CHAPTER- II

REVIEW OF LITERATURE

2.1 INTRODUCTION

Landfill mining is one of the important global environmental issues, and some possible improvements can be achieved at closed landfills. The closed landfills have a lot of space and potential resources that can be reclaimed with multi-functions. The studies have been carried out all over the world with different objectives of the landfill mining projects mentioned in Table 2.1. Highlighting the main objective of the present study, i.e., the studies on soil-like material of municipal solid waste have been reviewed here.

This chapter provides a brief review of the previous research on the physical, chemical, mineralogical, morphological, geotechnical, static/cyclic strength, liquefaction potential, and dynamic properties of MSW and MSW fines. The previous research is reviewed under the following subheadings:

- Characterization studies of MSW fines
    - Characterization of landfill-mined waste
    - Physico-chemical characterization of MSW fines
    - Geotechnical characterization of MSW fines
- Dynamic characterization studies of MSW and related soils
- Studies on reinforced MSW
- Potential re-usability and challenges in using Soil-like waste/MSW fine fraction
- Treatments required before field application

Table 2.1 The categories to evaluate the objectives of Landfill Mining projects.

Categories	Description
Environmental Protection	Groundwater protection, risk mitigation for surface water, groundwater, and air (landfill emissions), landfill stability, extraction of hazardous waste, reclaiming, landfill rehabilitation, and biological treatment for stabilization of organic matter.
Closure and post-closure	Monitoring of post-closure care.
Lifetime extension	Reduction of refilled waste volume, and reuse of land as landfill under favourable environmental conditions.
Recovery of excavated waste	• Soil recovery. • Energy Recovery. • Recyclable material recovery.
Waste characterization	Waste characterization.
Urbanization	Demand of land for urban development plan or industry use, construction of houses, industry, or recreation projects (parks), planted vegetation.
Studies	• Pilot studies and demonstration projects. • Landfill reclamation procedures. • Materials recovery feasibility. • Technical and economic feasibility studies. • Design parameters and infrastructure. • Technological routes for recovery of excavated waste.
Source@ Ortner et al. (2014); Márquez et al. (2019)	

2.2 CHARACTERIZATION STUDIES OF MSW FINES

2.2.1 Characterization of Landfill-Mined Waste

For decades, landfills were used to dispose of almost all municipal solid waste (MSW) and industrial wastes. Further, the source separation of commodities such as metals, paper, hazardous materials, and glass, as well as waste incineration, has now become a part of solid waste management (SWM). Landfills (particularly old landfills) are a diverse source of waste (Paap et al., 2011), and the volume, composition, and placement practices of most of these landfills are poorly documented (Jones et al.,2013). Site-specific investigations, such as test excavations or drillings into the landfill body are required as part of the exploration step to analyze the composition of the landfilled waste (Krook et al.,2012). To investigate the mining potential of any landfill, it is necessary to investigate the composition of the mined waste materials. The waste composition of any landfill, on the other hand, is determined by several factors, including waste legislation, disparities in waste management and recycling systems, socioeconomic status, and culture (Quaghebeur et al., 2013). The characterization studies have been done all over the world for various landfills as per the project requirements are discussed below:

2.2.1.1 Indian Landfill Studies

Coad (1997) investigated the waste characterization of the Deonar Dumpsite near Mumbai, which was mined in 1989, on a pilot scale basis to recover the decomposed waste as compost. The percentage of soil-like material sieved through 8 mm was 63.5%.

Kurain et al. (2003) studied the waste disposed of in an open dumping site of the Kodungaiyur and Perungudi sites, in Chennai. The sites were in operation since 1985. The study was conducted with the purpose of waste characterization and the reusability of soil-like material as compost. The study characterizes the excavated waste into three categories i.e., combustible, non-combustible, and soil (< 20mm). An average of 46 samples (Kodungaiyur site) and 12 samples (Perungudi site) were considered for the characterization and found to have 67.8% and 40.1% soil-like materials respectively.

Mor et al. (2006) studied the waste from the Ghazipur landfill site, in Delhi, India. The samples were collected from nine different boreholes at a depth of 0–3 m, 3–6 m, and 6–9 m, and a total of 25 samples were collected. Based on wt% of a wet material average of 49 ± 20%, 59.6 ± 18.3%, and 68.9 ± 12.3% at the location of 0-3 m, 3.-6 m, and 6-9 m, respectively was found to be compostable material. The total average of about 7.3 ± 7.2% (plastic), 3.7 ± 3.4 (paper), 23.3 ± 4.5 (cloth), 2.7 ± 1.7 (metal), and 3.3 ± 2.9

(stone) was also found. The purpose of the study was to estimate the methane production from the Ghazipur landfill site.

Singh et al. (2008) studied the physical and chemical characteristics of the Pirana landfill site, Ahmadabad, intending to estimate the quality and toxicity of waste concerning heavy metal and its impact on groundwater quality. The solid waste samples were collected from 0-25 cm depth. The samples represent 72% of organic matter, 13.4% earth material, 6.74% of plastic, 5.69% paper, 1.38% glass, and <1% metals.

Mali et al. (2011) characterized the MSW of a landfill at Urali Devachi in Pune operating since 1983. The mean organic content was found to be 69.3% from the collected samples and due to high organic and moisture content, biological treatment was suggested for the site.

Havangi et al. (2017) studied the reutilization of a specific portion of MSW collected from the Ghazipur landfill site, Delhi as an embankment material. The sample was collected from three different locations with approximate ages of 5, 10, and 15 years old. The waste was segregated through 80 mm, 35 mm, 16 mm, and 4mm sieves. The percentage content of metals, wood, paper, rubber, and glass was observed to be less than 1%. Most of the textiles and plastics were retained on the 80 mm sieve and about 82% of the passing 80 mm was mentioned as soil-like material.

Ramaiah et al. (2017) conducted a study to find the mechanical properties of the Ghazipur dump (age: 3-12+ years) and the Okhla dump (age: 3-10+ years) site in India. The waste was collected from 4 different points for each site and 70-80% was characterized below 20 mm and the remaining other materials like gravel, plastic, textile, wood, etc.

Somani et al. (2018) conducted a characterization study of the aged waste collected from three dumpsites in India, i.e., Okhla landfill (Delhi), Jawaharagr landfill (Hyderabad), and Ukkayyapalli landfill (Kadapa) started in 1994, 1999, and 1965 respectively. The study further investigates the initial chemical and physical tests on soil-like material (< 4.75 mm). The percentage of soil-like material excavated from all three sites was more than 70%. The inert waste was significantly high in the Okhla landfill as compared to the other two sites and the paper waste was found to be negligible in all the sites. The study aimed to check the reutilization of soil-like material for other purposes.

Singh and Chandel (2020) conducted the study for the Mulund dumpsite, Mumbai, which is the second largest dumpsite in Mumbai and operating since 1968 and was shut down in the year 2018. The waste was collected from the 5 zones (A-E) and the storage time of the selected zones varied between 1–10 years. Using sieve analysis on a dry basis, the excavated waste was classified into particle sizes of >80 mm, 80-40 mm, 40-20 mm, 20-4 mm, and 4 mm. The <4 mm (fine fraction) particle size was highest for all zones with an average of 45% in the dumpsite. The fine fraction increment with depth also depicts that the waste had degraded more in the bottom layers.

Cheela et al. (2021) investigated the landfill waste located in Visakhapatnam city in Andhra Pradesh to evaluate the amount of energy that could be recovered from aged waste (around 5–20 years) recovered from a landfill. It was observed that soil-like material constitutes around 56.6%, 53.7%, and 45.9%, and plastic around 23.1%, 18.6%, and 16.8% for the age of waste < 5 years, 5-10 years, and 10-15 years, respectively.

2.2.1.2 Landfill Studies Around the World

Hogland et al. (2004) investigated the waste collected from Masalycke and Gladsax landfills in Sweden. The excavated waste at these two sites ranged in age from

17 to 22 and 23 to 25 years. The samples were collected from different depths from 0.5-8m. It was found that the soil-like material from Masalycke landfill increases from 40.7% (0.5-2m) to 65.5% (6-8m) with depth and 81.15% (5-6m) to 84.9% (6-7m) for Gladsax landfill. The majority of Masalycke landfill waste was unaffected by degradation, and no significant amount of biogas was detected during excavations. Three size fractions were obtained after the screening: 18mm, 18-50mm, and 50mm. For the first and second fractions, soil amendment and anaerobic digestion with energy extraction were suggested.

Hull et al. (2005) investigated the composition and characteristics of excavated waste from Burlington County landfill in New Jersey operated from 1989 to 1999. Based on the waste age map of the landfill, 13 bore holes were selected and 49 samples were taken. The representative samples consist of 50% of the mass as a fine fraction and the rest 50% as miscellaneous items, wood, other plastics (not PETE or HDPE containers), and paper.

Jain et al. (2005) studied heavy metal content in soil reclaimed from Alachua County Southwest Landfill in Florida. The collected sample was sieved through 50 mm, 12.5 mm, 6.3 mm, and 0.425 mm sieves. The average composition of the waste from 78 represented samples was 44.6% (fines <0.425 mm) 14.5% (Intermediate >0.425mm and <6.3 mm), 12.9% (plastic), and 11.7% (paper).

Zhao et al. (2007) investigated the refuse from a closed landfill site in Shanghai. The considered waste was of age 0 to 10 years. It was observed that with the age (0 to 10 years) the percentage of fines <15mm increased from 10 to 45%. The refuse was found to be exceptionally stable 8-10 years after placement.

Prechthai et al. (2008) studied the recycling potential of stabilized municipal solid waste from Nonthaburi dumpsite in Thailand. Approximately 69% of the soil was removed from waste by screening, with the remaining 31% found in waste fractions larger than 50 mm in size. The quality of waste fractions >50 mm composed primarily of plastics demonstrated a high potential for recycling as refuse-derived fuel (RDF). The remaining waste fractions between 25 and 50 mm were non-combustible waste that need to be landfilled.

Sormunen et al. (2008) investigated the two finished landfills, i.e., Ammassuo and Kujala in Finland operated for 17 and 48 years, respectively. The major weight fraction in Ammassuo was inert materials (30-40%, primarily stones), with the other fractions contributing 22%. At all the depths in Kujala, residuals (soils and unrecognizable materials) made up the majority of the fraction (54-75%).

Siddiqui et al. (2012) presented and compared the long-term landfill behaviour of mechanically biologically treated (MBT) wastes from the UK and Germany that have been pre-treated to different standards. Two different waste materials were investigated i.e., aerobically treated MBT waste from the United Kingdom and anaerobically and aerobically treated MBT waste from Germany. For both categories of waste, it was found more than 50% of waste was undefined (almost 25% >5mm and 25% < 5mm). Glass was the second most common material (22.8% in the UK and 24.3% in the German MBT waste). The results show that the MBT waste can be stabilized in a year, and the biogas yield and leachate strength of German MBT waste are significantly lower than those of the UK MBT waste.

Quaghebeur et al. (2013) investigated the valorization options for the materials stored at the REMO site in Belgium using excavation tests performed at locations containing either municipal solid waste (MSW) or industrial waste (IW). The amount of combustibles present in the excavated waste was about 23 to 50%. All waste samples recovered from the landfill contained a high concentration of (40-60% of fine-grained (10 mm) mineral waste.

Van Vossen (2013) studied the characterization of 60 landfills from Europe for sustainable material and energy recovery. The average waste composition was summarised in which 54.8% of the waste was found to be soil-like.

Zhou et al. (2014) studied the characteristics and the recovery potential of plastic wastes obtained from the Yingchun landfill site, in China. The landfill was constructed in 1989 and was closed in 2004. The waste was segregated through a 10 mm sieve to obtain the plastic from it. It was observed from 22 samples of stored solid waste that the plastic waste accounted for 10.62 ± 5.12% on average, ranging from 2.95% to 21.76% and 63.6% of the samples contained more than 10% of plastic waste.

Masi et al. (2015) investigated the possible reuse of MSW from the old, closed dumpsite of Lavello, Italy. The landfill was active from the 1950s to the early 1980s. A total of 7 samples were taken from the site at a depth of 0.5 to 1 m and were composite together as one sample. It was seen that the fine fraction was about 70.4% and 63.6% when sieved through 10mm and 4mm respectively. The organic finer fraction, which accounts for 70% of the extracted material in the study was suggested to be used in a variety of environmental applications.

Zhou et al. (2015a) studied the cost-benefit of landfill mining and material recycling for the waste collected from the Yingchun landfill site, in China. It was observed that the soil -like material in the waste contributes up to 75.02% by its wet weight and 14.69% was combustible.

Wolfsberger et al. (2015) studied the resource potential of two sanitary landfill sites in Austria. One site received untreated waste, whereas in the second mechanically–

biologically treated waste was dumped. The landfills had resource potential of 52% (compartment 2) of landfill 1 and 32% (compartment 1) and 47% (compartment 2) of landfill 2. The percentage fines (<40mm) in all the 3 compartments of the two landfills were 68%, 84%, and 77% respectively.

Dewaele and Brunet (2016) investigated the Barrie municipal solid waste landfill which has been opened in 1960. The project was initiated with the aim of reclamation of the landfill to reduce the environmental impact which was expected to result in a recovery of air space, thus extending the operational life of the landfill. For this project, landfill reclamation refers to the process of excavating existing waste fill, screening to remove the daily cover soil (soil component), and then re-landfilling the remaining large waste fraction with a higher level of compaction and less soil cover than was originally used. The fines component averaged 52-53% over the course of the project (2009-2015), but the percentage varied significantly from day to day.

Jani et al. (2016) investigated the Hogbytorp landfill in Sweden for the characterization of the excavated fines and waste composition. The average size distribution of landfill categorized 38% of waste under 0-10mm, 38% under 10-40mm, and 24% >40mm. The study shows the high recycling potential of the excavated waste as waste to material and energy because of the high concentration of stones, asphalt, and limestone (36.1%) and because of the concentration of plastics, wood, paper, and textile (29.9%). The study shows that 98% of the total fines were <4mm and 80% were <2mm.

Monkare et al. (2016) investigated the waste mined from two finished MSW landfills in Kuopio (1 to 10 years old, referred to as new landfill) and Lohja (24 to 40-year-old, referred to as old landfill) to characterize fine fraction. In Kuopio, the fine fraction (20 mm) accounted for 45 ± 7% of landfill content, while in Lohja, it accounted for 58 ± 11%. Sieving revealed that almost 86.5 % of the fine fraction was smaller than 11.2 mm and resembled soil.

Bhatnagar et al. (2017) investigated the waste of a dump site (Kudjape, Estonia) with the primary goals of extracting soil-like final cover material with the function of methane degradation and estimating the value of landfilled materials and assessing their market opportunities. The fine (<40 mm) and coarse (>40 mm) fractions of the excavated waste were 54% and 46%, respectively. The fine portion was sieved further (10 mm) and analyzed for metal recovery potential.

Hogland et al. (2018) investigated the four case studies in Estonia and Sweden: Kudjape, Torma, Hogbytorp, and Vika landfills with the objective of material recovery. The samples were collected from the four test pits and the four layers of each test pit in the Kudjape landfill. The fines <40mm obtained in this landfill were an average of 9.8%, with the maximum percentage of stones (22%) and plastic (20%). Torma landfill consists of about 16% of fines (<10mm), 14% of soft, and 27% of other kinds of plastic. In the Hogbytorp landfill, 75% of the waste was an undersized fraction (<40 mm) 38% of which can be considered soil-like and 25% (>40mm) was the oversized fraction. In the Vika landfill, 59% was fine material like soil and about 22% was oversized material.

Faitli et al. (2019) studied the residual municipal solid waste (RMSW) from Debrecen Landfill started in 1993 and will be closed in 2028. 72.6% of the total waste was below 20mm. For landfill mining analysis, a new sampling and average sample preparation protocol were developed that can be used in practice.

Parrodi et al. (2019) studied the characterization and potential of the fine fraction of the Mont-Saint-Guibert (MSG) landfill, in Belgium. The fine fractions (<90 mm) accounted for 77 wt.% of the total landfill-mined material in raw form. The dry-state material composition results indicate that amounts of 2.1-19.7 wt.% (combustibles), 31.1-35.4 wt.% (inert), and 0.6-1.8 wt.% (total metals) could be recovered from the fine fractions 90-10mm, while 37.8-55.6 wt.% (fine fractions<10 mm) could be processed further to increase the recovery amounts of the previous fractions and produce a substitute material for soil.

The different waste categorization from the past few research and projects has been compiled in Table 2.2. Table 2.3 shows the considered screen size to segregate the fines from the waste. There is no specific standard for waste segregation, so the researchers have considered the fine portion as per the requirement of the study. It can be observed that for most of the studies, the fine fraction is more than 50%.

Table 2.2. Characterization of the excavated landfill waste.

Study area/ Landfill	PL (%)	T (%)	R (%)	M (%)	HW (%)	MW (%)	S (%)	W (%)	G (%)	P (%)	Others (%)	<40 mm (%)	<20mm (%)	<10mm (%)	<8mm (%)	SLM (%)	Reference
Perungudi, India	11.0	2.3	14.5	0.2			18.5	11.6	0.8				40.1				Kurian et al., 2003
Kodungaiyur, India	0.5	0.6	0.5	0.1			28.3	0.5	0.4				67.8				
Deonar, India	1.5	NA	0.6	0.4			31.5	0.6	NA						63.5		
Ghazipur, Delhi (India) (waste age:3-3.5yrs)	3.3	4.5						1.1	0.4	0.6	0.8 Other 16.7 gravel		72.6				Ramaiah et al., 2017
Ghazipur, Delhi (India) (waste age:9-10yrs)	3.8	2						1.0	0.4	0.1	1.4 other 21.0 gravel		70.3				
Ghazipur, Delhi (India) (waste age:10-12yrs)	2.9	2.2						1.3	0.6	0.2	0.9 Other 17.0 gravel		74.9				
Ghazipur, Delhi (India) (waste age: 12^{+}yrs)	4.2	2.5						0.7	0.5	0.1	0.4 other 20.8 gravel		70.8				
Okhla, Delhi (India)	1.0	0.8						0.4	0.2	0.2	0.1 other		80.2				

(Waste age:4.5-5.5yrs)											17.1 gravel						
Okhla, Delhi (India) (Waste age:3-4yrs)	3.0	2.8						1.0	0.6	0.3	0.7 other 18.9 gravel		72.8				
Okhla. Delhi (India) (Waste age:2-2.5yrs)	4.0	6.2						2.0	1.2	1.0	1.0 other 23.9 gravel		60.3				
Okhla, Delhi (India) (Waste age: 10^+yrs)	1.6	1.8						0.4	0.2	0.1	0.1 other 15.5 gravel		80.3				
Okhla Delhi (India)	3.3	0.8						0.2	0.2		0.5 other 23.4 C&D waste					71.9	Somani et al., 2018
Jawaharnagar, Hyderabad (India)	2.7	1.4						1.5	2.6		0.5 other 15.4 C&D waste					73.1	
Ukkayyapalli, Kadapa (India)	3.7	1.01						1.3	1.73		1.5 other 16.2 C&D waste					75.2	
Torcy, France	18.4	6.6						4.2		10.5 card board	11.3 Inert 5					37.4	Gotteland et al., 2000

										6.6 paper	scrap						
Montech, France	25.1	1.1						7.1			4.9 Inert 5.6 scrap					40.8	
Filborna, Sweden	18.1	4.5	1.5	7.9			19.0	14.2	0.5			55.0					Cossu et al., 1995
Lavello, Italy	0.3			2			18.2		8.9		0.2 burnt 0.3 cellulosic 0.1 other			70.4			Masi et al., 2014
Edinburg, USA	22.0			17.0				5.0	8.0								Hogland et al., 1997
KDS, Tehran	8.9	3		2.6			2	1.7	2.4	10.6						68.8 (paste)	Keramati et al., 2018
Kuopio, Finland Middle layer	23.5	7.1		3.3				6.7		7.3	1.6		43.0			6.2	Kaartinen et al., (2013)
Kuopio, Finland Bottom layer	23.5	6.6		3.9				5.5		4.1	1.1		47.0			7	
Kudjape, Estonia islands	16.9 soft 1.09 PET	20.1	4.32	5.57 Fe 0.27 Al	1.13	0.06	22.28	7.44	0.8	6.96	3.20	9.87					Hogland et al., 2018
Torma, terrestrial Estonia	14.4 soft 0.5 PET	27.1	0.7	2.6 Fe 0.9 Al	0.6	0.3	5.4	5.6	5.8	5.7				14.3(>10mm) 16.0(<10mm)			
REMO, Belgium 1995-2000	25	3.1		2.2				4.1	0.5	14	4.1 Other 2 inert					45	Quaghebeur et al., 2013
Högbytorp,	0.66	2.73	0.19	0.47			28.07	15.20	5.6	4.48	3.21					27.30	Jani et al.,

Sweden	soft 6.8 other			Fe 0.45 other							Asphalt 4.81 limestone						2016
Yingchun, China	10.6	1.49		0.41			8.26	2.43	0.6	0.15	0.98					75.02	Zhou et al., 2015a
Pohlsche Heide, Germany	9.4	2.5		2.5			7.7	10.1	1.6	4.7	1.1 Compostable 3.9 Residual			23 14(10-20mm)		9.8	Wanka et al., 2017
Halbenrain, Austria	16.5	2.6		1.4 Fe 0.4 others				5.2	1.9	1.3	8.8 Inerts 12.7 Other					49.3	López et al.,2018
Lower Austria Waste age:13-20yrs	18.2	5.7		4.7				9.4	1.0	3.2	3.8 composite 0.1 Problematic substances 1.4 others					46.8 (residue) out of which 65.6% (fines)	Wolfsberger eta l., 2015
The federal state of Styria waste age:24-30yrs	16.9	3.2		1.8				2.5	0.5	2.1	1.6 composite 0.2 Problematic substances 1.3 others					67.1 (residue) out of which 79.1% (fines)	
The federal state of Styria waste age:25-	24.2	5.6		2.3				3.3	0.7	1.9	2.7 composite					51.5 (residue) out of	

29yrs											0.1 Problematic substances 1.4 others					which 66% (fines)	
Saravan, Iran 14m depth	18	2						2		10	11 rock &ceramic					57	Karimpour-Fard, 2019
Bandeirantes landfill, Brazil	20.9	3.5		5.6			0.1	4.1	1	15.1						49.7 paste	Machado et al., 2010
Metropolitan landfill, Brazil	18.7	4.5		1.5			5.9	5.2	1.7	19.7						4.2.9 paste	
Tri-Cities landfill, San Francisco deep old waste	2 soft 1.2 stiff			3.7				11		13	9.8 gravel		59.5				Zekkos et al., 2010
Tri-Cities landfill, San Francisco shallow fresh waste	6.4 soft 3.9 stiff			3.3				8		20	4.7 gravel		52.0				
Plastic (PL); Textile (T); Rubber (R); Metal (M); Hazardous waste (HW); Medical waste (MW) ; Stone (S); Wood (W); Glass (G); Paper (P); Soil-like material (SLM)																	

Table 2.3 Screen size considered for the segregation in past projects.

Landfill location	Soil to waste ratio (%)	Screen (mm)
Edinburg, NY, USA	75:25	24
Horicon, NY, USA	65:35	24
Hague, NY, USA	50:50	24
Chester, NY, USA	25:75	24
Coloni, NY, USA	20:80	24
Sandtown, Delaware, USA	46:54	24
Burghof, Germany	71:29	40
Schoneiche, Germany	77:23	40
Döbeln-Hohenlauft, Germany	62:38, 21:79	40, 8-40
Schoneiche, Germany	20-80, 30:70	40, 8-40
Dresden, Germany	74:26, 19:81	40, 8-40
Sengenbühl, Germany	11:89, 45:65	40, 8-40
Basslitz; Germany	50:50, 34:66	40, 8-40
Cagliari, Italy	31:69	40
Lavello, Italy	70.4:29.6, 63.6:36.4	10, 4
REMO, Belgium	45:55	10
Filborna, Sweden	65:35	24
Nonthaburi, Thailand	18:82	25
Kuopio, Finland	45:55	20
Lohja, Finland	58:42	20
Lower Austria	68:32	40
The federal state of Styria	84:16	40
Kodungaiyur, India	65:35	24
Perungudi, India	45:55	24
Deonar, Mumbai, India	70:30	24
Okhla Delhi (India)	72:28	4.75
Jawaharnagar, Hyderabad (India)	73:27	4.75
Ukkayyapalli, Kadapa (India)	75:25	4.75
References: Kurian et al., 2003; Prechthai et al., 2008; Quaghebeur et al., 2013; Masi et al., 2014; Wolfsberger et al., 2015; Mönkäre et al., 2016; Somani et al., 2018		

2.2.2 Physico-Chemical Characterization of MSW Fines

The physico-chemical characterization is generally done on the fine fraction of the waste or leachates/water extracted from the MSW. The fine fraction may vary accordingly as considered in the study/project. Although the fine fraction/soil-like material recovered from landfill mining closely resembles regular soil, several factors preclude its direct use in offshore applications. The physico-chemical characterization of this fine fraction of the waste influences its reusability. The organic content, total soluble solids and salts, the release of dark-colored leachate, heavy metal concentrations, and other factors must be considered before the off-field application of the fine fraction. Most of the studies on the reusability of the waste are very restricted to the chemical prospective only as MSW from most of the landfill sites has an objectionable range of contents which restricts its further use even having great potential. A few of the past studies around the globe have been discussed below.

Chu et al. (1994) investigated the leachates from two landfills i.e., Gin Drinkers' Bay (GDB) Landfill, Tsuen Wan (closed in 1979) and Junk Bay (JB) Landfill, Sai Kung in New Territories, Hong Kong. The primary goals of this study were to: (1) identify the major pollutants in raw leachate; (2) compare the characteristics of leachates from two landfills that differed in age, size, and waste deposited; (3) investigate the seasonal variability of leachate quality; and (4) generate usable design data for leachate treatment. The findings indicate that the leachates required additional treatment before they can be discharged into coastal waters. In general, the chemical properties of the two leachates were negatively ($P< 0.05$) correlated with the amount of rainfall before the sampling periods. However, the magnesium and pH of the leachates remained relatively constant over time. Except for trace metals, the JB leachate had higher average solids, inorganic and organic matter contents than the GDB leachate. The trace metals were present in trace amounts (1.0 mg/liter) in both landfill leachates. The average ammoniacal nitrogen concentrations were 1040 and 549 mg/liter, respectively, while COD values were 767 and 695 mg/liter for JB and GDB leachates respectively.

Kurian et al. (2003) discussed the findings of the mined decomposed materials from Kodungaiyur (KDG) and Perungudi (PDG) dump grounds, near Chennai, India. The waste samples were collected from 6 PDG locations and 18 KDG locations. The pH (1:10 water extract), and the moisture content (MC) were determined in the laboratory, and pH was found to be 8 (average) for both the sites, and MC was 24.4 and 39.5%, respectively for both the sites. It was seen that a few heavy metals in the recovered material exceed the Indian compost standard but are well within the USEPA compost limits.

Hull et al. (2005) investigated the physical and chemical characteristics of the waste extracted from the Burlington County landfill in New Jersey. Temperature, particle size, bulk density, volatile solids, and contamination were discovered to be related to the age of the deposits in the materials excavated from the landfill. The excavation, screening, and transport processes preceding sampling, as well as the six-week storage period following excavation, undoubtedly reduced the concentrations of volatile and semi-volatile compounds in the excavated material. The trace metals were found to be within the limits of NJDEP (New Jersey Department of Environmental Protection) and RDCSCC (Residential Direct Contact Soil Clean-up criteria). However, some elements exceeded the New Jersey soil background levels and the Rutgers Cooperative Extension recommended levels when sewage biosolids were applied to agricultural land.

Remon et al. (2005) examined the pedological and botanical characteristics of a former metallurgical landfill near the city of Saint-Etienne (Loire, France) to assess the risks of heavy metal mobility and the feasibility of remediation. In addition to very high heavy metal levels (Cu, Cr, Mn, Ni, Pb, Zn), the soil had a lack of clear horizonation, a relatively high pH, a high mineral and organic carbon content, a low nitrogen level, and a high C/N ratio.

Prechthai et al. (2008) checked the heavy metal concentration in the solid waste from Nonthaburi dumpsite in Thailand and its mobility potential based on its binding forms. The analysis revealed that Zn was the most concentrated heavy metal in solid waste, followed by Mn, Cu, Cr, Cd, Pb, Ni, and Hg. Mn, Zn, and Cd were mostly found in reducible form during the sequential extraction, indicating their susceptibility to leaching. Cu and Cr were found to be mostly oxidizable and stable under anaerobic conditions. Pb and Ni were found in residual, inert form. According to the estimated individual contamination factor, Zn has the highest affinity to leach. Except for Cr, the concentration of all heavy metals in the leachate was found to be below the National effluent standards. Despite being indicated as safe for disposal, its effect on plant life in any concentration was toxic in a seed germination toxicity test using the synthetic chelate ethylene diamine tetra acetic acid (EDTA).

Quaghebeur et al. (2013) evaluated the valorization options for materials stored at the REMO site in Houthalen (Belgium) that contained either municipal solid waste (MSW) or industrial waste (IW) at various locations. The fines contained high concentrations of heavy metals (Cu, Cr, Ni, and Zn) and offer opportunities for metal extraction and recovery, particularly for industrial waste (primarily shredder from ELV).

Bhalla et al. (2013) investigated the effect of age and seasonal variations on the leachate characteristics of a municipal solid waste (MSW) landfill site in Ludhiana, Punjab (India). It has been determined that leachate samples contain concentrations of organic and inorganic constituents that exceeded the allowable limits. The heavy metal concentrations were traced because the waste was domestic in nature.

De Medina-Salas et al. (2013) investigated the physical and chemical properties of MSW generated in Cosautlan de Carvajal, Veracruz, Mexico. The MSW had a maximum humidity of 65.9%, ashes ranging from 11 to 18.57%, and specific heat values ranging from 1.008 to 1.53 cal/g° C. In terms of chemical properties, the pH values of MSW were neutral, approximately 50% of the MSW was organic matter, and the maximum sulphur value was 1.862%.

Masi et al. (2014) chemically analyzed the waste fractions from Lavello's old, closed dumpsite (Basilicata Region-Southern Italy). It revealed the presence of heavy metals that were lower than the USEPA standards for the use of biosolids. The heavy metal concentrations in the finer fraction (4 mm) are on average 30% lower than in the 10mm fraction. The leaching potential of heavy metal was very low and well below the allowable heavy metal concentration in the US TCLP standard.

Naveen et al. (2014b) collected leachate samples from the Mavallipura landfill area near Bangalore to see its effect on the surrounding water bodies. Based on pH, TDS, conductivity, and alkalinity values, the leachate had significantly high salinity and alkalinity. The BOD5/COD ratio indicates that the leachate was of medium age.

Jani et al. (2016) discovered high concentrations of zinc, copper, barium, and chromium in an excavated fine fraction (10mm) from a Swedish landfill, the Hogbytorp, which was higher than the Swedish Environmental Protection Agency (SEPA) for contaminated soil. The moisture and organic content of the fine fractions were found to be 23.5% and 16.6%, respectively. The calorific value (1.7MJkg^{-1}), CH_4 potential (4.74m^3 t^{-1} dry matter), and Total Organic Carbon (TOC) (5.6%) were low and offered little energy potential.

Kaczala et al. (2017) characterized the physico-chemical and leachate properties of a fine fraction (10 mm) obtained from landfill mining activities in an Estonian landfill. Total chemical oxygen demand (COD_t), dissolved chemical oxygen demand (COD_d), total organic carbon (TOC), dissolved organic carbon (DOC), and metals (Zn, Cu, Pb, and Cd) were all measured and analyzed. According to the findings, approximately 70% of COD_t was in a particulate/colloidal state. The TOC released ranged from 2326 to 3530 mg/kg dry matter for test pits, indicating spatial differences in the landfill studied. For different test pits and sampling layers, DOC ranged between 365-874 and 317-940 mg/kg. Metal leaching rates were found to be low (0.2-1.5%). When compared to Zn (0.70%) and Cu (0.35%), Pb had a significantly higher average leaching rate (1.0%). Because of the high correlation coefficients, COD_t has the potential to be used as a surrogate indicator of TOC, DOC, and Zn.

Holzle (2017) investigated three landfills in Germany's Federal State of Bavaria that contained municipal solid waste (MSW) and construction and demolition (C&D) debris. The laboratory analyses of preliminary investigations were compared with the excavation results to determine the reliability of pre-feasibility studies. As a result, the objectives of this work were to (1) investigate the differences in the reliability of the drilling and grab crane investigation methods, (2) investigate the possibilities and limitations of preliminary investigations concerning soil compositions, (3) identify the behaviour of elements, and (4) derive guide values for sample numbers. Even for smaller investigations of 10 samples, using a grab crane resulted in better results. Both methods produced sufficiently accurate results to make predictions (standard error 5%, level of confidence 95%) for most heavy metals, cyanide, and PAH (Polycyclic aromatic hydrocarbons) in dry substance and sulphate, barium, Benzo[a]pyrene, pH, and electrical conductivity in soil type waste leachate analyses. While the concentrations of chrome and nickel were less accurate, the concentrations of hydrocarbons, TOC, DOC, PCB, and fluorine (leachate) were not predictable even for sample numbers as high as 59. The pollutant concentrations were frequently overestimated when drilling and underestimated when using a grab crane.

Parrodi et al. (2018) investigated the qualitative and quantitative information about the composition and characteristics of different fractions excavated from landfills all over the world. The goal of the study was to identify the key aspects to be considered when designing the processing approach in future landfill mining (LFM) and enhanced landfill mining (ELFM) investigations.

Burlakovs et al. (2018) investigated the fine fraction of waste from the Torma and Hogbytorp landfills and found results on the content of major and minor elements, as well as rare earth elements (REEs), which can indicate the potential value of recoverable resources. Significant concentrations of Mn (418-823 mg/kg), Ni (41-84 mg/kg), Co (10.7-19.3 mg/kg), and Cd (1.0-3.0 mg/kg) were found in fine fraction (<10 mm) of waste sampled from Hogbytorp landfill, while Cr (49-518 mg/kg) and Pb (30-264 mg/kg) were found in fine fraction (<10 mm) of waste sampled from Torma landfill, indicating wide heterogeneity.

Somani et al. (2019) investigated the leaching characteristics of an aged municipal solid waste fraction (finer than 4.75 mm) excavated from three old dumps in India. The leaching behaviour of this soil-like fraction was investigated to determine its suitability for use as an earth-fill material. The total dissolved solids (TDS), chemical oxygen demand (COD), colour release, and ammoniacal nitrogen were found to be significantly higher in the leachate from soil-like material than in the water extracted from the local soil. Some metals (arsenic, chromium, copper, cobalt, and nickel) were found in higher concentrations in the leachate from soil-like material than in the water extracted from the local soils. According to the findings, the soil-like fractions obtained from landfill mining must be screened for physico-chemical properties and pollution potential before being used as an earth fill material.

Holzle et al. (2019) analyse approximately 300 soil samples from eight excavated landfills to identify similarities in the substance concentrations within and between the landfills. The statistical tests made it possible to identify substance variations and correlations. Several heavy metals (particularly zinc), sulphate, and electrical conductivity, as well as ammonium nitrogen and biodegradability, were found to have concentration correlations. Sulphate, pH, and total organic carbon proved to be the most effective indicator elements for contamination prediction.

Singh and Chandel (2020) used physico-chemical and spectroscopic analysis to characterize a fine fraction, <4mm, aged 1-10 years old, obtained from the Mulund dumpsite in Mumbai. The pH (7.4-7.8) and electrical conductivity (0.70-1.92mS/cm) of the fine fraction met the Indian MSW compost standards; however, heavy metal levels were higher than the proposed standards. The fine fraction also contained a high concentration of metals such as aluminium (11 g/kg) and iron (78 g/kg), indicating the possibility of metal recovery. In addition, Fourier Transform Infrared Spectroscopy results show that the fine fraction had dominant inorganic peaks that became relatively homogeneous with age. The study suggests using fine fractions as a secondary resource; however, depending on the application, some prior treatment may be required.

Holzle et al. (2022) aimed to provide a global overview of soil-like material (SLM) in terms of heavy metal concentrations and its resource potential. A meta-analysis was prepared using 573 chemical analyses from 59 landfills in 12 countries. The average concentrations of arsenic, zinc, and nickel were found to be quite similar around the world, whereas those of lead, copper, and mercury showed significant differences between landfills. Chromium, nickel, lead, and zinc concentrations were found to be higher than most likely compost, while arsenic and mercury concentrations were typically lower. The concerns about the reuse of SLM in the earthworks included elevated zinc concentrations, followed by lead, copper, chromium, and cadmium. The concentrations of chromium and nickel, on the other hand, were found to be most similar to abundances in the Earth's crust. The heavy metal concentrations in SLM were not comparable to those found in ores anywhere in the world.

Singh and Chandel (2022a) investigated the mobility and chemical speciation of heavy metals (HMs) in a fine fraction (<4 mm) collected from a municipal solid waste dumpsite in Mumbai, India, to assess the feasibility of reclamation. A total of fifteen samples were collected at 1m depth intervals from five zones (named chronologically, zone A to zone E, with increasing waste age) to understand the temporal variation in mobility and potential pollution risk of heavy metals. The results showed that Zn was the most abundant in the fine fraction, followed by Cu > Cr > Pb > Ni > Cd. Furthermore, the concentration of HMs increased with the waste age. Except for Cd, which had a significant distribution in all forms, HMs were dominant in non-bioavailable forms. Furthermore, Cd (23%) and Zn (17%) had the highest mobility of all the HM studied, while Cr (0.4%) had the lowest.

The metal concentrations found in the fine fractions excavated from different landfills are presented in Table 2.4 and global standards for heavy metals concentration limits in soils/composts are also shown in Table 2.5. Table 2.6 shows the physico-chemical characteristics of the MSW fine fraction (water extract) for a few Indian landfill sites and the same has been compared with the drinking water limits.

Table 2.4 Metal concentrations found in MSW fine fractions of landfills (Conc. in mg/kg dry weight).

Landfill location	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn	Mn	Co	Fe
Nonthaburi, Thailand (Prechthai et al., 2008)		4.2	166.6	2245		47.8			947		
Lower Austria, Austria	16.0 - 23.0	1.6 - 4.8	130.0 - 170.0		0.4 - 0.6	45.0 - 60.0				6.6-17.0	

(Wolfsberger et al., 2015)											
Shanghai, China (Zhang et al., 2008)		1.5-2.8	143-229	78-221		30-51	98-173	228-323			
Matuali, Bangladesh (Karim et al., 2017)			10.10–81.19	14.41-137.7		0.84-9.89	5.66-87.89	19.41–163.8	9.66–82.89		
Khulna, Bangladesh (Karim et al., 2017)			1.72–2.96	4.72–14.66		0.42–0.90	11.18–69.6	12.46–29.4	16.28–24.26		
Kano, Nigeria (Anake et al., 2009)		22.3 ±19.3	81.2 ±61.3			6.0 ±8.72	2917 ±538				
Kaduna, Nigeria (Anake et al., 2009)		1.17 ±0.71	10.8 ±1.15			0.67 ±0.3	84.3 ±41.3				
Gboko dump site, Nigeria (Benjamin et al., 2012)	0.145	0.145	0.278			0.445	1.063				
Fiborna landfill, Sweden (Joseph et al., 2004)		1.6	0.39	53		12	88	500			
Shanghai landfill, China (Xiaoli et al., 2007)		1-3	110-160	300-540		44-61	280-440	970-1360			
Lavello, Italy (Masi et al., 2014)		54	145	1067		138			3385		
Kudjape landfill, Estonia (Kaczala et al., 2017)	4-6.4	1.12-1.21	54-123	191-362		29-44	128-477	1300-2000	313-383	5.6-8.1	29600-53900
Kuopio landfill, Finland (Kaartinen et al.,		<100	100-200	75-217		100	100-200	600-1100	700-1300		37000-41000

2013)											
Hogbytorp landfill, Sweden (Jani et al., 2016)	5.1 (1.7)	2.1 (0.6)			0.7 (0.2)	111.4 (33.7)	240 (65.3)	1848 (488)		23.3 (5.8)	28724 (8108)
Högbytorp landfill, Sweden (Hogland et al. 2018)		1.7	105	3394		66	130	2131	634	16	25035
Torma landfll, terrestrial Estonia (Hogland et al. 2018)		0.5	260	321		34	141	1046	356	7	49390
REMO, Belgium (Quaghebeur et al., 2013)	27.1 (15)	9.1 (8.6)	495.7 (118)	339.3 (55.3)	1.2 (1.2)	176.3 (60.7)		667 (211)			27,000 (750)
Burlington, USA (Hull et al., 2005)	9.1 (8.6)	1.2 (1.2)	26 (24)		0.4 (0.4)		487 (406)	487 (406)			
Okhla Delhi (India) (Somoni et al., 2018)		7.66	68.59	148.34		25.15	85.58	115.1	253.45	6.16	6660
Jawaharnagar, Hyderabad (India) (Somani et al., 2018)		8.53	88.75	329.9		20.48	81.46	129.6	134.88	5.09	5750
Ukkayyapalli, Kadapa (India) (Somani et al., 2018)		1.89	135.9	271.3		66.06	81.01	63.81	319.75	14.96	9282.5
Perungudi, India (Kurian et al., 2003)	0.077-1.561	0.82-1.77	110-261	75-217	0.039-0.78	21-50	53-112	167-503			
Kodungaiyur, India (Kurian et al., 2003)	0.83-5.6	0.9-3.07	191-657	127-968	0.61-2.73	31-247	81-320	205-1070			
Madurai dump site India (Anjanapri	32.1-41.2	19.9-22.3	98-206	298-310	2.55-4.28	53-85.3	29.-300	303-380			

ya and Lalitha, 2015)											
Mulund Mumbai, India depth 0-1 m (Singh and Chandel, 2021)		3.7	466.7	645.7		139.9	392.8	1232.			
Mulund Mumbai, India depth 1-2 m (Singh and Chandel, 2021)		3.8	524.9	735.6		165.5	178.1	998.2			
Mulund Mumbai, India depth 2-3 m (Singh and Chandel, 2021)		4.6	403.7	782.3		129.9	217.1	994.9			
Note: Values between brackets represent the standard deviation											

Table 2.5 Global standards for heavy metals concentration limits in soils/composts (Conc. in mg/kg).

Standards for soils	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn	Mn	Co	Fe	References
Canadian standards		1.4	64	63		50	70	200		40		Canadian Council of Ministers of the Environment, 1999
Dutch standards		13		190		100	530	720		190		VROM, 2001
Continental crust		0.1	25.4	14.5		5.59	15.1	30.5	105	19	45000	Wedephol, 1995
Swedish Environmental Protection Agency	25	15	150	200	2.5	120	400	500		35		SEPA 2002
Standards for composts												
India	10	5	50	300	0.15	50	100	1000				MSW Rules, 2000
USEPA	41	39	1200	1500	17	420	300	2800				Hogland,

Canada	10	3	50	60	0.15	60	150	500				1995
Germany		1.5	100	100	1	50	150	400				
Other standards												
VLAREBO limit values unrestricted use of soil	19	2.6	91	135	1.7	56	120	529				VLAREBO, (2008)
VLAREBO limit values for contaminated soil (type III)	103	6	240	396	4.8	95	560	881				
VLAREBO limit values for use of soil in or as construction material	205	10	880	375	5	250	1250	1250				
VLAREA limit values for use of waste as soil fertilizer and compost	150	6	250	375	5	50	300	900				VLAREA, 2009
VLAREA guidance value for use of waste in or as construction materials	250	10	1250	375	5	250	1250	1250				
Flemish regulations General	19	2.6	91	135	1.7	56	120	529				Zhou et al., 2015b
construction material (soil)	250	10	880	375	5	250	1250	1250				
fertilizer and compost	150	6	250	375	5	50	300	900				
construction material(waste)	250	10	1250	375	5	250	1250	1250				

Table 2.6 Physico-chemical characteristics of the MSW fine fraction (water extract) for a few Indian landfill sites.

Parameters	Okhla India	Bhalswa India	Noida India	Hyderabad India	Kadapa India	Perungudi, India	Drinking water (IS 10500:2012)
pH	7.12–7.41	7.60–8.15	7.50–8.10	7.7–7.95	7.95–8.04	8.06 (avg)	6.5–8.5
Total Soluble solids (mg/kg)	9160–17530	17380–25220	15000–20680	15620–22140	4880–5140		
Volatile dissolved solids (Organic) (mg/kg)	1460–3800	2900–4100	2160–3280	3580–5500	1480–1600		
Fixed dissolved solids (Inorganic) (mg/kg)	7700–10720	14480–21120	12840–17400	12040–16640	3400–3540		
Sulfates (mg/kg)	1780–5800	4400–9500	5330–8660	2850–4200	860–980		
Chlorides (mg/kg)	1950–2850	2500–4850	4710–5930	4050–4530	850–950		
Moisture content (%)	10–28	15–35	18–22	22–30	8–10	21.4–52	
Organic content (%)	4.8–8.2	12-24.5	10.2–15.6	8.2–14.5	5.5–6.5	8.9–15.8	
Electronic conductivity (mS/cm)	1558–2293	1952–2785	2250–2800	2170–2453	597–673		
TDS (mg/L)	1558–2293	1738–2522	1500–2068	1562–2214	488–514		500
Sulfate (mg/L)	178–580	440–950	533–866	285–420	86–98		200
Chloride (mg/L)	195–285	250–485	471–593	405–453	85–95		250
Fluoride (mg/L)	0.1–0.73	0.01–0.45			0.15–0.16		1
Bromide (mg/L)	0.18–0.20		0.15–0.16				
Calcium (mg/L)	18–92	144–395	220–420	135–145	45–52		75
Magnesium (mg/L)	28–44	42–63	120–150	54–63	15–19		
Bicarbonates (mg/L)	195–420	160–320	452–530	160–180	180–200		200
COD (mg/L)	170–280	170–368	452–530	165–198	140–148		
Ammoniacal nitrogen (mg/L)	15–18	8–28	10–25	4–6	3–4		
Chromiun (mg/L)	15–18	168–199	273–395	169–189	179–198	17.2	50
Nickle (mg/L)	110.79–130.2	94–146	221–268	104–120	105–124	134.4	20
Copper (mg/L)	121–156	75–216	50–164	227–249.25	116.19-120	53.1	50
Zinc (mg/L)	118–242	147–229	157–428	209–375	128–158	48.3	5000
Arsenic (mg/L)	13–34.5	8.8–30	68–322	36–122	52–64	1.83	10
Selenium (mg/L)	1.3–1.6	1.18–2	4–6	1.9–2.6	1.9–2.4		
Cadmium (mg/L)	6.9–7	6.9–7.5	11–16	6.6–7.0	6.9–7.1	9.5	3
Lead (mg/L)	27–34	23–33	33–39	26–30.5	31–34.5	139.5	10
Mercury (mg/L)						8.7	
Degree of contamination	73.86	87.61	77.94	129.48	53.97		
Intensity (PCU)	330–405	225–460	205–505	712–925	385–435		
References: (Kurian et al., 2003; Somani et al., 2020)							

2.2.3 Geotechnical Characterization of MSW Fines

There have been numerous studies on MSW to investigate its shear strength and mechanical behaviour. The focus of most of the studies i.e., field, laboratory, or numerical studies on waste was to determine the stability of the existing landfills or how to create a better landfill system. The mechanical properties of the wastes are critical in the operation, closure, and post-closure phases of the waste containment facility. Several researchers investigated the impact of various parameters on the strength and stiffness of MSW, such as composition, density, age or degradation, rate of loading, confining stress, moisture content, and so on. The composition of fibrous materials such as textiles, plastics, paper, and wood are well understood to have a significant influence on the mechanical response of MSW (Zhan et al., 2008; Reddy et al., 2009; Bray et al., 2009; Karimpour-Fard et al., 2011; Yuan et al., 2011; Ramaiah et al., 2014, 2015). The soil-waste mixture behaves similarly to fiber-reinforced soils, and the orientation of fibrous waste has a significant impact on the shear resistance and induces MSW anisotropy (Zekkos et al. 2010a, 2013a; Ramaiah and Ramana, 2017). It is impossible to fully characterize the technical qualities of waste due to its heterogeneous nature, understanding its basic behaviour and the likely range of essential engineering features is critical. Some of the studies focusing on the geotechnical characteristics of MSW are discussed below:

Gabr and Valero (1995) carried out geotechnical testing to evaluate the engineering properties of aged solid waste samples retrieved from a landfill that began accepting waste as early as 1940. The water content, specific gravity, Atterberg limits, gram-size distribution, compaction, permeability, consolidation, triaxial, and direct shear were all tested. At a water content of 31%, the maximum dry unit weight obtained using the standard Proctor test was approximately 9.3 kN/m^3. The compression index

(C_c) values derived from small-scale (63.5 mm in diameter) one-dimensional consolidation tests ranged between 0.4 and 0.9 for a void ratio range of approximately 1.0 to 3.0. The apparent effective strength parameters from the consolidated undrained (CU) triaxial tests were 34° (effective friction angle) and 16.8 kPa (effective cohesion). The results of the direct shear tests at various levels of horizontal displacement revealed that the friction angle was increased with the displacement while cohesion remained essentially constant. The direct shear tests yielded effective friction angles ranging from 20.5 to 39° with effective cohesion from 27.5 to 0 kPa.

Koda et al. (1998) conducted in-situ tests on two large landfills near Warsaw, Radiowo, and Lubna. Morphological analysis, settlement measurements, weight sounding test (WST), cone penetration test (CPT), and back analysis for slope failure are all part of the investigation. The shear strength parameters for non-composted wastes were confirmed using a slope failure test, whereas parameters for old and fresh wastes were validated using a back analysis of the landslides.

Ling et al. (1998) examined some empirical models for estimating landfill settlement. When the settlement was integrated using the best-fit parameters, the conventional settlement rate-time relationships using log t and power functions did not result in a satisfactory agreement. The hyperbolic function outperformed the log t and power functions in terms of long-term settlement prediction, with a correlation coefficient close to unity. The two parameters of the hyperbolic model were decreased with the increase in the water content of the waste materials.

Landva et al. (2000) presented laboratory testing results of municipal solid waste samples subjected to one-dimensional compression with lateral stress measurement. The split ring is a new apparatus designed to perform one-dimensional compression tests on refuse samples. Despite the relatively wide range of materials tested, the modified compression index values for MSW samples tested for the study were within a relatively narrow range (0.17-0.24). Similarly, the delayed compression coefficient value was also within a narrow range (0.010–0.016). The creep behaviour of the MSW material tested was similar to that of the plastic clays with high water content. The value of K_0 decreases as the amount of fibrous constituents increases. The total fiber content of MSW decreases over time because many organic fibers decomposed over time. Given an initial density, it is hypothesized that the final amount of instant and delayed compression of MSW material is practically independent of the stress-strain path taken.

Kumar (2000) proposed a correlation between two parameters, i.e., reference compressibility and rate of compression, required to predict the refuse settlement using the Power Creep Law based on an analysis of published data measured in the field from four landfills. The proposed correlation agrees with the measured settlements better than the settlements predicted using average values or some arbitrary combination of the parameters.

Park et al. (2002) investigated the long-term settlement characteristics by predicting the settlement curves using several prediction methods on fresh MSW sites. It was discovered that, except for the power creep law, most of the proposed methods successfully predicted long-term settlement only when accelerated logarithmic compression due to biodegradable MSW decomposition was included in the settlement prediction.

Song et al. (2003) investigated the geotechnical properties of solid waste soils from the Nanji-Do landfill site near the Han River in Seoul City for use as road sub-base materials. The field and laboratory experiments show that the shear strength and bearing capacity of the solid waste soil decreases as the organic matter content increases, whereas the maximum dry unit weight and the coefficient of compressibility increase. Solid waste soils containing organic matter have a higher void ratio than ordinary soils such as sand and silty sand. Furthermore, the specific gravity and dry unit weight were lower than the regular soils.

Dixon and Jones (2005) reported a summary of measurement and interpretation issues for the following key engineering parameters: unit weight, compressibility, shear strength, lateral stiffness, in-situ horizontal stress, and hydraulic conductivity. Some of the key findings were:

- Initially, the unit weight of waste was determined by waste composition, daily cover, and degree of compaction during placement. The unit weight of waste becomes more dependent on the depth of burial, the degree of decomposition, and the climatic conditions as it ages.
- For the sake of simplicity, the total settlement of the MSW landfill can be defined as the sum of primary and secondary compression.
- Back-analysis of failures is the most reliable method of obtaining data, but it is not without challenges due to difficulties in obtaining adequate detailed field information.
- The direct shear box produces the most reliable information of any method available in the laboratory for determining shear strength.
- Understanding leachate pressure distributions, and thus effective stresses, within the waste body, requires knowledge of waste hydraulic conductivity. The controlling factors are structure and stress dependency.

Durmusoglu et al. (2005) created a one-dimensional multiphase numerical model to simulate the vertical settlement of a deformable settling MSW landfill involving liquid and gas flows. The rate of gas generation is an exponentially decaying function of time. The governing equations of gas migration, liquid flow, and landfill deformation were included in the gas generation model developed using a first-order kinetic single-bioreactor approach. The resulting equations were solved using the Galerkin finite element method. The developed model can be used to estimate the transient and final settlements caused by waste decomposition and gas generation in MSW landfills. In settling landfills, the proposed model can estimate waste porosity, gas pressure, liquid pressure, gas saturation, liquid saturation, and stress distributions. The results of the deformable landfill were compared to those of a rigid solid skeleton landfill. The depth of waste in deformable landfills was 27% lower than in rigid landfills due to settlement.

Zekkos et al. (2005) created a hyperbolic model to simulate the effect of compaction effort, soil content, and overburden stress on MSW unit weight. The hyperbolic model, calibrated against laboratory and field data, provides a rational basis for developing landfill-specific MSW unit weight profiles for design. To a depth of approximately 60m below the ground surface, the hyperbolic model was fitted to the available in-situ landfill unit weight data. A consistent trend between unit weight with compaction and confinement was identified and recommended for the MSW unit weight profile. To provide greater accuracy when needed, a methodology for developing landfill-specific MSW unit weight profiles was developed.

Dixon and Langer (2006) proposed a new and improved waste component classification system that meets the requirements of a geotechnical classification system. The system categorized the waste based on its material engineering properties (e.g., shear, compressive, and tensile strength), component size distribution, component shape (reinforcing, compressible, and incompressible), and degree of degradability.

Sharma and De (2007) describe the settlement mechanisms and methods for estimating the settlements of MSW landfills, including bioreactor landfills. The coefficients of secondary compression for solid waste due to self-weight and external load are estimated using field monitoring results and data from the published literature. The paper discusses the application of these coefficients to post-closure maintenance and development plans, as well as their use for long-term settlement estimation. Field data show that pre-treating landfill wastes can reduce the post-development settlements of MSW landfills.

Athanasopoulos et al. (2008) investigated the effects of fibrous waste materials on the stress-strain-strength response of MSW in a systematic manner. A preliminary direct shear test was performed, and the results show that the orientation of the fibrous materials concerning the shear surface is critical and significantly affects the stress-displacement-strength response.

Zhan et al. (2008) conducted field and laboratory studies on the Suzhou landfill in China to investigate the changes in the shear strength of MSW as a function of fill age. The field study included sampling from five boreholes advanced to the landfill's bottom, cone penetration tests, and pore fluid pressure monitoring. According to the triaxial test results, the MSW samples exhibited strain-hardening and contractive behaviour. The slope stability of the Suzhou landfill was evaluated using measurements of shear strength properties and pore pressures.

Bray et al. (2009) conducted a large-scale laboratory testing program on MSW retrieved from a landfill in the San Francisco Bay area, using direct shear, triaxial, and simple shear tests. The shear strength of MSW was evaluated with waste composition, fibrous particle orientation, confining stress, rate of loading, stress path, stress-strain compatibility, and unit weight. According to the results of this testing program, the direct shear test is appropriate for evaluating the shear strength of MSW along its weakest orientation.

Hossain et al. (2009) investigated the effect of shredding MSW on compressibility and strength properties. Its measured properties can be linked to an R-value, which is the waste particle size to apparatus size ratio. The R-values indicate that shredding of MSW has the greatest impact on initial compression. The R-value does not affect the creep or biological strain rate of the tested MSW. Shredding reduces the shear strength because lightweight reinforcing materials are shredded into smaller pieces during specimen preparation.

Pinto (2009) addresses general waste material characteristics for static and seismic conditions. The paper discusses the static and dynamic response of barriers, the performance of solid waste landfills during earthquakes, the benefits of quality assurance, instrumentation, and monitoring to assess waste landfill safety control, and the benefits of risk analysis to guide future investigations.

Singh et al. (2009) presented the results of shear strength testing of intact and recompacted municipal solid waste samples using large triaxial compression and large direct shear apparatus. It was suggested that recompacted samples could be used to obtain reasonable estimates of cohesion and friction angle for MSW; however, intact samples may be required to establish MSW's pre-failure deformation behaviour.

Stark et al. (2009) investigated municipal solid waste (MSW) shear strength using back analysis of failed waste slopes as well as field and laboratory test results. The study concluded that MSW shear strength is affected by a variety of factors, including waste type, composition, compaction, daily cover material, moisture conditions, leachate management, age, and overburden pressure, and that these factors should be considered during the design process.

Chen et al. (2009) investigated changes in the mechanical compressibility of MSW as a function of MSW fill age and embedding depth. For the confined compression tests, 31 borehole samples from the Qizhishan landfill in Suzhou, China were used. The test results revealed that the compressible components of MSW (i.e., organics, plastics, paper, wood, and textiles) decreased with fill age and should be considered in settlement prediction.

Babu et al. (2010) proposed a generalized constitutive model for municipal solid waste that incorporates the effects of mechanical creep and time-dependent biodegradation to predict total landfill compression under the incremental loading and over time.

Zekkos et al. (2010b) reviewed existing MSW classification systems and presented field and laboratory waste characterization programs from two major projects at the OII and Tri-Cities landfills. The four-phase characterization procedure is intended to capture MSW characteristics that may have a significant impact on its mechanical properties. The proposed system was designed to capture the key aspects of waste composition that are currently thought to influence the geotechnical properties of MSW.

Singh and Fleming (2011) proposed a nonlinear elastic model with lower- and upper-bound model parameters that predict the stress-strain behaviour of MSW reasonably. Even in the absence of adequate information on waste age or composition, the proposed model can be used to fairly predict the mechanical behaviour of MSW.

Fard et al. (2011) presented the findings of a large-scale triaxial laboratory testing program at the Federal University of Bahia in Salvador, Brazil. The effect of confining pressure, unit weight, fiber content, loading rate, and over-consolidation on the mechanical response of MSW was investigated. The MSW shear strength increased with the increase in fiber content for both drained and undrained tests.

Hyun et al. (2011) carried out geotechnical testing to evaluate the engineering properties of old municipal solid waste samples collected from the Whamyung MSW landfill site in Busan, Korea. Water content, specific gravity, Atterberg limits, grain-size distribution, compaction, small- and large-scale consolidation, triaxial compression (CU), and direct shear tests were all performed.

Reddy et al. (2011) investigated the geotechnical properties of synthetic municipal solid waste (MSW) at different stages of degradation in the laboratory. The gas composition and organic content of the synthetic MSW were used to quantify the degradation, and samples exhumed from the bioreactor cells at various stages of degradation were tested for geotechnical properties. The compression ratio was reduced from 0.34 for newly generated waste to 0.15 for mostly degraded waste. The direct shear tests revealed that both fresh and degraded synthetic MSW exhibited continuous strength gain as horizontal deformation increased, with cohesion increasing from 1 kPa for fresh MSW to 16-40 kPa for degraded MSW and friction angle decreasing from 35° for fresh MSW to 28º for degraded MSW.

Babu et al. (2012) investigated the geotechnical properties of the MSW collected from the landfill site in Bengaluru. Triaxial compression and one-dimensional compression tests were used to calculate these properties.

Zekkos et al. (2012) performed a laboratory investigation on MSW from a landfill located in northern California using a large-scale triaxial (TX) apparatus (d = 300 mm, h = 600–630 mm). On the drained stress-strain response of MSW, the effects of waste composition, confining stress, unit weight, loading rate, and stress path were investigated. The composition of waste has a significant impact on its stress-strain response. As confining stress increases, the friction angle decreases. The friction angles obtained from triaxial tests are greater than those obtained in direct shear tests where shearing occurs typically parallel to the orientation of the fibrous waste particles.

Gomes et al. (2013) presented the laboratory (triaxial tests) and in-situ (standard penetration tests (SPT) and cone penetration tests (CPT)) test results to determine the shear strength of municipal solid waste. The effect of strain levels, waste composition, and waste age on shear strength parameters was discussed, and some correlations between the SPT and CPT tests were established to estimate the municipal solid waste (MSW) friction angles from the SPT tests.

Zekkos et al. (2013a) investigated the effect of fibrous waste reinforcement on the shear resistance of soil-waste mixtures using a large (30 cm × 30 cm × 18 cm) direct shear box. Soil-waste mixtures with waste fibrous constituents, such as paperboard, plastic, and wood, were tested in municipal solid waste (MSW) landfills. The experimental results confirm that the shearing response of soil-waste mixtures is comparable to that of FRS and provides a foundation for explaining the fiber reinforcement effect of MSW. The orientation of the reinforcement had a significant impact on the shear strength of the specimens. The greatest increase in shear resistance of the specimens was observed for a reinforcement angle of 60° concerning the shear plane, which was consistent with previous FRS research findings.

Karimpour Fard et al. (2014) used a computer-controlled large shear box apparatus to perform tests on MSW samples with normal stress levels ranging from 20 to 200 kPa. The impact of fiber content, fiber orientation, aging, and shearing rate on MSW response was investigated. The results showed that the shear strength of MSW increases with normal stress, but no strain hardening was observed in their mechanical response, despite the presence of reinforcement elements in MSW and in contrast to the results of triaxial tests.

Babu et al. (2015) presented the results of extensive laboratory testing of the shear strength properties of mechanically biologically treated municipal solid waste (MBT-MSW). On reconstituted compost reject MSW samples, direct shear tests, and small-scale and large-scale consolidated undrained and drained triaxial tests were performed. The triaxial test results revealed that the MSW samples exhibited strain-hardening behaviour, with MSW strength increasing as unit weight increased. In the consolidated undrained tests, the friction angle increased with the increase in unit weight from 8^o to 55^o. When compared to the consolidated drained tests, the consolidated undrained tests had lower friction angle values.

Ramaiah et al. (2015) used large-scale triaxial testing under drained conditions to assess the shear strength and stiffness properties of reconstituted 3-year-old municipal solid waste (MSW) collected from a waste site in Delhi. The stress-strain behaviour of specimens containing fibrous elements did not show a peak strength, whereas specimens prepared with only the 20mm fraction of the MSW showed one. The stress-strain response of triaxial specimens prepared with fibrous elements was like the behaviour of this material in one-dimensional compression, most likely due to the fibrous elements' lateral restraining effect.

Yang et al. (2016) performed laboratory tests to determine the permeability coefficients of municipal solid waste from the Jiangcungou Landfill. The distribution of leachate and stability in the landfill were computed and analyzed based on the results.

These findings revealed that the permeability coefficient ranged from 1.0 $\times 10^{-7}$ cm sec^{-1} to 6.0 $\times 10^{-3}$ cm sec^{-1}. The paper used numerical methods to investigate landfill seepage and slope stability.

Zekkos et al. (2016) carried out a large-scale experimental testing program that included 143 one-dimensional compression tests from five landfills in Arizona, California, Michigan, Texas, and Greece to systematically assess the compressibility characteristics of MSW subjected to a compressive load. The compressibility parameters were affected by the waste composition and unit weight. It was also discovered that the type of waste constituent (paper, plastic, or wood) as well as the anisotropic structure of the waste can influence the compressibility properties of soil-waste mixtures.

Abreu and Vilar (2017) investigated the shear strength of municipal solid waste (MSW) exhumed from disposal sites in a humid subtropical environment. Landfilled wastes ranging in age from 2 to 25 years were characterized using physical, chemical, and biochemical tests and tested in a large-scale direct shear device. During shearing, the direct shear tests revealed strain-hardening and contractive volume behaviour.

Fei and Zekkos (2017) compared MSW shear responses obtained from two testing methods, large-size simple shear (SS) and direct shear (DS). At vertical effective stresses ranging from 50 to 500 kPa, eight DS tests and eleven SS tests were performed. With s ratios ranging from 73 to 101%, shear strength in SS testing was found to be equal to or lower than the shear strength in DS testing. The friction angle in SS testing was higher but the cohesion was lower than in DS testing.

Feng et al. (2017) studied the geotechnical properties of MSW from a Chinese landfill. To test the hydraulic conductivity and shear behaviour of the MSW, a large-scale rigid-wall permeameter and a direct-shear apparatus were used. The MSW's composition changed with age. The unit weight increased from 7.2 to 12.5 kN/m^3 as the depth increased from 0 to 16 m, while the void ratio decreased from 2.5 to 1.76. The MSW's hydraulic conductivity ranged between 4.6×10^{-4} and 6.7×10^{-3} cm/s. Throughout the shearing process, displacement-hardening was observed, and shear strength increased with normal stress, displacement rate, and unit weight.

Ramaiah et al. (2017) presented the physical and mechanical properties of emplaced municipal solid waste (MSW) recovered from various locations of the Ghazipur and Okhla dumps in Delhi, India. A 300 x 300 mm direct shear (DS) shear box was used to test the mechanical compressibility and shear strength of the collected MSW. The MSW compression ratios ranged between 0.11 and 0.17 at these two dumps. The mobilized shear strength parameters, namely the apparent cohesion intercept and friction angle of MSW, are best described by 13 kPa and 23º at 25 mm displacement and 17 kPa and 34º at 55 mm displacement, respectively.

Zekkos et al. (2017) performed constant load and constant volume simple shear testing on relatively fresh municipal solid waste (MSW) from two landfills in the United States, one in Michigan and the other in Texas, at respective natural moisture content below field capacity. The comparisons of constant volume and constant load simple shear testing results revealed significant differences in MSW shear response, with constant volume shear resistance being lower than constant load shear resistance.

Karimpour-Fard (2018) evaluated the geotechnical properties of MSW from the Saravan Dumpsite in Iran. MSW samples of varying ages and conditions were collected, and geotechnical tests, including moisture and organic content, composition, grain size distribution, and direct shear tests, were carried out. Back-calculation analyses on unstable slopes at the site produced in situ shear strengths of MSW comparable to those obtained in laboratory tests. The results demonstrated that the soil-like fraction, moisture, and organic content decrease with depth and age, resulting in an increase in foil-like contents and a decrease in MSW shear strength.

Gajjar et al. (2019) proposed the existing Pirana landfill MSW (Ahmedabad, Gujarat) as fill material for a reinforced earth (RE) wall with uniaxial geogrid reinforcement and evaluated its load-displacement characteristics under gradual incremental loadings. Under dry conditions, sand, MSW, sand sandwiched between MSW, and mix 1(sand):3(MSW) composites were used as backfill material. From the results and analysis, it was concluded that MSW can be effectively used as backfill material in RE walls based on MSW-reinforcement interaction and tensile strain compatibility of reinforcement playing role in load dispersion under maximum loadings.

The geotechnical properties of the few landfill-mined materials have been defined in Table 2.7 below.

Table 2.7 Geotechnical properties of MSW.

Landfill area	Age (yrs)	Grain size of MSW	G_s	PI	Compaction parameters		C_c	C_v m^2/sec	Shear strength parameters		k m/s	References
					MDD (kN/m^3)	OMC (%)			c (kPa)	ϕ (°)		
Deonar landfill, India	4-12	63.5% (< 8mm); 31.5% (> 25mm)			9.41	14						Kurian et al., 2003
Kodungaiyur landfill, India	15	56%–68% (< 2mm)			8.8–11.77	30%–40%						
Perungudi landfill, India	15	33%–41% (<2mm)			9.4–9.7	23%–30%						
Kadapa, India		5.36% (clay); 2.68% (silt); 91.96% (sand)										Somani et al., 2018
Hyderabad, India		4.48 % (clay); 1.31 % (silt); 94.20% (sand)										
New Delhi, India		3.30% (clay); 2.96 % (silt); 93.74% (sand)										
CRRI (India)	5-25	5–10% (boulder); 15–20(course gravel);18–20% (fine gravel); 30–37%(sand);28.5–32% (silt +sand)	1.93	NP	16	14	0.14–0.19		10–25 (DST) Dry state	28–38	10^{-8} to 10^{-9}	Central Road Research Institute, 2016
Aged MSW (Delhi)	10-20	2–8% (boulder); 8–15% (course gravel); 12–20%	2.20 – 2.52	NP	13.5–15.2	20-30			20–24	34–36	10^{-7}	Datta et al., 2021a

		(fine gravel); 45–50%(sand) 20–25% (silt +sand)							(DST) Saturated state			
Okhla landfill, Delhi	3.4	76.4% (<20mm) 18.8(gravel) 2.8(textile) 3.0(plastic)	2.0	NP(<20mm)	Compacted density (7.5)		0.11–0.17		9.9	25.1		Ramaiah et al., 2017
									DST at 25mm displacement			
									16.2	37.4		
									DST at 55mm displacement			
Ghazipur landfill, Delhi	10-12	77.9% (<20mm) 17(gravel) 2.2(textile) 2.9(plastic)	2.15	NP (<20 mm)	Compacted density (7.5)		0.13–0.16		10	23		
									DST at 25mm displacement			
									11.1	35.4		
									DST at 55mm displacement			
Ghazipur landfill, Delhi	5	79%(<80mm); 32%(>35mm+16 mm);47% (<16 mm); 18%(>4mm); 29%(<4mm)	1.84 (<35 mm) 1.80 (<16 mm) 1.93 (<4 mm)	NP	15.7 (<35mm) 15.7 (<16mm) 16.0 (<4mm)	16 (<35mm) 18 (<16mm) 14 (<4mm)	0.141	$2.43*10^{-6}$	20	35	1.55×10^{-9} to 1.21×10^{-8}	Havangi et al., 2017
	10	65%(<80mm); 21%(>35mm+16 mm);44% (<16 mm); 17%(>4mm); 27%(<4mm)					0.160	$4.14*10^{-6}$	25	28		

	15	68%(<80mm); 20%(>35mm+16 mm);48% (<16 mm); 14%(>4mm); 34%(<4mm)					0.190	$5.56*10^{-6}$	10	38		
Masalycke, Sweden		78.16%(sand); 21.84%(gravel)										Hogland et al., 2004
Kuopio, Finland		57.44% (sand); 42.56%(garvel)										Winterstetter et al., 2018
Kuopio, Finland	5-10	20–25%(boulder); 25–50% (course gravel); 15–20% (fine gravel); 15–30%(sand)										Kaartinen et al., 2013
Seoul (Korea)			2.44–2.58		6.8–15.6				5–25 (DST) Dry state	12–35		Song et al., 2003
California, USA				19–32	15.2–18.5	19–32	0.04					Oettle et al., 2010
Hogbytrop, Sweden		98.67%(sand); 1.33%(gravel)										Jani et al., 2016

Gs specific gravity; PI plasticity index; NP non-plastic; MDD maximum dry density; OMC optimum moisture content; k coefficient of permeability; Cc compression index; DST direct shear test; c cohesion intercept; ϕ angle of shearing resistance, *Rc*= relative compaction, UU= unconsolidated undrained

2.3 DYNAMIC CHARACTERIZATION STUDIES OF MSW

Most of the dynamic studies conducted were aimed at designing or testing the performance of landfills against cyclic loads, seismic loads, and excavator cyclic loading (Sattler et al., 2020). The seismic response analysis requires the maximum or small strain shear modulus (G_{max}) or shear wave velocity (V_s); material damping ratio (D); and secant shear modulus (G), which is usually represented as a strain-dependent normalized shear modulus reduction curve (G/G_{max}). G_{max} is related to V_s and material density (ρ).

The material's *Vs* can be measured in situ or using various laboratory techniques. Seismic downhole, seismic cross-hole, suspension logging, spectral analysis of surface waves (SASW), multichannel analysis of surface waves (MASW), and the microtremor analysis method (MAM) are some of the in-situ methods. The last three methods are less intrusive, less expensive, faster, and provide more reliable data (Zekkos et al., 2008; Ramaiah et al., 2016c; Alidoust et al., 2018). There are a few laboratory tests that can be used to determine the V_s, such as the bender element test (BE) and the resonant column (RC) test. There have been studies on the modulus reduction and material damping ratio curves for MSW over the last two decades. These studies can be broadly classified as in-situ testing, laboratory testing of intact or reconstituted MSW, and data inversion using recorded ground motions. The composition of MSW has a significant impact on the dynamic parameters. A few past studies have been mentioned below.

Matasovic et al. (1995) used the field observation data from the Operating Industries Inc. (OII) solid waste landfills in southern California for back-calculation of dynamic properties of solid waste. The shear wave velocity calculated from down-hole and in-hole field methods combined with the records of strong motion obtained from the recent earthquake was used to calculate the modulus of reduction and damping for the OII landfill solid waste for small and intermediate strain ranges.

Augello et al. (1998) did back-analyses of the Operating Industries, Inc. landfill's recorded seismic response to estimate strain-dependent shear modulus reduction and material damping relationships for solid waste. The accelerograms from five earthquake events were used to perform two-dimensional dynamic finite element analyses. The sensitivity of the computed results to the variations in shear wave velocity, shear modulus reduction, damping, and Poisson's ratio was investigated. The analysis revealed that the strain-dependent shear modulus reduction and material damping relationships for the solid waste at this site were best characterized by those of medium plasticity clay.

Matasovic et al. (1998a) interpreted and analyzed the observational data from solid waste landfills during earthquakes. The data from several California earthquakes showed that most of the landfill’s performance was good to excellent during earthquakes. The recorded strong ground motion data indicates that the amplification of both peak and spectral accelerations can occur at the top of the landfills.

Matasovic et al. (1998b) used field measurements of shear wave velocity and unit weight to calculate the small-strain shear modulus values for solid waste. On reconstituted solid waste specimens, large-diameter (457 mm) cyclic direct simple shear (DSS) testing was performed to investigate the modulus reduction and damping characteristics of solid waste at large strains. The results of two-dimensional finite element back analyses of site-recorded strong motion data were combined with the results of DSS testing to establish solid waste modulus reduction and damping ratio curves over the range of cyclic shear strain required for the site closure design.

Kavazanjian et al. (1999) performed large-diameter (457 mm) static and dynamic laboratory tests on reconstituted samples of MSW. The samples of MSW obtained from the depth of 35 m were reconstituted at field moisture content to maintain the field density. The results show that the compressibility of MSW depends on the waste content. The direct shear test results indicate that the waste exhibits ductile hyperbolic behaviour under static loading and hysteretic under cyclic loading conditions.

Towhata et al. (2004) investigated the dynamic behaviour of two wastes, i.e., organic waste and inflammable waste which include small plastic sheets. Triaxial drained tests revealed that significant shear resistance was generated due to the plastic sheet and other fibrous components. The cyclic test results show that the damping ratio of the waste was higher than the soil and results were confirmed through the shake table test also.

Thusyanthan et al. (2004) used dynamic centrifuge modeling to investigate the seismic behaviour of MSW. The tests were carried out on a model waste that had physical properties like MSW. The model was validated for different earthquake intensities and frequencies. The amplification factor varies with frequency and is approximately 2.5 near the natural frequency of model waste, according to frequency analysis of acceleration signals. Between 3 and 5 Hz, higher amplification factors in the range of 5 to 10 were observed.

Zekkos et al. (2006) presented the laboratory test results to evaluate the dynamic properties of the MSW from the Tri-Cities landfill in the San Francisco Bay Area. The composition of the waste was found to be the most important factor that affects the dynamic properties of the waste. The small-strain shear modulus was significantly affected by composition, confining stress, unit weight, the time under confinement, and the loading frequency. The normalized shear modulus reduction and material damping curves are affected primarily by the specimen composition and confining stress.

Towhata and Uno (2008) conducted a large triaxial test on the waste from the landfill. The paper addresses triaxial compression, cyclic behaviour, and mitigation of creep using preloading and includes modulus and damping ratio changing with strain amplitude. The creep tests revealed that preloading, which involves increasing stress and then decreasing it to a working level, can stop long-term ground settlement. The cyclic loading revealed modulus and damping ratio variations with strain amplitude. The modulus degradation and damping ratio ranges are comparable to those of soils that have been safely treated with existing techniques.

Zekkos et al. (2008) presented results of more than 90 large-size (diameter 300 mm) cyclic triaxial tests on waste. The different parameters were investigated to check their importance on the waste dynamic properties summarized in Table 2.8. The dynamic properties computed through the cyclic triaxial tests of MSW were compared to the other literature in Figure 2.1.

Table. 2.8 Effect of different parameters on the dynamic properties of municipal solid waste (**Source @** Zekkos et al., 2008).

Properties	Small-strain shear modulus, G_{max}	Normalized shear modulus reduction curve, G/G_{max} versus shear strain, γ	Material damping curve, λ versus shear strain, γ
Composition	Most important	Most important	Most important
Confining stress	Important	Important	Likely important
Unit weight	Important	Not important	Not important
Confinement time	Important	Not important	Not important
Loading frequency	Less important	Not important	Not important

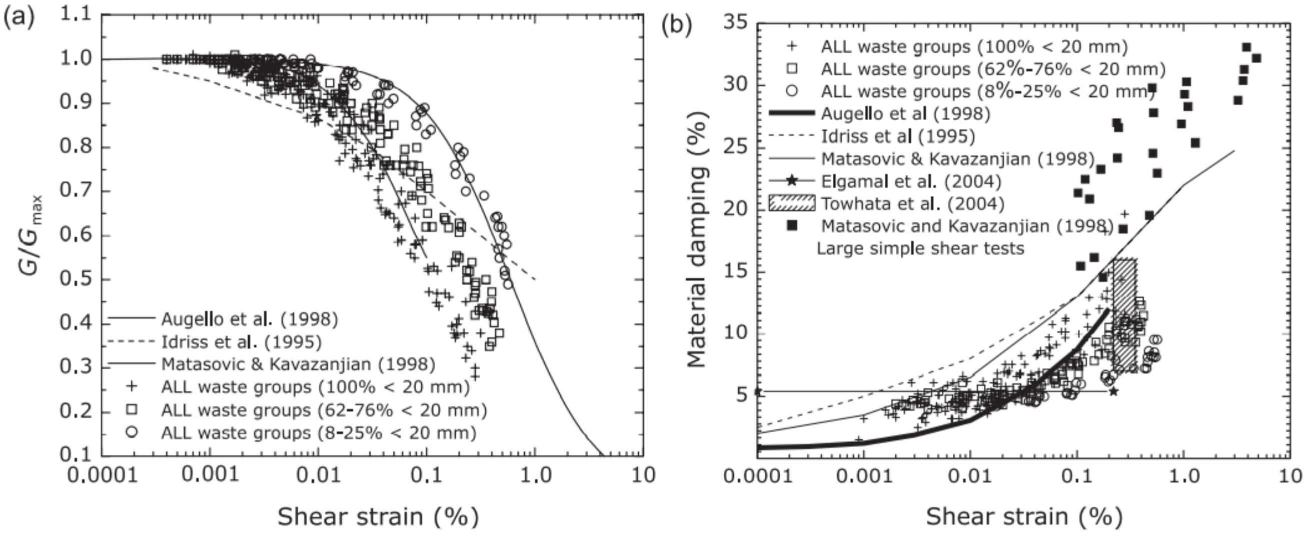

Figure 2.1 Cyclic triaxial test results and comparison with literature: (a) normalized shear modulus reduction curve (b) material dumping curve as a function of shear strain. (**Source @** Zekkos et al. 2008)

Choudhury and Savoikar (2009) based on extensive data provided by various researchers, analyzed the dynamic properties of landfill materials using curve-fitting techniques and proposed a simple mathematical equation. Wherever possible, the resulting profiles are compared to laboratory and field data. These properties are difficult to generalize and may differ between landfills. As a result, in the absence of landfill-specific field data under seismic conditions, the proposed simple mathematical models for these landfill properties can be used to design municipal solid waste landfills. The fitted models with equations from the past data for field shear wave velocity, normalized shear modulus, and damping ratio can be seen in Figure 2.2 below.

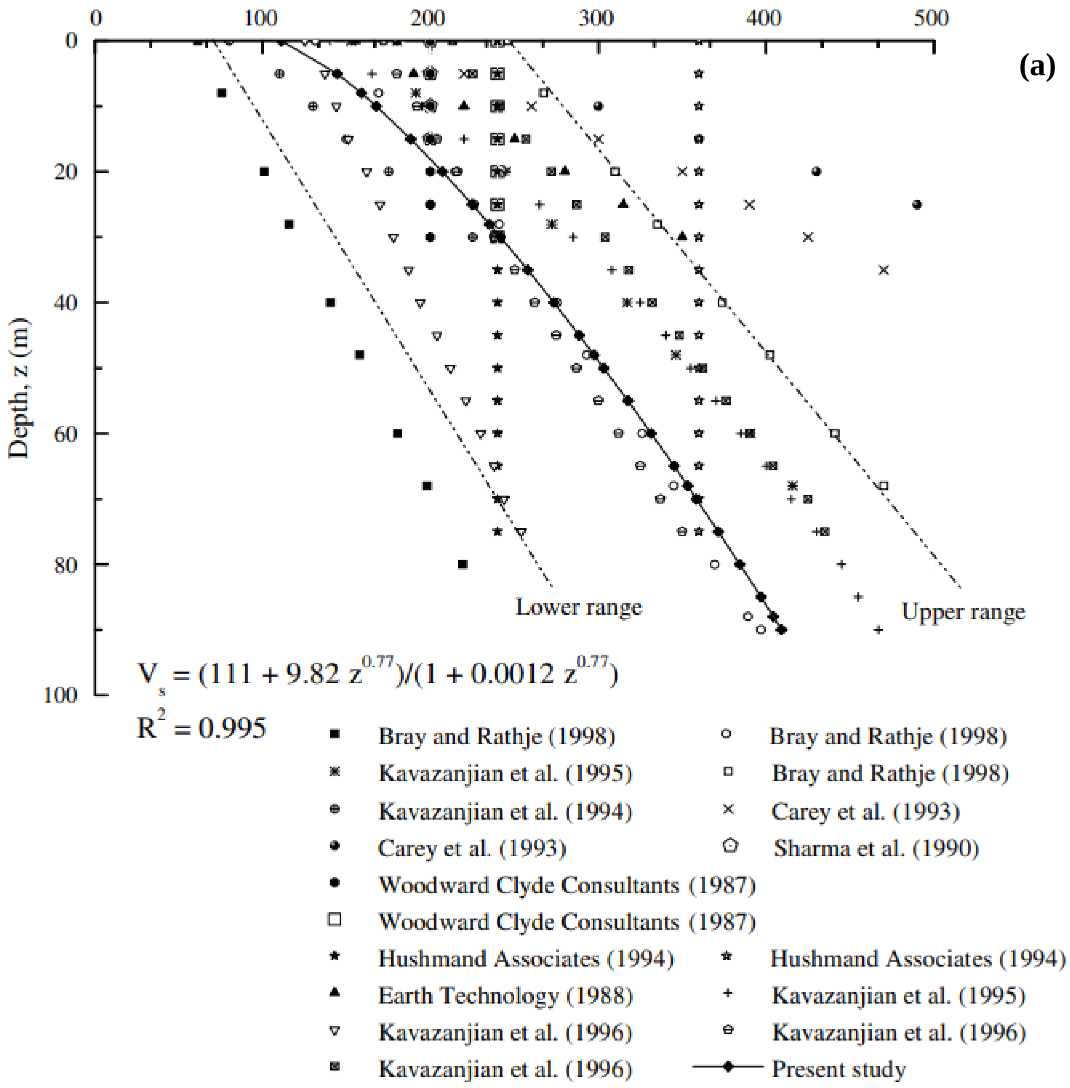

Figure 2.2 (a) Plot of the variation of shear wave velocity (V_s) of MSW landfills with depth (z). (**Source @** Choudhury and Savoikar 2009)

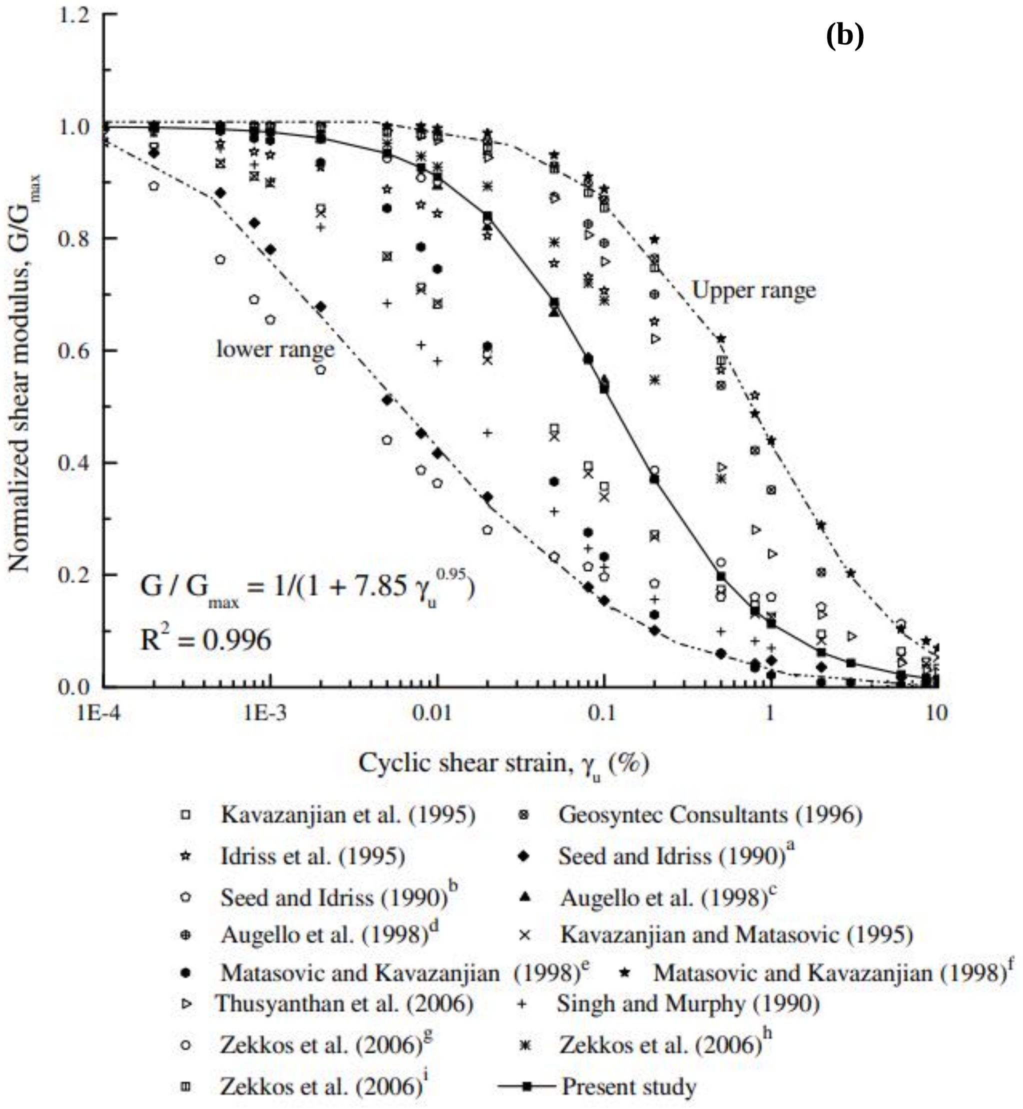

Figure 2.2 (b) Plot of the variation of normalized shear modulus (G/G$_{max}$) of MSW landfills with the percentage cyclic shear strain. a for clay; b for peat; c lower bound; d upper bound; e average values; f recommended (upper bound); g for 100% composition of waste of particle size smaller than 20 mm; h for 62–75% composition of waste of particle size smaller than 20 mm; i for 8–25% composition of waste of particle size smaller than 20 mm. (**Source @** Choudhury and Savoikar 2009)

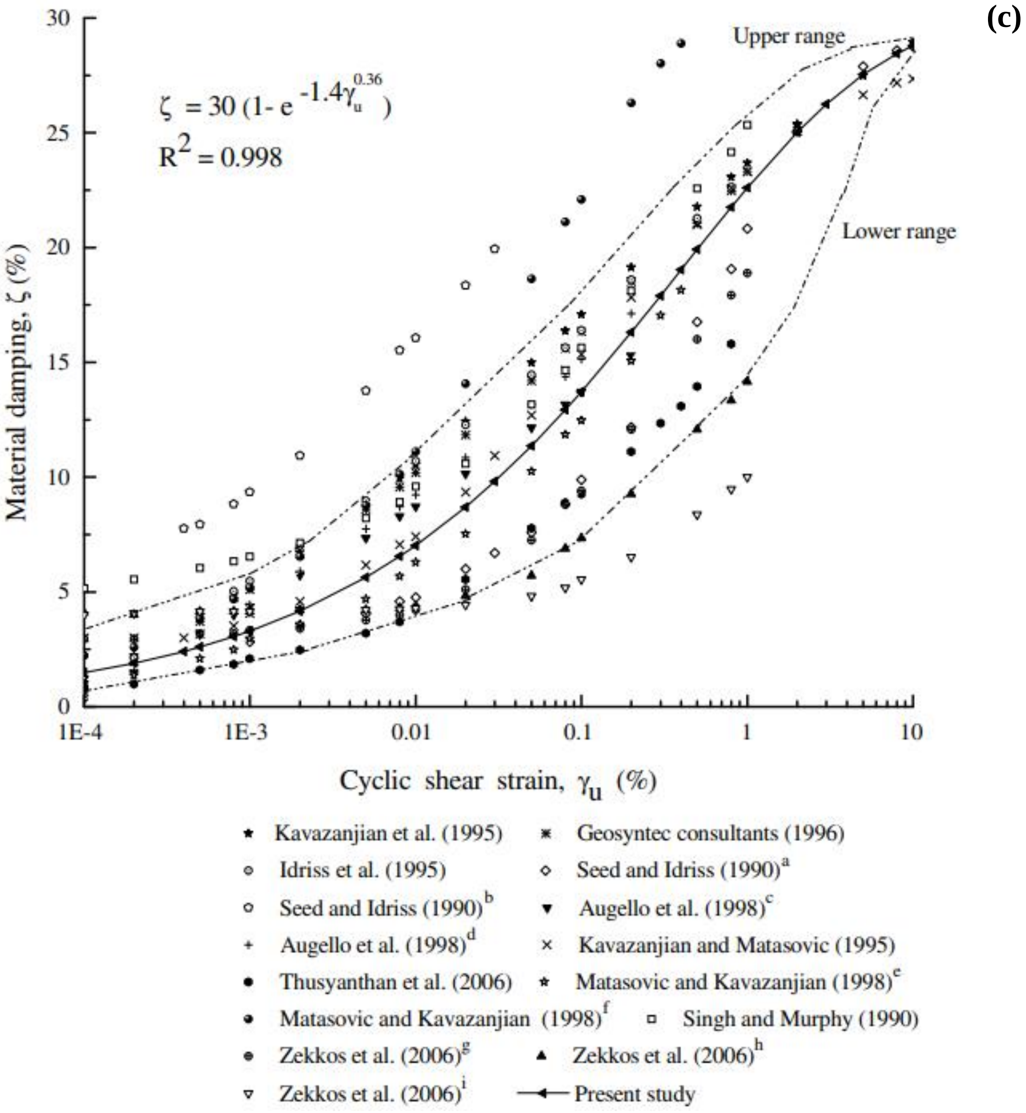

Figure 2.2 (c) Plot of the variation of the material damping ratio of MSW landfills with the percentage cyclic shear strain. a for clay; b for peat; c lower bound; d upper bound; e recommended (lower bound); f average values; g for 100% composition of waste of particle size smaller than 20 mm; h for 62–75% composition of waste of particle size smaller than 20 mm; i for 8–25% composition of waste of particle size smaller than 20 mm. (**Source @** Choudhury and Savoikar 2009)

Sahadewa et al. (2011) employed a surface wave-based methodology that employs a linear array of 16 geophones and combines active and passive measurements (Multichannel Analysis of Surface Wave technique) (Microtremor Analysis Method). The methodology was used to measure the shear wave velocity (V_s) at 13 different locations across four landfills in southeast Michigan. The V_s was found to be generally consistent across the landfills, with significant differences attributed to waste composition variability, site conditions, and landfill operation practices. In general, the shear wave velocities increase with depth. Near the surface, values as low as 75 m/sec are measured, rising to 175-210 m/sec at depths of about 25 m.

Yuan et al. (2011) investigated the influence of waste composition and compacted unit weight on the shear wave velocity, small-strain shear modulus, strain-dependent shear modulus reduction, and damping ratio curves of MSW through large-scale cyclic simple shear tests on reconstituted samples of MSW from Tri-Cities landfill in Fremont, California, USA. The specimens were reconstituted with 100%, 65%, and 35% of the material that passed through a 20 mm screen, as well as four different levels of compaction effort. The test results show that shear wave velocity and small-strain shear modulus are highly dependent on unit weight. The composition of waste had a significant impact on damping, as well as shear wave velocity, small-strain shear modulus, and modulus reduction.

Naveen et al. (2014a) presented the results of cyclic triaxial tests performed on municipal solid waste (MSW) collected from the Mavallipura landfill area and open dump site in Bangalore. The dynamic shear modulus of dumped waste ranged from 0.8 MPa to 4.2 MPa, while that of dry waste ranged from 2 MPa to 4.2 MPa. The dynamic shear modulus of the waste increases with confining pressure and shear strain for both dry and dumped wastes. The damping ratios for dumped waste ranged from 14% to 32%. The damping ratio for dry waste ranged from 14% to 18%. With increasing confining pressure, the damping ratio decreases.

Ramaiah et al. (2015) used a large-scale triaxial test under drained conditions to evaluate the shear strength and stiffness properties of reconstituted 3-year-old municipal solid waste (MSW) collected from a waste site in Delhi. The stress-strain behaviour of specimens containing fibrous elements did not show a peak strength, whereas specimens prepared with only the 20mm fraction of the MSW showed one.

Ramaiah et al. (2016a) conducted a statistical analysis of 146 in-situ shear wave velocity (V_s) profiles obtained from 37 municipal solid waste (MSW) landfill sites around the world to produce a simple linear relationship between MSW V_s and depth up to 30 m.

Ramaiah et al. (2016b) used field and large-scale laboratory tests to assess the dynamic properties of municipal solid waste from two dumpsites in Delhi. On reconstituted MSW specimens, large-scale undrained cyclic triaxial (CTX) tests were performed to investigate the effect of various parameters such as composition, confining pressure, number of loading cycles, loading frequency, and saturation on the dynamic properties. The extensive large-scale undrained cyclic triaxial test results revealed that the composition of MSW has a significant effect on its undrained cyclic behaviour.

Keramati et al. (2016) presented the results of strain-controlled cyclic triaxial tests on fresh MSW materials with a diameter of 100 mm to estimate the shear stiffness and damping properties. The results revealed that the damping ratio for MSW materials is significantly higher when soils are present.

Castelli et al. (2017) used field and laboratory tests to investigate the small-strain shear modulus, the strain-dependent normalized shear modulus reduction, and the material-damping relationships of MSW. The shear wave velocity profiles and dynamic properties of the deposited waste materials were determined using the seismic dilatometer multichannel test (SDMT). The vertical distribution of the compression wave velocity (V_p) and shear wave velocity (V_s) was estimated using seismic refraction tomography and multichannel analysis of surface waves (MASW), respectively. The dynamic properties of MSW were also investigated using resonant column torsional shear (RCTS), and cyclic triaxial devices (CTX). In terms of Poisson's ratio, shear wave velocity, and small-strain shear modulus, the experimental results obtained by in-situ and laboratory tests were compared to those reported in the literature.

Alidoust et al. (2018) conducted extensive strain-controlled cyclic triaxial testing on MSW samples retrieved from a landfill in the Kahrizak area of Tehran province. The tests were carried out on fresh MSW specimens (100 mm in diameter) with varying percentages of fibers in the consolidated undrained condition. The potential reinforcing capability of fibers and their effects on MSW composition changes were investigated under various conditions such as confining pressure, loading frequency, Poisson's ratio, and loading cycles. According to the findings, increasing fiber content in the specimens resulted in improved elastic behaviour of MSW under dynamic loadings, regardless of test conditions, such that the normalized shear modulus reduction curves shifted to the right, while the damping ratio curves showed no specific trend.

Keramati et al. (2018) investigated the effect of shear strain, confining stress, and loading frequency on the shear modulus and damping ratio considering 18 cyclic triaxial tests. According to the findings, the shear modulus values of fresh Tehran Kahrizak Disposal Site MSW materials ranged from 350 to 2400 kPa for various shear strains, confining stress, and loading frequency, and the damping ratio values ranged from 8 to 20%. The shear modulus of MSW materials increases with the increase in shear strain, confining stress, and loading frequency. The damping ratio decreases with the increase in shear strain, confining stress, and loading frequency, and it is relatively constant with a slight decrease. As a result, changing the confining stress and loading frequency has little effect on the damping ratio.

Naveen et al. (2018) conducted extensive field and laboratory studies on MSW disposed of at the Mavallipura landfills, which have been in operation for approximately 12 years. The results show that the static test is performed at low strain and takes longer than the dynamic test, which is performed at a significantly higher strain. The geophysical testing (multichannel analysis of surface waves) revealed that the landfill site is very loose and still in the process of deterioration.

Matasovic et al. (2019) presented preliminary findings of a field experimental program to investigate the dynamic properties of municipal solid waste (MSW) disposed of and mixed with hazardous waste at a hazardous waste landfill in Southern California. The research was carried out in both the linear and nonlinear strain ranges. Crosshole, downhole, and SASW sounding were used for the linear portion of the testing. The nonlinear portion of the testing was carried out using four normal stress levels as a proxy for testing at greater depths (i.e., at higher confining stresses). The results of the in-situ linear and nonlinear testing were consistent with and supplemented the findings of large-diameter DSS (or cyclic triaxial) testing and back-analysis of strong motion data at the OII landfill site, where the waste of similar composition and age was disposed of.

Keramati et al. (2019) investigated the effect of aging on the dynamic properties of Municipal Solid Waste (MSW) including damping ratio and shear modulus. On fresh and old reconstituted cylindrical specimens taken from Mansoory Prototype Landfill (MPL) in Kahrizak Landfill, Tehran, Iran, a series of consolidated undrained (CU) cyclic triaxial tests were performed. The results revealed that the shear modulus of old samples

(7.5 years old) was greater than that of fresh samples of the same unit weight. It should be noted that the shear moduli difference was more pronounced in low-strain ranges. The results also revealed that the damping ratio, which was entirely dependent on the constituents of the specimen, had a decreasing trend over time.

Alidoust et al. (2021) conducted an undrained cyclic triaxial test to investigate the dynamic response of the MSW in the presence of influential factors such as the number of loading cycles, loading frequency, confining stress, and aging. The research looks for similarities between the normalized shear modulus and damping ratio curves of MSW and clayey soil. The progression of decomposition in the organic content of MSW, as well as compaction caused by landfill operations, improves MSW uniformity. This increase in uniformity reduces the discreteness of the MSW, resulting in more shear stiffness under cyclic loadings. However, due to the unknown nature of MSW, the damping ratio results do not follow a specific trend.

2.4 STUDIES ON REINFORCED MSW

Other than the fine fraction or soil-like portion (fine fraction depends on the particle size selected for the particular study), MSW consists of other materials like plastics, cardboard, textile, glass, ceramics, rubber, metals, etc. (Zekkos et al., 2010a; Bhatnagar et al., 2017; Somani et al., 2018; Parrodi et al., 2018) which can be recycled and reused. This waste also acts as a fibrous material in the MSW, several studies show the reinforcing effect of these materials by enhancing the strength of MSW as compared to only organic content (Kavazanjian et al., 1999; Athanasopoulos et al., 2008). The soil reinforced with randomly distributed fibers has various successful applications like retaining structures, embankments, subgrade stabilization, etc. The various studies also show that the inclusion of geosynthetics and bio-based fibers (natural fibers) improves the physical and mechanical properties of soil (Haeri et al., 2000; Yetimoglu and Salbas, 2003; Punthutaecha et al., 2006; Tang et al., 2010; Fatahi et al., 2013; Hamidi and Hooresfand, 2013; Chen et al., 2015; Kumar and Gupta, 2016; Debnath and Dey, 2017; Yoo and Abbas, 2020). Also, some studies show reinforcement increases liquefaction resistance and dynamic characteristics of soils (ranging from clays to gravel) (Krishnaswamy and Isaac (1994, 1995); Altun et al., 2008; Ye et al., 2017; Ghadr et al., 2020). The fiber-reinforced waste also behaves as reinforced soil and even the orientation of this fibrous matter impacts the shear resistance (Zekkos et al., 2013a). The previous dynamic studies on MSW are mostly site-specific (remolded or intact MSW samples) to determine the potential reinforcing capability of fibers and find its material damping ratio and shear modulus parameters which are generally required for the seismic response analysis of landfills (Towhata et al., 2004; Ramaiah et al., 2016(a,b and c); Alidoust et al., 2018; Keramati et al., 2018; Zekkos et al., (2008, 2010c).

The other kind of planar reinforcement is known as, geosynthetics made of either polymetric (polypropylene, polyester, polyethylene, polyamide, PVC, etc) or natural materials (made of natural fibers: jute, coir, cotton, wool, etc). There are multiple uses of geotextiles in the design of municipal solid waste landfills mainly related to separation, filtration, drainage, reinforcement, and cushioning. Sometimes even the foundation soil of the landfill requires stabilization and reinforcement using geotextiles, geogrids, or randomly distributed fiber reinforcements. The general parameters that influence the interaction of the material with geogrids or geonets are properties of the material and test method, the position and number of geogrid layers, and stiffness, size, and shape of geogrid aperture (Kaluđer et al., 2021). Geogrids are generally used for vertical expansion (increasing the height of waste mass) of landfills and their slope reinforcement. High-strength geotextiles and geogrids provided for structural support to the cover systems have been widely reported in past studies (Carroll and Chouery-Curtis, 1991; Christopher, 1991; Koerner and Soong, 2005). The tensile strength of the reinforcement and the efficiency with which the reinforcement is anchored at the berms determine the stability of the landfill cover system.

In conventional soil reinforcement, geosynthetics are widely used for steep slope stability, retaining walls, increasing resistance to traffic load, and foundation treatment (Giroud and Noiray, 1981). Many studies investigated soils or other wastes like coal ashes reinforcement mechanisms through field and laboratory tests (Haeri et al., 2000; Bera et al., 2009). Also, few studies have concluded that geogrids mainly reinforce lateral restraint, and improve the bearing capacity, and the tensioned membrane effect (Hufenus et al., 2006; Subaida et al., 2009). MSW differs from conventional soils because of its particle size and shape, and mechanical, chemical, and engineering behaviour. The engineering behaviour of reinforced MSW might differ from the reinforced soils. The theories applicable to the reinforced soils may not be applied exactly in the case of reinforced MSW, so for this long-term field, monitoring is required to examine the engineering performance of the reinforced waste (Ke et al., 2021). Similar field monitoring of the structures with reinforced soils has been studied in the past to observe the stress state and engineering performance (Yoo and Kim, 2008; Cao et al., 2016; King et al., 2017).

2.5 POTENTIAL RE-USABILITY AND CHALLENGES IN USING SOIL-LIKE WASTE/MSW FINE FRACTION

The increasing demand for naturally available raw materials has resulted in the discovery of new non-traditional sources and material recovery. One possible alternative source is landfill mining. In recent years, there has been increased interest in the recovery of soil-like material (SLM) from landfills (Jones et al., 2013). The fate of the fine fraction could have a remarkable impact on the economics of a landfill mining project. According to certain research, the fine soil type fraction could be used as a substrate for the intermediate or final covers of present landfilling processes, thus generating revenue (Jennings et al., 20007; Hogland et al., 2010).

These waste fine fractions or soil-like materials obtained from landfill mining operations are generally utilized as a soil cover in the same operating landfills. It has been already clear from the discussions in the above sections that contamination could be a great concern in the reusability of this material. Still, it can potentially be used for any purpose after some treatments, such as compost for re-vegetation/soil conditioning/eco-forestry, landfill cover material, infrastructure development, road and railway embankments, deep/shallow earth fill, and backfill material. Depending on the end utilization, the height of the fill, and characteristics of the site and the fill material, the design opinion and treatment measure can be given as (a) unrestricted use: material can be directly used without any treatment; (b) reuse with isolation layers: isolation in the form of low permeability layer or geomembrane to avoid infiltration; (c) reuse with a leachate management system in addition to sealing layer: a proper drainage system in the bottom layer with addition to isolation of the base; (d) reuse after treatment: it is an expensive option that may include treatment of material like blending, immobilization/solidification using binders, size separation, washing, carbonation, thermal treatment, biological stabilization, bio cementation (Datta et al., 2021a).

Chandana et al. (2021) tried to give a holistic characterization scheme for the LFMSF (landfill-mined soil fraction). An algorithm was proposed to help in deciding on LFMSF for different utilization schemes. Based on AASHTO (American Association of State Highway and Transportation Officials) and INDOT (Indiana Department of

Transportation) standards, LFMSF was classified as inorganic LFMSF and organic LFMSF. These regulations specify that the OM be less than 3% to be considered an inorganic material for use as a geomaterial. Inorganic LFMSF was suggested to be used as structural fill material in reclamation projects, embankment construction, and subgrade material. Organic LFMSF, on the other hand, could be useful as a biofertilizer or acid-neutralizing material.

2.5.1 MSW Compost/Soil Conditioner

The MSW fines can be used unrestricted for soil conditioning or vegetation for non-edible cash crops for the sites distant from the urban areas and the water table deep below. The organic carbon and nutrients in the fines enhanced vegetation growth (Datta et al., 2021b). MSW's Soil Organic Matter (SOM) fraction could be extracted and used to make compost. Because of the increased SOM, compost improves the biological, physical, and chemical properties of the soil (Nasner et al., 2017). The MSW compost (MSWC) has the potential to be a useful recycling tool. Its safe use in agriculture, however, is contingent on the manufacturing of high-quality compost, particularly compost that is mature and low in metals and salt content. The best method for reducing metal content and enhancing MSWC quality is early source separation, which may require separation before or at curbside collection (Meena et al., 2019). Because the chemical and physical composition of MSW compost varies with time and source, the quality of MSW compost must be carefully monitored on an annual basis (Hicklenton et al., 2001). Meena et al. (2016) discovered that adding organic amendments to salt-affected soils increased nutrient concentrations, particularly NPK, organic carbon, microbial biomass, and enzymatic activities. The MSWC enhances the soil structure and permeability, boosts salt leaching, reduces surface evaporation, inhibits salt accumulation in surface soils, and releases CO_2 during compost respiration and decomposition

(Raychev et al., 2001). Masi et al. (2014) also concluded that the investigated fine material of size less than 4 mm from an old landfill can be used for various purposes, including temporary storage, the creation of "bio-soils" (obtained by mixing agronomic soil) for use in environmental remediation activities or geo-environmental applications, the replacement of the soil layer, or the cultivation of non-edible crops. Waste soil (size 5 mm) was discovered to have a high potential for recycling in environmental remediation activities in the scenario of an irregular landfill in Beijing. A full-scale reclamation operation in a landfill must first remove stone, glass, metal, and plastic from waste soil (Rong et al., 2017). Due to the presence of nutrients and Rhizobium in MSW fines are mined from landfills, making them suitable to use as bio-fertilizers for agricultural and horticultural activities (Chandana et al., 2021). Some past research, it was found high concentrations of Al (9–12 g/kg) and Mn (0.4–0.8 g/kg) which may damage the growth of the plants by affecting the roots (Burlakovs et al., 2018; Jani and Hogland, 2018). Such contradictory findings highlight the issues related to the diversity of the excavated fines from the landfills, which is primarily due to the characteristics of the dumped waste and their decomposition behaviour over time, as well as how to standardize testing protocols to avoid the negative effect of heavy metal accumulation in plants caused by using MSW fines as a fertilizer.

2.5.2 Reusability as Landfill Cover

Most of the past studies suggested that the fines obtained from any landfill can be utilized as a cover material on the same site (Hogland, 2002; Hull et al., 2005; Jain et al., 2005; Kurian et al., 2003; Burlakovs et al., 2016; Bhatnagar et al., 2017; Somani et al., 2018) also can be seen in Table 9. However, the presence of organic matter and moisture content in LFMSF may aid in the breeding of flies and mosquitoes, which may discourage its use for such purposes (Environmental Protection Agency Ireland, 2014).

2.5.3 Engineered Fill Material

The MSW fines can be used as filling material in the low-lying areas with a proper top and bottom sealing of the layered earth fill. This comes under the reuse of material with isolation. The material can be used for shallow filling of the area with no load bearing that can be used as parks, playing fields, golf areas, etc. filling the open deep pits with MSW fines near the water table may require a proper liner with drainage system and a top cover to avoid contamination (Datta et al., 2021a). In most of the geotechnical studies conducted on MSW or MSW fines, it is suggested that the material can be used as geomaterial with limited applications or required some treatments.

Chandana et al. (2021) suggested MSW fines can be used as a construction and structural fill material in reclamation projects; however, they must meet the same testing protocols as the conventional materials used in such projects. The MSW fines are a candidate material for constructing permeable reactive barriers for acid-contaminated soils and immobilizing acid-mined drainage due to the presence of carbonates and metal hydroxides, in addition to organic matter.

The unrestricted reuse of fine extracted from landfill sites in embankments for roads, railways, and water retaining structures is not possible due to the presence of high organics, which will result in excessive long-term secondary settlements. This issue, along with the possibility of soluble salt release and dark-colored leachate, suggests that some pre-treatment in the form of blending with local soils or some binder is required (Oettle et al., 2010). A detailed study was carried out on the MSW collected from Ghazipur, East Delhi as an embankment by Havangi et al. (2017). The MSW was proposed for the widening of NH-24 from 4 lanes to 16 lanes. The size of the considered MSW for the study was the fraction passing through the 16 mm sieve (which contains very little plastic). Given the higher percentage of this material in MSW (44-48%), as well as the fact that its maximum dry density meets MORTH specifications (MORTH, 2013), this fraction can be used directly for embankment construction. To obtain the final material for embankment construction, this should be mixed with material retained on 37.5 mm/35 mm and 16 mm after air blowing.

Mechanically stabilized earth walls (MSE walls) are increasingly being used in the construction of approach roads for flyovers, bridges, rail overbridges, and other transportation infrastructure. In such cases, structural fill in large quantities is required for the construction of MSE walls. Although the presence of excessive organic matter and salts make it impossible to use it as structural fill for such a large project (Datta et al., 2021a) there are still some limited studies that suggest it can be used as backfill material. Gajjar et al. (2019) conducted a large-size model test to evaluate the suitability of MSW as a backfill material in reinforced earth (RE) walls. The load settlement and load-displacement tests were performed on the sand, MSW, and sand sandwiched (20 mm) between MSW and a mixture of 1(sand):3 (MSW). It was observed that the average displacement of a RE wall with a backfill material of 1 (Sand):3 (MSW) was very low when compared to sand, MSW, and sand sandwiched between MSW. The model study suggested using the considered MSW in the RE wall after segregation, even if the considered MSW consists of organic matter of about 22-25%.

The use of MSW fines as geomaterial or engineering fill material is still debatable. MSW fines look like soil particles, that’s why termed soil-like material and even according to geotechnical characterization, the material can be categorized by the soil classification system. The chemical and physical aspects of the material, i.e., its organic matter (OM), moisture content (MC), and presence of toxic or hazardous heavy metals make it unsuitable for its bulk use in the fields. A well-defined treatment system is required before this material can be applied in some geotechnical applications as geomaterial. Even before using it in fields for large projects, it is required to conduct time-dependent large field studies to know the actual behaviour of the material. Moreover, the heterogeneity of the MSW fines makes it more complex to use as a geomaterial. The properties of the fines excavated would be always site-specific, so the suggested treatment and utilization would also be very specific.

2.5.4 Construction Material

The MSW fines may contain significant concentrations of metals and rare earth elements like copper, iron, zinc, etc. depending upon the source of the material. Because of the rise in living standards, these elements are in higher demand. The previous studies also suggested that landfill-mined waste may contain high concentrations of certain metals, making it appealing for material recovery (Jani et al., 2014; Quaghebeur et al., 2013; Bhatnagar et al., 2017). Burlakovs et al. (2016), studied the content of metallic elements in the fraction < 10 mm of excavated waste and found average concentrations of Fe (10,000 mg/kg), Mg, and Zn (1,000 mg/kg) and above 100 mg/kg of metals like Mn, Ba, Cu, Pb and Sr. Al and Fe recovery from the fine fractions are of interest as their concentrations in the fines could yield around 2-2.5 wt.% of Al and 1.5-2 wt.% of Fe (Kaartinen et al., 2013). According to preliminary results obtained by (Quaghebeur et al., 2013), removing the magnetic metals from the fraction < 10 mm could result in a reduction of more than 50 wt.% of the total amount of metals in the same fraction.

However, because most of the metals in the fine fraction are present in their oxidized state and may need to be reduced to their elemental state, the speciation of metals (mineralogical bonding) in the fine fraction of waste must be known to assess their recoverability. Metal recovery from the fine fraction is a potential area that requires additional attention to meet the nation's growing demand, as most metal resources are depleting.

Another use of fine fraction would be as geopolymer or fired brick. Goel and Kalamdhad (2017) investigated the replacement of topsoil with degraded MSW and found that degraded MSW can replace 20% of topsoil while achieving maximum durability. Singh and Chandel (2022b) used the fine fraction of MSW <4 mm as clay replacement in the production of fired bricks. The results show that adding fine fractions reduced the density of fired bricks significantly. The fine fraction incorporated bricks have an advantage in transportation due to their lower bulk density. Furthermore, the thermal conductivity of fine fraction incorporated bricks was significantly lower than that of control bricks, implying improved insulation and energy savings. Although the compressive strength of fine fraction incorporated bricks decreased as fine fraction concentration increased and increased as temperature increased. The results show that the fine fraction could replace 6%, 11%, and 23% of clay at 800 ºC, 900 ºC, and 1000 ºC temperatures, respectively.

The mass utilization of MSW fines for construction material, whether by extracting resources from it or as a replacement is still a challenge and required intensive studies (especially chemical analysis). There are studies of MSW ashes (bottom ash or fly ash) used in mortar/concrete (Jurič et al., 2006; Shan et al., 2011; Tyrer, 2013; Abba et al., 2014; Singh et al., 2022b;) and partial or full replacement of MSW bottom ash in brick (Lin, 2006). Although there are almost no studies to validate the use of MSW fines excavated from landfills uses as fines in mortar/ concert or as geopolymers. This could be a new area to explore for the researcher.

2.6 TREATMENTS REQUIRED BEFORE FIELD APPLICATION

The fine fractions obtained after the pre-treatment (sieving and segregation) of the waste excavated from the landfill sites cannot be used in the fields directly and may need advanced treatment before the application. The organic content present in the MSW fines causes significant restrictions for using it as a geomaterial. The presence of high organic content also increases the biological activities in the material and may limit its usage due to the decomposition of organic matter and hence need attention. The organic matter in MSW fines is derived from a variety of biodegradable landfilled materials, including soil organic content from daily covers and their degraded products, and its content varies with landfill age, with younger landfills containing more organic matter (Monkare et al., 2016). The biological activity in MSW fines can be measured through biogas (methane) production potential or oxygen consumption (Monkare et al., 2015). Other than organic content, MSW fines also contain some hazardous compounds and heavy metals which need to be treated or controlled.

A few of the treatments are mentioned in the flow chart in Figure 2.3. The simplest and cheapest method is washing the MSW fines. Soil washing could be used to remove organic contaminants from the fine fraction (Bilitewski, 1995). The washing method was successfully used to remove soluble salts and heavy metals from the MSW incinerated bottom ash (Sorlini et al., 2011). The waste's heterogeneity makes conventional mechanical separation nearly impossible, especially for the mineral fine fraction. Furthermore, dry sieving techniques do not affect the adhering surface minerals of the other waste groups. These adhering impurities have a significant impact on the quality of the recyclables. For washing and segregation of the aged waste (10-60 mm) wet mechanical waste treatment can be effective. A wet jigger can be used to separate the waste into different streams based on their densities. This method is simple, inexpensive, and robust (Wanka et al., 2017). The other easy method is to blend the MSW fine fraction with some locally available soil. A fraction of aged MSW passing 76 mm was mixed with locally available soil and suggested for use as an engineered fill-in application with moderate settlement tolerances (Oettle et al., 2010). The blending reduces the organic content and concentration of soluble salts in MSW fines and improves the engineering properties of the excavated fines. Another method suggested by a few researchers is thermal heating, the heating of the MSW fines burns the organic content in the material (Somani et al., 2018). Hyks et al. (2011) heated the MSW bottom ash to a temperature range of 930–1080 ºC and found reduced in the leaching of some contaminants due to the chemical transformations and/or encapsulation. The problem of the leaching of hazardous matter of heavy metal can also be addressed by blending the MSW fines with some binders, like cement, asphalt, lime, etc. This method has been successfully used in the case of MSW incinerated ashes for immobilizing or solidification of the heavy metals in the material (Chen et al., 2008; Cioffi et al., 2011). The thermal method seems to be easy but requires an external source for burning and controlled thermal plants for large applications as these fines have poor potential heating value (Quaghebeur et al., 2013).

The above-discussed techniques are rather simple and need a less controlled environment. Another recent and emerging technique used for stabilizing and cementing materials (construction or geo-materials) is bio-cementation. Bio-cementation employs microorganisms to produce calcium carbonate. Microorganisms can produce minerals in the form of organic-inorganic compounds that act as binding agents when they react with chemical components via microbiologically induced calcium carbonate precipitation (MICP) (Prozorov, 2015). This method has been used to heal the micro-cracks in the concretes as self-healing concrete (Lors et al., 2020) and soil stabilization (Mujah et al., 2017). Sharma et al. (2020) also used this technique to immobilize Pb through the consortia of bacteria and blue-green algae in the sand and MSW (bottom ash). Applying the bio-cementation technique in a controlled environment is rather simple and easy but its field application is still a challenge and needs further research.

One of the very effective and natural methods is bio-stabilization. Stabilization not only improves the quality of the waste but also reduces the organic and inorganic pollutants (Hrad et al., 2013). Moisture and the organic matter content of the waste material have a significant impact on waste stability (Shalini et al., 2010). The waste can be stabilized using biotechnological anaerobic and aerobic processes, and these methods could potentially be used for MSW fines. Waste pre-treatment methods such as particle size reduction and process conditions such as recirculation of leachate and adjustment of moisture content, pH, and temperature improve bioprocesses (Mali et al., 2012). Monkare et al. (2015) evaluated the feasibility of biotechnological methods for reducing the organic matter content in MSW fine fraction with the goal of stabilization. Four laboratory leach bed reactors (LBR) were used in an experiment to simulate different stabilization methods. The methods investigated were anaerobic LBR stabilization (with and without semicontinuous water addition, and with and without leachate recirculation) and aerobic LBR stabilization (with water addition). The quantity and composition of biogas (CH4) and quality of leachate (chemical oxygen demand (COD), ammonium nitrogen, anions, molecular weight distribution) were also examined. The method was suggested to stabilize the heap of MSW fines near a landfill mining site. In the extended work scaled anaerobic and aerobic treatment of fine fraction (<20mm), with or without continuous irrigation was studied and cost estimation of different bio-stabilization treatment techniques was discussed (Monkare et al., 2019). The effect of the untreated raw municipal solid waste and mechanical and biological pre-treated municipal solid waste was studied on geotechnical properties and was suggested not to use the geotechnical parameters of these two interchangeably. It was acknowledged that particle size may have a significant impact on the hydraulic conductivity of both types of municipal solid waste. However, there were no such strong correlations between the compression ratios and shear strengths of the untreated and pre-treated municipal solid waste (Petrovic, 2016).

All the treatment methods discussed above have the potential to be used in the field. Depending on the technique and characteristics of the waste, proper infrastructure and on-ground plan are required which involves funding. To utilize these MSW fines in bulk quantity for any geotechnical or construction purpose, it would be a major challenge to execute the plan in the field which includes handling the material in bulk, controlling the required environment according to the suggested treatment, transporting, and placing the material, etc. Furthermore, these treatments can raise the cost of a material that was previously considered waste. The entire process of landfill mining of MSW fines, from the excavation to the final geomaterial, could be prohibitively expensive, discouraging its use. Economically this may not look non-profitable but from an environmental point using this waste becomes a need.

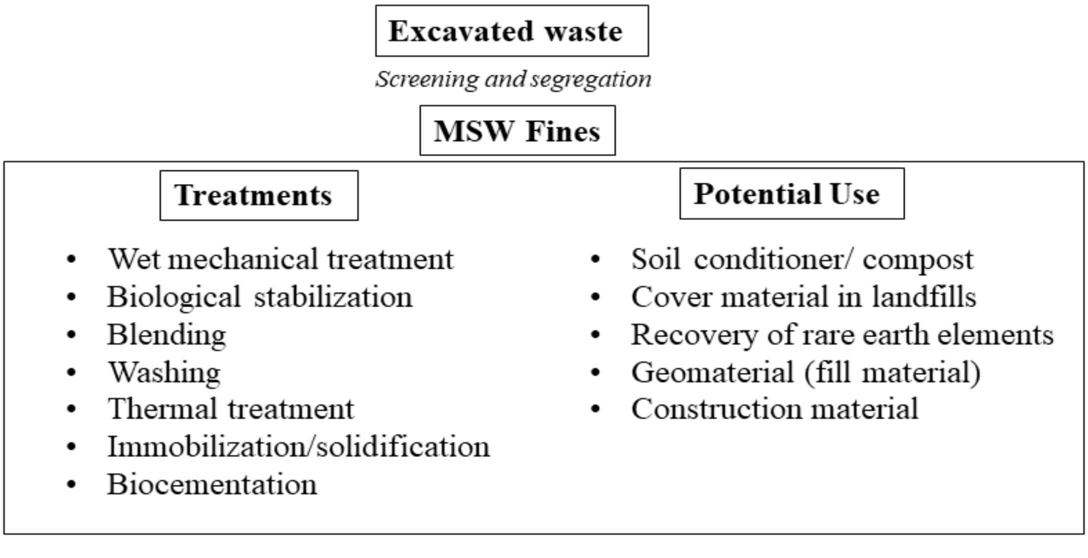

Figure 2.3 Potential use and considered treatments for MSW fine fraction

2.7 SUMMARY

This chapter outlined the major studies conducted on municipal solid waste (MSW) from landfill sites. Maximum studies which have been conducted were related to the physical characterization of the waste, as the heterogeneity of the MSW is a key parameter that influences the other properties. Due to this heterogeneity commenting on its properties in general, giving some specific range, or developing some model makes it a very difficult task. Still, the search and analysis of the published literature produced a wide range of data on MSW physico-chemical, geotechnical, and dynamic properties from different landfills. The laboratory-related research conducted on MSW is specifically done considering particles below a particular size, which may be due to the constrain of equipment size in the laboratory. The field related, i.e., landfill studies are more focused to understand the behaviour of landfill material and monitoring the stability and settlement of landfills during their serving period and after closure. Landfill mining can be a very helpful tool to recover and reutilize the different potions of waste. Although there have been studies highlighting the socio-economic and environmental effects of landfill mining there are very limited studies that show the reusability of the different portions of the waste. The soil-like material almost composes 50% of the landfill-mined material and makes it a potential material that can be used in bulk for its field application in the agriculture or construction industry. To use the finer fraction of waste/MSW fines as a geomaterial, extensive geotechnical/chemical/ physical studies are required as the material can look like soil but behave extensively different under static/dynamic loading conditions due to its micro-level heterogeneity.