; Rodrigues & Mondelli, 2022). However, information is missing on how the hierarchy of the law can affect the design and operation of landfills (van Elk & Boscov, 2016). With treatment alternatives becoming available, typical values of properties and parameters essential to landfill engineering may evolve due to changes in the waste stream (Kavazanjian, 2006).

Previous studies showed that the stress-strain response of waste is controlled by friction forces between granular particles and tensile forces of fibrous components, which is similar to results found for reinforced soils (Machado & Karimpour-Fard, 2011; Marçal et al., 2020). Only friction forces act at low strains (concave downward curve), according to Kölsch (1995). When tensile forces are mobilized, the overall shear strength gradually exceeds frictional strength (concave upward curve), reaching a peak and decreasing when fibers tear and slip out at high strains (concave downward curve). The model suggests that tensile strength increases with normal stress since fiber anchoring improves. The failure envelope is therefore bilinear. The author classified particles smaller than 8 mm as grains (three sides short) and larger than 8 mm as fibers (one side long, two sides short), foils (two sides long, one side short), and boxes (three sides long). Large-scale direct shear tests performed by Bray et al. (2009) and Zekkos et al. (2010) showed that the shear strength of MSW

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is highly anisotropic. Fibers were classified as particles larger than 20 mm, mostly made of soft plastic, paper, wood, and gravel. When fibers were parallel to the horizontal shear plane, the stress-displacement curve was concave downwards until reaching the maximum displacement of the testing device. Fiber orientation angles other than 0° provided concave upward stress-displacement curves and higher shear stress values. These studies also highlighted the influence of unit weight (γ) and displacement rate.

The average composition of MSW in Brazil is 45.3% food, garden, and wood waste, 16.8% plastic, 10.4% paper and cardboard, 5.6% textile, leather, and rubber, 2.7% glass, 2.3% metal, 1.4% multilayered packaging, and 15.5% sanitary, contaminated recyclable, unidentified, and incorrectly sorted waste (ABRELPE, 2020). Maximizing the recovery of recyclable and organic materials may result in changes in shear strength, compressibility, and permeability compared with the currently considered parameters. Direct shear and triaxial tests on fresh and aged MSW samples from many locations showed a strain-hardening behavior attributed to the reinforcing effect of plastic, textile, and other fibrous components (Vilar & Carvalho, 2004; Martins, 2006; Cardim, 2008; Karimpour-Fard et al., 2011; Abreu, 2015; Araújo Neto et al., 2021). High organic matter contents and biodegradation, which affects the extent of settlements, physical properties, and pore pressures, were related to variations in the long-term mechanical response of Brazilian landfills (Melo et al., 2016; Abreu & Vilar, 2017; Jucá et al., 2021).

These findings suggest that data from laboratory testing, field measurements, and back analyses performed to date may not be suitable for future landfills. This study aims to present and discuss compaction and shear strength parameters of MSW rejected from MRFs in the city of São Paulo, where some progress has been made in waste management. The presented results contribute to the database on MSW in Brazil and provide mechanical properties required for the analysis of slope stability of landfills in order to ensure safety and prevent pollution and health risks. Pre-treated dry waste can be used for other geotechnical purposes, such as backfill and embankment construction, if geoenvironmental parameters are suitable.

2. Materials and methods

2.1 MSW samples

In São Paulo, the most populated city in Brazil, with over 12 million inhabitants (IBGE, 2022), waste management services are provided by Ecourbis Ambiental, which is in charge of the southeastern region (989.86 km^2), and Logística Ambiental de São Paulo (LOGA), in charge of the northwestern region (535.56 km^2). In total, 14 sampling campaigns were conducted in material recovery facilities managed by Ecourbis (MRF-Ecourbis) and Loga (MRF-Loga) from May 2017 to May 2018. According to the local authority, MRFs received part of the 91 thousand tons of dry waste from the selective collection performed door-to-door and in pick-up points during the sampling period (SPREGULA, 2022). Materials were sorted by size, mass, and shape, using rotating sieves and ballistic separators. Metals were detected using magnetic and inductive sensors and plastic, paper, and cardboard were detected using air blowers (2D items) and optical sensors (3D items). Recyclable items separated at every step were manually analyzed before shipment for commercialization (Correa et al., 2022).

MSW samples were collected from input and rejected streams of both MRFs. The material was shredded in a knife mill with a final sieve of 6 mm and stored at 4° C after gravimetric and particle size distribution analyses to enable the subsequent laboratory testing program. Mondelli et al. (2022) discussed in detail the geoenvironmental characterization of all samples. In this study, geotechnical characterization tests were performed only for MSW from the rejected stream. On average, its composition included 7.0% paper, 6.8% cardboard, 0.6% non-ferrous metal, 0.3% ferrous metal, 1.6% Tetra Pak packaging, 15.8% glass, 23.3% plastic, 3.5% textile, 0.8% rubber, 1.2% wood, 1.6% styrofoam, 1.6% electronic waste, 35.6% rejects (e.g., food, garden waste, used napkins, and used diapers), and 0.3% hazardous waste. Table 1 shows the composition of each campaign.

2.2 Compaction tests

Standard Proctor compaction tests were performed on MSW samples collected during campaigns 1 and 6 at each MRF. The material was placed in three layers into a 1,000-cm^3 mold. Each layer was compacted with 26 blows using a 2.5-kg hammer falling from a height of 30.5 cm (energy = 583 kJ/m^3), according to ABNT (2016). After determining the total weight of mold plus waste, duplicate samples were dried at 65°C for 24 hours. The standard temperature of 100°C was not used to avoid mass loss. This procedure was repeated five times to obtain the correlation between dry unit weight (γ_d) and moisture content (w).

2.3 Direct shear tests

Direct shear tests were performed on MSW samples collected during campaigns 2, 3, 4, 5, and 7 at each MRF. The material was placed in the Proctor mold in a single layer compacted with 26 blows and then transferred to the 60 mm square shear box. Compaction was not conducted in the shear box due to the circular shape of the hammer, preventing it from reaching the corners. Figure 1 describes the steps.

The normal stress range was chosen based on the age of samples at the time of the testing program (2-3 years) and compaction parameters from standard Proctor tests. Feng et al. (2017) collected 0.3-, 2-, and 4-year-old samples from the Laogang landfill, in China, at depths of 4, 11, and

Table 1. Composition of MSW rejected from MRFs in the city of São Paulo (Mondelli et al., 2022).

Material (%)	Campaigns at MRF-Ecourbis							Campaigns at MRF-Loga						
	1	2	3	4	5	6	7	1	2	3	4	5	6	7
Paper	9.9	0.0	1.6	2.4	5.4	0.0	2.6	10.2	11.7	24.7	12.9	3.1	9.8	3.1
Cardboard	7.1	0.0	0.0	2.5	2.6	0.2	0.3	1.4	1.5	45.5	17.1	9.4	0.0	7.4
Non-ferrous metal	0.2	0.0	0.0	0.0	1.8	0.0	0.2	0.5	4.4	0.0	0.0	0.0	0.8	0.0
Ferrous metal	0.8	1.1	0.1	0.3	0.0	0.0	0.0	0.6	0.8	0.0	0.0	0.0	0.0	0.0
Tetra Pak	2.1	5.5	0.7	1.5	1.8	3.4	0.9	0.0	1.9	0.0	0.0	2.6	1.6	0.0
Glass	45.4	22.1	19.6	12.8	23.6	11.7	24.7	26.6	2.9	10.9	9.9	3.7	5.0	2.8
1-PET	3.2	2.3	4.3	5.5	2.8	2.8	4.7	6.6	15.6	0.3	3.0	1.7	0.7	1.7
2-HDPE	1.6	0.4	0.0	2.3	0.1	0.7	0.4	20.5	4.5	0.1	0.3	4.0	0.0	1.2
3-PVC	0.0	0.0	0.2	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4-LDPE	0.5	1.3	2.6	3.6	1.8	0.7	2.4	0.7	1.7	4.5	1.0	3.4	1.3	2.1
5-PP	0.9	1.0	0.9	1.0	1.0	1.2	0.3	11.0	12.6	0.7	0.3	2.6	0.8	1.2
6-PS	0.0	0.9	0.4	0.1	0.0	0.0	0.0	1.0	1.4	0.4	0.2	0.7	0.5	0.6
7-Others	8.5	5.0	0.2	0.3	1.1	0.2	0.1	2.7	9.4	0.9	0.8	1.1	0.1	0.0
Non-identified plastic	0.0	7.5	13.7	20.1	6.9	6.3	9.7	0.8	1.6	4.5	16.3	10.9	14.2	23.3
Textile	2.1	8.4	0.2	1.2	0.1	0.0	2.5	1.3	0.0	0.5	5.2	6.6	13.6	7.1
Leather	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rubber	0.0	0.0	0.0	2.4	0.0	0.0	0.0	2.8	5.8	0.0	0.2	0.0	0.0	0.2
Wood	0.8	0.0	2.9	0.3	6.1	0.0	0.0	0.4	6.3	0.0	0.0	0.0	0.0	0.0
Styrofoam	0.5	2.8	1.7	1.2	1.6	0.4	0.5	1.3	1.5	2.3	1.0	6.3	0.5	1.4
Electronic	0.1	0.6	3.0	8.0	0.0	4.0	0.8	0.9	1.3	0.0	0.0	0.9	0.0	2.8
Rejects	14.1	41.1	47.7	34.2	43.0	67.5	49.7	9.8	15.2	4.7	31.9	42.9	51.2	45.3
Hazardous	2.2	0.0	0.1	0.2	0.0	0.5	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0

16 m, respectively. Specimens in this study were consolidated and sheared at 50, 100, and 150 kPa to simulate depths of 10 to 15 m, considering a range from 5 to 10 kN/m^3 for γ_d. The displacement rate should be estimated as the ratio between the relative lateral displacement and the total time estimated for failure, according to ASTM (2011). However, no failures occurred up to the maximum displacement of the device (about 11 to 12 mm) during previous tests on the material. The rate of 0.3 mm/min was adopted, in line with other studies with shredded MSW (Bareither et al., 2012; Zhao et al., 2014).

3. Results and discussion

3.1 Compaction tests

Figure 2 shows compaction curves. The maximum dry unit weight ($\gamma_{d,max}$) was 9.5 and 10.0 kN/m^3 and the optimum moisture content (w_{opt}) was 20% and 21% for MSW samples collected during campaigns 1 and 6 at MRF-Ecourbis, respectively. Moreover, $\gamma_{d,max}$ ranged from 6.6 to 8.1 kN/m^3 and w_{opt} ranged from 30% to 42% for samples collected during campaigns 1 and 6 at MRF-Loga, respectively. These parameters were similar to other studies in Brazil (Calle, 2007; Araújo Neto et al., 2021). From the fourth to the fifth compaction test on the sample collected during campaign 1 of MRF-Loga, there was a slight decrease in the dry unit weight. But, in general, γ_d remained almost constant with w increasing above 30%. This possibly occurred due to the difficulty in compacting on the wet side of w_{opt} since the material may not densify when it is close to full saturation. Similar behavior was observed in compaction curves of MSW presented by Gabr & Valero (1995) and Reddy et al. (2009).

Pulat & Yukselen-Aksoy (2013) showed that $\gamma_{d,max}$ decreases and w_{opt} increases as the paper, cardboard, plastic, or organic content increase in synthetic waste samples tested in the modified Proctor test. These effects may explain the findings of this study. Considering both campaigns 1, the lowest $\gamma_{d,max}$ and the highest w_{opt} of the sample from MRF-Loga can be associated with increased plastic content compared with MRF-Ecourbis (43.2% against 14.7%). In the case of both campaigns 6, the lowest $\gamma_{d,max}$ and highest w_{opt} of the sample from MRF-Loga can be associated with increased paper and plastic content compared with MRF-Ecourbis (9.8% against 0% and 17.6% against 12.2%, respectively).

3.2 Direct shear tests

Figures 3 and 4 show the results of duplicate direct shear tests (1 and 2) on MSW samples collected during campaigns 2, 3, 4 5, and 7 at MRF-Ecourbis and MRF-Loga, respectively. The primary consolidation of all specimens was completed in a few minutes, as they were shredded and compacted. Most stress-displacement curves have a continuous concave-downward shape. Two hypotheses were suggested for strain hardening regardless of specimen composition and applied normal stress, based on the findings of other studies with direct shear tests:

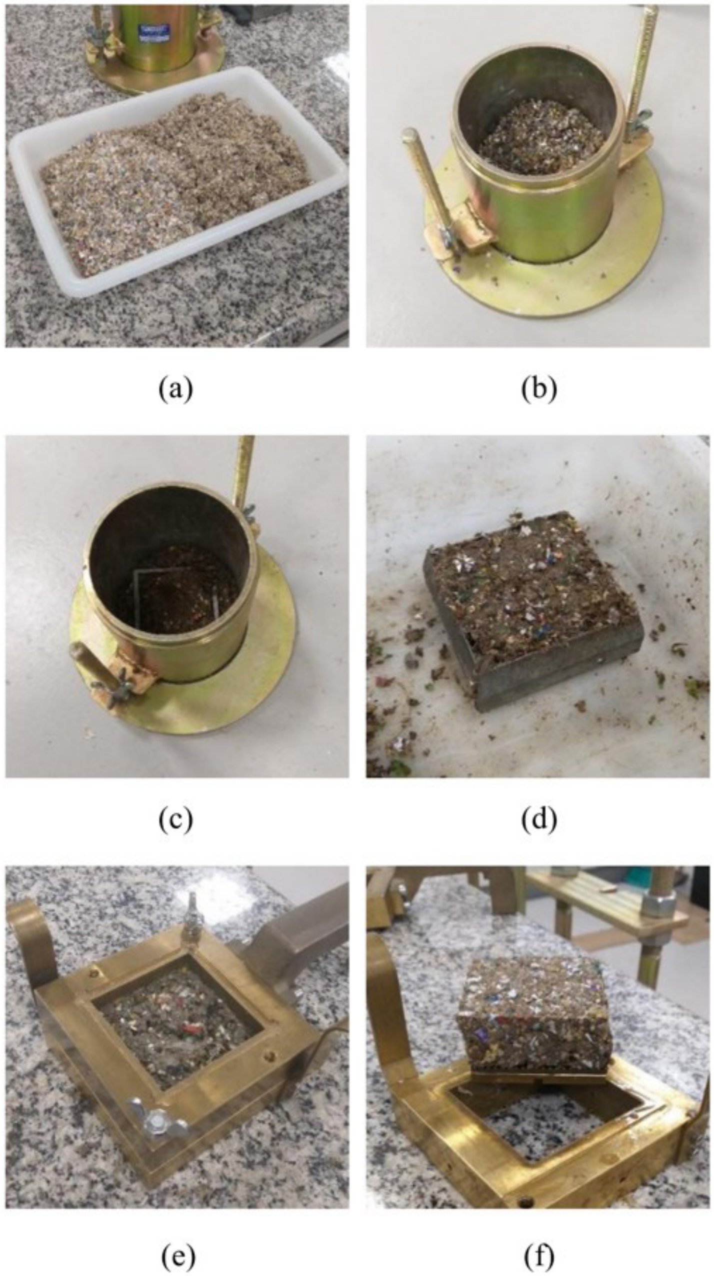

Figure 1. Direct shear test: (a) MSW sample, (b) placement into the mold, (c) single-layer compaction, (d) specimen preparation, (e) transfer to the shear box, and (f) specimen after shearing.

(1) Frictional strength controlled shear strength because soft plastic, paper, textile, wood, and other fibrous particles were shredded into sizes too small to produce a reinforcing effect, but the displacement range was insufficient to fully mobilize it.
(2) Fibers generated tensile forces that contributed to the overall response, regardless of their particle size, but to a minor extent because they were nearly parallel to the shear plane after compaction (Zekkos et al., 2010).

Displacements of 5% to 20% of the specimen length are commonly adopted to obtain shear strength envelopes in the absence of failure or peak strength (Abreu, 2015), as observed in this study. The chosen displacements were 3, 6, and 9 mm or 5%, 10%, and 15% of the specimen length, respectively. A displacement of 12 mm was not included because it was not reached in some tests. Figures 3 and 4 show Mohr-Coulomb envelopes at the third displacement level. No significant discontinuities were found; thus, the linear

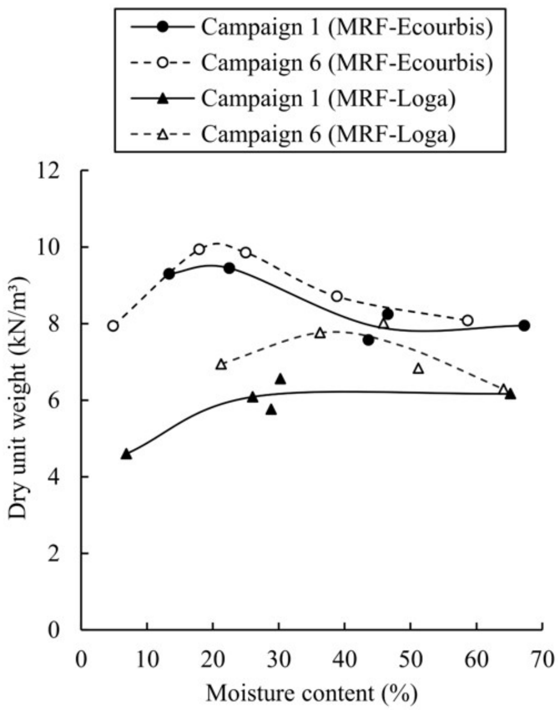

Figure 2. Standard Proctor compaction curves of MSW rejected from MRFs in the city of São Paulo.

failure criterion was reasonably adequate to describe the relationship between shear and normal stresses ($R^2 \geq 0.7331$). Both the friction angle (ϕ) and cohesion intercept (c) were displacement-dependent (Tables 2 and 3).

3.3 Data analyses

Table 4 presents the conditions and results of many direct shear tests on MSW performed in Brazil. Different displacement failure criteria were adopted, but this table includes only shear strength parameters at a displacement of 10% of the specimen length to enable comparison. Figure 5 shows that most ϕ and c values are in line with the literature, except for the sample collected during campaign 3 at MRF-Loga, for which ϕ was lower than 8°. The composition of this sample includes 70% paper and cardboard, and the corresponding specimens were prepared at moisture contents above 130%. Previous studies reported the ϕ of 33° for shredded paper (Gabr et al., 2007). Thus, excess pore pressures may have caused low friction angles. Although the initial plan was to compact specimens at moisture contents close to the optimum values, transferring them to the shear box was feasible after adding water.

A considerable variation in the cohesion intercept was observed, even between duplicates (e.g., c increased from

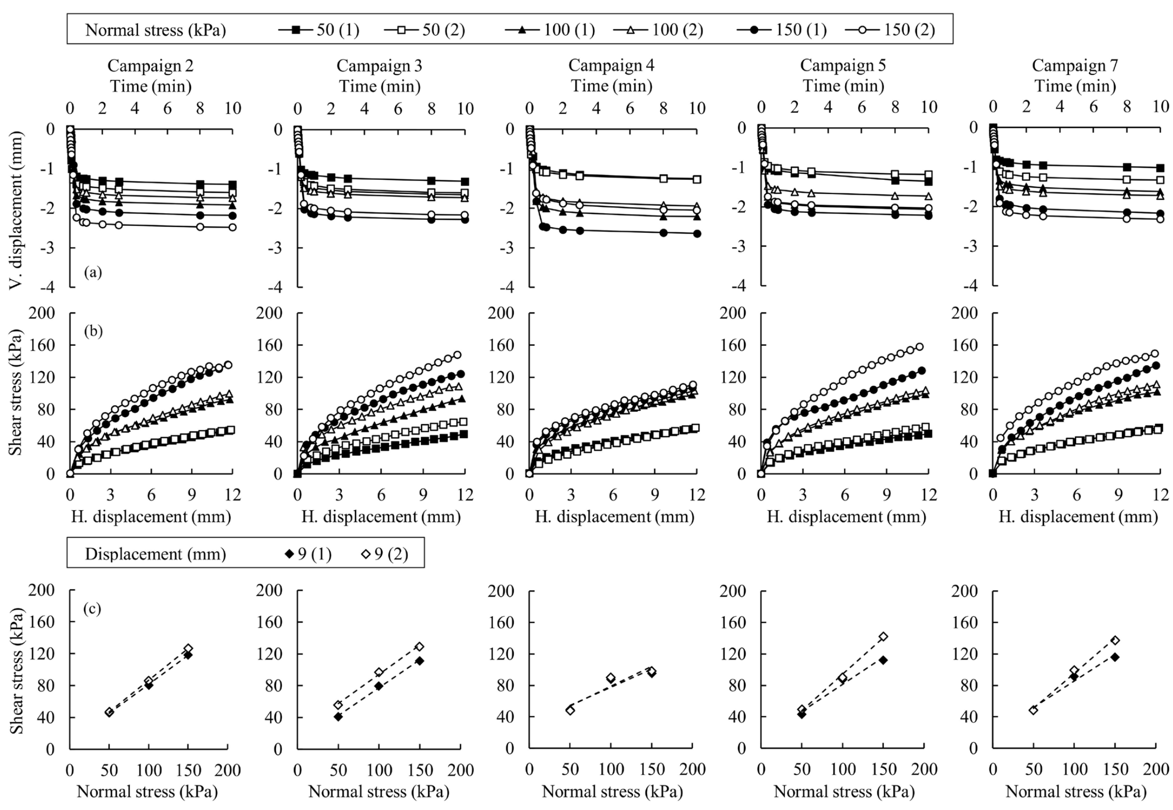

Figure 3. Duplicate direct shear tests performed on MSW rejected from MRF-Ecourbis: (a) consolidation curves, (b) stress-displacement curves, and (c) Mohr-Coulomb envelopes.

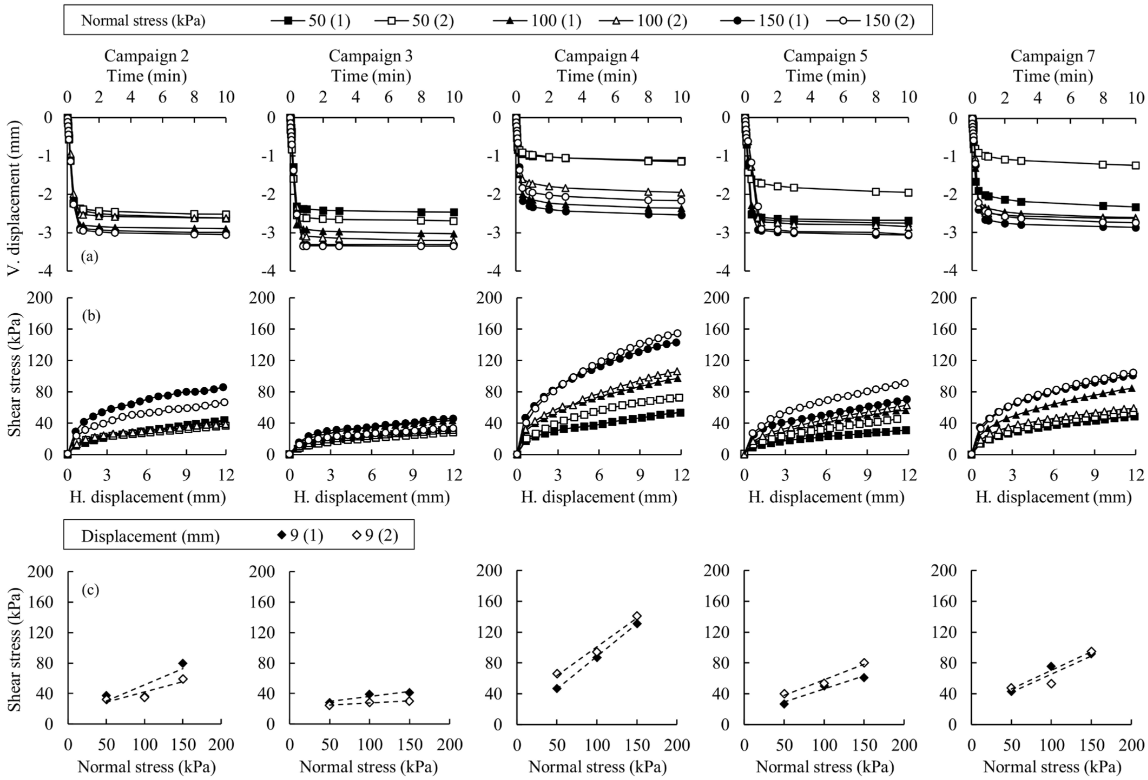

Figure 4. Duplicate direct shear tests performed on MSW rejected from MRF-Loga: (a) consolidation curves, (b) stress-displacement curves, and (c) Mohr-Coulomb envelopes.

Table 2. Shear strength parameters of MSW rejected from MRF-Ecourbis.

Displacement (mm)	Test	Campaign 2		Campaign 3		Campaign 4		Campaign 5		Campaign 7	
		ϕ (°)	*c* (kPa)	ϕ (°)	*c* (kPa)	ϕ (°)	*c* (kPa)	ϕ (°)	*c* (kPa)	ϕ (°)	*c* (kPa)
3 (5%)	1	21.5	7.5	24.0	1.0	19.4	16.7	25.9	3.3	20.3	13.7
6 (10%)	1	29.6	8.3	30.6	3.4	22.4	24.6	29.1	10.7	28.8	16.0
9 (15%)	1	36.1	8.7	35.1	7.1	24.8	31.3	34.6	12.2	34.0	18.2
3 (5%)	2	27.2	0.0	24.1	12.1	23.5	6.0	28.9	1.7	29.2	1.5
6 (10%)	2	34.2	2.4	31.8	15.1	25.8	17.0	37.8	0.0	36.1	5.3
9 (15%)	2	38.5	7.0	36.3	20.7	26.7	28.4	42.9	1.3	41.8	6.0

Table 3. Shear strength parameters of MSW rejected from MRF-Loga.

Displacement (mm)	Test	Campaign 2		Campaign 3		Campaign 4		Campaign 5		Campaign 7	
		ϕ (°)	*c* (kPa)	ϕ (°)	*c* (kPa)	ϕ (°)	*c* (kPa)	ϕ (°)	*c* (kPa)	ϕ (°)	*c* (kPa)
3 (5%)	1	18.4	1.0	7.5	12.0	29.0	2.0	13.5	5.9	19.5	11.5
6 (10%)	1	21.9	3.9	6.8	19.3	36.5	0.6	15.6	10.5	23.2	17.8
9 (15%)	1	23.0	8.9	7.4	23.1	40.2	3.9	18.8	12.3	25.8	21.9
3 (5%)	2	10.1	12.0	3.7	12.8	24.4	16.2	16.5	7.3	18.9	9.3
6 (10%)	2	13.8	12.1	3.4	17.7	31.3	22.8	19.9	12.3	22.3	15.3
9 (15%)	2	15.0	15.2	3.2	22.0	36.8	26.1	22.0	17.7	25.2	18.4

Table 4. Summary of direct shear tests on MSW performed in Brazil.

Author (year)	Description	Max. particle size (mm)	Initial conditions		Displacement (mm) [a]	ϕ (°)	c (kPa)
			γ (kN/m³)	w (%)			
Lamare Neto (2004)	MBT waste	19.0	8.3	-	-	42.6 [c]	6.0 [c]
	MBT waste	9.5	7.3	-	-	37.2 [c]	11.0 [c]
Martins (2006)	Fresh waste	-	10.0	69	70 (10%)	14.6	21.2
	Fresh waste	-	8.0	68	70 (10%)	16.8	13.5
	MBT waste	-	8.0	56	70 (10%)	10.5	37.1
Calle (2007)	MBT waste	9.5	9.0	-	≈6 (10%) [b]	37.0	34.0
	MBT waste	9.5	6.7	-	≈6 (10%) [b]	34.0	28.0
	MBT waste	2.0	6.7	-	≈6 (10%) [b]	34.0	20.0
	MBT waste	9.5	7.0	-	≈6 (10%) [b]	32.0	50.0
	MBT waste	9.5	5.2	-	≈6 (10%) [b]	34.0	18.0
	MBT waste	2.0	5.2	-	≈6 (10%) [b]	32.0	22.0
Cardim (2008)	Fresh waste	-	6.0	301	100 (10%)	33.2	0.3
	Fresh waste	-	6.0	278	100 (10%)	33.8	0.0
	Fresh waste	-	6.0	274	100 (10%)	28.1	3.1
Abreu (2015)	Landfilled waste	85.0	8.7	42	50 (10%)	18.0	9.8
	Landfilled waste	85.0	10.3	44	50 (10%)	23.0	2.9
	Landfilled waste	85.0	14.3	51	50 (10%)	22.0	3.0
	Landfilled waste	85.0	15.1	51	50 (10%)	23.0	1.9
	Landfilled waste	85.0	9.3	43	50 (10%)	26.0	0.0
	Landfilled waste	85.0	9.1	44	50 (10%)	23.0	2.6
Araújo Neto et al. (2021)	Landfilled waste	30.0	5.7	28	-	16.0 [d]	17.0 [d]
This study	MRF waste	6.0	13.5	63	6 (10%)	29.6	8.3
	MRF waste	6.0	13.4	68	6 (10%)	34.2	2.4
	MRF waste	6.0	13.7	40	6 (10%)	30.6	3.4
	MRF waste	6.0	13.8	44	6 (10%)	31.8	15.1
	MRF waste	6.0	13.7	53	6 (10%)	22.4	24.6
	MRF waste	6.0	14.1	51	6 (10%)	25.8	17.0
	MRF waste	6.0	15.2	49	6 (10%)	29.1	10.7
	MRF waste	6.0	14.8	53	6 (10%)	37.8	0.0
	MRF waste	6.0	13.9	41	6 (10%)	28.8	16.0
	MRF waste	6.0	13.1	41	6 (10%)	36.1	5.3
	MRF waste	6.0	8.7	92	6 (10%)	21.9	3.9
	MRF waste	6.0	7.7	82	6 (10%)	13.8	12.1
	MRF waste	6.0	9.5	148	6 (10%)	6.8	19.3
	MRF waste	6.0	8.6	139	6 (10%)	3.4	17.7
	MRF waste	6.0	12.6	45	6 (10%)	36.5	0.6
	MRF waste	6.0	13.1	49	6 (10%)	31.3	22.8
	MRF waste	6.0	10.8	107	6 (10%)	15.6	10.5
	MRF waste	6.0	10.7	103	6 (10%)	19.9	12.3
	MRF waste	6.0	11.1	104	6 (10%)	23.2	17.8
	MRF waste	6.0	11.7	109	6 (10%)	22.3	15.3

Legend: MBT = Mechanical-biological treatment; MRF = Material recovery facility. [a]Percentage of the specimen length in parentheses. [b]Displacement in mm estimated based on the specimen height of 41.6 mm and strain of 14%. [c]Parameter determined at a normalized displacement of 10%, which correlation with displacement in mm was not reported. [d]Parameter determined at a strain of 10%, which correlation with displacement in mm was not reported.

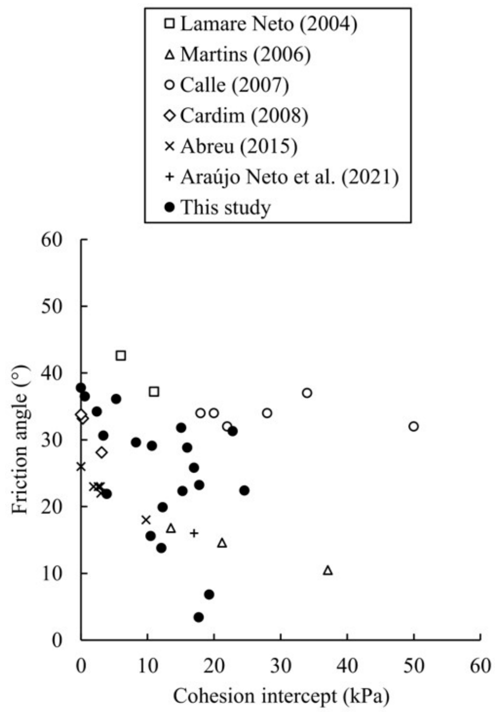

Figure 5. Shear strength parameters of direct shear tests on MSW performed in Brazil.

0.6 kPa in the first test to 22.8 kPa in the second test on the MSW sample collected during campaign 4 at MRF-Loga). Some authors show the influence of soft plastic and fiber content on *c* values (Calle, 2007; Borgatto et al., 2014; Abreu & Vilar, 2017). The wide range was probably due to differences in the internal arrangement of particles and specimen composition from test to test.

4. Conclusion

Pre-treated dry MSW samples from MRFs in the city of São Paulo were tested for compaction and shear strength. Standard Proctor compaction and direct shear tests showed responses similar to previous studies conducted in Brazil. Despite source separation and mechanical sorting, high content of recyclable materials was observed in the rejected stream, highlighting some challenges of implementing the National Solid Waste Policy, such as the contamination with food waste, the lack of plastic identification codes on packaging, and inefficiencies of current reverse logistics systems.

The maximum dry unit weight ranged from 6.6 to 10.0 kN/m^3 and the optimum moisture content from 20% to 42%, depending on the composition of the sample. Shear stress increased up to the maximum displacement in the direct shear test, but its values seemed to be affected by the unit weight and moisture content. The friction angle and cohesion intercept at displacements of 5%, 10%, and 15% of the specimen length varied widely, similar to the literature. Further studies are required to better understand the mechanisms behind the shear strength of shredded MSW, using higher normal stress and displacement levels and a rigorous control of specimen preparation.

In any case, removing biodegradable materials (food and garden waste) and shredding MSW may be advantageous for the monitoring of physical and mechanical properties in landfills. Pre-treatment can help minimize the temporal variation of particle size distribution and the extent of settlements, providing a more homogeneous porous medium. Therefore, permeability, moisture content, unit weight, and shear strength tend to change less over time. However, the spatial variation of geotechnical parameters within the waste mass is expected to be lower if the waste composition is less heterogeneous. This is challenging not only due to the aforementioned factors, but also due to alterations in consumption patterns and the development of new materials that are not recyclable until feasible solutions become available.

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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

Mariana Barbosa Juarez: conceptualization, data curation, methodology, analysis, writing – original draft. Giulliana Mondelli: conceptualization, methodology, supervision, writing – review & editing. Heraldo Luiz Giacheti: discussion, writing – review & editing.

Data availability

All data produced or examined in the course of the current study are included in this article.

List of symbols

c	Cohesion intercept
w	Moisture content
w_{opt}	Optimum moisture content
HDPE	High-density polyethylene
LDPE	Low-density polyethylene
Others	Mixed plastic with or without other material
MSW	Municipal solid waste

PET	Polyethylene terephthalate
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride
γ_d	Dry unit weight
$\gamma_{d,max}$	Maximum dry unit weight
ϕ	Friction angle

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