Geo-environmental and geotechnical characterization of municipal solid waste from the selective collection in São Paulo city, Brazil

Giulliana Mondelli¹ · Mariana Barbosa Juarez¹ · Christiane Jacinto¹ · Márcio Adilson de Oliveira¹ · Lúcia Helena Gomes Coelho¹ · Cinthia Bergamo Biancardi¹ · José Leonardo de Castro Faria¹

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Abstract

This paper presents the characterization of municipal solid waste (MSW) randomly collected from two material recovery facilities in São Paulo city, before (input — recyclables) and after (output — rejects) the sorting processes. Geo-environmental and geotechnical tests were performed on shredded samples and a digestion method was applied to detect the metals As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn concentrations using an ICP OES. The objective was to assist future activities of integrated solid waste management and soil pollution. Results showed different particle sizes comparing the input (44.6%) and the output MSW (75.1%) passing through the 100-mm sieve. Organic matter and ash contents indicated the influence of inorganic carbon due to the plastics' presence, with values varying between 6 and 13%. The pH values obtained were neutral and the electrical conductivity of the MSW rejects suggested a higher amount of ions, with values above 1000 $\mu\text{S}/\text{cm}$. Metals analyses show that Cd, Cu, Ni, Pb, and Zn are present in high concentrations, depending on the types of the materials. Standard Proctor compaction curves yielded maximum dry unit weight varying from 6.6 to 10.0 kN/m^3 and optimum moisture contents from 20 to 42%. Cohesion ranged from 1.3 to 31.3 kPa and friction angle from 3.2 to 42.9°. The results are comparable with those obtained for other countries using different MSW treatments and contribute to the data basis for MSW from the selective collection, aiming the integrated solid waste management, serving for other countries that adopt MSW sorting and recycling.

Keywords Waste management · Contamination · Municipal solid waste characterization · Selective collection · Material recovery facilities (MRFs), Shear strength

Introduction

Municipal solid wastes (MSW) have different physical, chemical, and biological properties because they are very heterogeneous about their geo-environmental and geotechnical parameters. Due to their varied origins, the consumption patterns, and the cultural, climatic, and social differences in characteristics according to their generation locality.

Considerable advances in MSW destinations are necessary. The biggest cities have been suffering from problems related to the higher quantities of materials, and the smallest

ones are increasingly unable to treat their waste (Andrade and Ferreira 2011). Many technologies have been developed in recent years to solve these problems, like landfill mining, which uses the collection of minerals and solid reuse; environmental education and social policies, such as the 5 R's; ecological reform and integrated solid waste management systems, with selective collection and processing sorting facilities or mechanical–biological treatment plants, those avoid the greenhouse gases emissions (Brum and Hillig 2010; Krook et al. 2012; Calabrò et al. 2015). It is also essential to pay attention to the sanitary landfills, since, if poorly designed, implanted, and operated; they can generate the same or more dangerous impacts than the irregular discharges (Oliveira and Pasqual 2004).

In Brazil, the National Solid Waste Policy (Brasil 2010) determines that only non-reusable and non-recyclable materials, also called rejects, must be sent to final disposal at appropriate sites, previously chosen through environmental, hydrogeological, geological, and geotechnical

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✉ Giulliana Mondelli
g.mondelli@ufabc.edu.br

¹ Engineering, Modelling, and Applied Social Sciences
Centre, Federal University of ABC, Av. dos Estados 5001,
Santo André, São Paulo 09210-580, Brazil

studies, as requirements for sanitary landfills projects. This policy defines a hierarchy of actions for the solid waste destination before final disposal, aiming to reduce the amount of waste finally disposed into landfills. Firstly, is recommended no generation, followed by reduction, reuse, recycling, treatment, and finally the environmentally adequate final disposal of the rejects. Adequate characterization and destination of the MSW which can be treated or reused, or the rejects directly disposed of into the landfills, is, therefore, extremely important to reach sustainable solid waste management. Within all these aspects above, what should be the project of future landfills? It is thought that all geotechnical, environmental, and generation estimation parameters may change considerably, and even from region to region, depending on how they contextualize their rejects.

However, Brazil has about 29.4 million tons of MSW per year disposed of without any sanitary measures in open dumps, uncontrolled landfills, street margins, valley bottoms, and water bodies, following a pattern similar to that found in other developing countries (Gómez-Puentes et al. 2014; Abrelpe 2020). This practice can lead to problems such as contamination of water bodies, silting, flooding, and proliferation of diseases by agents, vectors, or substances (Mucelin and Bellini 2008).

According to Abrelpe (2020), the composition of the MSW collected from 186 Brazilian municipalities presents organic matter (45.3%), plastic (16.8%), rejects as sanitary waste, undefined materials and recyclable packaging with contamination (14.1%), paper and cardboard (10.4%), textiles, leather and rubber (5.6%), glass (2.7%), metal (2.3%), multilayer packaging (1.4%), and other materials (1.4%).

Most of the studies conducted in Brazil are focused on the total waste mass, that is, without considering the effects of selective collection and other treatments. Therefore, there is a lack of information about the specific characteristics of MSW rejects defined by the National Solid Waste Policy, assuming its implementation in the future. With the gravimetric analysis, this portion must pass through geotechnical characterization tests such as grain size distribution, dry, wet and saturated unit weight, moisture content, permeability, compaction, settlement, and shear strength, added by biodegradation and mineralogical measurements over time, as studied by Wolny-Koładka et al. (2020).

The geo-environmental and geotechnical MSW characterization are important to estimate the service life of the sanitary landfills, since depending on what is considered as rejects, geomechanical and microbiological properties expected for these may be incompatible with those used today (Gomes 1989; Carvalho 1999; Abreu 2015). It is worth mentioning here the great responsibility of the stakeholders involved in the technological evolution (government agencies, public authorities, designers, educational institutions,

among others), ensuring the environmental safety and sustainability principles compliance.

This paper aims to present the results of geo-environmental and geotechnical tests performed with door-to-door selective collected MSW from São Paulo city, Brazil. Aiming to know and compare the inputs and outputs of the material recovery facilities (MRFs) in an operation in the city, the following tests were carried out: gravimetric analyses, grain size distribution, pH, electrical conductivity, moisture, organic matter, ash, and metal contents. Compaction and shear strength tests were carried out only on the output samples (rejects) to predict the geo-mechanical behavior of the future landfills in case of implementation of the MSW treatment hierarchy foreseen by the National Solid Waste Policy.

These results contribute to the database regarding the characterization of MSW from the selective collection before and after screening processes serving as a reference to MSW treatment policies with similar characteristics in other countries and cities. The research hypothesis is if the geo-environmental and geotechnical characterization of the MSW from the selective collection and after sorting might change when disposed into landfills without any prior treatment in comparison with the results of mixed MSW.

Materials and methods

MSW sampling

According to Paschoalin Filho et al. (2014), São Paulo city is responsible for the generation of about 20.1 thousand tons/day of MSW, with 35% of potential recyclables. The waste management is divided into the Southeast and Northwest regions, under the companies Ecourbis Ambiental and Loga — Logística Ambiental responsibility, respectively. Samples analyzed in this study were collected from the two material recovery facilities (MRFs) located in the municipality, since they receive most of the dry items from the selective collection carried out once a week in 75 districts — about 80 tons/day each, during the sampling period, from May 2017 to May 2018. To facilitate the data comprehension, the notations MRF-Ecourbis and MRF-Loga were used. Figure 1 presents the location of the study MRFs in São Paulo city, Brazil.

The mechanical sorting process occurs through the following steps: opening of the plastic bags, transporting materials to a rotating sieve for grouping by size, separating medium size items in ballistic equipment, and identification of paper and plastic using optical sensors and metals with magnetic and induction sensors. Both have cooperative members responsible for inspecting and controlling the quality of the output. Each plant has a capacity of 250 tons/day, although they receive less

Fig. 1 São Paulo city and the study MRF locations

than half of the estimated value (80 tons/day–1600 tons/month). During the COVID-19 pandemic, practically all manual facilities closed, and only the mechanical ones, or the MRFs, did not have their activities suspended in the city. The MRF-Ecourbis sends its MSW rejects to the Central de Tratamento Leste landfill and the MRF-Loga to the Caieiras city landfill.

Sampling methodology included fourteen campaigns performed on alternating weekdays and schedules, as shown in Online Resource 1 in the Supplementary Material. Only door-to-door selective collection trucks arriving at the MRFs were considered. The procedures described by ABNT NBR 10007 (2004) and MODECOM (1993) standards were adopted as a basis, aiming to incorporate a greater diversity of materials, districts with different social-economical aspects, and cultural events. Samples were collected randomly from the input (I) — before (I_1) and after (I_2) passing through the bag breaker — and the output (O) of mechanical and manual sorting processes.

Gravimetric composition and grain size distribution

The sampling process considered the amount necessary for sorting and analyzing data from the volume/weight ratio of the collected materials. For coarse sieving, steel sieves with openings of 100, 75, 50, 37.5, 25, 19, and 9.5 mm were assembled. For the finest materials, sieves with openings of 4.75, 2, 1.18, 0.6, 0.42, 0.25, 0.15, and 0.075 mm were used. There were not enough fine grains for the sedimentation step. Before geo-environmental tests, the output groups were subdivided into the recyclable portion (O_{rec}), and the MSW rejects itself (O_{rej}).

The materials were shredded in a knife mill with a final sieve of 6 mm opening, homogenized, and stored at 4 °C. As known, shredding and particle size to apparatus size ratio affect compression and shear strength, and such relations have not been greatly investigated (Hossain et al. 2009). Pre-treatment was also adopted by other authors to enable laboratory tests (Landva and Clark 1990; Gabr et al. 2007; Reddy

et al. 2009; Bareither et al. 2012; Zhao et al. 2014; Feng et al. 2017). Volume minimization is an interesting technique to be explored since suitable areas for landfills implantation are scarce in the Metropolitan Region of São Paulo.

Figure 2 presents a flowchart with photos with each methodological step adopted for grain size distribution, gravimetric analyses, and sample treatment for storage and characterization tests.

Moisture, organic matter, and ash contents

Based on ABNT NBR 6457 (2016), the moisture content (w) was obtained by heating the shredded samples at 65 °C for 24 h. Organic matter (OM) test followed ABNT NBR 13600 (1996). Samples were the same used for w determination, thus continuing the drying process in a muffle furnace at 440 ± 5 °C for 12 h. The procedure to establish the ash content was similar to the OM, but burning at 550 °C. After 2 h, the material was stored in a desiccator until reaching room temperature, weighed, and returned to the muffle for

2 h at the same temperature, as described by Camargo et al. (2009). Once it achieved mass constancy, the weighing procedure was repeated.

pH and electrical conductivity

Determination of pH and electrical conductivity (EC) followed Camargo et al. (2009). For pH, 10 g of sample was mixed with 50 mL of deionized water. Then, samples were shaken horizontally at 220 rpm for 5 min. After resting for 15 min, pH values were measured. For EC, 5 g of sample was mixed with 50 mL of deionized water. Then, samples were shaken horizontally at 220 rpm for 30 s. After resting for 30 min, this process was repeated five times. In the end, EC values were measured.

Metals analysis

The metals chosen to be analyzed were identified considering their frequency of occurrence, as also the local

Fig. 2 MSW samplings preparation and analysis in the laboratory

legislation and other similar studies, besides their acuteness. Therefore, arsenic (As), cadmium (Cd), lead (Pb), chrome (Cr), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), and zinc (Zn) were assessed; all of them were mentioned in standard ABNT NBR 10004 (2004), as well as in European and North American legislation. Mercury (Hg) was not assessed, because of its volatile property.

For metal determination, an inductively coupled plasma optical emission spectrometry (ICP OES) was used. The equipment used Argon plasma, together with the ICP Expert 2 software for obtaining the data. The wavelengths (λ) were selected with the optimal emission for each metal to avoid major interference, resulting in quantification limits (LOQ) of: As ($\lambda = 193.696$ nm, $LOQ = 3$ mg L⁻¹); Cd ($\lambda = 214.493$ nm, $LOQ = 0.01$ mg L⁻¹); Cr ($\lambda = 267.716$ nm, $LOQ = 0.01$ mg L⁻¹); Cu ($\lambda = 327.395$ nm, $LOQ = 0.01$ mg L⁻¹); Fe ($\lambda = 238.204$ nm, $LOQ = 0.01$ mg L⁻¹); Mn ($\lambda = 257.610$ nm, $LOQ = 0.01$ mg L⁻¹); Ni ($\lambda = 231.604$ nm, $LOQ = 0.01$ mg L⁻¹); Pb ($\lambda = 220.353$ nm, $LOQ = 0.01$ mg L⁻¹); and Zn ($\lambda = 213.857$ nm, $LOQ = 0.001$ mg L⁻¹).

For ICP OES analysis, ashes after muffle at 550 °C were treated with nitroperchloric digestion (Watson 1994) to degrade the remaining organic material and disaggregate the metals present. The acid digestion aims sample mineralization to destroy the sample matrix and make the metallic elements available for further analysis. This way, the total amount of the chemical elements is determined, regardless of the chemical form in which it appears in the waste.

Initially, 1 g of sample was weighed and transferred to digestion tubes with the addition of 6 mL of perchloric acid and nitric acid mixture (2:1 v/v). Samples remained for 10 h in the digester block at 120 °C until no more gas releasing. After digestion, tubes with remaining contents were transferred to a 25-mL flask, and volumes were adjusted with distilled water.

Compaction

Based on ABNT NBR 7182 (2016), Standard Proctor tests were performed for O_{rec} and O_{rej} samples of Campaigns 1 and 6 from both MRFs. The material was homogenized and arranged in three identical layers inside a 10-mm-diameter mold. Each layer was compacted with 26 blows using a 2.5-kg-soil hammer. After weighing and volume measuring, MSW portions in duplicate were dried at 65 °C for 24 h.

Shear strength

Direct shear tests were performed in duplicate for O_{rec} and O_{rej} samples of Campaigns 2, 3, 4, 5, and 7 from both MRFs. Samples were previously compacted in a single layer inside the standard Proctor mold and transferred to the shear box (60 × 60 mm). Although the original idea

was to shape the specimens in consonance with standard Proctor tests results, for some of them, this procedure was only feasible after water addition. Thus, it is not possible to ensure that the initial moisture content matches the optimum one.

According to ASTM D3080 (2011), the test was divided into two phases: consolidation and shear. Preliminary tests were carried out with Campaign 2 from MRF-Loga to observe the material's behavior and the limit of the equipment. These tests showed maximum horizontal displacement varying between 11 and 12 mm, and the shear stress did not achieve a peak. The displacement rate of 0.3 mm/min was selected, as also adopted by Bareither et al. (2012) and Zhao et al. (2014).

A total of 20 specimens were consolidated using normal stresses of 50 kPa, 100 kPa, and 150 kPa. These values were chosen based on the material's age, supposing landfill depths of 10 to 15 m. The Mohr–Coulomb failure envelopes and shear strength parameters were determined for 3 mm, 6 mm, and 9 mm of displacement, equivalent to 5%, 10%, and 15% of the specimen's width, respectively.

Results and discussion

Gravimetric composition and grain size distribution

Tables 1 and 2 present gravimetric analysis of input and output samples collected from MRF-Ecourbis and MRF-Loga, respectively.

Particle-size curves obtained are exhibited in Figs. 3 and 4, respectively. It is possible to note that both MRFs had a similar profile for the input and the output, with O samples presenting the finest particles. Observing the I samples, the variation of percentage passing through the 100.0-mm sieve is 43.3–57.2% for MRF-Loga and 34.1–4.7% for MRF-Ecourbis. It is also evident that the driest MSW has particles higher than 50 mm since the materials passing through this sieve range from 2 to 14%. This fact shows that regardless of months, populations that supply MRFs do not change their consumption profile.

Observing O sample curves, there is a higher proportion of materials passing through the 100-mm sieve. The highest percentage accumulated was 78.3% for MRF-Loga (Campaign 1) and 90.6% for MRF-Ecourbis (Campaign 3). As expected, this result shows that the sorting process separates the waste by type, being able to change the items' size as well as break up those compacted. Campaign 3 from MRF-Loga presented an outlier behavior, which curve was similar to the I samples, attributed to the composition characterized by an expressive amount of paper and cardboard (Table 2).

Table 1 Gravimetric composition (%) of MSW samples collected from MRF-Ecoubis in São Paulo city (SP), Brazil

Material (%)	Input samples										Output samples									
	1	2	3	4	5	6	7	Avg. ⁽¹⁾	SD ⁽²⁾	1	2	3	4	5	6	7	Avg. ⁽¹⁾	SD ⁽²⁾		
Paper	5.7	8.2	12.0	3.0	15.0	12.5	14.2	10.1	4.5	9.9	0	1.6	2.4	5.4	0	2.6	3.1	3.5		
Cardboard	16.6	21.1	10.2	22.3	8.6	24.3	10.2	16.2	6.5	7.1	0	0	2.5	2.6	0.2	0.3	1.8	2.6		
Aluminum	0.2	0.6	2.6	0	3.3	0.1	2.4	1.3	1.4	0.2	0	0	0	1.8	0	0.2	0.3	0.7		
Ferrous metals	3.1	2.2	3.7	1.6	4.3	4.0	1.8	3.0	1.1	0.8	1.1	0.1	0.3	0	0	0	0.3	0.4		
Tetra Pack	7.2	7.1	6.5	5.7	2.9	5.9	3.3	5.5	1.7	2.1	5.5	0.7	1.5	1.8	3.4	0.9	2.3	1.7		
Glass	11.0	9.3	14.4	1.9	22.7	0	11.3	10.1	7.6	45.4	22.1	19.6	12.8	23.6	11.7	24.7	22.9	11.2		
PET ⁽³⁾	6.4	8.2	6.3	4.4	7.5	3.6	6.2	6.1	1.6	3.2	2.3	4.3	5.5	2.8	2.8	4.7	3.7	1.2		
HDPE ⁽⁴⁾	5.8	4.8	14.8	1.0	8.4	2.1	7.7	6.4	4.6	1.6	0.4	0	2.3	0.1	0.7	0.4	0.8	0.9		
PVC ⁽⁵⁾	0	0	0	0	0	0	0	0	0.0	0	0	0.2	0	0	0.2	0	0.1	0.1		
LDPE ⁽⁶⁾	0.2	3.7	0.6	0.9	3.4	2.4	2.6	2.0	1.4	0.5	1.3	2.6	3.6	1.8	0.7	2.4	1.9	1.1		
PP ⁽⁷⁾	1.3	1.8	2.3	0.4	1.4	1.4	0.7	1.3	0.6	0.9	1.0	0.9	1.0	1.0	1.2	0.3	0.9	0.3		
PS ⁽⁸⁾	0	0	0.4	0	0	0	0	0.1	0.2	0	0.9	0.4	0.1	0	0	0	0.2	0.3		
Other plastics ⁽⁹⁾	5.6	0.8	0.2	0.4	0.5	0.9	0.6	1.3	1.9	8.5	5.0	0.2	0.3	1.1	0.2	0.1	2.2	3.3		
Undefined plastics ⁽¹⁰⁾	6.0	15.1	8.9	7.2	9.1	13.4	14.0	10.5	3.6	0	7.5	13.7	20.1	6.9	6.3	9.7	9.2	6.3		
Textile	6.2	1.3	1.8	18.5	10.8	2.4	5.7	6.7	6.2	2.1	8.4	0.2	1.2	0.1	0	2.5	2.1	3.0		
Leather	1.0	1.8	7.9	0	0	0	0	1.5	2.9	0	0	0	0	0	0	0	0	0.0		
Rubber	11.7	2.5	1.2	1.5	0	1.9	7.3	3.7	4.2	0	0	0	2.4	0	0	0	0.4	0.9		
Wood	0.4	0.9	1.1	0	0	0	0	0.3	0.5	0.8	0	2.9	0.3	6.1	0	0	1.4	2.3		
Styrofoam	4.0	0.7	0.5	0.2	1.2	3.0	1.8	1.6	1.4	0.5	2.8	1.7	1.2	1.6	0.4	0.5	1.2	0.9		
Electronic	0.5	0.2	4.5	1.2	0	11.0	3.3	2.9	3.9	0.1	0.6	3.0	8.0	0	4.0	0.8	2.4	2.9		
Rejects	7.2	9.4	0.2	8.5	0.5	10.8	5.7	6.0	4.2	14.1	41.1	47.7	34.2	43.0	67.5	49.7	42.5	16.2		
Hazardous ⁽¹¹⁾	0	0.3	0	21.2	0.3	0	1.3	3.3	7.9	2.2	0	0.1	0.2	0	0.5	0	0.4	0.8		

⁽¹⁾ Average; ⁽²⁾ standard deviation; ⁽³⁾ polyethylene terephthalate; ⁽⁴⁾ high-density polyethylene; ⁽⁵⁾ polyvinyl chloride; ⁽⁶⁾ low-density polyethylene; ⁽⁷⁾ polypropylene; ⁽⁸⁾ polystyrene; ⁽⁹⁾ plastics that cannot be classified with any other typology investigated; ⁽¹⁰⁾ plastics that do not have a label indicating their typology; ⁽¹¹⁾ batteries, lamps, and medicines

Moisture, organic matter, and ash contents

Observing the results for MRF-Ecoubis and MRF-Loga in Table 3, OM and ash levels are practically the same for all samples, varying from 3.0 to 11.7%, which are in the same level of magnitude detected by Gala et al. (2020), ranging from 1.0 to 11.7% post-consumer plastic film waste from mixed MSW in Spain. Such expected behavior is due to a strong relationship between OM and ash, with no more degradable organic carbon. For w , the sorting process promotes higher values in the outputs, except for Campaigns 2 and 5 from MRF-Ecoubis and Campaign 5 from MRF-Loga. This last sample presented a large amount of leather and paper in the input, which retains humidity (Table 2). The maximum w value (49.2%) was detected for Orec from Campaign 6 from MRF-Loga. This sample also presented the highest MSW reject percentage (51.2%), justifying this result.

For the MRF-Ecoubis, the maximum w value was found for the Orec sample of Campaign 4 (29.1%), in which a large amount of Styrofoam (20.1%) was presented (Table 1), which can retain humidity on its pores. Minimum w was

1.2% for Orec of Campaigns 2 and 7, with high amounts of glass (22.1% and 24.7%, respectively) and electronic material (8.4%) for Campaign 2. The higher values of w found for rejects are following that found by Wolny-Koładka et al. (2020) for residue derivate from fuel (RDF) and undersized fraction of MSW (UFMSW) from Poland, of 20.2 ± 1.9 and $35.5 \pm 2.0\%$, respectively. For plastic film after manual sorting, Gala et al. (2020) found w ranging from 3.0 to 15.9%.

OM and ash levels were higher for I and Orec samples, except for Campaigns 2 and 5 from MRF-Ecoubis and 2 and 3 from MRF-Loga. Again, the sorting process influenced these values since a big part of the carbon is presented in the organic form in papers, and in the inorganic form in many plastics, which were treated as recyclable material, while only a few ends up as rejects.

An expressive amount of rubber (5.8%) and wood (6.3%) is present in the output of Campaign 2 from MRF-Loga, in addition to some plastics such as PET, PP, and others, which can increase OM and ash (Tables 2 and 3). For the output samples of Campaign 3, paper (24.7%) and cardboard (45.5%) (Table 2) can also increase the OM content, changing the expected pattern. Therefore, the maximum values of

Table 2 Gravimetric composition (%) of MSW samples collected from MRF-Loga in São Paulo city (SP), Brazil

Material (%)	Input samples									Output samples								
	1	2	3	4	5	6	7	Avg. ⁽¹⁾	SD ⁽²⁾	1	2	3	4	5	6	7	Avg. ⁽¹⁾	SD ⁽²⁾
Paper	8.1	7.1	5.5	24.8	25.8	29.3	9.4	15.7	10.4	10.2	11.7	24.7	12.9	3.1	9.8	3.1	10.8	7.3
Cardboard	33.0	38.2	28.1	29.4	26.8	11.3	20.3	26.7	8.7	1.4	1.5	45.5	17.1	9.4	0	7.4	11.8	16.0
Aluminum	1.1	4.9	0.7	2.9	1.0	0	0.2	1.5	1.8	0.5	4.4	0	0	0	0.8	0	0.8	1.6
Ferrous metals	8.1	10.6	0.8	3.4	1.3	0.8	0	3.6	4.1	0.6	0.8	0	0	0	0	0	0.2	0.3
Tetra Pack	8.3	6.1	5.9	5.2	1.9	3.5	0.9	4.6	2.6	0	1.9	0	0	2.6	1.6	0	0.9	1.1
Glass	7.5	3.8	15.4	16.4	10.9	9.9	6.6	10.1	4.6	26.6	2.9	10.9	9.9	3.7	5.0	2.8	8.8	8.5
PET ⁽³⁾	9.0	4.5	13.4	4.7	7.7	4.7	8.6	7.5	3.2	6.6	15.6	0.3	3.0	1.7	0.7	1.7	4.2	5.4
HDPE ⁽⁴⁾	4.7	10	7.0	3.5	1.3	1.5	2.4	4.4	3.2	20.5	4.5	0.1	0.3	4.0	0	1.2	4.4	7.4
PVC ⁽⁵⁾	0	0	0	0	0	0	0	0	0.0	0	0	0	0	0	0	0	0	0.0
LDPE ⁽⁶⁾	2.7	0.9	3.3	1.1	5.9	1.5	2.5	2.5	1.7	0.7	1.7	4.5	1.0	3.4	1.3	2.1	2.1	1.4
PP ⁽⁷⁾	0.9	1.4	8.8	0.3	2.2	0.5	3.5	2.5	3.0	11.0	12.6	0.7	0.3	2.6	0.8	1.2	4.2	5.3
PS ⁽⁸⁾	0.3	0	0	0	0	0.4	0.5	0.2	0.2	1.0	1.4	0.4	0.2	0.7	0.5	0.6	0.7	0.4
Other plastics ⁽⁹⁾	2.8	2.0	0.1	0.7	0.2	0.1	0	0.8	1.1	2.7	9.4	0.9	0.8	1.1	0.1	0	2.1	3.3
Undefined plastics ⁽¹⁰⁾	1.4	2.1	1.5	0.6	8.1	4.0	21.0	5.5	7.3	0.8	1.6	4.5	16.3	10.9	14.2	23.3	10.2	8.4
Textile	6.0	0.9	3.1	1.0	0.7	0	0.9	1.8	2.1	1.3	0	0.5	5.2	6.6	13.6	7.1	4.9	4.8
Leather	0	0	0	0	4.6	0	0	0.7	1.7	0	0	0	0	0	0	0	0	0.0
Rubber	0.4	0.6	0	0	0	0	0	0.1	0.3	2.8	5.8	0	0.2	0	0	0.2	1.3	2.2
Wood	0	1.9	1.9	0.1	0	0	0	0.6	0.9	0.4	6.3	0	0	0	0	0	0.9	2.4
Styrofoam	0.9	0.4	1.4	0.3	0.6	0.1	2.1	0.8	0.7	1.3	1.5	2.3	1.0	6.3	0.5	1.4	2.0	2.0
Electronic	0	0.9	0	0	0	6.3	0	1.0	2.3	0.9	1.3	0	0	0.9	0	2.8	0.8	1.0
Rejects	2.6	3.6	3.1	5.5	1.1	26.2	20.1	8.9	10.0	9.8	15.2	4.7	31.9	42.9	51.2	45.3	28.7	18.7
Hazardous ⁽¹¹⁾	2.2	0	0	0	0	0	0.9	0.4	0.8	1.1	0	0	0	0	0	0	0.2	0.4

⁽¹⁾ Average; ⁽²⁾ standard deviation; ⁽³⁾ polyethylene terephthalate; ⁽⁴⁾ high-density polyethylene; ⁽⁵⁾ Ppolyvinyl chloride; ⁽⁶⁾ low-density polyethylene; ⁽⁷⁾ polypropylene; ⁽⁸⁾ polystyrene; ⁽⁹⁾ plastics that cannot be classified with any other typology investigated; ⁽¹⁰⁾ plastics that do not have a label indicating their typology; ⁽¹¹⁾ batteries, lamps, and medicines

17.7% for OM and 17.8% for ash (Table 3) for the input of Campaign 7 present significant amounts of rejects (20.1%) and unidentified plastics (21%). And about the minimums, 5.2% for OM and 5.4% for ash in Orej of Campaign 5, which had less of these materials. Despite the presence of leather in the input of Campaign 5 (Table 2), it is not possible to make the same relation above since the quantity of the material (4.6%) was probably not enough to change the properties studied.

For the MRF-Ecourbis, the maximum values were 13.6% for OM and 13.7% for ash for the I sample of Campaign 7 (Table 3), which presents significant amounts of paper (14.2%), Styrofoam (14%), and rejects (7%) (Table 1). While the minimum, 3.0% for OM and 3.1% for ash were found in the Orec of Campaign 6, which contains 24.7% glass (Table 1). It is also worth mentioning that the second highest value of OM and ash (11.6% and 11.7%) in the input of Campaign 4, which can be justified by leather presence, representing 21.2% of the total mass.

The pH measurements are close to neutral, tending to alkalinity, following those obtained by Evangelou et al. (2016) and Wolny-Kołodziej et al. (2020). In general, I and

Orec samples presented the highest pH values, except for Campaigns 5 and 6 from MRF-Ecourbis and for Campaign 4 from MRF-Loga. The O samples of Campaign 5 from MRF-Ecourbis were the only ones indicating the presence of Tetra Pack (Table 1), which has a mixed composition of cardboard, plastic, and aluminum, which may have influenced a subtle pH drop. The highest incidence of electronics in the I sample of Campaign 6 (10.8%) may also have influenced the pH drop (Tables 1 and 3).

For MRF-Ecourbis, EC values varied widely between different campaigns (Table 3), not showing a standardized behavior of I or Orec/Orej samples. Such differences can be due to the larger amounts of glass in the output, Campaigns 5 and 7 (23.6% and 24.7%, respectively), as well as in the input (22.7% and 11.3%, respectively) (Table 1). The Orej sample of Campaign 4 presents the highest value of EC (2787 $\mu\text{S}/\text{cm}$), which may be due to the highest Styrofoam level (Table 1). For MRF-Loga, except Campaigns 2 and 5, Orej samples were more conductive than I and Orec samples (Table 3). In the case of Campaign 2, the I sample is more conductive because 10.6% of ferrous metals and 4.6% of non-ferrous metals were found (Table 2).

Fig. 3 Grain size distribution curves of the MSW samples collected from MRF-Ecourbis, São Paulo (SP), Brazil

Fig. 4 Grain size distribution curves of the MSW samples collected from MRF-Loga, São Paulo (SP), Brazil

Table 3 Moisture content (w), organic matter (OM), ash content, pH, and electrical conductivity (EC) values for MSW samples from the study MRFs in São Paulo city (SP), Brazil

MRF	Campaign	Sample ⁽¹⁾	w (%)	OM (%)	ash (%)	pH	EC (μS/cm)
Ecourbis	1	I	2.2	8.2	8.3	8.1	597
Ecourbis	1	Orec	9.5	9.3	9.4	7.7	949
Ecourbis	1	Orej	3.6	6.0	6.0	8.0	617
Ecourbis	2	I	2.7	6.9	7.0	7.8	680
Ecourbis	2	Orec	1.2	8.5	8.6	8.0	2300
Ecourbis	2	Orej	1.6	8.2	8.3	6.9	1901
Ecourbis	3	I	2.6	7.8	7.9	7.9	1047
Ecourbis	3	Orec	14.8	7.4	7.6	8.0	699
Ecourbis	3	Orej	26.5	4.5	4.6	7.6	1380
Ecourbis	4	I	1.6	11.6	11.7	7.8	684
Ecourbis	4	Orec	24	7.2	7.2	7.7	830
Ecourbis	4	Orej	29.1	5.8	5.9	7.2	2787
Ecourbis	5	I	2.5	9.0	9.0	7.0	1092
Ecourbis	5	Orec	1.7	3.6	3.6	6.9	1023
Ecourbis	5	Orej	2.0	4.0	4.1	7.4	1124
Ecourbis	6	I	3.7	10.7	10.7	6.9	829
Ecourbis	6	Orec	15.9	8.0	8.7	7.2	709
Ecourbis	6	Orej	23.5	3.0	3.1	7.4	679
Ecourbis	7	I	2.3	13.6	13.7	7.8	806
Ecourbis	7	Orec	1.2	7.1	7.2	7.5	794
Ecourbis	7	Orej	8.4	3.4	3.6	7.6	782
Loga	1	I	3.9	10.2	10.5	7.1	352
Loga	1	Orec	12.7	11.6	11.6	7.9	726
Loga	1	Orej	19.1	10.6	10.7	7.7	1160
Loga	2	I	1.9	8.0	8.0	7.0	865
Loga	2	Orec	3.3	8.8	8.9	8.1	309
Loga	2	Orej	3.7	9.8	9.9	8.0	500
Loga	3	I	1.5	13.8	13.9	7.5	309
Loga	3	Orec	2.7	7.4	7.5	7.4	461
Loga	3	Orej	3.3	11.5	11.5	6.8	2220
Loga	4	I	2.4	9.0	9.1	6.5	545
Loga	4	Orec	15.8	10.4	10.6	7.1	462
Loga	4	Orej	26.9	8.6	8.7	7.3	1053
Loga	5	I	17.6	7.1	7.1	7.5	1384
Loga	5	Orec	2.8	7.2	7.3	7.5	1300
Loga	5	Orej	6.9	5.2	5.4	7.4	1005
Loga	6	I	2.9	9.6	8.8	7.4	763
Loga	6	Orec	6.6	5.9	6.0	7.3	706
Loga	6	Orej	49.2	5.4	5.5	7.4	921
Loga	7	I	3.2	17.7	17.8	7.9	418
Loga	7	Orec	2.3	16.2	16.4	7.7	547
Loga	7	Orej	28.7	14.1	13.4	7.7	1022

⁽¹⁾I input; Orec output recyclables; Orej output rejects

Metals analysis

Tables 4 and 5 present metal analysis converted to milligrams per kilogram on a dry basis at 550 °C (ash). The results were compared with the CONAMA Resolution Number 420 (Brasil 2009) for contaminated soil

prevention values since it is the only local reference for pollution index.

For the Orej sample of Campaign 6 and Orec sample of Campaign 7, high Cu concentrations were detected for the MRF-Ecourbis, 38,558 and 30,285 mg/kg, respectively. These samples presented the highest incidence of

Table 4 Metals concentrations (mg/kg) for MSW samples from MRF-Ecourbis in São Paulo city (SP), Brazil, where Orec is the recyclable portion and Orej is the rejects portion, and CONAMA is the default value based on the Brazilian Resolution No. 420/2009

MRF	Campaign	Sample ⁽¹⁾	As	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Zn
Ecourbis	1	I	1.16	0.53	33.4	6,075	3,001	200	10.9	29.1	847
Ecourbis	1	Orec	2.84	0.50	18.6	187	12,452	92	11.0	22.5	505
Ecourbis	1	Orej	2.38	0.39	19.2	242	9,791	101	14.7	58.2	290
Ecourbis	2	I	1.50	0.42	10.5	24,665	14,694	326	8.6	16.6	503
Ecourbis	2	Orec	1.44	0.65	19.3	9,672	3,884	184	9.7	218	2,680
Ecourbis	2	Orej	1.12	3.15	15.7	10,330	3,970	85	21.7	453	3,314
Ecourbis	3	I	2.11	0.64	40.1	21,845	13,911	269	18.8	33.2	1,502
Ecourbis	3	Orec	2.11	4.85	12.1	1,156	4,685	64	14.4	49.2	1,093
Ecourbis	3	Orej	2.14	2.69	12.0	198	9,000	100	14.0	20.1	813
Ecourbis	4	I	1.87	0	23.4	358	6,902	351	13.4	29.3	910
Ecourbis	4	Orec	1.41	1.31	182	179	3,927	68	12.9	625	280
Ecourbis	4	Orej	1.11	1.00	39.6	449	4,305	80	11.2	22.5	504
Ecourbis	5	I	2.74	0.69	69.8	365	6,061	675	12.0	44.6	410
Ecourbis	5	Orec	0	0.88	29.7	6,150	4,413	3,767	13.5	74.1	1,568
Ecourbis	5	Orej	1.36	2.26	29.1	311	3,825	337	10.6	390	929
Ecourbis	6	I	3.26	0.65	75.5	447	11,013	864	19.0	134	957
Ecourbis	6	Orec	0.93	0.23	24.1	59	8,534	207	7.5	15.2	444
Ecourbis	6	Orej	0.93	4.55	94.0	38,558	6,052	141	38	677	770
Ecourbis	7	I	4.47	1.68	76.2	709	10,240	1,280	91	944	1,305
Ecourbis	7	Orec	0.77	0.76	22.5	30,285	6,278	1,123	187	1,603	1,998
Ecourbis	7	Orej	0.35	0.50	10.9	6,287	3,924	71	11.4	347	263
CONAMA			15	1.3	75	60	-	-	30	72	300

⁽¹⁾I input; Orec output recyclables; Orej output rejects**Table 5** Metals concentrations (mg/kg) for MSW samples from MRF-Loga in São Paulo city (SP), Brazil, where CONAMA is the default value based on the Brazilian Resolution N. 420/2009

MRF	Campaign	Sample ⁽¹⁾	As	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Zn
Loga	1	I	2.2	2.9	65.6	298	10,794	422	15.5	194	807
Loga	1	Orec	2.1	1.7	50.6	38,249	9,480	1,250	30.3	1,245	932
Loga	1	Orej	2.1	1.8	63.1	39,673	9,672	1,687	965	5,454	127
Loga	2	I	3.1	0.5	38.9	12,406	8,804	678	675	52.2	503
Loga	2	Orec	2.0	1.8	39.1	483	10,177	171	13.4	86.3	476
Loga	2	Orej	2.0	0.9	33.8	37,369	9,281	1,007	16.8	5,316	886
Loga	3	I	2.6	10.8	36.3	15,521	11,037	1,456	46.1	1,356	1,067
Loga	3	Orec	3.1	2.9	39.2	1,977	10,346	604	24.4	52.4	1,096
Loga	3	Orej	1.4	0.8	37.4	12,735	47,223	166	19.8	45.8	1,647
Loga	4	I	1.1	31.1	26.5	30,192	3,841	186	424	12,285	3,371
Loga	4	Orec	2.8	1.5	17.2	1,370	3,100	71.7	10.2	108.3	724
Loga	4	Orej	1.7	7.4	58.6	530	4,923	99.8	65.1	152.8	661
Loga	5	I	1.7	12.1	211	28,476	11,068	754	61.5	137	516
Loga	5	Orec	2.3	0.4	27.3	10,673	3,516	416	11.6	717	434
Loga	5	Orej	2.8	4.0	73.2	13,978	12,470	1,499	35.6	127	582
Loga	6	I	1.8	3.6	74.6	627	8,721	374	10.3	171.2	1,300
Loga	6	Orec	10.5	10.5	61.4	708	11,238	1,642	145	55.6	1,256
Loga	6	Orej	1.3	9.0	31.4	186	6,580	759	23.7	62.6	766
Loga	7	I	3.5	0.7	56.3	478	1,966	782	13.6	121.6	444
Loga	7	Orec	1.4	1.4	43.5	347	10,600	247	9.1	110.2	352
Loga	7	Orej	2.1	0.9	38.5	6,874	8,013	465	51.9	149.6	1,269
CONAMA			15	1.3	75	60	-	-	30	72	300

⁽¹⁾I input; Orec output recyclables; Orej output rejects

rejects, 67.5%, and 49.7%, respectively (Table 1), covering a wide variety of materials. During the tests, Cu wires were observed among the ashes of some samples. It is also evident that Cu presented the highest concentrations among other metals analyzed. Also, Cu concentrations were found in I samples from Campaigns 2 (24,665 mg/kg) and 3 (21,845 mg/kg). The first case may be due to the presence of Styrofoam, which can use copper oxide in its production (Oliveira 2012) and, consequently, present residues of it in the final product. In Campaign 3, the second highest incidence of non-ferrous metals (3.7%) was detected, where Cu fits, as well as the highest incidence of fabric (7.9%), which can use copper-based dyes to its dyeing (Chagas 2009).

High concentrations of Cu were also detected for MRF-Loga. The highest ones were those found for Orec and Orej samples of Campaign 1 (38,249 mg/kg and 39,673 mg/kg, respectively), and for Orej of Campaign 2 (37,369 mg/kg). In the latter, the highest occurrences of non-ferrous metals (4.4%) and wood (6.3%) were found, which may have been treated with copper oxide to prevent pests. Campaign 1 did not observe the same patterns or any other behavior, justified by the high Cu concentration. Except for these higher levels, the other samples with Cu concentrations varying from 186 to 709 mg/kg followed the levels verified by Wolny-Kołodka et al. (2020) for refuse-derived fuel and undersized fraction from municipal solid waste samples, of 110.2 ± 12.1 and 371.1 ± 62.6 mg/kg, respectively.

The As concentrations are below the standard value (15 mg/kg) for all tested samples. The Cd concentrations for MRF-Ecoubis remained below the default value for almost all samples, except for Orej from Campaigns 2, 3, 5, and 6, I from Campaign 7, and Orec from Campaigns 3 and 4. For MRF-Loga, almost all samples exceeded the default value. Then I sample from Campaign 4 registered the highest Cd concentration of 31.1 mg/kg. Glass occurrence in I samples from MRF-Loga and Cd compounds used as pigments for glass, which probably justifies high levels.

For Cr, only a few samples exceeded the limit of 75 mg/kg, such as samples I of the Campaigns 6 and 7 from MRF-Ecoubis and Campaign 6 from MRF-Loga, Orej of the Campaign 6 from MRF-Ecoubis and Orec for Campaigns 4 from MRF-Ecoubis, and Campaign 6 from MRF-Loga. The high value of 211 mg/kg in sample I of Campaign 5 from MRF-Loga can be due to leather, which uses Cr compounds in its manufacturing process. Comparing these data with those obtained by Gala et al. (2020) for post-consumer plastic films, As, Cd, Cu, and Mn concentrations are the highest, and the others are in the same order of magnitude or variation. Compared with Wolny-Kołodka et al. (2020), Cd, Cr, and Zn are in the same order of magnitude, and As concentrations of the present study are lower.

All remaining metals, including Ni for MRF-Loga, except Fe and Mn which are not included in the CONAMA

resolution, indicate contamination of the dry MSW ashes. Even in the absence of other comparison parameters for the Fe concentration, the concentrations of MRF-Loga were higher than for MRF-Ecoubis, but there is no relationship with gravimetry that justifies these concentrations.

According to Mor et al. (2006), MSW pollutants leaching can contaminate the surface and groundwater through discharge of metals and percolation of other potentially toxic substances. High levels of Fe, Cu, Zn, and Pb (above $0.3 \text{ mg} \cdot \text{L}^{-1}$) were reported in the groundwater sampling stations located more than 1 km far from a landfill in Chennai, India (Vasanthi et al. 2008). Similar results were reported by Abd El-Salam and Abu-Zuid (2015), those highlighted the alarming concentrations of Fe ($11 \text{ mg} \cdot \text{L}^{-1}$) and Mn ($1.4 \text{ mg} \cdot \text{L}^{-1}$) in the groundwater in Alexandria, in Egypt, due to landfill leachate.

The main sources of heavy metals in MSW are batteries, waste electrical and electronic equipment, rubber, and other hazardous household waste such as dyes, paints, and additives in plastic and other products (Ishchenko 2019). Therefore, the knowledge of composition and leaching behaviors of heavy metals in MSW may prevent environmental contamination, especially when landfills are closed.

Compaction

Standard Proctor test results are presented in Fig. 5. For the output samples of Campaigns 1 and 6 from MRF-Ecoubis, the $\gamma_{\text{dry,max}}$ values were 9.5 kN/m^3 and 10.0 kN/m^3 , respectively, both for the w_{opt} of 20%. For the output samples of Campaign 1 from MRF-Loga, the $\gamma_{\text{dry,max}}$ was 6.2 kN/m^3 , and the w_{opt} was 35%; for Campaign 6, the values were 7.8 kN/m^3 and 40%. The higher γ_{dry} was obtained for MRF-Ecoubis samples and was consistent with the higher percentage of glass, almost twice the MRF-Loga samples.

The higher dry densities obtained for the MRF-Ecoubis are analogous to those reported for MSW landfilled more than 10 years ago (Gabr and Valero 1995; Fucale 2005; Naveen et al. 2014) and are consistent with the twice percentage of glass present, in comparison with the MRF-Loga. The latter proved to be lighter, according to the dry density close to 7 kN/m^3 , as commonly adopted for landfills dimensioning.

The same trends reported by Pulat and Yukseen-Aksoy (2013) regarding paper and plastic were observed. For Campaign 6 from MRF-Loga, where paper represented approximately 10% of the gravimetric composition, the $\gamma_{\text{dry,max}}$ decreased, and the w_{opt} increased in comparison with Campaign 6 from MRF-Ecoubis, where there was no paper. The same effect was observed for Campaign 1 attributed to the plastic concentration about 43% in MRF-Loga and 15% for MRF-Ecoubis. There is also a possible contribution of the percentage of textiles that have higher individual moisture

Fig. 5 Standard Proctor compaction curves obtained for shredded MSW samples from study MRFs in São Paulo city (SP), Brazil

content (Carvalho 1999), with 14% in the MRF-Loga sample and nil in the MRF-Ecourbis sample. The same effect occurred for Collections 1, attributed to the plastic portion of 43% for MRF-Loga and 15% for MRF-Ecourbis.

Shear strength

During the consolidation phase of direct shear tests, all samples showed similar curves, with the primary consolidation phase completed in a few minutes. The stress-displacement response of all specimens after shearing indicated resistance increasing up to the limit of the equipment. However, the values achieved by MRF-Ecourbis were higher.

At 9 mm of horizontal displacement and normal stress of 150 kPa, the shear stresses of this group ranged from 95 to 145 kPa, while for Campaigns 2, 3, 5, and 7 from MRF-Loga varied between 30 and 95 kPa. This dissimilarity can be associated with the increase in initial moisture content for MRF-Loga samples. Campaign 4 from MRF-Loga presented lower w_{initial} , and shear stresses were 131 kPa and 141 kPa. The gravimetric composition of this sample indicated 10% of glass, 22% of plastic, and 32% of rejects. These characteristics are similar to the amounts of the MRF-Ecourbis samples and different of the other samples of the MRF-Loga, such as Campaigns 5 and 7, with approximately 44% of rejects and 3% of glass, and Campaigns 2 and 3 with 15% and 5% of rejects, respectively (Tables 1 and 2).

Table 6 summarizes the γ_{dry} and w_{initial} (average of three tests performed) of specimens and shear strength parameters determined at 9 mm or 15% displacement. Significant differences between c values obtained for Campaigns 3 and 5 from MRF-Ecourbis and 2, 4, and 7 from MRF-Loga can be noticed. These increases may indicate “cohesion due to fiber reinforcement effect,” but the displacements achieved were

relatively low, perhaps insufficient for the mobilization of tensile forces (Kolsch 1995).

The results obtained agree with the predicted ranges for shredded MSW, from 1.3 to 31.3 kPa for c and 3.2 to 42.9° for ϕ , as shown in the scatter plot of Fig. 6. The exception is Campaign 3 from MRF-Loga, predominantly composed of paper and cardboard. For this sample, which specimens were molded with w_{initial} above 130% to facilitate transfer from the Proctor cylinder to the shear box, the ϕ values were less than 10°. The lowest γ_{dry} and highest w_{initial} belong to the campaigns from MRF-Loga which gravimetric composition was quite different from MRF-Ecourbis, containing higher percentages of paper, cardboard, and textile and lower percentages of glass.

In general, the results of geotechnical tests presented good compatibility with the results obtained without shredding or even without coming from the selective collection and can extrapolate for use in other countries. The results of geo-environmental tests indistinctly show a strong dependence on the materials present in the MSW, indicating the need for gravimetric analysis on a case-by-case basis.

Conclusion

The present methodology adopted was adapted from tests elaborated for soils and sediments and was satisfactory since results were comparable with those used by other countries. Moisture content tends to be higher for the MSW rejects and OM and ash for inputs and recyclables materials. Sample pH ranged from neutral to slightly alkaline, and EC values were higher for Orej samples. The dimensions of waste considered as rejects decrease after the sorting process. Compaction curves presented no clear peak and metal concentrations, and shear strength

Table 6 Summary of the direct shear results for shredded MSW samples from both MRFs in São Paulo city (SP), Brazil

MRF	Campaign	Sample ⁽¹⁾	Test	γ_{dry} (%) ⁽²⁾	w (%) ⁽³⁾	c (kPa) ⁽⁴⁾	φ (°) ⁽⁵⁾
Ecourbis	2	Orec + Orej	1	8.3	63	8.7	36.1
Ecourbis	2	Orec + Orej	2	8.0	68	7.0	38.5
Ecourbis	3	Orec + Orej	1	9.8	40	7.1	35.1
Ecourbis	3	Orec + Orej	2	9.6	44	20.7	36.3
Ecourbis	4	Orec + Orej	1	8.9	53	31.3	24.8
Ecourbis	4	Orec + Orej	2	9.3	51	28.4	26.7
Ecourbis	5	Orec + Orej	1	10.2	49	12.2	34.6
Ecourbis	5	Orec + Orej	2	9.7	53	1.3	42.9
Ecourbis	7	Orec + Orej	1	9.9	41	18.2	34.0
Ecourbis	7	Orec + Orej	2	9.3	41	6.0	41.8
Loga	2	Orec + Orej	1	4.5	92	8.9	23.0
Loga	2	Orec + Orej	2	4.2	82	15.2	15.0
Loga	3	Orec + Orej	1	3.8	148	23.1	7.4
Loga	3	Orec + Orej	2	3.6	139	22.0	3.2
Loga	4	Orec + Orej	1	8.7	45	3.9	40.2
Loga	4	Orec + Orej	2	8.7	49	26.1	36.8
Loga	5	Orec + Orej	1	5.2	107	12.3	18.8
Loga	5	Orec + Orej	2	5.3	103	17.7	22.0
Loga	7	Orec + Orej	1	5.5	104	21.9	25.8
Loga	7	Orec + Orej	2	5.6	109	18.4	25.2

⁽¹⁾Orec output recyclables; Orej output rejects; ⁽²⁾ γ_{dry} dry density; ⁽³⁾ w moisture content; ⁽⁴⁾ c cohesion; ⁽⁵⁾ φ friction angle

Fig. 6 Shear strength parameters obtained using direct shear tests of shredded MSW by several authors, including the present study

parameters are more susceptible to specimen composition and moisture content than the selective collection followed by the sorting process involved. High metal concentration occurred due to dried and burned MSW, which reduced the mass and eliminated much of the OM, leaving only ashes and concentrating metals. The small-scale direct shear testing program indicated cohesion ranging from 1.3 to 31.3 kPa and friction angle from 3.2 to 42.9°, both of them similar to results found in the literature for MSW in general. Finally, the presented geo-environmental and geotechnical characterization of the dry MSW of the São

Paulo city enables the comprehension of expected behaviors of waste to be disposed into sanitary landfills and also contributes to the next steps of the integrated solid waste management, allowing the estimative of parameters to design the intermediate treatment processes, like the home, mechanical and manual sorting processes themselves and the biological and thermal plants implementation, and also serving as an example for MSW from other regions.

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Author contribution Draft and original manuscripts were written by GM, LHGC, and MBJ, and structured by GM that coordinated the project. Investigation including Material and Methods, and Results was carried out by MBJ, CJ, MAO, CBB, and JLFC, as part of their master's and undergraduate's degrees projects at the Federal University of ABC. LHGC enabled the performance of the ICP tests as well as the tests execution and interpretation of the results.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

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