Effect of Material Composition on Geotechnical Properties—Study on Synthetic Municipal Solid Waste

Vidit Singh and Taro Uchimura *

Graduate School of Science and Engineering, Saitama University, Saitama 338-8570, Japan; singh.v.647@ms.saitama-u.ac.jp
* Correspondence: uchimurataro@mail.saitama-u.ac.jp

Abstract: The geotechnical properties of municipal solid waste (MSW) are required to design and maintain a landfill structure. Several landfill failures occurring in recent times have led to the loss of revenue and people. This study aims to investigate the impact of material composition on the geotechnical properties of fresh synthetic municipal solid waste (SMSW), which imitates the real waste produced in India. The study aims to understand the contribution of each material, such as paper, plastic, and organic matter, on the shear behavior of SMSW, which is essential for designing landfills and ensuring their safety and performance. A modified proctor test and a large-scale direct shear test were used to determine the unit weight and shear strength of SMSW, respectively. The synthetic waste's unit weight and shear strength were found to be consistent with values that had already been published. The shear strength parameters of SMSW include cohesion, which was determined to be at the lower bound of the envelope, and friction angle within the envelope. Lower unit weight, less fine soil-like material, and dry material are thought to be the causes of the observed variation in the behavior of actual waste in synthetic waste. The findings of this experiment demonstrated that as the proportion of paper increases, the cohesion (C) increases, and the friction angle (Φ) decreases. Cohesion and friction angle both decrease as the proportion of plastic increases. Cohesion and friction angle both increase with an increase in the organic percentage. These findings demonstrate that each material contributes differently to the shear behavior of SMSW. Hence, the material composition’s effect should be considered while designing a landfill for improved safety and reliability.

Keywords: synthetic municipal solid waste; geotechnical properties; unit weight; shear strength; material composition; heterogeneity

1. Introduction

The landfilling of waste is one of the most economical ways of disposing the municipal solid waste (MSW) in a controlled and engineered manner compared to other waste management strategies, such as recycling, composting, incineration, etc. As per the central pollution control board (CPCB, 2022), almost 26% of waste in India is unaccounted for, and 30% ends up in landfills. Other than India, the United States, France, and China are some countries that use landfills as a primary waste management technique. MSW typically contains plastic, paper, metals, textiles, wood, organic-food waste, demolition waste, garden waste, and soils. However, because of variations in lifestyle and regulation, the materials found in the MSW deposition vary from location to location and are continually changing. Because of increased efforts to recycle and treat MSW, the transformation rate will accelerate during the next decade. Moreover, because of heterogeneity and the time-dependent deterioration of organic materials, it is exceedingly challenging to evaluate the geotechnical characteristics of the waste entirely.

While it is essential to understand fundamental behavior, it is equally vital to understand the expected limits of the essential engineering characteristics. There have been
several MSW landfill slope failures recently, including those which occurred in Gazipur, Delhi landfill (2017, 2 deaths), Koshe, Ethiopia landfill (2017, 113 deaths), Meethomulla, and Sri Lanka (2017, 32 deaths) and also mentioned in Table 1. These failures have serious adverse economic effects and occasionally even lead to fatalities. As the world’s population is increasing, this will lead to an increase in waste generation. Therefore, we should properly manage the waste. A new theory of the zero waste concept will help create a strategy to minimize waste generation. A closed-loop system in which all materials are reused, recycled, or composted, and significantly less material is transferred to a landfill or an incinerator is the goal of the philosophy and strategy known as “zero waste”. It is founded on a circular economy, which emphasizes conserving resources and minimizing waste. Regarding sustainability and the environment, communities and businesses can significantly benefit from implementing zero-waste policies. Zero waste will assist us in reducing waste which considerably lessens the environmental impact of human activity while conserving natural resources and minimizing pollution. The zero-waste principle can help create a more sustainable future for people and the environment. Eventually, less generation of waste will lead to less waste in landfill.

Table 1. Recent MSW landfill failures.

<table>
<thead>
<tr>
<th>No.</th>
<th>Landfill</th>
<th>Failure Reason</th>
<th>Casualties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mahad, India (2020)</td>
<td>Improper Design</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Maputo, Mozambique (2018)</td>
<td>Overfilling</td>
<td>17</td>
</tr>
<tr>
<td>3</td>
<td>Meethotamulla, Sri Lanka</td>
<td>Rainfall</td>
<td>32</td>
</tr>
<tr>
<td>4</td>
<td>Ghazipur, India (2017)</td>
<td>Overfilling</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>Koshe, Ethiopia (2017)</td>
<td>Improper Design</td>
<td>113</td>
</tr>
<tr>
<td>6</td>
<td>Shenzhen, China (2015)</td>
<td>Human Negligence</td>
<td>73</td>
</tr>
<tr>
<td>7</td>
<td>Jardim Gramacho, Brazil</td>
<td>Improper Design</td>
<td>2</td>
</tr>
</tbody>
</table>

To accurately assess the stability of landfills, it is essential to have a thorough understanding of how each constituent of MSW impacts shear strength. Geotechnical properties such as shear strength, compressibility, permeability, and unit weight are critical factors in landfill lining design, settlement, and leachate flow. Ideally, testing should be conducted on undisturbed materials, but laboratory tests are often conducted on disturbed materials due to the difficulty in obtaining such samples. The design and stability of landfills are influenced by the geotechnical properties of MSW, which are, in turn, affected by the composition of MSW. Therefore, this paper evaluates the effect of paper, plastic, and organic fraction on the geotechnical properties of MSW [1,2] by creating a laboratory waste called synthetic municipal solid waste (SMSW) that is specifically made to perform the testing and control the composition. The objective is to investigate whether changes in waste composition result in corresponding variations in its mechanical properties. Previous studies have employed synthetic waste (SMSW) to assess the geotechnical properties of MSW. These studies involved creating SMSW mixtures from controlled components and conducting conventional geotechnical tests to examine waste’s mechanical properties under controlled conditions. SMSW allows for complete control over composition, material type, and particle size, providing the ability to identify the impact of different components on properties, which are among the advantages of using SMSW [2–4]. The focus has been on paper, plastic, and organic content comprising most typical MSW components. The experiments were performed by creating a total of nine sets of SMSW samples by changing and controlling the fractions of paper by 10% to 20% and 30%, plastic by 10%, 25%, and 35%, and organic matter by 15%, 45%, and 55%. Performing these experiments will provide valuable insights into the mechanical properties of municipal solid waste and compare them to the published values. The research conducted by the authors of [5,6] proposes a sustainable solution for the backfill material of MSE/RE walls.

The vertical expansion of landfills is also currently used to properly manage waste by increasing the storage capacity of the landfill by creating a retaining wall around the landfill.
The conventional approach for constructing MSE/RE walls involves using high-quality granular materials for backfilling. However, the availability of such materials is limited and costly. On the other hand, MSW is an abundant resource, and its use as backfill material can address the issues of limited availability and high cost. In the vertical expansion of landfills, the MSW behaves as a backfill material. The density of the backfill material is an important property needed to design it properly. This study will provide insights into the mixtures’ MDD (maximum dry density). Therefore, controlling and managing waste composition will help us achieve a stable backfill. The segregation of the waste material from the source will be essential in controlling the composition. The research also highlights MSW’s heterogeneous nature, which can significantly change mechanical properties. The stability of municipal solid waste (MSW) in landfills is crucial to prevent environmental hazards and ensure the safety of human health. The shear strength of MSW plays a significant role in its stability. Previous studies have shown that most landfills’ failures are due to slope failure, which makes it essential to assess the shear strength of MSW. This research focuses on assessing the shear strength of MSW by performing a direct shear test on nine samples of segregated municipal solid waste (SMSW). The study’s results will provide valuable insights into the effect of the composition analysis on the shear strength of SMSW mixtures. This information is crucial for designing stable landfills, as it will help manage the composition of waste materials to achieve optimum shear strength. The research emphasizes the importance of assessing the shear strength of MSW to prevent slope failure and maintain the stability of landfills. In summary, this study aims to enhance our comprehension of how certain materials influence the geotechnical characteristics of freshly generated waste.

**Background**

Mohr–Coulomb strength criteria are used to characterize the shear strength of waste materials. These properties indicate that the shear strength of MSWs is primarily dependent on stress-related factors, such as friction, especially at higher confining pressure levels, but also shows considerable cohesion at lower confining pressure levels [7,8]. Cohesion (c) ranges from 0 to 50 kPa, and the angle of friction (Φ) ranges from 25° to 41° [9]. The shear strength of MSW is characterized by the shear stress at 5–25% axial strain, and at high strain levels, the angle of friction (Φ) is 45°–53° [10].

This shear envelope generally comprises a completely cohesive material with a cohesiveness (c) of 24 kPa and a purely frictional material (Φ) of 33° at more significant normal stress [11,12]. In addition, prior research has undertaken laboratory experiments and back-calculations of unsteady waste slopes, producing a linear shear strength with a cohesion (c) of 25 and friction angle (Φ) of 35° [13]. Several investigations have given shear parameter values with cohesion varied from 0 to 80 kPa and friction angle varying from 0° to 60°. For fresh waste, the cohesion varies from 0–150 kPa, and the friction angle varies from 12°–40° as mentioned in Table 2. Thus, determining the ideal cohesion and friction angle values for designing and evaluating landfills is critical.

<table>
<thead>
<tr>
<th>SMSW</th>
<th>Friction Angle</th>
<th>Cohesion</th>
</tr>
</thead>
<tbody>
<tr>
<td>H.F. Pulat and Y.Y. Aksoy, 2017 (SMSW size—2 mm to 25 mm of fresh and aged SMSW)</td>
<td>20–28</td>
<td>32–40</td>
</tr>
<tr>
<td>H. Hettiarachchi et al., 2011 (SMSW size—10 mm)</td>
<td>12–39</td>
<td>0–150</td>
</tr>
<tr>
<td>K. Reddy et al., 2009 (SMSW size—1.5 mm, 35% smaller than 0.1 mm and 10% larger than 10 mm)</td>
<td>27–29</td>
<td>16–19</td>
</tr>
<tr>
<td>K. Reddy et al., 2008 (shredded fresh waste, SMSW size—40 mm)</td>
<td>26–30</td>
<td>32–64</td>
</tr>
<tr>
<td>N. Dixon et al., 2008 (SMSW size—120–500 mm)</td>
<td>34</td>
<td>0</td>
</tr>
<tr>
<td>Hossain, 2002 (shredded landfill waste, SMSW size—50 mm)</td>
<td>24–32</td>
<td>-</td>
</tr>
<tr>
<td>Caicedo et al., 2002 (unshredded fresh waste)</td>
<td>23</td>
<td>78</td>
</tr>
<tr>
<td>Landva and Clark, 1990 (shredded fresh waste)</td>
<td>24</td>
<td>23</td>
</tr>
</tbody>
</table>
The research was performed to explore the impact of fiber orientation on the strength properties of MSW obtained from San Francisco, utilizing large-scale direct shear testing (30 cm × 30 cm) [14]. The findings demonstrated that the orientation of fibrous material had a substantial influence on the shear strength of waste. When the fibrous material was oriented perpendicularly to the shear surface, it behaved substantially more strongly than when it was parallel. The MSW sample exhibited the highest shear strength with a 60° orientation of fibrous material among the various orientations tested. MSW’s recommended shear strength envelope is (c) of 15 kPa and (Φ) of 36°. It is also observed that MSW samples with a higher fibrous content exhibited greater strength than those with lower fibrous content. Additionally, the triaxial test revealed that MSW samples with a high plastic fraction could withstand higher stresses at large strains than those with a lower plastic fraction. Despite these findings, several uncertainties remain regarding the shear strength of MSW, such as:

- The impact of material size on the shear strength of the MSW;
- The effect of dynamic loading on the shear strength of MSW;
- The impact of each material composition on the shear strength of MSW;
- The significance of sample preparation and sample testing procedure in the laboratory.

Due to the presence of various materials, assessing the mechanical properties of MSW poses a challenge. While testing undisturbed samples is optimal, obtaining such samples is difficult. This study aims to address this challenge by conducting laboratory tests on shear strength and density using nine samples of synthetic municipal solid waste (SMSW). The objective is to explore the relationship between mechanical parameters and waste composition. The objective is to determine if there is a correlation between controlled changes in waste classification, the mixing of waste components, and changes in the mechanical behavior of SMSW.

The understanding of MSW at present is quite complicated. Engineers and scholars have been using soil-based knowledge and applying it to MSW. While this approach has been helpful to some extent, it is not the most suitable method for comprehending waste behavior because of its heterogeneity. The MSW is a mix of complex materials that changes its properties over time and behaves very differently from the soil. Therefore, there is a need to understand geotechnical properties more elaborately and understandably. As seen in (Table 3), the geotechnical parameters of MSW are necessary for landfill design and stability studies.

<table>
<thead>
<tr>
<th>Design Constraints</th>
<th>Shear Strength</th>
<th>Unit Weight</th>
<th>Permeability</th>
<th>Lateral Stiffness</th>
<th>Horizontal Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liner Stability</td>
<td>✔</td>
<td></td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subgrade Stability</td>
<td>✔</td>
<td></td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cover System</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope Stability</td>
<td>✔</td>
<td></td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas/Leachate</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subgrade Stability</td>
<td>✔</td>
<td></td>
<td>✔</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. Materials and Method

2.1. Synthetic Waste

Synthetic waste is made in the laboratory specifically for testing by mixing different materials in the required composition. A classification system is required for the characteristics of MSW. Waste in the landfill changes its property, such as size and shape, because of decomposition, compaction, and overburden pressures. MSW comprises a diverse range of waste predominantly generated from households and commercial sources and is broadly categorized into organic and inorganic waste. Organic waste includes paper,
textiles, garden, and food waste, while inorganic waste comprises rubber, metals, glass, and plastics. Previous studies have proposed that synthetic waste can be utilized to examine the geotechnical characteristics of MSW [5]. Using synthetic waste instead of municipal waste has several advantages, including better control of material composition (reducing uncertainty in components based on size, shape, and material properties) as well as using cleaner components (overcoming health and safety concerns and ensuring laboratory environmental control).

A typical MSW reference material classification was conducted by performing a sorting analysis on the sample obtained from the Jawahar Nagar landfill in Hyderabad, India. Synthetic waste material was carefully selected to imitate the components found in real MSW. Specific proportions of selected components were mixed to create each synthetic waste sample, as presented in Figure 1. Nine synthetic waste samples were generated to investigate how paper, plastic, and organic components affect the waste’s unit weight and shear strength. All components used to create the synthetic waste were dry except those representing organic material. It is worth noting that moisture content in organic material is a critical factor that influences the properties of MSW. Therefore, when interpreting results and comparing them with real waste, the moisture content in the synthetic waste material should be considered.

![Figure 1. Synthetic waste components are used to create the samples.](image)

While creating the synthetic waste samples, the components were mixed in the required proportion to create a homogeneous mixture. Overall, the selection and composition of the synthetic waste material used in this study were based on the reference composition and were designed to imitate the real MSW components. The careful selection and preparation of the synthetic waste material ensured the accuracy and reliability of the test results, providing valuable insights into the properties of MSW.

**Synthetic Municipal Solid Waste Composition Used for Testing**

Table 4 provides a detailed breakdown of the components used to create each synthetic waste sample. Each material is chosen to mimic those found in real MSW, as referenced in previous studies. The percentage of each material mixed to form each synthetic waste
sample is presented in Table 5, with the classification presented in Figure 1. Out of the nine samples tested, SW-01 was created to closely replicate real MSW, while SW-02 and SW-03 were made to show how paper affects the mechanical properties of synthetic waste. SW-04, SW-05, and SW-06 were made to determine the influence of plastic on mechanical properties. SW-07, SW-08, and SW-09 were created to investigate the significance of the organic material. Through the use of SMSW, the study could conduct controlled testing.

Table 4. Components used to replace MSW material to construct SMSW.

<table>
<thead>
<tr>
<th>Material</th>
<th>Replacement</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
<td>A4 Paper and Cardboard</td>
<td>15–200 mm</td>
</tr>
<tr>
<td>Plastic</td>
<td>Waste Plastic Bags and PET Shredded Plastic</td>
<td>10–100 mm</td>
</tr>
<tr>
<td>Metals</td>
<td>Metal Sheets</td>
<td>&lt;40 mm</td>
</tr>
<tr>
<td>Wood</td>
<td>Shredded Wood</td>
<td>&lt;20 mm</td>
</tr>
<tr>
<td>Soil</td>
<td>Sand and Clay Mix</td>
<td>&gt;4.75 μm</td>
</tr>
<tr>
<td>Organic</td>
<td>Garden waste, Food waste, and Peat Moss</td>
<td>40–200 mm</td>
</tr>
<tr>
<td>Textile</td>
<td>Textile (cut)</td>
<td>10–100 mm</td>
</tr>
</tbody>
</table>

Table 5. Synthetic waste compositions are used to create SMSW samples.

<table>
<thead>
<tr>
<th>Components</th>
<th>SW-01</th>
<th>SW-02</th>
<th>SW-03</th>
<th>SW-04</th>
<th>SW-05</th>
<th>SW-06</th>
<th>SW-07</th>
<th>SW-08</th>
<th>SW-09</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal</td>
<td>5.10</td>
<td>5.81</td>
<td>4.52</td>
<td>5.39</td>
<td>4.50</td>
<td>3.90</td>
<td>6.18</td>
<td>4</td>
<td>3.27</td>
</tr>
<tr>
<td>Garden Waste</td>
<td>2</td>
<td>2.28</td>
<td>1.77</td>
<td>2.12</td>
<td>1.76</td>
<td>1.53</td>
<td>2.42</td>
<td>1.57</td>
<td>1.28</td>
</tr>
<tr>
<td>Wood</td>
<td>6</td>
<td>6.83</td>
<td>5.32</td>
<td>6.35</td>
<td>5.29</td>
<td>4.59</td>
<td>7.27</td>
<td>4.70</td>
<td>3.85</td>
</tr>
<tr>
<td>Cardboard</td>
<td>4.10</td>
<td>4.67</td>
<td>3.63</td>
<td>4.34</td>
<td>3.61</td>
<td>3.13</td>
<td>4.97</td>
<td>3.21</td>
<td>2.63</td>
</tr>
<tr>
<td>Soil</td>
<td>4</td>
<td>4.55</td>
<td>3.55</td>
<td>4.23</td>
<td>3.53</td>
<td>3.06</td>
<td>4.85</td>
<td>3.13</td>
<td>2.57</td>
</tr>
<tr>
<td>Plastic</td>
<td>15.10</td>
<td>17.19</td>
<td>13.39</td>
<td>10</td>
<td>25</td>
<td>35</td>
<td>18.29</td>
<td>11.83</td>
<td>9.69</td>
</tr>
<tr>
<td>Textile</td>
<td>3.65</td>
<td>4.15</td>
<td>3.24</td>
<td>3.86</td>
<td>3.22</td>
<td>2.79</td>
<td>4.42</td>
<td>2.86</td>
<td>2.34</td>
</tr>
<tr>
<td>Organic</td>
<td>30</td>
<td>34.15</td>
<td>26.60</td>
<td>31.73</td>
<td>26.44</td>
<td>22.93</td>
<td>15</td>
<td>45</td>
<td>55</td>
</tr>
<tr>
<td>Sand</td>
<td>9</td>
<td>10.24</td>
<td>7.98</td>
<td>9.52</td>
<td>7.93</td>
<td>6.88</td>
<td>10.90</td>
<td>7.05</td>
<td>5.77</td>
</tr>
</tbody>
</table>

The composition of paper, plastic, and organic components in each synthetic waste sample was carefully selected based on the minimum and maximum percentages of these components found in real MSW. This approach ensured that the synthetic waste samples accurately represented a range of materials in MSW, and the test results could be represented in real-world conditions.

To conduct tests using traditional geotechnical equipment, it was necessary to limit the size of the synthetic waste material to 20 mm. This restriction was imposed to facilitate standard testing methods and ensure that the resulting data could be compared with data from previous studies. By adhering to this size limit, accurate and consistent test results were obtained using conventional geotechnical equipment.

2.2. Methods

By performing laboratory testing, the current research aims to investigate the unit weight and strength characteristics of SMSW. Some of the tests were repeated on the samples to assess the repeatability of the result. To confirm the validity and reproducibility of the test results, before testing, the SMSW material was shredded and mixed into the desired composition to make the necessary samples. The modified proctor tests were then carried out to determine each of the samples’ maximum dry density (MDD) and optimum moisture content (OMC) in compliance with JGS standards.

The sample was created for the direct shear test at the measured MDD and OMC. Then, the test was conducted to assess the shear strength of the SMSW material. The direct shear test provided valuable data on the strength characteristics of the sample.
2.2.1. Modified Proctor Test

This test of the SMSW was conducted using a cylindrical mold with an inner diameter of 15 cm and 17.5 cm in height. To ensure the mold was filled to the desired capacity, a tamper was used to compact the SMSW. The filling process was completed in five layers, each compacting 25 times. The experiment utilized a drop hammer with a consistent drop height of 45 cm and a weight of 2.5 kg, providing a consistent method for compacting the sample. Water content was added to the SMSW in increments of 15%, ranging from 15% to 90% in each test. Following each test, the sample material is collected from the top and bottom of the sample. The moisture content of the material was assessed by oven-drying at a temperature of 70 °C for 24 h. Oven drying is a widely accepted method for measuring moisture content in soil samples, as it provides accurate and reliable results. The apparatus used to perform this test can be shown below (Figure 2).

![Figure 2. Proctor test instruments.](image)

\[
\text{Bulk Unit Weight, } \gamma_b = \frac{W}{V} = \frac{\text{Weight of MSW}}{\text{Volume of Mold}} \tag{1}
\]

\[
\text{Dry Unit Weight, } \gamma_d = \frac{\gamma_b}{1 + \text{M.C}} \tag{2}
\]

The SMSW’s unit weight and dry density were determined by applying Equations (1) and (2); M.C represents moisture content.

2.2.2. Direct Shear Test

Experiments were carried out using direct shear apparatus. The shear box used in the study had the following measurements: 40 cm × 30 cm × 21 cm. The large size of the apparatus provided the opportunity to use a large size of material, and the shear displacement was limited to 40 mm. In the experiment, the shear force was applied in a strain-controlled test using an electronically connected rotary motor, which controlled the shear at a 1–2 mm/min rate. The rotary motor allowed for precise shear rate control, ensuring consistent and accurate results. The normal load is applied to the material using four connected hydraulic compressor cylinders and measured with the help of a load cell. To measure the vertical and horizontal deformations of the sample, linear variable displacement transducers (LVDTs) were utilized. Two vertical LVDTs were installed at the top of the apparatus to measure the vertical deformation. At the same time, one was
connected at the back of the lower shear box to measure horizontal deformation, as seen in Figure 3.

![Figure 3. Large-scale direct shear apparatus.](image)

With its specific dimensions, shear rate, and stress application, the direct shear apparatus allowed for precise and accurate measurements. The test used in this investigation was conducted in two stages. The sample was first filled into three layers; then, each layer was compressed by dropping a 5 kg hammer at a height of 30 cm above the material surface. The number of impacts per layer for ideal compaction was controlled to achieve the required compaction. Each sample was examined under normal stresses of 10 kPa, 20 kPa, and 30 kPa, allowing for the evaluation of the material’s shear strength under various stress situations. A linear variable displacement transducer (LVDT), which offered precise measurements of the sample’s deformation behavior, was used to assess the sample’s total vertical and horizontal deformations. After the compaction stage, the waste samples were subjected to shearing at a 1 mm/min rate, as recommended by the authors of [14].

The shearing test was continued until the shear deformation reached 40 mm, providing valuable data on the material’s deformation behavior under different stress conditions.

Figures 3 and 4 above show the apparatus used for performing the DST. To perform the DST, a constant vertical load was maintained on the SMSW sample while the horizontal displacement, the horizontal shear force, and the vertical displacement were measured and recorded using the data collection system. After each DST test, the sample was disassembled, and its components were inspected to observe any physical changes.
3. Results

3.1. Proctor Test

Modified proctor tests were performed on nine different material compositions to calculate the MDD and OMC of synthetic municipal solid waste. Figure 5 describes the variation of different compositions on the unit weight of SMSW. As mentioned by the authors of [2], every material affects the properties of SMSW differently. The unit weight of solid waste mixed with paper, plastic, and organic material varies depending on the percentage of each component. Adding paper increases the density until a maximum is reached, and then it decreases. The paper becomes softer when water is added, and when compacted, it becomes remolded and rearranged, resulting in a denser arrangement. With a further increase, the water becomes absorbed by a paper which leads to the improper lubrication of the sample and subsequently decreases density. Plastic content increases, and the unit weight decreases as the percentage of plastic increases. The increase in plastic material makes the sample lighter (it takes more volume for the same weight), and while compacting the sample, it tries to regain its elastic shape, decreasing unit weight. With the increase in organic content, the unit weight increases, as in Table 6.

Table 6. Calculated MDD and OMC values of SMSW.

<table>
<thead>
<tr>
<th>Sample</th>
<th>SW-01</th>
<th>SW-02</th>
<th>SW-03</th>
<th>SW-04</th>
<th>SW-05</th>
<th>SW-06</th>
<th>SW-07</th>
<th>SW-08</th>
<th>SW-09</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDD kN/m³</td>
<td>2.87</td>
<td>3.94</td>
<td>3.16</td>
<td>3.61</td>
<td>3.32</td>
<td>3.09</td>
<td>3.73</td>
<td>4.14</td>
<td>4.5</td>
</tr>
<tr>
<td>OMC %</td>
<td>62</td>
<td>85</td>
<td>76</td>
<td>88</td>
<td>77</td>
<td>67</td>
<td>82</td>
<td>78</td>
<td>85</td>
</tr>
</tbody>
</table>

These results can be attributed to using finer and shredded organic material. The behavior of the mix is affected by the size and compressibility of the components as well as their ability to interlock with each other. Adding water to the mix increases the unit weight by causing the components to stick together more. Increasing the solid content per unit volume leads to a denser packing arrangement and an increase in unit weight [15]. This study highlights the significant impact that individual materials have on MSW. Therefore, analyzing the composition of MSW can provide a clear range of unit weight based on changes in material composition. It is crucial to consider the composition of MSW when interpreting compaction characteristics, as its composition greatly influences waste density. Thus, site-specific assessments are recommended to ensure accurate waste unit weight and composition determination.
3.2. Direct Shear Test Result

The tests examined how synthetic municipal solid waste behaved in shear stress under various material compositions. The study’s results are presented in Figure 6, which shows the correlation between vertical deformation and normal stress, and Figure 7, which displays the correlation between shear stress and horizontal deformation. The Coulomb’s failure envelopes in this study were defined using the mobilized shear strength at a 40–50 mm displacement range. The horizontal displacement is limited due to equipment restrictions. These were used to calculate the shear strength parameter, cohesion (c), and friction angle (\(\Phi\)). In addition to measuring shear strength, we have also used vertical displacement transducers to measure how the sample settled during the consolidation stage. It provides valuable insights into how the waste composition behaves while applying a compression load.

In some tests, peak or ultimate shear was recorded, indicating that the waste composition had reached its maximum strength. However, in several tests, the displacement was insufficient to mobilize ultimate strength, suggesting that other factors affected the waste composition’s behavior.

The results provide insights into the compressible behavior of solid municipal waste (SMSW) during consolidation. The impact of the paper on SMSW settlement behavior is shown in Figure 6a. The findings indicate that the sample’s settlement increases as the percentage of paper increases. This behavior can be attributed to the compressible property of paper. Paper subjected to compression tends to get crushed or rearranged, increasing its compressible behavior.
Similarly, Figure 6b demonstrates the impact of plastic on compressible behavior. The results indicate that plastic’s compressible and softer nature affects the sample compression behavior. As the percentage of plastic increases, the compressibility of the sample also increases. This behavior can be attributed to the property of plastic material also undergoing particle rearrangement and compression under stress, increasing its compressible nature.

The effect of organic material differed from that of paper and plastic, as shown in Figure 6c. As the percentage of organic matter increases, the compressibility of the sample decreases. The study also shows that highly compressible materials such as paper, plastic, and textiles undergo maximum settlement and particle rearrangement, increasing their compressible nature. These materials are classified as light and highly compressible waste components [5]. The experiments show insights into solid municipal waste (SMSW) behavior when subjected to stress and various factors that impact its compressible nature. By examining the effects of different materials, such as paper, plastic, and organic matter, on SMSW settlement behavior, the study offers a comprehensive view of the factors contributing to its compressibility.
The above Figure 7 shows the shear behavior of all nine SMSW samples. The above graph (a) displays the shear behavior of SMSW (waste mixed with shredded wastepaper) as the percentage of paper in the mixture varies. The shear response of the SMSW samples does not exhibit a clear trend as the proportion of paper changes. The cohesion of a soil sample refers to its ability to resist shear stress, while the friction angle refers to the angle at which the soil particles begin to move against each other due to shear stress.

However, when the normal stress is low at 10 kPa, the sample containing 30% paper (SW-03) displays better resistance to shearing when compared to the samples with 10% (SW-01) and 20% (SW-02) paper. When the normal stress is higher, at 20 and 30 kPa, the sample with 10% paper (SW-01) performs better regarding shear resistance than the samples with 20% and 30% paper (SW-02 and SW-03). This behavior is thought to be due to the internal bonding structure of the materials. When the SMSW mixture contains a higher proportion of paper, the particles have a greater tendency to stick together during compaction, leading to better interlocking and an increase in stiffness in the shear response at low normal pressures. However, as the normal pressure increases, the rearrangement of the materials disturbs the internal particle structure of the SMSW, leading to a reduction in
shear resistance at higher stress levels. Cohesion, friction angle, and the shear parameters of soil samples are significant factors that influence the soil’s strength and stability. In this context, it has been observed that the percentage of paper added to samples can influence these parameters. As seen in Figure 8a, as the percentage of paper increases, the cohesion value increases, while the friction angle value tends to decrease. This means that the soil becomes more cohesive but less resistant to sliding or shearing. The magnitude of the variation of shear parameters can be seen in Figure 8a. For SW-01, the observed cohesion value is 3.02 kPa, and the friction angle is 24.4°. For SW-02, the observed value of cohesion is 3.79 kPa and friction angle is 20.9°, and the SW-03 sample has a cohesion of 5.1 kPa and friction angle of 19.5°, respectively.

Figure 8. Shear stress–normal stress curve for synthetic waste: (a) for paper, (b) for plastic, (c) for organic content.

Figure 7b depicts the shear behavior of the SMSW samples with varying percentages of plastic. As the proportion of plastic in the mixture increases, the shear resistance of the samples decreases. Across all three normal pressure conditions (10 kPa, 20 kPa, and 30 kPa), the sample with 10% plastic (SW-04) exhibits a stiffer response than the samples
with 25% (SW-05) and 35% (SW-06) plastic. The behavior of decreasing shear resistance with increasing proportions of plastic can be attributed to the properties of plastic, which is a softer and lighter material but also reduces the shear resistance of the SMSW, i.e., reduction in shear resistance. When present in high proportions, the mixture increases the tendency of the SMSW particles to slip or slide over each other—ultimately leading to a decrease in the shear resistance of the SMSW. It is important to note that the impact of plastic on the shear response of SMSW is meaningful; therefore, it is essential to address and analyze its properties based on composition. When plastic is added to a soil sample, it changes the physical properties of the sample. This happens because the plastic makes the soil softer, which leads to a weaker response when the sample is subjected to shear. The effect of plastic composition on the shear parameter of SMSW can be observed through the values obtained for different samples, as presented in Figure 8b. SW-04 has a cohesion of 3.94 kPa and a friction angle of 21.75°. The cohesion and friction angle of SW-05 is 3.35 kPa and 20.32°, respectively. The cohesion and friction angle of SW-06 is 3.1 and 19.23°, respectively.

Figure 7c illustrates the shear response of soil samples with varying proportions of organic matter. The results suggest that as the percentage of organic matter in the samples increases, the shear response. It can be observed by comparing the behavior of three different soil samples: SW-07 has 45% organic content, SW-08 has 15% organic content, and SW-09 has 55% organic content. The results show that SW-09 has better shear resistance than the other two samples. This behavior can be attributed to the finer and shredded organic material used in the study. When the organic matter is mixed with water and compacted, it adheres to the other particles in the sample. It leads to a denser arrangement of particles, which results in a higher degree of interlocking between them.

This interlocking, in turn, increases the shear resistance of the soil sample. It should be emphasized that the shear characteristics of SMSW are substantially enhanced by organic matter. The cohesion and friction angle values are as follows: the cohesion and friction angle of SW-07 is 2.50 kPa and 22.7°, respectively. The cohesion and friction angle of SW-08 is 2.88 kPa and 23.4°, respectively. The cohesion and friction angle SW-09 are 3.41 kPa and 24.7°, respectively.

4. Discussion

We assessed the results obtained from geotechnical testing to determine if the synthetic waste exhibits comparable unit weight and shear behavior to the real MSW and previously recorded SMSW in the literature. This analysis is necessary to ensure that the synthetic waste used in the study is representative of real-world conditions and can be used to make accurate predictions. Furthermore, the results obtained from the geotechnical testing can be used to analyze the shear behavior of SMSW. This information can be used to design landfill structures, predict slope stability, and evaluate potential geotechnical failures.

Measured SMSW Geotechnical Properties

The unit weight of all the samples of SMSW was determined by conducting a modified proctor test, and the results are presented in Figure 5. There is a considerable amount of uncertainty associated with the unit weight of MSW, and several studies have reported varying unit weight values for MSW. The authors of [10] performed a test on MSW and reported a bulk unit weight within the range of 7–10 kN/m³, and ref. [16] reported a dry unit weight of 2–7 kN/m³. The authors of [17] collected and performed testing on landfill waste and reported a bulk density of 5.4–8 kN/m³. Ref. [18] Calculated a bulk unit weight of 7.7–10.4 kN/m³; ref. [19] reported a bulk unit weight of 8–10 kN/m³, calculated from the field measurement. The authors of [3] performed tests on SMSW particles with an average size of 1.5 mm, where 10% of particles were more than 10 mm, and 35% of particles were finer than 0.1 mm, and the results showed a unit weight range of 4.7–6 kN/m³. Ref. [20] calculated the unit weight of MSW to range from 10 kN/m³ near the surface to 16 kN/m³ at a depth, while [21] estimated the bulk unit weight of fresh SMSW from 3 to 6 kN/m³. Ref. [2] calculated the unit weight of SMSW particles with a varying size of particle from
0.1 mm to 20 mm, resulting in a range of 2.2–5 kN/m$^3$. The obtained dry unit weight of the SMSW was in the range of 3–5 kN/m$^3$.

When comparing the results obtained from synthetic waste and real waste materials, it is crucial to consider certain precautions. In this study, it is essential to note that the calculated unit weight of the synthetic waste is slightly lower than that of real municipal solid waste (MSW), as reported in the existing literature. Additionally, it is important to recognize that the synthetic waste material used in the study was created by replacing certain components of real waste. Therefore, it may not entirely represent the common components of real waste. Therefore, when interpreting and comparing the results of this study, it is important to consider these potential limitations and how they may impact the overall conclusions drawn from the research. Proper consideration of these factors will ensure that the study’s findings are accurately understood and applied appropriately. It is also important to note that the material used in this study is a dry unit weight, neglecting the small amount of moisture in the organic material. Overall, it is essential to exercise caution when comparing the results of synthetic waste and real waste materials. The differences in the composition and unit weight of these materials can significantly impact the findings of any study. Acknowledging and accounting for these differences can ensure that their results accurately reflect the reality of waste materials and avoid potential misinterpretations.

The authors of [22] commented that the dry unit weight of MSW 2–4 kN/m$^3$ is equal to the bulk unit weight of MSW in a range of 6–9 kN/m$^3$ for the same waste in a field capacity. The MSW unit weight is at the lower limit of the previously determined values when the waste has less moisture content (i.e., mixing of water is prohibited) [23]. The results of this study suggest that the low unit weight values obtained for synthetic MSW are not unrealistic. This finding is supported by the fact that the material used in the study was light and dry, which can result in lower unit weight. However, it is important to note that the MSW found in landfills has undergone significant compaction through compaction rollers and sheep foot rollers. These processes compress the waste and reduce its volume, which can increase unit weight. It is worth mentioning that laboratory experiments typically use dead loads to simulate the weight of waste materials. These dead loads may not accurately replicate the compaction process in landfills. Therefore, it is important to consider the limitations of laboratory experiments when interpreting the results.

In light of these factors, further research is needed to fully comprehend the impact of moisture content and compaction on the geotechnical properties of MSW. Understanding how these factors influence the behavior of waste materials is crucial for developing effective waste management strategies. By investigating these factors more closely, researchers can better understand how waste materials behave under different conditions and develop more accurate models for predicting their behavior.

Large-scale direct shear tests were conducted on MSW samples collected from Canadian landfills. The dimensions of the DST apparatus were 434 mm × 287 mm, and a shearing rate of about 1.5 mm/min was employed. Based on the analysis, the calculated range of cohesion was found to be 10–23 kPa, and the friction angle ranged between 24° and 42° kPa. Ref. [24] conducted a similar large-scale direct shear test on MSW samples collected from a landfill in Arizona. The side dimension of the apparatus used in their study was 1.2 m, and the results indicated that the cohesion was 5 kPa, while the friction angle was between 33° and 35°. Ref. [25] performed a DST on MSW samples of a particle size less than 5 cm. The Mohr–Coulomb strength envelope revealed that the cohesion was 27 kPa, and the friction angle was 42°. Ref. [26] conducted a large-scale direct shear test on MSW samples collected from a landfill in Verona, Italy. The author attempted to perform the test on both disturbed and undisturbed samples collected from the field. The analysis revealed that there was very little difference in the shear strength parameter between the disturbed sample and the undisturbed sample. The cohesion of the disturbed sample was 22 kPa, while the friction angle was 17°, and for the undisturbed sample, the cohesion was 24 kPa, while the friction angle was 18° [27]. The results of a large-scale direct shear test on MSW samples collected from Californian landfills were presented. The shear envelope
was reported as a cohesion of 43 kPa and a friction angle of 31°. Ref. [12] conducted a large-scale direct shear test on MSW samples and reported that the mean value of cohesion was 25 kPa, and the friction angle was 35°. Ref. [9] performed a large-scale direct shear test on the sorted municipal solid waste (MSW) sample. The analysis revealed that the calculated shear parameters were in the range of cohesion of 0–8 kPa and friction angle of 27°–40°. The higher friction angle was attributed to the presence of sand in the composition mix. Ref. [28] conducted the test on SMSW material, where the shear box used had a diameter of 63.5 cm, and the particle size was 1.5 mm. The analysis indicated that the resulting cohesion was in the range of 16–19 kPa, while the friction angle ranged between 27° and 29°. Ref. [14] performed a large-scale direct shear test (300 mm × 300 mm) on a sample collected from San Franciscan landfills. The analysis revealed that the cohesion was 15 kPa, and the friction angle was 36°. Ref. [21] conducted a direct shear test to investigate the factors affecting the shear strength of MSW. The author found that an increase led to increased cohesion but a slight decrease in the friction angle. Additionally, if the sample constituents contained more plastic waste, it led to a decrease in both the cohesion and friction angle. The variation in shear strength values between synthetic and real waste is linked to the higher unit weight of the waste. It can be attributed to the use of wet material and finer particles, resulting in higher particle interlocking and the mobilization of tensile stresses in reinforcing elements. The test results for friction values between synthetic and real waste are comparable, but there are wide variations in cohesion. The main factor that affects shear behavior is a large amount of sand soil-like material present in the real waste, which can be up to 60–70% by the mass of the sample. Additionally, the significant moisture content in real waste is another important factor. The synthetic waste shear envelope and cohesion were found to be within the lower bounds of the envelope, while the friction angle was within the envelope [5,12,14]. According to the present study, the cohesion ranges from 3 to 5 kPa, and the friction angle ranges from 18 to 25°. This material has less cohesion value because the material used is fresh and has less cohesive behavior; due to degradation, the proportion of finer particles increases, which increases cohesion. It is important to exercise caution while comparing the calculated values with the literature values since the shear strength envelope is often published without information on the boundary conditions, the type of material used, and the size and shape of the material, leading to a misleading interpretation and comparison of results. The calculated shear strength values provide a good basis for comparison with the real waste values. The SMSW composition was created, and experiments were carried out to assess the effect of various ingredients on the shear strength of MSW. It is important to understand how each material affects the geotechnical properties of the MSW sample, even though it may not accurately represent real field conditions. While there are several benefits of using SMSW over MSW, some limitations also need to be addressed. One of the primary limitations is that MSW in landfills consists of several unknown mixtures, and the arrangement of material is difficult to replicate in the laboratory.

The MSW in landfills undergoes compaction due to overburden pressure, and over time, it also undergoes partial to full decomposition, depending on the age of the waste. Previous research has shown the decomposition effect on the geotechnical properties of MSW and concluded that the organic content of waste is reduced from 84.1% to 58% due to degradation. The unit weight of the sample increases due to the decrease in particle size of the material, initially containing 20% of particles finer than 10mm, which increased to 38% due to degradation. The friction angle decreases from 30° to 12° due to degradation, while cohesion does not exhibit any consistent trend and varies from 29 to 65 kPa [29]. It is important to note that different materials undergo decomposition differently, depending on the time. The authors of [30] created a new constitutive model for MSW, considering the effect of biodegradation by analyzing the change-in-void ratio and settlement characteristics. Therefore, SMSW studies need to be conducted, considering the different degrees of decomposition and how different materials affect the decomposition property of the material. While it may be difficult to replicate the exact conditions found
in landfills, the knowledge gained from such studies can help us better understand the geotechnical properties of MSW and their impact on the environment.

5. Conclusions

A family of synthetic wastes was designed based on the results of the waste-sorting analysis conducted on the waste collected from Hyderabad, India. Synthetic waste samples were created by substituting representable alternatives for MSW components. A total of nine samples were created by using ten different waste materials. The study aimed to assess the impact of specific materials, such as paper, plastic, and organic content, on the geotechnical characteristics of fresh SMSW. From this study, it was found that the composition of the material significantly affects the MSW properties.

The shear behavior of synthetic municipal solid waste composition was examined by performing a large-scale direct shear test. In most of the test results, no peak failure was observed. The SMSW samples contain softer components; some of these components can undergo larger deformation (i.e., plastic) under shear. Peak strength is expected not to be mobilized in such a test. During the experiments, the slope of the shear stress versus horizontal deformation tended toward the horizontal. However, some of the tests could not achieve this due to limitations in shear displacement. The friction angle of SMSW has a comparable value with the friction angle of the real MSW but has lesser cohesion compared to real MSW. The maximum dry density of the samples is at the lower end of the published values.

Waste entering landfills constantly changes because of the continuous change in legislation and consumer behavior. Therefore, landfill facility design must consider these potential changes in the MSW mechanical properties. It is important to calculate the mechanical properties of MSW, considering different compositions, moisture content, shear strength, and unit weight. In comparison, there is a need for additional research to expand the scope of the synthetic waste materials studied. Evaluating the impact of unit weight and material composition and findings outlined in this paper support the notion that the proposed classification framework can be linked to the mechanical behavior of these materials. The research leads to the following conclusions:

- The shear strength parameters of SW-01, SW-02, and SW-03 are compared. It is observed as the proportion of paper increases, the cohesion increases, and the friction angle decreases. When samples SW-01 and SW-03 are compared, cohesion increases by 66.67%, and the friction angle decreases by 20%.
- The shear strength parameters of SW-04, SW-05, and SW-06 are compared, and the percentage of plastic increases in cohesion while the friction angle decreases. When comparing SW-04 and SW-06, the cohesion decreased by 25%, and the friction angle decreased by 11%.
- The samples SW-07, SW-08, and SW-09 are compared; with the increase in the organic content, the cohesion and friction angle increase. The samples SW-07 and SW-09 are compared, and the cohesion is increased by 36.41%, while the friction angle increased by 9%.

The study’s findings suggest that the waste’s shear strength and unit weight are significantly influenced by the sample’s composition, highlighting the importance of conducting site-specific evaluations. The above results show that the material shear strength is mainly governed by the friction angle of fresh SMSW, as observed in the previous study. Additionally, paper particles have been shown to affect the shear strength of synthetic municipal solid waste the most compared to plastic and organic material. Researchers and practitioners utilize the classification framework while reporting mechanical test results for MSW. It could enhance information sharing, simplify the interpretation of measurements, and support the development of constitutive models that account for composition-related factors in waste materials. As the classification framework continues to evolve, it could potentially serve as a basis for evaluating the potential impact of changing waste types on landfill engineering practices. Extreme caution should be taken while using results
obtained from synthetic waste materials in design applications (it is not recommended to use values obtained using SMSW). It is because the synthetic waste used in testing had different testing conditions compared to real municipal solid waste (MSW). One of the key differences was that the synthetic waste was dry and had less moisture content than typically found in real MSW.

Additionally, the unit weight of the synthetic waste was at the lower end of the range of values typically observed in the literature reports for MSW. It also typically contains moisture, which can have an impact on the mechanical behavior of the waste. Therefore, it is essential to exercise caution when using synthetic waste results in design applications and to recognize the limitations associated with such materials. SMSW is used to study the changes in mechanical behavior, depending upon its associated changes. Based on the findings of this study, several future experimental recommendations can be suggested. Firstly, it is important to investigate the impact of moisture content on the geotechnical properties of synthetic municipal solid waste (SMSW). Furthermore, it would be helpful to study the effect of material composition on the biodegradation behavior of SMSW and use the degraded material to determine the geotechnical properties of MSW. By doing this, we can understand how changes in waste composition impact the biodegradation behavior of SMSW and then evaluate its geotechnical behavior. These experiments can be conducted using SMSW, allowing for controlled testing and evaluating specific waste components. By conducting these experiments, we can gain a more comprehensive understanding of the geotechnical properties of MSW.

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