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Characterization of Physicochemical and Mechanical Properties of Dumped Municipal Solid Waste in Sri Lanka as Affected by the Climate Zone and Dumping Age

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Abstract: Due to the rapid increase in population and urbanization, municipal solid waste (MSW) generation is increasing. Sri Lanka especially faces serious difficulty in finding new sites for MSW disposal due to lack of available space, and the rehabilitation of existing MSW dumping sites for extending their service is required to achieve sustainable urban development. To examine suitable rehabilitation techniques, the identification of physicochemical and mechanical properties of dumped MSW fully considering climatic conditions, waste composition, and time since dumping is essential. In this study, therefore, the physicochemical and mechanical properties of dumped MSW taken from existing MSW dumping sites in three climate zones in Sri Lanka, namely Karadiyana site in the wet zone, Udapalatha in the intermediate zone, and Hambantota in the dry zone with different times since dumping, were investigated. The results showed that the waste composition and biodegradation of organic materials affected the physicochemical and mechanical properties of dumped waste. The measured compaction parameters of the "old" sites at Udapalatha and Hambantota were higher compared to the "new" sites. Compaction parameters at the Karadiyana site, on the other hand, were low even >20 years since dumping, probably due to the high amount of scarcely compacted materials. In direct shear tests, both strain hardening and softening of the waste samples were observed depending on the difference in vertical stress. Based on the Pearson correlations among measured physicochemical and mechanical parameters, it was found that loss on ignition (LOI) would be a good indicator to quickly assess mechanical parameters of "new" and "old" waste materials due to small sensitivities to waste age and climate conditions in Sri Lanka. Especially, LOI correlated well to measured specific gravity and compaction properties and the r^2 values of correlations exceeded |0.80|.

Keywords: municipal solid waste (MSW); open dumping; waste composition; waste age; compaction; shear strength

1. Introduction

The implementation of 'reduce, reuse, and recycle' concept is essential to establish a sound waste management system for sustainable urban development and to achieve a circular economy in a society [1-3]. Most developing countries, however, are facing severe environmental and social problems due to the open dumping of municipal solid waste (MSW), a common waste disposal method in developing countries, due to many factors such as lack of technical skills and economic and social obstacles [4, 5]. Moreover, local authorities who have the responsibility to manage the generated MSW are facing serious difficulties in finding available new land for MSW disposal, especially in expanding urban areas with rapid increase of population [6-8].

One practical option to solve the environmental and social problems induced by MSW open dumping is to rehabilitate existing MSW dumping sites and to extend their capacity for dumped MSW (i.e., service time), preventing secondary environmental pollution and slope failure (landslide) [8-10]. To implement the rehabilitation of MSW dumping sites, a combinational engineering approach consisting of excavation and compaction of buried waste to reduce the volume of waste, slope cut, and ground leveling to avoid landslides, an earthen cover to prevent waste scattering and intrusion of surface water, improvement of ground strength, and control of environmental pollution (treatment of landfill leachate and groundwater) [11, 12] should be carried out. The rehabilitation of existing MSW landfills, moreover, would contribute to the post-closure land uses of MSW dumping sites [13, 14].

Many studies have been done to characterize the physicochemical and mechanical properties of dumped MSW by laboratory tests using samples taken from MSW dumping sites [15-21] and field investigations [13, 22-26]. For example, Zekkos et al. [27] investigated the depth profile of unit weight (i.e., density) of buried waste at MSW dumping sites using reported data and showed that the unit weight increased with age after dumping and depth. Moreover, a careful definition through a constitutive relationship based on a three-phase model (solid, liquid, and gas) was done by Stolz et al. [28]. With regard to mechanical properties, previous studies investigated compressibility and shear strength (drained/undrained) mainly by compaction and direct shear tests. Reddy et al. [11, 25] showed that compacted densities decreased with age after dumping and that the cohesion of tested waste samples varied greatly by the presence of biodegradable organic materials. Zekkos et al. [27] also reported that biodegradable organic materials were good indicators of compressibility and shear strength, and higher organic contents in MSW gave higher compressibility and lower shear strength. Stolz et al. [29, 30] characterized the water retention properties, pore size distribution, and gas permeability of MSW samples under compression. Zhan at al. [10] carefully measured shear strength of dumped MSW of different ages and showed that cohesion decreased and internal friction increased with the age of MSW. Ramaiah et al. [31] also reported that cohesion decreased and internal friction increased with increase of fill age of MSW. Gabr et al. [32], on the other hand, investigated the shear strength of buried MSW samples in MSW landfills with a leachate circulation system and found both cohesion and internal friction of waste samples decreased with age since dumping (i.e., increase of biodegradation of organic materials). In addition, Machado et al. [33–35] investigated the effects of biodegradation on the mechanical properties of MSW and found that easily biodegradable organic materials decreased the shear strength of "young/fresh" MSW, but that fiber materials increased the shear strength of MSW with increasing decomposition of organic materials. They also suggested that the biodegradation generated the fibrous materials that reduced the ultimate tensile strength and Young's modulus.

Difficulties to characterize the physicochemical and mechanical properties of dumped MSW as well as wide range of values for mechanical properties in previous studies, in general, are attributed to the wide variation of composition and configuration of dumped MSW in countries and regions with different climate zones (i.e., heterogeneity of materials), and inclusion of both biodegradable and non-biodegradable (inert) materials

in dumped MSW. All these characteristics affect not only the laboratory testing results of physicochemical and mechanical properties but also the long-term performance and behavior of MSW dumping sites, emphasizing the importance of studies on "site-specific" characteristics of dumped MSW.

Among developing countries, Sri Lanka has very limited available land for the establishment of new MSW landfills, and most of the MSW collected from local authorities has been disposed of at existing open dumping sites [13, 36]. During rainy seasons, many slopes collapse at MSW dumping sites every year. Especially, a big collapse of MSW dumping site at Meethotamulla, Colombo on 14th April 2017 caused enormous damage with 32 casualties and huge property destruction [13]. Currently, the MSW generation per capita per day is reported as 0.4–1.0 kg [37], and urban population as ~19% [38]; however, it can be estimated that the MSW generation increases due to the rapid urbanization and growth in population. Thus, the rehabilitation of existing open MSW dumping sites to extend their service life and the construction of new sites for MSW disposal are an urgent issue in Sri Lanka. In addition, Sri Lanka has three distinct climate zones: wet, intermediate, and dry zones categorized by annual rainfall (annual rainfall: >2500 mm in the wet zone, 1500–2000 mm in the intermediate zone, and 800-1200 mm for the dry zone) [39]. This means "site-specific" characteristics of dumped MSW should be fully considered when we rehabilitate existing and construct new MSW disposal sites.

The objectives of this study, therefore, were 1) to characterize the physicochemical and mechanical properties of dumped MSW taken from existing MSW dumping sites in three climate zones in Sri Lanka (Karadiyana site in the wet zone, Udapalatha in the intermediate zone, and Hambantota in the dry zone) with different periods after dumping [<3 years after being dumped (young) and >3 years after being dumped (old)], including additional data analyses and discussion based on previously published measurements [40] and the literature, and 2) to examine the relationships among measured physicochemical parameters and mechanical parameters.

2. Materials and Methods

2.1. Sampling locations

Waste samples were collected from three MSW dumping sites: (a) Karadiyana, (b) Udapalatha, and (c) Hambanthota in Sri Lanka [39,40]. The sampling was carried out in March 2017 at the Karadiyana site, and from March to May 2013 at Udapalatha and Hambanthota sites. The sampling locations and photographs are shown in Figure 1 with site information such as daily waste intake and climatic zones. The Karadiyana site is located in the wet zone, the Udapalatha site is located in the intermediate zone, and the Hambantota site is located in the dry zone [39]. Based on the number of years since dumping waste, MSW was labeled "young" (<3 years since being dumped) or "old" (>3 years since being dumped) in this study (see Tables 1). Waste samples of ~50kg were taken from waste layers at 1-m depth intervals (Udapaltha and Hambantota sites) or 2-m depth intervals (Karadiyana site). Subsoil below the waste layer was also taken from the Udapaltha and Hambantota sites. At the Karadiyana site, a soil sample at the depth of 2–3 m was also taken from the original ground. Among samples tested in this study, the samples from Karadiyana site were the oldest, and the waste was more than 20 years old (according to the interview with the Waste Management Authority of Western Province in Sri Lanka [41]).









Sampling site	Local authority	Population	Site location	Annual rainfall and temperature	Daily waste intake (tons/day)	Climate zone
(a) Karadiyana	Colombo District, Western Province	1,185,458	06° 48′54.2″ N 79° 54′08.2″ E	>2500 mm 25–27.5°C	632	Wet zone
(b) Udapalatha	Udapalatha Pradeshiya Saba, Central Province	97,567	07° 07′58.1″ N 80° 34′48.7″ E	1500-2000 mm 17.5–25.0°C	1.78	Intermediate zone
(c) Hambanthota	Hambanthota Municipal Council, Southern Province	22,691	06° 10′36.0″ N 81° 07′40.5″ E	800-1200 mm 25–32.5°C	9.9	Dry zone

Figure 1. Sampling locations of tested materials: (a) Karadiyana (b) Udapalatha, and (c) Hambanthota MSW dumping sites. Information of sampling sites is also given (map data © 2021 Google).

2.2. Waste composition and physicochemical properties

Waste composition was determined following ASTM D5231-92 (2016) [15] and Dixon and Langer (2016) [42]. The samples were sorted by hand and sieved with a set of sieves of 9.5, 4.74, and 2 mm, as shown in Figure 2. In addition to waste composition analysis, a sieve analysis was carried out to determine particle size distribution (PSD) of particles greater than 0.075 mm according to ASTM C136/C136M-19 [16] and the hydrometer test for particle size less than 0.075 mm. Specific density (G_s) of the samples was determined according to ASTM D854-14 [43], and the loss on ignition (LOI) test according to ASTM D 7348-13 [18] determined the organic content of the dumped MSW. Atterberg limit tests were carried out to determine the liquid and plastic limits of the samples according to ASTM D4318-17e1 [19]. The pH of the waste materials was determined according to ASTM D472-19 [20], and the electrical conductivity was tested to conform with JGS 0212-2009 [21].



Figure 2. Sorted waste materials taken from Karadiyana site.

2.3. Compaction and direct shear tests

Sieved samples <9.5 mm were used for compaction and direct shear tests. For the compaction test, the sample was packed into a mold with a diameter and height of 10 cm in three equal layers with a rammer of 2.5 kg and a drop height of 305 mm to determine the maximum dry unit weight (γ_d) and optimum moisture contents (w_{opt}) (standard compaction energy of 600 kN-m/m^3 [44]. Direct shear tests [45] were conducted to determine cohesion and internal friction angle for the tested sample in a mold with 100-mm diameter and 40-mm height. The tested samples were first compacted in a mold to the desired degree of compaction (~90%) by adjusting the initial water content of samples to the approximately optimum water contents (w_{opt}; see Table 3). Horizontal and vertical displacement transducers were attached the data logger to monitor the shear displacement and vertical strain. A constant strain rate of 0.15 mm/min was used to shear the samples under three different vertical stress conditions of 25 kPa, 50 kPa, and 75 kPa. The direct shear test apparatus is shown in Figure 3a.



Figure 3. (a) Direct shear test apparatus and (b) tested sample of Karadiyana site (<9.5 mm).

3. Results and Discussion

3.1. Waste composition and particle size distribution

The waste composition of the tested materials is shown in Table 2. For all tested samples, there were no obvious easily biodegradable organic materials (e.g., kitchen waste) because those materials became residues (2–4.75 mm and <2.0 mm) after biodegradation by mixing with fine materials such as sand and crushed inert materials. It is noted that fresh MSW in Sri Lanka is normally rich in kitchen waste containing easily biodegradable organic materials (e.g., ~70% of fresh MSW contains kitchen waste [4, 50]). For all investigated sites, the % of residues (2–4.75 mm and <2.0 mm) was the highest among all constituents. Especially, the sum of "Gravel" and "Residues" exceeded 80% at the Hambantota sites (new and old), meaning the dumped waste was very small, inert, and hard-to-biodegradable materials such as plastic, vinyl, and glass. For the Karadiyana and Udapalatha sites, on the other hand, those inert and hard-to-biodegrade materials were dumped to some % of the total, and "Glass and Wood" were rich in Karadiyana, and "Cementitious materials" and "Vinyl" were rich in the new Udapalatha site. Measured PSD curves for dumped waste are shown in Figure 4. It can be clearly seen that the sample from Karadiyana site was richer in coarse fraction >9.5 mm compared to the other sites. Those coarse fractions mainly consisted of large pieces of "Ceramic", "Rubber and Textile", and "Metals" (Figure 2).

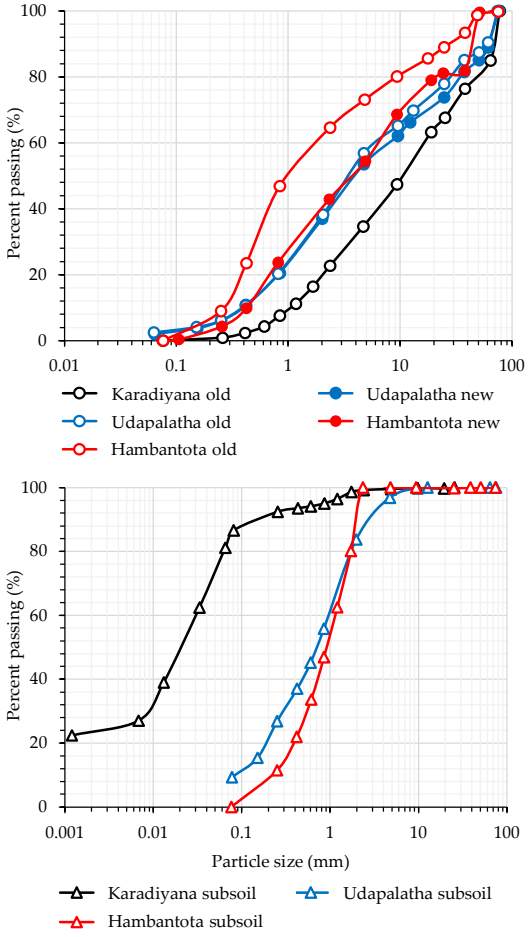


Figure 4. Particle size distributions (PSD) of the tested samples (modified after [40]).

3.2. Physicochemical properties

Measured physicochemical properties are summarized in Table 1, and their depth profiles are shown in Figure 5. In order to compare the measured physicochemical and mechanical properties in this study, data in reports from Sri Lanka, Karadiyana and Jaffna MSW dumping sites [46] and others [25, 47–49]were tabulated The values of field gravimetric water content (w_f) for the waste layers were 50–120% at Karadiyana site (wet climate zone) and Udapalatha site (intermediate climate zone). For the Hambantota site located in the dry zone, on the other hand, w_f values were approximately 20–60%. The measured pH values for waste layers at all sites including subsoil and the original ground did not vary much and ranged mostly from 6 to 8. All the tested samples were non-plastic or low plasticity with a plastic index (I_P) < 20.

The site-specific characteristics of waste samples were clearly shown in the depth profiles of measured specific gravity (G_s), electric conductivity (EC), and LOI. The Udapalatha sites (new and old) (Figure. 5a) gave smaller G_s and higher EC and LOI values (especially, those for the Udapalatha new site) compared to those of the Hambantota sites (new and old) (Figure 5c). This means that the residues of 2.0–4.75 mm and <2 mm in waste samples from the Udapalatha site were rich in organic materials with low G_s (e.g., biodegraded kitchen waste). For the Hambantota site, on the other hand, the residues were rich in inert and inorganic materials (Table 2), resulting in high G_s values similar to those of soil minerals (2.64–2.76 g/cm^3). For the Karadiyana site (Figure 5a), the G_s values were a little higher and the EC and LOI values smaller than those for the Udapalatha site, indicating that the biodegradability of dumped organic waste was more advanced due to the longer period since dumping.

3.3. Mechanical properties of tested samples

3.3.1 Compaction properties

Compaction curves of tested waste samples are shown in Figure 6, and the measured values of the maximum dry unit weight (γ_{dmax}) and optimum moisture content (w_{opt}) are summarized in Table 3. Looking at the compaction curves of the Udapalatha and Hambantota sites, measured γ_d and w_{opt} values from old waste samples were higher compared to new waste samples. This can be affected by the biodegradability of dumped organic waste, i.e., "young" dumped organic waste was hardly compacted due to a cushion effect [11]. For the compaction curve of the Karadiyana site, the measured γ_d and w_{opt} values were relatively low (γ_{dmax} = 10.8 kN/m^3 and w_{opt} = 39.3%) even though the sample was "old" with >20 years since dumping. This can be mainly due to the constituents of the dumped waste, i.e., the waste of Karadiyana was rich in hardly compacted materials such as "Plastic" and "Glass and wood" compared to other waste samples tested in this study (Table 2) [40]. Especially, the waste samples of Hambantota sites (new and old) gave higher γ_d values (14.1 kN/m^3 for new and 16.3–17.3 kN/m^3 for old) with lower w_{opt} values (20.5% for new and 13.4–17.0% for old). This can be due to the high G_s of residues of 2.0–4.75 mm and <2 mm.

Typical reported values of γ_d and w_{opt} for waste samples of different ages including Sri Lankan samples [46] are also summarized in Table 3. It can be clearly seen that the γ_d values of "old" waste were higher than those of "young". The w_{opt} values, on the other hand, showed no relationship with tested waste age, indicating that the w_{opt} varies highly depending on the waste constituents. Among of reported values, Nawagamuwa and Thirojan [46] have carried out compaction tests from Karadiyana (intermediate climate zone) and Jaffna (dry climate zone) waste dumping sites in Sri Lanka. It is interesting that both γ_d and w_{opt} values in [46] are similar to those measured values in this study, irrespective of the difference in waste age since dumping (Karadiyana: 1–2 years [46], and >20 years in this study) and the difference in the location (Jaffna in [46] and Hambantota in this study). Further studies and data are needed, but this evidence implies that the

compaction properties of waste samples dumped at existing MSW sites in Sri Lanka are highly affected by the climatic condition (i.e., wet, intermediate, and dry zones).

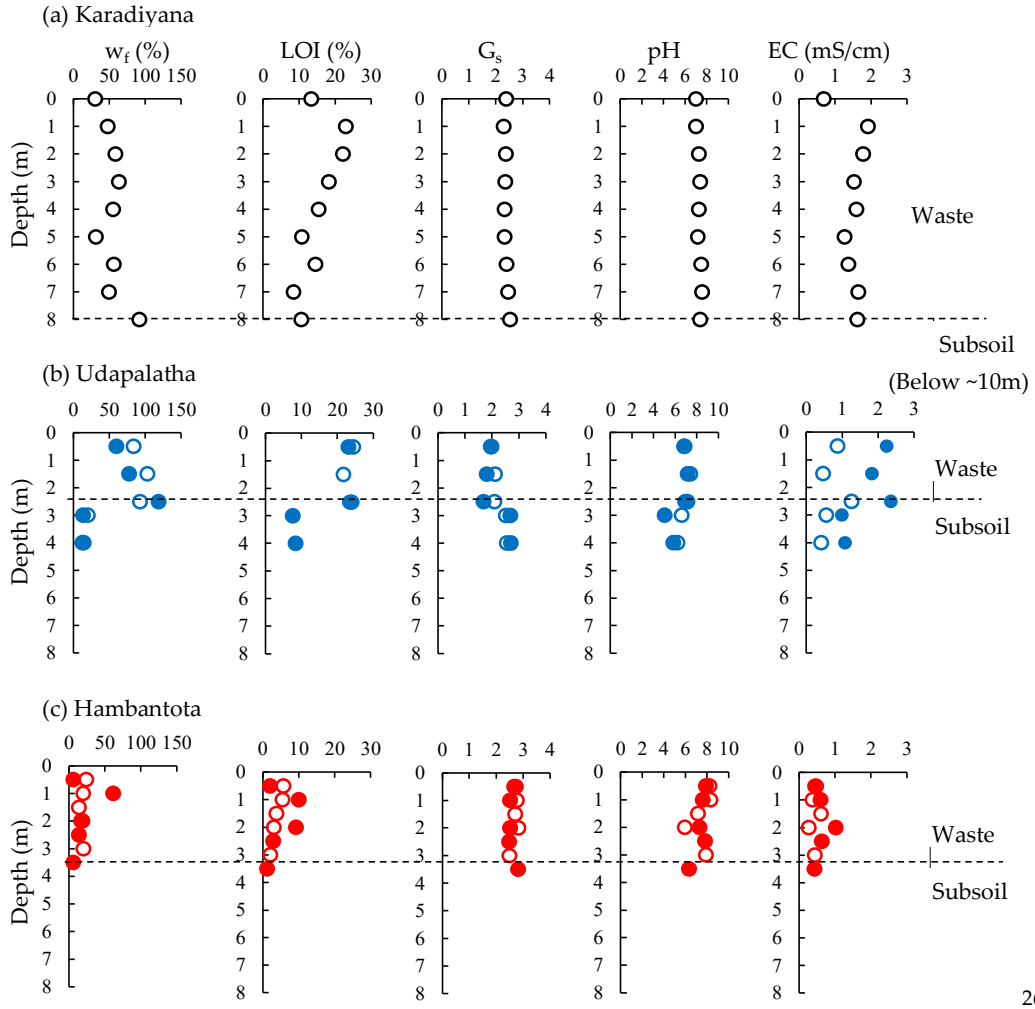


Figure 5. Depth profiles of physical and chemical properties at waste dumping sites (modified after [39, 40]). Closed circles represent "Old" and open circles represent "New".

Table 1. Physical and chemical properties of tested samples (modified after [40]). Literature data from Sri Lankan dumping sites [46] is also given.

Sample location	Age (year)	Depth (m)	Description	w_f (%)	$\gamma_{d,\ In\text{-}situ}$ (kN m^{-3})	Atterberg Limits w_L (%)	Atterberg Limits w_P (%)	Atterberg Limits I_P	G_s	pH	EC (mS cm^{-1})	LOI (%)
Karadiyana site												
Old	> 20	0.0-2.0	Blackish dumped waste	45.5	-	-	-	-	2.26	7.1	1.46	19.5
		2.0-4.0		59.0	-	-	-	-	2.26	7.3	1.63	18.7
		4.0-6.0		47.8	-	-	-	-	2.35	7.3	1.41	13.6
		6.0-8.0		65.9	4.68	68.2	54.3	13.9	2.66	7.5	1.55	11.2
Original soil	-	2.0-3.0	Peaty soil	137	5.04	54.2	36.1	18.1	2.42	6.5	5.37	20.9
Udapalatha site												
New	< 3	0.0-1.0	Blackish dumped waste with fine sand	60.2	6.41	NM*	NM*	NP**	1.96	6.9	2.24	23.1
		1.0-2.0	Blackish dumped waste with clay and sand	77.7	7.03	NM*	NM*	NP**	1.81	7.2	1.83	31.6
		2.0-2.75	Blackish dumped waste with fine sand	119	-	NM*	NM*	NP**	1.69	6.9	2.36	24.0
Old	7-11	0.0-1.0	Black, dumped waste	83.8	5.31	NM*	NM*	NP**	1.99	6.8	0.88	24.4
		1.0-2.0		103	5.17	NM*	NM*	NP**	2.12	7.4	0.47	21.7
		2.0-3.0		93	4.56	NM*	NM*	NP**	2.1	7.1	1.26	23.6
Subsoil	-	1.0-2.0	Brown, medium to fine sand with gravel	12	-	-	-	-	2.54	6	0.04	2.07
Hambanthota site												
New	< 1	0.5-1.0	Blackish dumped waste with clay and sand	61.9	7.8	25.7	NM*	-	2.52	7.6	0.6	9.96
Old (pit 1)	7-8	0.0-0.5	Blackish dumped waste with clay and sand	17.8	10.4	-	-	-	2.64	7.3	0.236	7.10
		0.5-1.0		36.2	10.3	-	-	-	2.72	7.3	0.308	7.44
Old (pit 2)		0.0-0.5		24.1	12.1	29.5	NM*	-	2.66	8.2	0.48	5.78
		0.5-1.0		19.9	8.45	30.6	15.5	15.1	2.76	8.3	0.38	5.50
Subsoil	-	1.0-2.0	Gray, weathered silty sandy clay	18.6	-	24.8	22.9	1.89	2.67	7.5	0.07	3.44
Nawagamuwa and Thirojan [18]												
Karadiyana	1	1-2	-	-	-	61.7	36.8	24.9	1.73	-	-	72-80
	2	1-2	-	-	-	50.3	36.0	15.6	1.66	-	-	
Jaffna	7-10	1-3	-	-	-	20.4	15.9	4.5	1.84	-	-	35-44
	10-13		-	-	-	18.5	16.1	2.4	2.08	-	-	18-23
	13-15		-	-	-	20.5	15.5	4.0	2.24	-	-	

NM*: Not measurable, NP**; Non-plastic

Table 2. Waste compositions of tested samples (modified after [40]).

Material	Karadiyana old	Udapalatha new	Udapalatha old	Hambanthota new	Hambanthota old
Paper	0.6	0.1	1.7	0.0	0.0
Plastic	5.4	3.2	2.3	0.0	0.0
Vinyl	5.2	7.7	6.8	3.6	8.8
Glass, ceramic, and metal	4.0	6.7	5.9	3.3	3.4
Leather & Rubber	1.4	0.1	2.8	0.0	0.0
Textile	1.9	1.0	4.6	1.1	0.4
Grass and Wood	13.8	10.8	6.5	0.6	4.5
Cementitious material	3.0	13.4	4.2	0.0	0.0
Gravel (>9.50 mm)	8.3	5.7	9.0	17.5	8.2
Residues (2.0–4.75 mm)	33.2	17.1	21.6	31.5	30.7
Residues (<2.0 mm)	22.9	34.3	34.6	42.4	44.0
Others	0.4	0.0	0.0	0.0	0.0
Total	100	100	100	100	100

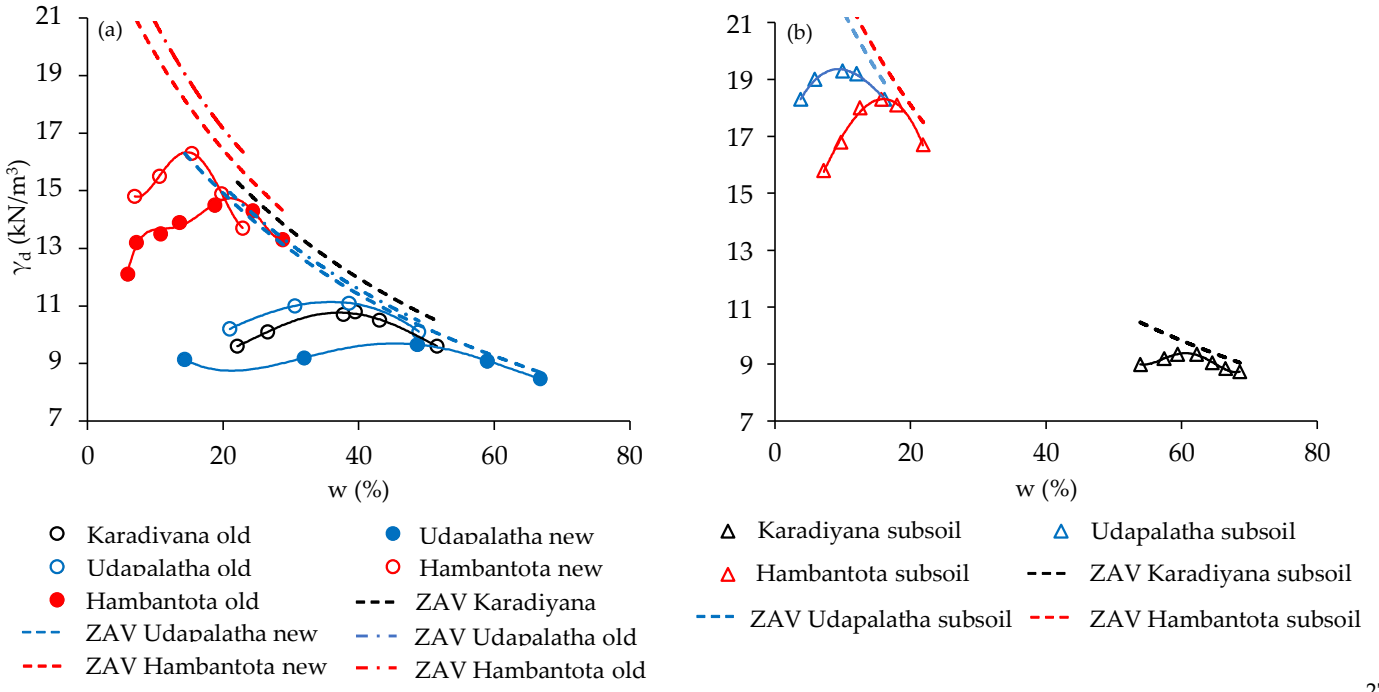


Figure 6. Compaction curves of tested samples (modified after [40]).

Table 3. Summary of compaction and shear parameters of tested samples (modified after [40]). Literature data from [46] and others are also given.

Sample Details (age after dumping)	Depth	Compaction		Direct shear stress			Shear strength parameters*		Measured SD range (%)	Reference
	(m)	w_{opt} (%)	γ_{dmax} (kN m^{-3})	τ (kN m^{-2}) σ_v = 25 kPa	σ_v = 50 kPa	σ_v = 75 kPa	c (kN m^{-2})	ϕ (°)		
Karadiyana site										
Old (>20 years)	6.0-8.0	39.3	10.8	53.7	74.8	98.1	35	48	15	This study
Original soil	2.0-3.0	62.1	9.3	-	-	-	-	-		
Udapalatha site										
New (<3 years)	0.0-1.0	39.7	10.9	34.9	53.9	63.3	20	31		
	1.0-2.0	33.7	10.5	45.4	70.4	78.2	26	38		
	2.0-2.75	48.6	9.7	45.4	56.8	72.7	30	30		
Old (7–11 years)	0.0-1.0	39.0	10.8	23.8	54.5	63.7	23	29		
	1.0-2.0	39.9	11.1	45.3	58.9	88.4	13	44		
	2.0-3.0	36.2	11.3	38.6	54.4	69.8	24	32		
Subsoil	1.0-2.0	11.0	19.3	-	-	-	-	-		
Hambanthota site										
New (<1 year)	0.5-1.0	20.5	14.1	37.6	63.5	77.2	24	35		
Old (pit 1) (7–11 years)	0.0-0.5	13.4	17.3	-	-	-	-	-		
	0.5-1.0	16.1	16.3	-	-	-	-	-		
Old (pit 2) (7–11 years)	0.0-0.5	15.4	16.8	38.0	59.2	88.1	11.7	45.1		
	0.5-1.0	17.0	16.8	52.4	73.9	94.7	31.3	40.3		
Subsoil	1.0-2.0	16.6	18.3	-	-	-	-	-		
Literatures										
[Sri Lanka: Intermediate climate zone]										
Karadiyana (<1 year)	1-2	46	9.60	-	-	-	10.5	56	15	[46]
Karadiyana (<2 years)	1-2	47	9.15	-	-	-	15.1	49.5	15	
[Sri Lanka: Dry climate zone]										
Jaffna (7–10 years)	1-3	20.3	15.2	-	-	-	27.6	28	15	
Jaffna (10–13 years)	1-3	16.7	15.6	-	-	-	34.0	41.5	15	[46]
Jaffna (13–15 years)	1-3	16.5	15.4	-	-	-	17.7	44	15	
[Other regions]										
Fresh Landfill	-	70	4.10	180	240	560	31-64	26-30	15	[13]
Landfills (<1 years)	-	67	10.0	13	56	117	23	24	15	[48]
Landfill (<2 years)	-	-	11-17	-	-	-	9-14	20-29	10	[49]
Landfill (12–34 years)	-	-	12.6-15.8	-	-	-	14	36	5	[9]
Landfill (2–25 years)	1-9	39-52.3	5.1-10.1	50	100	250	4.4-13.7	22-30	15	[47]

NA*: Not available

3.3.2 Shear strength

Experimental results of shear stress (τ) and vertical displacement (ε_v) as a function of shear displacement (SD) for tested waste samples at vertical stresses (σ_v) of 25, 50, and 75 kPa are shown in Figure 7. The measured τ increased with the increase of SD when tested at σ_v = 50 and 75 kPa, meaning that those samples showed strain hardening. The measured τ at low 25 kPa for the samples of Udapaltha new and old [Figure 7(c, d) and (e, f)], and Hambantota new [Figure 7(g, h)], on the other hand, showed strain softening behavior, and the peak of τ values was observed at approximately SD = 10 mm. The strain hardening behavior could be due to the inclusion of inert fibrous materials (<9.5 mm), i.e., those materials (plastic, vinyl, leather, and rubber) contributed to the reinforcement of tested samples and helped to resist the shear displacement at σ_v = 50 and 75 kPa in the direct shear test [10, 35]. While the strain softening behavior was observed in some tested samples at σ_v = 25 kPa, those inert fibrous materials did not assist the share displacement, resulting in the gradual decrease of τ with increasing of SD.

Compared to τ-SD relationships, measured ε_v-SD relationships showed a big difference among tested samples. For Karadiyana old (Figures 7a and 7b), a small change in ε_v was observed at all σ_v conditions, indicating that no volume expansion/reduction occurred during the shear displacement process. For Udapalatha new and old (Figures 7c–7f), a small ε_v change was seen at σ_v = 50 and 75 kPa, but a volume expansion (negative value of ε_v) was observed at σ_v = 25 kPa. For Hambantota new and old (Figures 7g–7j), the volume expansion/reduction was dependent on the SD range, i.e., the ε_v became positive (volume reduction) when SD = 0–5 mm and then the ε_v became negative (SD >5 mm).

Based on the measured τ-SD and ε_v-SD relationships in this study, cohesion (c) and internal friction (ϕ) were calculated by using Mohr's circle [51] and are summarized in Table 3 with reported data. Karadiyana old showed the highest c and ϕ (c = 35 kPa and ϕ = 48°) among tested samples in this study. For both Udapalatha and Hambantota sites, measured ϕ values for "old" waste samples (ϕ = 29–45°) tended to become higher than those of "new" waste samples (ϕ = 31–38°) while the measured c values for "old" waste samples (c = 12–24 kPa) became lower than those of "new" waste samples (c = 20–30 kPa). The results imply that the cohesion of dumped waste decreased with age after dumping due to the degradation of biodegradable materials which subsequently increased the internal friction angle with age (due to the non-degradation of inert materials).

The measured c and ϕ in this study ranged generally within the reported values (Table 3). Having a look at Karadiyana data from Sri Lanka (intermediate climate zone) [46], it can be seen that the c value of "old" waste samples in this study (c = 35 kPa) is much bigger than those of "young" waste samples (c = 10~15 kPa) irrespective of a small difference in ϕ for both data sets. This is an opposite trend to the test data above (Udapalatha and Hambantota sites in this study), but it is supposed that the composition of tested waste samples of both studies were different. On the other hand, there were no distinct differences in c and ϕ among data from waste samples taken from dry zones, i.e., Hambantota in this study and Jaffna in Sri Lanka [46].

As discussed in Figure 7, the shear stress (τ) of waste samples is dependent on the vertical stress (σ_v). Figure 8 shows a comparison of the measured τ in this study with the reported τ- σ_v relations for MSW materials summarized in Kavazanjian [52] and Jones et al. [53]. Most of the measured τ in this study ranged in the envelope of τ- σ_v relationships reported by Jones et al. [53], but some data from the Karadiyana site ("old") was higher than that of the envelope, and it can be seen that the measured τ in this study was higher than the suggested line by Kavazanjian [52]. The results suggest strongly that the mechanical properties of waste materials including "fresh" and "old" are highly dependent on the local conditions (i.e., site-specific) and those site-specific features such as the climate, geography, and management system of a dumping site affect the mechanical properties of waste samples.

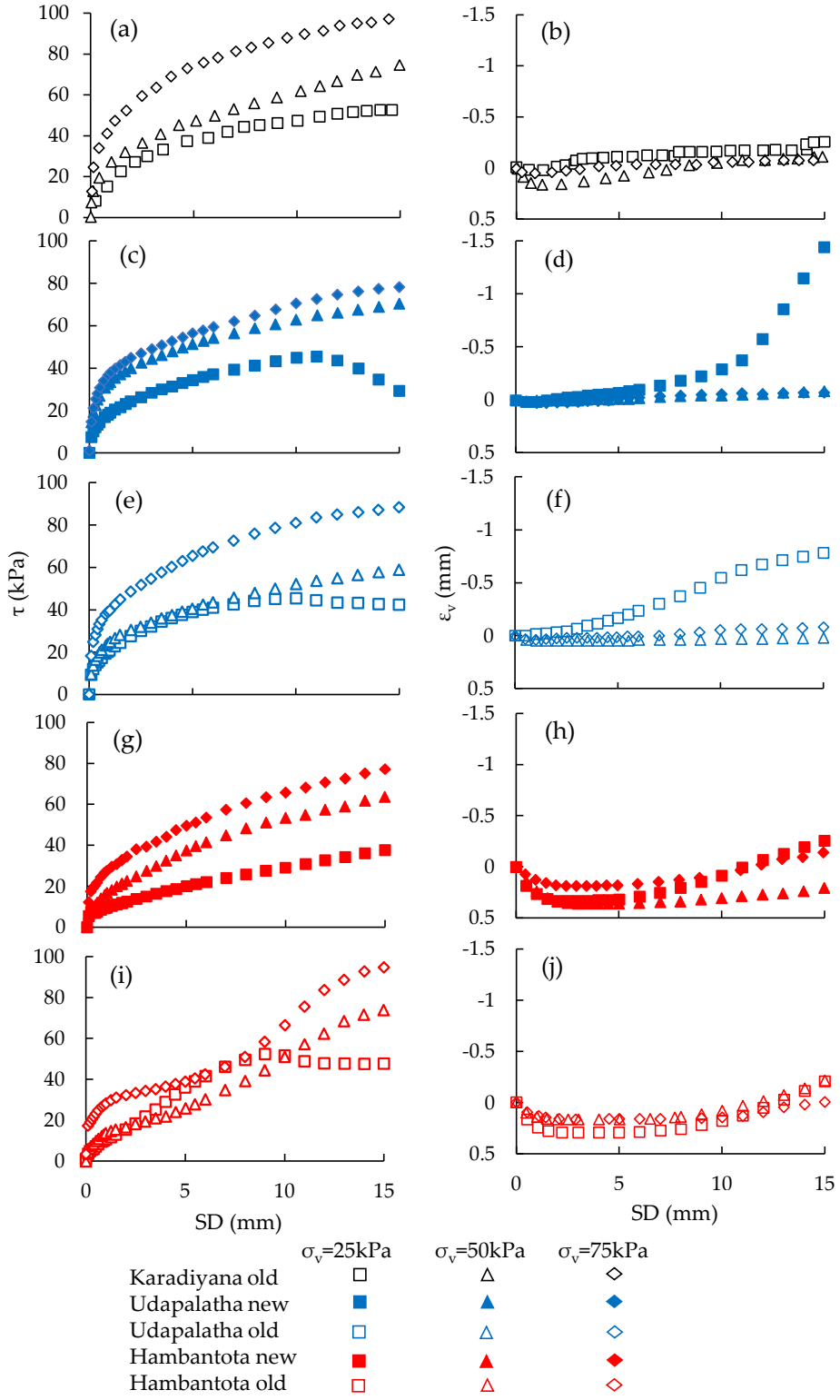


Figure 7. Shear stress (τ) and vertical displacement (ε_v) as a function of shear displacement (SD) for (a, b) Karadiyana old, (c, d) Udapalatha new, (e, f) Udapalatha old, (g, h) Hambanthota new, and (i, j) Hambantota old.

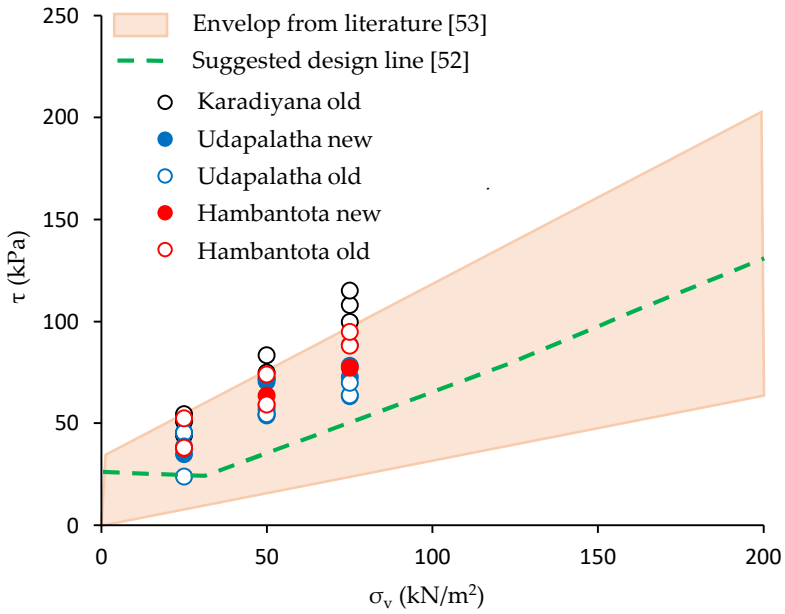


Figure 8. Comparison of measured shear strength (τ) at SD = 15mm to the reported range of τ-σ_v relationship in previous studies.

3.3.3 Links between physicochemical and mechanical parameters

In order to examine the correlations among measured physicochemical parameters and mechanical parameters in this study, a Pearson correlation matrix was constructed and is shown in Table 4. Among the measured physicochemical parameters in this study (G_s, LOI, pH, and EC), the LOI overall correlated better to measured mechanical parameters. Especiallly, the r^2 values of correlations with compaction parameters such as the maximum dry unit weight (γ_{dmax}) and optimum moisture content (w_{opt}) exceeded |0.80|. The LOI also correlated well with the G_s of tested samples. It is noted that other physicochemical parameters (G_s, pH, and EC) were also correlated with ϕ (r^2 > |0.85|), however, the correlations with other mechanical parameters (γ_{dmax}, w_{opt}, and c) were low. This indicates that G_s, pH, and EC were not suitable indicators to characterize the mechanical properties. In addition, the LOI had moderate correlations with pH and EC (r^2 > |0.60|), indicating that higher LOI samples tended to become lower pH and higher EC probably due to the biodegradation of dumped MSW.

All the correlations with LOI are shown in Figure 9. In the figures, the "fresh" and "degraded" MSW samples reported by Reddy et al.[11] and buried MSW waste aged 2–25 years reported by Abreu et al. [47] are also given for comparison with G_s and the compaction parameters such as γ_{dmax} and w_{opt}. As shown in the figure, LOI reasonably captured the mechanical parameters with linear regression lines for both "new" and "old" waste samples irrespective of the locations in different climate zones (small sensitivity to climate conditions). This suggests that LOI can be a convenient indicator to estimate mechanical parameters for both "fresh" and "aged" dumped waste. It can be observed that the reported values of [11] and [47] deviated to some extent from the linear regression lines in this study (Figure 9a-9c). This was maybe caused mainly by the difference of waste constituents in tested MSW materials. Further studies are needed to discuss the links between the physicochemical and mechanical parameters of dumped waste materials fully considering the difference in waste constituents. The easily measurable LOI, however, is expected to be a good indicator for making a quick assessment of the compaction and shear strength properties of "fresh" and "old" waste materials and is thus able to contribute to the rehabilitation of existing MSW dumping sites in Sri Lanka.

Table 4. Pearson correlation matrix for the measured physicochemical and mechanical parameters. Values >|0.80| are given in bold.

Parameters	G_s	LOI (%)	pH	EC (mS cm^{-1})	γ_{dmax} (kN m^{-3})	w_{opt} (%)	c (kN m^{-2})	ϕ (°)	No. of samples
G_s	1	**-0.89**	0.64	-0.70	0.70	-0.68	-0.47	**0.91**	17
LOI		1	-0.68	0.61	**-0.86**	**0.80**	0.58	-0.76	20
pH			1	-0.51	0.71	-0.69	-0.18	**0.89**	20
EC				1	-0.78	0.78	0.45	**-0.85**	20
$\gamma_{d,\ max}$					1	**-0.97**	-0.31	**0.81**	12
w_{opt}						1	0.30	-0.79	12
c							1	-0.46	9
ϕ								1	9

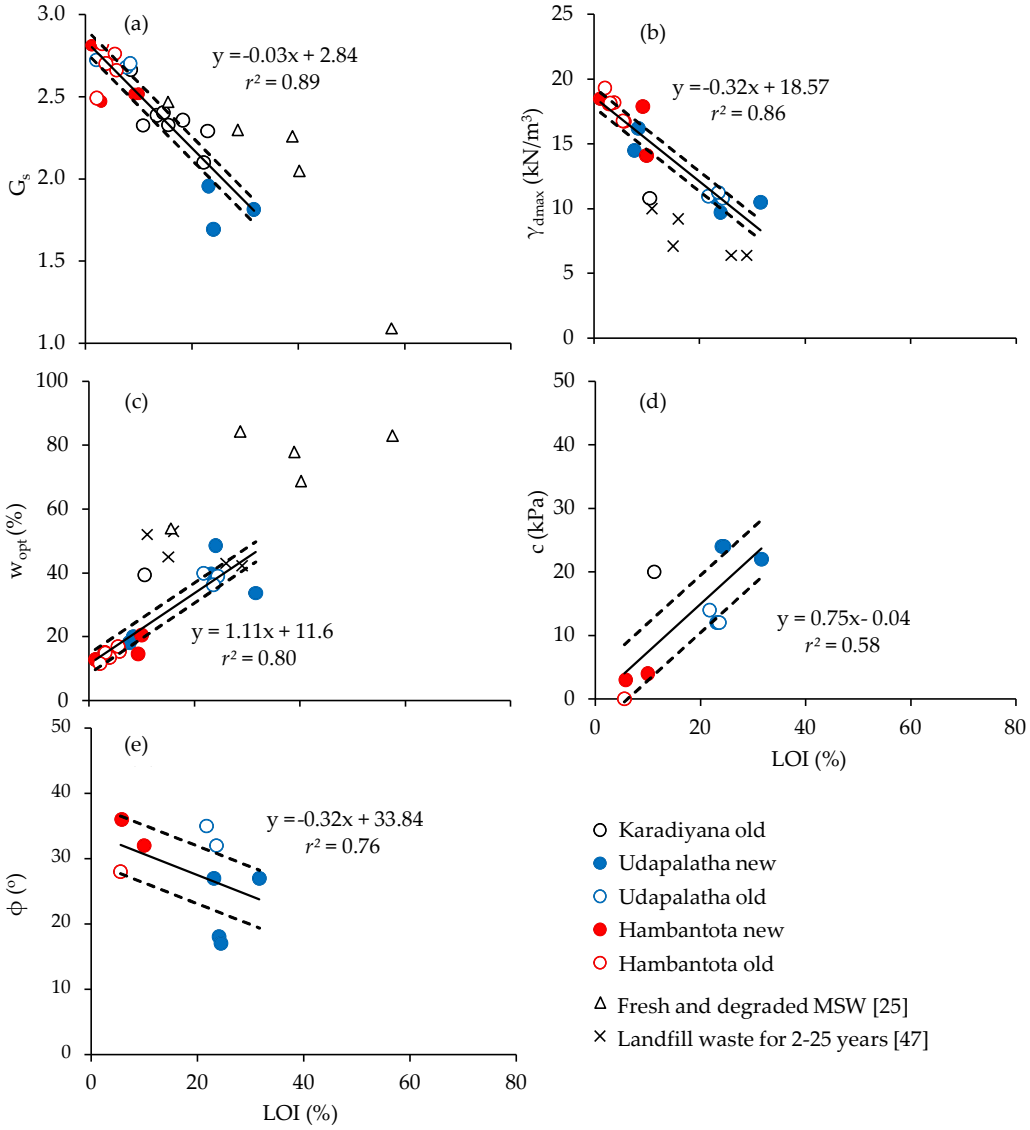


Figure 9. Relationships between LOI and (a) Gs, (b) γ_{dmax} (c) w_{opt}, (d) c , and (e) ϕ. Linear regression lines are given as solid lines, and 95% confidential intervals are given as broken lines.

4. Conclusions

This study aimed 1) to characterize the physicochemical and mechanical properties of dumped MSW taken from existing MSW dumping sites in three climate zones in Sri Lanka (Karadiyana site in the wet zone, Udapalatha in the intermediate zone, and Hambantota in the dry zone) with different periods after dumping [<3 years after being dumped (young) and >3 years after being dumped (old)] and 2) to examine the relationships among measured physicochemical parameters and mechanical parameters. The waste composition and biodegradation of organic materials (i.e., "age after dumping") affected the physicochemical properties of dumped waste. The biodegradation of organic materials also affected the compaction of dumped waste, and measured compaction parameters (γ_d and w_{opt}) from "old" sites at Udapalatha and Hambantota were higher compared to "new" sites. The waste composition also affected the compaction greatly, and the measured γ_d and w_{opt} from the Karadiyana site was relatively low even though the sample age was >20 years since dumping, probably due to higher amounts of hardly compacted materials such as "Plastic" and "Glass and wood" compared to others. In the results of direct shear tests, both strain hardening and softening were observed in the tested waste samples depending on the difference in vertical stress in this study. In addition, both volume expansion and reduction were observed in tested waste samples depending on the difference in waste composition. Based on the Pearson correlations among measured physicochemical parameters and mechanical parameters, LOI was a good indicator for quickly assessing mechanical parameters of the "fresh" and "old" waste materials in this study due to insignificant sensitivity of waste age and climate condition in Sri Lanka.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the information security conditions of the project.

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