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Geotechnical Characterization of Synthetic Municipal Waste at Different Stages of Decomposition

B.V.S. Viswanadham[1] , Basil Jaimon[2], and Vineet Gajamer[3]

[1]*Professor, Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, India, email: viswam@civil.iitb.ac.in*

[2]*Formerly M.Tech. Student, Division of Civil Engineering, School of Engineering, Cochin University of Science and Technology, Koch, India, email: basil.jaimon@gmail.com*

[3] *Research Scholar, Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, India, email: v.gajamer@iitb.ac.in*

ABSTRACT

For ensuring the integrity and stability of construction, it is important that the properties of the constituent materials are thoroughly known. In landfills, municipal solid waste (MSW) is the major constituent whose properties keep changing over time due to the process of microbial decomposition. Therefore, it is important to understand the variation in the properties of MSW with degradation as the stability of landfills will be significantly affected by the transient properties. In this study, the geotechnical properties of MSW have been investigated. Considering the need of developing controlled components of MSW, synthetic waste material has been developed representing the real MSW produced in Mumbai, India at various stages of decomposition. The various stages for which the synthetic MSW was modelled are young (0-1 years), average (3-5 years), and old (>10 years). The constituents adopted for the developed synthetic waste material were coco-pith, fine sand, kaolin clay, shredded bits of polythene sheets, newspaper, sawdust, thermocol balls, aluminium foil, and cloth. For modelling the MSW at different stages of decomposition, mainly the proportions of coco pith, fine sand and kaolin clay have been varied. Geotechnical testing such as the geotechnical properties of the synthetic MSW have been extensively studied and compared to the existing literature. The developed synthetic municipal solid waste could also model important behaviour such as settlement and variation of shear strength properties.

Keywords: Municipal Solid Waste, Landfills, Synthetic waste, Biodegradation

1 INTRODUCTION

The global generation rate of municipal solid waste (MSW) has almost doubled from 1.3 billion tonnes/yr (2012) to 2.01 billion tonnes/yr (2018) (Kaza et al., 2018). Due to the massive generation of MSW, complete recycling is not possible and hence many countries opt for storing MSW in landfill, which is an economical alternative. Landfilling is not only economical but also comparatively an eco-friendlier approach for disposing of MSW compared to other methods such as incineration and sea dumping. MSW is commonly known as 'garbage' or 'trash' and is generated due to normal day-to-day activity. Some common constituents of MSW are food scraps, packaging, bottles, wood, cans, office disposable, textiles, metals, construction debris etc. The composition of MSW has been observed to vary from one region to another, depending upon the socio-economic status, demography and regulations of the region.

The behaviour and integrity of landfills are a major concern, as failures can have a damaging impact on the environment. To ensure the stability and integrity of landfills it is important to have a sound understanding of the geotechnical properties of MSW such as compressibility, shear strength and hydraulic conductivity. Numerous studies have been performed to understand the behavior of MSW by reseachers (Bray et al., 2009; Fei & Zekkos, 2018; Hartwell et al., 2021; Mondelli et al., 2022; Sivakumar Babu et al., 2015; Zekkos & Fei, 2017) and it has been found that the behavior of MSW is significantly affected by its unit weight, moisture content, stress level, degree of decomposition and void ratio (Fei & Zekkos, 2013). It has been observed that the studies have significant variations amongst them as climate, operational practices, composition, compaction effort, age and size of the sample greatly influence the geotechnical properties of MSW.

However, it is not always possible to perform experiments with real-field MSW due to health concerns and the non-availability of access to landfills. Studies have been done by researchers such as (Dixon & Jones, 2005; Pincus et al., 1995; Thusyanthan et al., 2006, Reddy et al., 2009a & 2011;) on synthetic municipal solid waste (SMSW), which were prepared by combining materials in a well-defined proportion to represent the MSW in the field. The geotechnical properties of the SMSW can be controlled and matched to the properties of real-field MSW by varying the content of the constituents of different particle sizes.

The properties of MSW are highly affected by the degree of decomposition and very limited studies have been conducted to investigate the properties of MSW at different stages of decomposition. This study aims to model the MSW in Mumbai, India at three stages of decomposition by developing an SMSW mixture. Since the content of various waste materials can greatly influence the properties of the SMSW, great attention has been paid to proportioning the constituents of the SMSW. An extensive geotechnical investigation has been performed in this study to assess the variability in the geotechnical properties with age and comparisons have been made to existing literature.

2 PROPORTIONING AND CHARACTERIZATION OF SMSW

The proportioning of the SMSW has been done to model the MSW produced in Mumbai, India which generates about 40% biodegradable and 60% non-biodegradable waste. The MSW composition of three parts of Mumbai city has been considered to proportion the components of the SMSW. The three parts of the city chosen in this study are Island City, Eastern suburb and Western suburb. The biodegradable content in the MSW produced by the city lies in the rage of 35 to 43% by mass.

Also considering the composition of MSW generated in IIT Bombay, three categories of SMSW have been proportioned representing the MSW at three stages of decomposition. The SMSW developed mainly constitutes coco-pith compost, kaolin clay and Goa sand. The proportions of these major constituents are varied which largely determines the age of the SMSW by modelling its geotechnical properties. It is to be noted here that, in this study, the proportioning of the constituents is done in such a manner that the developed SMSW models the behavior of MSW at different stages and it does not depict the actual decomposition process of MSW. The age group of the three samples have been selected as young (0-1 year), average (3-5 years) and old (>10 years). The indicative name used to represent the three age groups are Sample 1 (S1), Sample 2 (S2) and Sample 3 (S3) for young, average and old SMSW, respectively.

Coco-pith and fine sand used in the study were finer than 0.425 mm, whereas the kaolin clay used in the mix was finer than 75 µm. Further, newspaper cut to 2 mm x 2 mm bits and polythene sheets and cloth cut to 3 mm x 3 mm pieces were also used. To impart frictional properties, aluminum foil cut into small bits of size 3 mm x 3 mm was used in the SMSW. Also, sawdust finer than 0.6 mm, retained on 75 µm and thermocol balls of size lesser than 2 mm have been blended in the SMSW. Table 1 shows the composition of the three types of SMSW by mass.

Bray et al., (2009) have performed an extensive large-scale laboratory testing to understand the shear strength of MSW in depth, which highlights the effect of presence of large fibrous particles. The fibrous material which are larger than 20 mm affect the shear strength of MSW. Significant increase in the shear resistance was observed when shearing was done across the length of the fibrous particle. However, the current study does not account for the effect of fibrous particles as the maximum particles size considered in the study is 3 mm. The different constituents and the synthetic waste developed have been shown in Figure 1.

Figure 1: *Components of SMSW: (a) Coco-pith (b) Kaolin clay (c) Fine sand (d) Polythene sheets (e) Newspaper (f) Saw dust (g) Thermocol beads (h) Aluminium foil bits (i) Cloth (j) Synthetic MSW*

Table 1. *Synthetic waste sample constituents*

Waste constituent		Size (mm)	Percentage by mass (%)		
			S1	S2	S3
Biodegradable	Coco-pith compost	< 0.425	38	28	18
	Newspaper	3	22	28	34
	Saw dust	0.075-0.6	22	28	34
	Cloth	2	4	4	4
Non-biodegradable	Kaolin clay	<0.075	5	3	2
	Goa sand	<0.425	4	4	4
	Polythene sheets	3	1	1	1
	Thermocol balls	< 3	2	2	2
	Aluminium	3	2	2	1

3 GEOTECHNICAL TESTING OF SMSW

3.1 Specific gravity of synthetic waste

In geotechnical engineering, specific gravity is defined as the ratio of the density of the soil solids to the density of gas-free distilled water at 20°C (ASTM D854-2014). Generally, a pycnometer is used to determine the specific gravity of the soil solids but the same method cannot be applied to SMSW, as particles having lesser specific gravity than water will float in the test setup. Thus, the intraparticle space in the SMSW will affect the measurement of specific gravity. To negate such an effect, a helium gas pycnometer was used which works on the principle of gas displacement and ideal gas law. It was observed that the size, shape and material composition largely affected the specific gravity of the samples. The specific gravity for S1, S2, and S3 were 1.93, 2.02, and 2.20, respectively. The increase in the specific gravity with age was also observed by Reddy et al. (2011) where the specific gravity varied between 1.09 to 2.47 for fresh to highly degraded waste. Other studies such as Breitmeyer (2011) calculated the value of specific gravity of fresh MSW from a landfill in the United States as 1.34. Wu et al. (2012) investigated the specific gravity of an old landfill in China at various depths namely shallow, medium and deep depths. The specific gravity increased with depth from 1.51 to 2.14. Therefore, it can be said that the three formulated samples are representing the relationship between specific gravity and the age of real MSW.

3.2 Particle size distribution

The particle size distribution (PSD) of all three samples has been obtained by conducting sieve analysis in accordance with IS: 2720 (Part 4) (2006). The percentage finer than 0.075 mm in all three samples was less than 1%. It can be pointed out that the sizes of particles were in the range of 0.20 mm to 0.25 mm (Fig. 2). The coefficient of uniformity (C_u), for S1, S2, and S3 were found to be 3.2, 2.85, and 2.75, respectively. On comparing the PSD of the developed SMSW with the literature, it can be seen that the curve for all three samples lies in the vicinity of Mixture 'A' of Thusyanthan et al. (2006) and Reddy et al. (2009a), which have given good representation of real MSW.

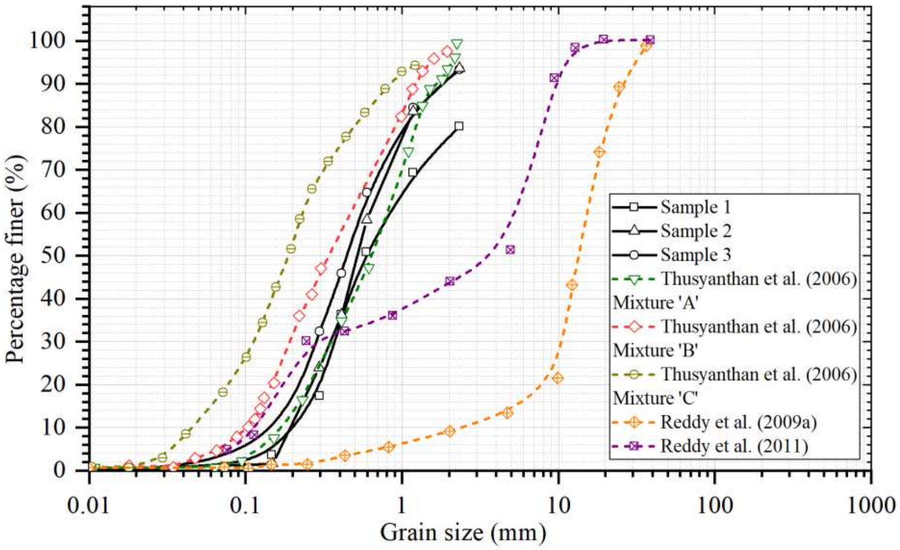

Figure 2: *Comparison of particle size distribution of SMSW*

3.3 Hydraulic conductivity characteristics

Investigating the hydraulic conductivity of landfills is of prime importance, as the generated leachate will lead to increase in the pore pressure within the landfill. This may cause slope instability and subsequently catastrophic failure. It has to be well accounted for, that the fresh MSW placed with less compaction energy will have more voids and hence higher hydraulic conductivity, but with degradation, the particle size decreases, which leads to a reduction in the hydraulic conductivity. For determining the hydraulic conductivity of S1, constant head permeability test was conducted in a cylindrical rigid wall permeameter of diameter 80 mm and height 60 mm, in accordance with IS: 2720 (Part 17) (2002), at an optimum moisture content of 81% and maximum dry unit weight of 4.1 kN/m^3 (standard Proctor compaction). Due to the finer gradation of S2 and S3, falling head permeability test was conducted in a rigid wall permeameter according to IS: 2720 (Part 17) (2002). The samples S2 and S3 were compacted to a maximum dry unit weight of 6.22 kN/m^3 and 9.55 kN/m^3 at an optimum moisture content's of 39% and 38% (standard Proctor compaction), respectively.

The average hydraulic conductivity of S1, S2 and S3 was obtained as 1.01×10^{-5} m/s, 1.01×10^{-7} m/s and 5.86×10^{-8} m/sec, respectively. The variation in the hydraulic conductivity with age is in good conjunction with previous studies laid out in Table 2. It can be observed that the hydraulic conductivity is reduced by an order of 3 on undergoing full degradation. The reduction in the hydraulic conductivity of MSW due to the generation of fines on degradation was successfully modelled by SMSW.

Hydraulic conductivity is also influenced by the confining pressure and its density, Figure 3 presents the comparison of the current study with some studies from the literature. The data obtained in the current study follows the trend observed in previous studies where the hydraulic conductivity is observed to decrease with the increase in density.

Table 2. *Comparison of hydraulic conductivity of waste at different stages of decomposition*

Source	**Hydraulic Conductivity (m/sec)**		
	S1	**S2**	**S3**
Present study	1.01×10^{-5}	1.01×10^{-7}	5.86×10^{-8}
Powrie and Beaven (1999)	1.5×10^{-2}	-	3.7×10^{-6}
Hossain et al. (2008)	9×10^{-5}	4×10^{-5}	1×10^{-5}
Reddy et al. (2009b)	1×10^{-4}	-	1×10^{-8}
Reddy et al. (2011)	3×10^{-5}	5×10^{-7}	5×10^{-8}

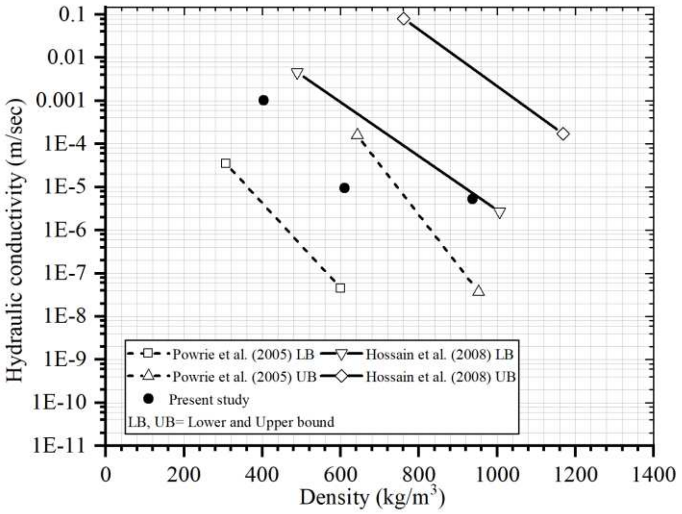

Figure 3: *Comparison of variation of hydraulic conductivity with density of MSW*

3.4 Compressibility characteristics

It is important to know the final settlement of a landfill as it increases the efficiency of the placement of waste and also develops a better understanding of voids present within the landfill once the waste starts to decompose. This is vital as it is instrumental in designing the final capping system and determining the interaction between the side barrier system and the settling mass. The settlement of a landfill is affected by various factors such as the type of disposed waste, placement density, moisture content, pH, porosity etc., and hence the compressibility characteristics vary from one landfill to another. MSW settlements are caused mainly due to four reasons (Fei & Zekkos, 2012, 2013; Hettiarachchi et al., 2009; Hossain & Gabr, 2005; Lü et al., 2019; Ren et al., 2022; Sharma & De, 2007; Sivakumar Babu et al., 2010, 2015): a) Mechanical compression: It occurs by the means of densification, crushing, distortion, reorientation of particles and displacement of particles into larger voids; b) Chemical process: Processes such as corrosion combustion and oxidation causes reduction in the volume of the waste; c) Dissolution: The percolating liquid dissolves soluble substances forming leachate; d) Biological decomposition: Compression of waste also occurs due to the aerobic and anaerobic decomposition depending upon the humidity and the organic content of the waste material.

The most significant portion of settlement occurs in the placement of waste due to physical and mechanical processes, this is known as primary settlement. The chemical and biological processes also cause a substantial amount of settlement over a longer period of time which happens at a slower rate, which is known as secondary settlement.

In geotechnical engineering, the change in the void ratio during primary settlement is expressed in terms of compression index (C_c), given by:

$$C_c = \frac{\Delta e}{\log\left(\frac{\sigma_1}{\sigma_0}\right)} \tag{1}$$

Where, σ_0 is the initial vertical stress, σ_1 is the final vertical stress and Δe is the change in void ratio.
Due to the difficulties in estimating C_c in the field, a modified parameter known as the coefficient of primary compression index or compression ratio (C_{ce}) is generally used (Thusyanthan et al., 2006), which is defined as:

$$C_{ce} = \frac{\Delta H}{H_0 \log\left(\frac{\sigma_1}{\sigma_0}\right)} \tag{2}$$

Where ΔH is the change in thickness of the waste layer and H_0 is the initial thickness of the waste layer. Oedometer tests were conducted on all three synthetically developed samples at the previously mentioned optimum moisture content and maximum dry density in accordance with IS: 2720 (Part 15)

(2002). The values of the compression index for S1, S2 and S3 were obtained as 0.56, 0.34 and 0.29. Further, the values of compression ratio were also obtained for S1, S2 and S3 as 0.218, 0.192 and 0.158, respectively. Table 3 shows the comparison of the compression ratio obtained in this study with the values obtained previously by other researchers.

Table 3. *Comparison of compression ratio/ coefficient of compression index of MSW samples at different ages or depths*

Source	Compression Ratio	Remarks
Dixon et al. (2008)	0.30	SMSW, large scale test (500×500×750 mm) with maximum particle size of 500 mm
Thusyanthan (2006)	0.25	Synthetic sample prepared in laboratory
Reddy et al. (2009a)	0.16-0.31	SMSW with an average particle size of 1.5 mm
Reddy et al. (2011)	0.35, 0.26, 0.15	SMSW at 0%, 50% and 82% degree of decomposition
Staub et al. (2013)	0.319, 0.329	Large-scale test conducted on French MSW
Zekkos et al. (2016)	0.01-0.26	Large-scale testing conducted on 143 samples
Zhang et al. (2020)	0.233–0.247	Large-scale testing conducted on mechanically biologically treated MSW

MSW also undergoes secondary compression due to the biochemical and physiochemical processes which continues until the mass is completely decomposed. The major settlement in this stage is caused to because of the combination of creep loading due to self-weight with plastic rearrangement of particles due to degradation. In this study, the three samples S1, S2 and S3 were allowed to consolidate under a vertical pressure of 400 kPa for 6 weeks. Figure 4 presents the plot of void ratio versus time for calculating the secondary compression ratio *(C_α)* which can be obtained as:

$$C_\alpha = \frac{\Delta e}{\log(\frac{t_2}{t_1})} \tag{3}$$

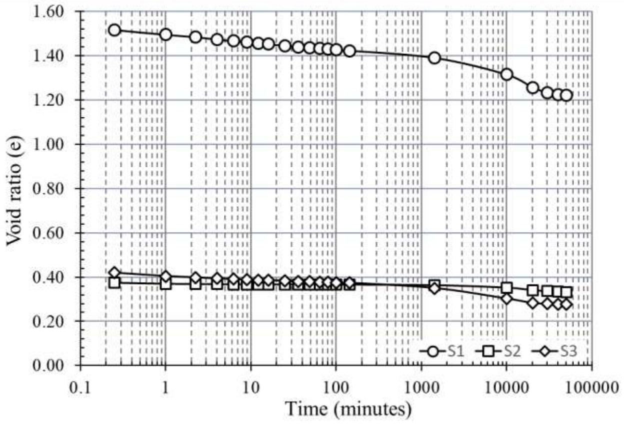

Figure 4: *Secondary compression curve for the SMSW at 400 kPa*

It was observed that $C_\alpha$decreases with the increase in the degree of decomposition. This is due to the ceasing of settlement of old-age waste as it has attained more stabilization. The values of C_α obtained for S1, S2 and S3 are 0.0553, 0.0217 and 0.016, respectively.

3.5 Shear strength parameters

Cohesion, frictional resistance and interlocking impart strength and stability to the MSW mass. It is important to understand the shear strength parameters of MSW to assess its behaviours under different conditions. The strength of MSW depends upon factors such as compaction effort, degree of decomposition, constituents, etc. In this study, direct shear tests on samples of size, 100 mm x 100 mm x 33 mm have been done to determine the shear strength parameters of the SMSW at saturated and unsaturated conditions conforming to IS: 2720 (Part 13) (2002). The samples for all three age categories of waste were prepared at optimum moisture content and maximum dry unit weight (standard Proctor compaction). For the saturated sample, to maintain drained conditions, loading was performed at a very slow rate of 0.025 mm/min. For the case of unsaturated samples, the loading was done at a rate of

0.625 mm/min. The samples were allowed to consolidate under the applied vertical stress of 50 kPa for 2 days. Figure 5 shows the shear stress vs horizontal displacement response obtained by performing direct shear tests at three different normal stresses of 50, 100 and 150 kPa. It can be seen that the stress variation obtained for both saturated and unsaturated cases, is similar to the variation obtained by other researchers (Dixon et al., 2008; Hossain, 2002; Reddy et al. 2009a) where peak behaviour is not observed, rather constant increase in the shear strength with displacement is observed (Fig. 5). Due to the absence of peak shear stress, the shear strength corresponding to a horizontal strain of approximately 12% and 17.5% have been used for saturated and unsaturated samples, respectively in the study to estimate the shear strength parameters (Fig. 6). The obtained shear strength parameters have been summarised in Table 4.

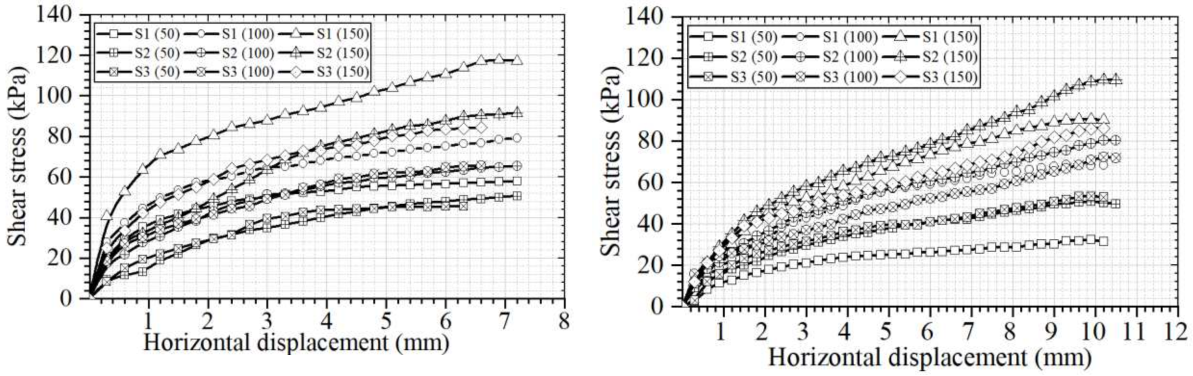

Figure 5: *Shear stress vs horizontal displacement for saturated (left) and unsaturated (right) SMSW under different normal stresses*

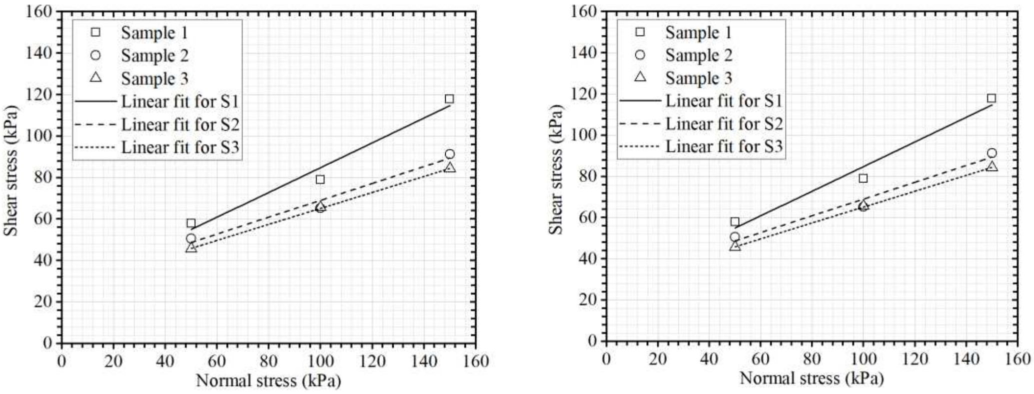

Figure 6: *Shear stress vs normal stress for unsaturated (left) and saturated (right) SMSW*

Table 4. *Shear strength parameters of the developed SMSW*

	Parameters	Sample 1	Sample 2	Sample 3
Unsaturated	Cohesion (kPa)	5.71	21.17	36.52
	Internal angle of friction (degrees)	30.11	30.54	19.11
Saturated	Cohesion (kPa)	25.03	28.27	20.20
	Internal angle of friction (degrees)	30.87	22.19	21.15

In a study conducted by Reddy et al. (2011), the reported value of the shear strength parameters of the SMSW at 0% degree of degradation was 0 kPa cohesion and friction angle of 36°. When the SMSW was subjected to two different degrees of degradation by leachate recirculation, the values of cohesion and the internal angle of friction were obtained as 18 kPa, 38 kPa, and 30°, 28°, respectively. Therefore, it can be said that the developed SMSW could capture the trend of decrease in the internal angle of friction and increase in cohesion with age satisfactorily by varying its composition. The saturated shear strength parameters obtained are important as MSW in bioreactor landfill are saturated due to leachate recirculation and the shear strength parameters can be used to assess the stability of the bioreactor landfills. It has to be mentioned here that due to the dependency of shear strength of MSW on a number of variables, researchers have reported contradictory findings on the effect of aging on the shear strength of MSW (Keramati et al., 2020). It can be said that the obtained values of cohesion and internal angle of friction are in the acceptable range on comparing them to the comprehensive record presented by Keramati et al. (2020).

Further, Unconfined Compressive Strength (UCS) tests were conducted on the samples per IS 2720 (Part 10) (2006). Samples for S2 and S3 were moulded at OMC but due to the low cohesion of S1, the sample was prepared at a water content of OMC+15 %. The samples were 15 cm in height and 7.5 cm in diameter and were tested at a strain rate of 1.2 mm/min. S1 failed by total collapse as depicted in Figure 7 prematurely. In the case of S2 a significant increase in the UCS was observed on comparison to S1 and showed a slight peak stress at an axial strain of 7.5% after which cracks were observed on the sample. Further increase in the UCS was achieved in S3 which reached its peak deviator stress at a lesser axial strain of approximately 6.5% compared to that of S2. The failure of the sample not only caused cracks in S3 but also bulging of the sample was observed during failure (Fig. 7).

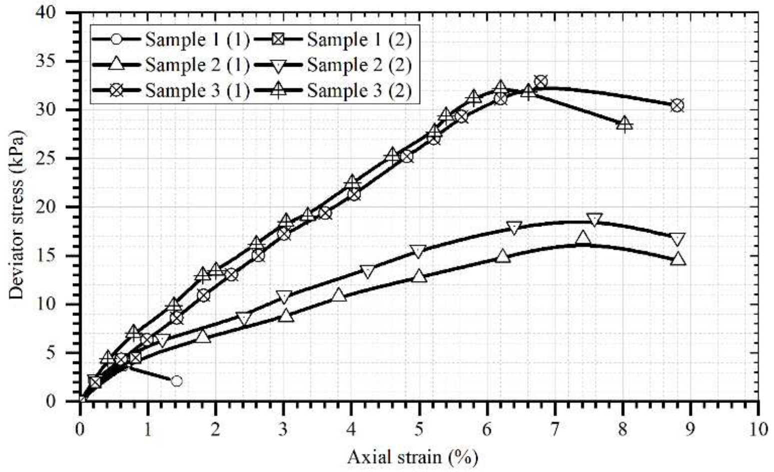

Figure 7: *Unconfined compressive strength of synthetic waste samples*

The UCS values obtained for S1, S2 and S3 were 4.8 kPa, 18 kPa and 33 kPa, respectively. The increase in the UCS value is attributed to the increase in cohesion due to the increase in the fine content and to the increase in the density of the SMSW. The UCS test clearly portrays the effect of age and density of MSW on its strength.

4 CONCLUSIONS

Handling of MSW may cause health hazards and is often landfills are inaccessible due to regulatory restrictions. Also considering the difficulty in using MSW samples in the laboratory due to their large particle size, SMSW can be adopted to perform studies related to MSW. Studies related to MSW are complicated due to the variation in properties caused due to decomposition and it is important that the change in properties is incorporated in assessing the behaviour of the material. Previous researchers have considered the effect of biodegradation by recirculating the generated leachate and allowing actual decomposition to occur, however, in this study, a simple approach has been adopted in which the degree of decomposition is represented by appropriately proportioning the constituents of the SMSW.

Thus, in this study, SMSW was developed representing three different ages namely young, average and old using coco-pith compost, kaolin clay, goa sand, plastic sheets, thermocol beads, newspaper, cloth, sawdust and aluminium foils. The composition of MSW in Mumbai, India was considered and the proportioning was carefully done to represent the MSW of Mumbai. Subsequently, the geotechnical properties of the developed SMSW were investigated and compared to studies done by other researchers to ensure that the SMSW models the real field MSW satisfactorily.

The specific gravity values obtained for samples 1, 2 and 3 were 1.93, 2.02, and 2.20, respectively. The maximum particle size in the SMSW was 3 mm and most of the particles lay in the range of 0.1-1 mm, with less than 1% of particles lying below 0.075 mm. Considering the particle size distribution of the SMSW, constant head test and falling head test were conducted on the three waste samples. The hydraulic conductivity of the waste samples decreased with age. The values of hydraulic conductivity for samples 1, 2 and 3 were 1.008×10^{-5}, 1.01×10^{-7} and 5.86×10^{-8} m/sec, respectively. The values of compression ratios obtained for samples 1, 2 and 3 were 0.56, 0.34, and 0.29, respectively. To determine the coefficient of secondary compression, the sample is kept at a vertical stress of 400 kPa for 6 weeks. The values of the $C\alpha$ obtained are comparable to the ones obtained in the literature.

The shear strength parameters were obtained by performing direct shear tests on saturated and unsaturated samples in this study. The composition of the samples was successful in imparting both frictional and cohesive properties and could also capture the increase in cohesion for the older samples which is caused due to the generation of more fines. Therefore, the proportioning of the constituents was accurately done in the SMSW for three categories based on the degree of decomposition. The geotechnical properties of the three samples were tested and are found to be in agreement with typical values from previous studies. Further, the UCS of the samples were investigated and failure modes were observed. Sample 1 failed by total collapse while samples 2 and 3 failed by crack formation where cracking was accompanied by bulging in the case of sample 3. The SMSW developed in this study could satisfactorily model the behaviour of the real field MSW and can be used for further studies.

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