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Assessment of the Geotechnical Properties of Municipal Solid Waste and Its Effect on the Surrounding Soil: A Review

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ABSTRACT

Due to rapid growing of population and active lifestyle, massive amounts of municipal solid waste (MSW) are produced worldwide. The MSW can harm the environment and threaten the land if the dumping sites are not managed scientifically. The geotechnical properties of MSW are the key parameters required in the landfill operations and waste management facilities. Hence, presence of the geotechnical properties data of the waste can assist engineers in selecting possible solutions for extension of the landfill and obtaining prior background data for the evaluation and design of landfills. MSW disposal changes the geotechnical properties of soil. Also, alterations in the geotechnical properties of soils may contribute to the physical and physico-chemical interactions between soil and contaminants of the dumping sites. As leachate, which is generated by the waste, penetrates into the soil, it moves pollutants into the soil and influences the strength and stability of the soil. The main objective of this research is to summarize the most recent literature of the physical and mechanical properties of MSW, and their influence on the geotechnical properties of soil. The findings of numerous investigations on the physical and mechanical characteristics of MSW and soil influenced by MSW are presented and discussed. Depending on the reviewed research studies, it can be observed that the engineering characteristics of MSW are complicated and varied for various reasons. The waste components and degradation process can cause an increase in moisture content and unit weight, and a decrease in organic content, hydraulic conductivity and compressibility of MSW. Additionally, MSW sites significantly impact the physical and mechanical characteristics of underlain and surrounding soil and deteriorate the soil quality. Further, it was noticed that the influence of dumping on soil is reduced with depth due to less interaction between the soil and waste.

1. Introduction

Municipal solid waste (MSW) is a form of solid waste material which can be found in the environment [1]. The MSW, typically referred to as "garbage," is an unavoidable by-product of human activity that is dumped [2]. The generation of solid waste is a normal issue due to human activities, and the quantity of generated solid waste is proportional with population growth [3–5]. MSW materials are rising at an exponential rate [1]. Every day, massive amounts of MSW are produced all over the world [6,7]. It is predicted that the quantity of garbage generated worldwide will rise from 12.7 billion tons in 2000 to around 19 billion tons in 2025 and around 27 billion tons in 2050 [8]. In most regions, the management systems of MSW are usually ranked third in municipal responsibilities after water supply and sanitation services [9]. However, one of the main environmental issues in cities is the

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disposal and management of MSW [9–13]. MSW is commonly thrown off in low-lying locations, such as open dumps in emerging countries or landfills in developed regions, without any safeguards or control mechanisms, resulting in soil and groundwater pollution [3,14,15]. While rain falls into interaction with solid waste, it generates leachate that eventually finds its way into water sources and soil layers [14–16]. Leachate is the liquid that has many negative effects on the soil, water, and the environment in general, and it is one of the most serious issues with landfills [16]. The majority of non-sanitary landfills were designed or built without an adequate leachate containment liner system. Thus, leachate can easily migrate and pollute the surrounding soil [14,16,17]. On the other hand, with dumping of the garbage immediately onto the land surface, a variety of pollutants, which include heavy metals such as lead, copper, mercury, and cadmium, were capable of penetrating quickly, polluting the soil [2,9,18]. This process may have a long-term impact on soil engineering characteristics [11,16]. Hence, the major environmental issue linked with waste disposal areas and improper landfilling of solid waste is the potential damage to the soil [2,9,19,20].

The stability of engineered landfill systems is influenced by the behavior of the municipality solid waste (MSW) [21]. For addressing several engineering issues in landfills, such as leachate seepage, cracking, and slope stability, it is necessary to evaluate the geotechnical characteristics of MSW. Composition, unit weight, hydraulic conductivity, and compressibility of MSW are all significant geotechnical characteristics for the design of landfills [6]. A lot of these issues in landfills have arisen as a result of the complex behavior and unknown geotechnical features of MSW [21]. Hence, evaluation of the geotechnical properties of MSW is a fundamental requirement for addressing engineering problems in landfills.

The age and type of the contaminants would impact the geotechnical characteristics of the soil well [22]. The studies performed by Raman & Sathiya Narayanan, [2], Ali et al., [9] Azeez et al., [10], Emeka et al., [11], Sharma et al., [14], Harun et al., [17], Thakur et al., [23], Sujatha et al., [24], Frempong & Yanful, [25], Nayak et al., [26], Mohammed et al., [27], Essienubong et al., [28] revealed that the physical and mechanical characteristics of contaminated soils were changed compared to the uncontaminated soils. Thus, assessing the impact of waste on soil engineering properties is an import issue and should be taken into consideration in the evaluation of the stability of landfill systems.

The main objective of this paper is to provide a comprehensive review of the MSW disposal sites, highlighting the behavior of MSW and their impact on the geotechnical properties of the surrounding soil. The physical properties of contaminated and natural soils, such as pH, organic content, specific gravity, and Atterberg limits, and the mechanical properties, such as compaction, hydraulic conductivity, shear strength, and CBR have been reviewed in detail.

2. Municipal solid waste (MSW) composition in disposal sites

MSW compositions vary based on its types and sources [14,23]. Food and garden wastes, plastics, paper products, textiles, rubber, wood, ashes, and soils are common MSW components [29,30]. The waste components include a variety of particle sizes, from small particles of soil to huge waste objects such as wastes of demolition (reinforced concrete and masonry). Lifestyle modifications, regulation, seasonal conditions, pre-treatment, and recycling operations all contribute to solid waste evolution over time. The proportion of waste components varies from a site to the next, as well as within a single site [31]. Thereby MSW components differ from country to country, for instance, waste streams of developed countries typically contain more biodegradable items and fewer plastics, whereas countries with pre-treatment plans and developed recycling (e.g., the utilization of mechanical and biologically pretreated waste) have waste streams with less biodegradable material and more consistent and coherent classifying. These variances in waste components result in essential and important disparities in assessing geotechnical characteristics of waste [6,29,32].

Machado et al., [21] evaluated MSW geotechnical characteristics in two Brazilian landfills (Bandeirantes Landfill and Metropolitan Center Landfill). They indicated that the average quantity of plastic waste in the two landfills was around 20%, which is a considerable amount. On the other hand, Sharma et al., [14] showed that the majority of the MSW produced from metropolitan areas in Himachal Pradesh, India, from Solan, Mandi, Sundernagar, and Baddi towns, was made up of organic waste. The organic waste percentage in these areas of Himachal Pradesh was 57.67% (Solan), 52.83% (Sundernagar), 56% (Mandi), and 50.83% (Baddi). Also, Thakur et al., [23] obtained high organic content in waste, 56.1%, which mostly consisted of food, kitchen and vegetable waste, and 10.3% of plastic waste. In addition, U. K. Singh et al., [8] indicated similar results, they showed high organic and earth material components, 72% and 13.40%, respectively. Table 1 shows the total MSW composition in landfill sites of the reviewed studies.

Table 1: Municipal Solid Waste (MSW) composition

Refs.	Landfill sites	MSW composition (%)											
		Organic waste	Paper	Plastic	Metal	Glass	Inert	Rubber	Textile	Paste	Wood	Rock & Ceramic	Earth material
[21]	Bandeirantes Landfill site		15.1	20.9	5.6	1			3.5	49.7	4.1	0.1	
	Metropolitan Center Landfill site		19.7	18.7	1.5	1.7			4.5	42.9	5.2	5.9	
[14]	Solan town site	57.67	17.17	6.33	1.67	3.33	5.67	2.67	5.33				
	Mandi town site	56	18.17	6.33	2.17	3.17	6	3.17	5.67				
	Sundernagar town site	52.83	20.83	6.67	2.17	3.17	6	3.17	5.17				
	Baddi town site	50.83	11.5	13.67	2	3.17	9	1.83	8				
[23]	Una town site, Himachal Pradesh, India	56.1	12.2	10.3	1.2	1.0	10.5			8.7			
[8]	Pirana landfill site	72	5.69	6.74	0.79	1.38							13.40

3. Assessed properties of municipal solid waste (MSW)

Studying the MSW geotechnical characteristics is fundamental for dealing with various engineering issues in landfills, including leachate seepage, slope stability, cracking, and settlement [6], it also has great impact on the waste management facilities. The strength properties and physical parameters of the MSW, which constitute the majority of a landfill, impact the general stability of landfill slopes. These elements play an essential role in interactions between the landfill structures and the waste mass, such as cover liner, leachate collecting method, and gas collecting method [21]. The MSW physical properties, such as organic content, moisture content, and unit weight, were generally studied in the literature. Further, MSW mechanical properties, including compressibility, hydraulic conductivity, and shear strength, were also researched in past investigations. Table 2 presents the physical and mechanical parameters of MSW found in studied literature.

Table 2: Physical and mechanical properties of MSW reported in literature

Refs.	Physical properties			Mechanical properties		
	Organic content	Moisture content	Unit weight	Hydraulic conductivity	Compressibility	Shear strength
[30]	✓	✓		✓		✓
[21]		✓	✓	✓		
[6]		✓	✓	✓		✓
[31]	✓			✓	✓	
[32]						✓
[33]				✓	✓	
[34]			✓	✓		
[35]	✓	✓	✓	✓		
[36]	✓				✓	
[37]	✓				✓	

4. Assessed properties of the soil affected by municipal solid waste (MSW)

Excessive intake of municipal household waste that has not been separated is likely to make physical and chemical alterations in soil. Consequently, interactions between biophysical and chemical soil activities may be distorted. Additionally, it could lead to the buildup of heavy metals and nitrates in the soil [9]. Organic matter can decrease bulk density while enhancing hydraulic conductivity and total porosity in heavy clay soils [38]. The soil liner integrity might be jeopardized by changes in its hydraulic properties, chemical composition, and mineralogical constituents, which could lead to contamination [25]. The previous studies examined the effect of MSW on the physical characteristics of soil, such as pH, organic content, specific gravity, and Atterberg limits. In addition, mechanical properties such as compaction, hydraulic conductivity, California Bearing Ratio (CBR), and shear strength were also investigated in literature. Table 3 presents the physical and mechanical parameters of a soil affected by MSW found in the reviewed literature.

Table 3: Conducted physical and mechanical properties of soil affected by MSW in literature

Refs.	Mechanical properties							
	pH	**Organic content**	**Specific gravity**	**Atterberg limits**	**Compaction**	**Hydraulic conductivity**	**CBR**	**Shear strength**
[11]	✓	✓						
[10]	✓	✓						
[25]	✓			✓		✓		
[19]					✓	✓		✓
[24]		✓	✓	✓	✓	✓		✓
[2]	✓							
[9]	✓	✓						
[23]			✓		✓	✓	✓	
[27]	✓	✓						
[14]			✓		✓	✓	✓	✓
[28]	✓			✓		✓		
[26]					✓	✓		
[17]				✓	✓			
[39]								✓

5. Review of geotechnical properties of municipal solid waste (MSW)

Table 4 presents physical and mechanical properties of MSW in literature, and they are discussed in the following subsections.

Table 4: Physical and mechanical properties of MSW presented in past studies

Refs.	**Physical properties**			**Mechanical properties**				
	Organic content (%)	**Moisture content (%)**	**Unit weight (kN/m^3)**	**Hydraulic conductivity (m/s)**	**Compressibility**		**Shear strength**	
					Primary compression	**Secondary compression**	**Cohesion (kPa)**	**Friction angle (◦)**
[30]	84.1-58.0	119-285 (Dry weight basis) 50-74 (Wet weight basis)					29 to 65	30 to 12
[21]		70-120 MCL (fresh MSW) 70-90 MCL (Aged) 45-110 BCL(Aged)	13 - 17.5	10^{-5} to 10^{-8}				
[6]		30-68.9	7.2 - 12.5 Depth (0-16) m				29.1 to 18.3 Depth (0-16) m	15.7 to 21.9 Depth (0-16) m
[31]	57.5-15.5			10^{-5} to 10^{-10}	0.34 to 0.15	0.015 to 0.011		
[32]							39 to 53	17 to 27
[33]					0.128 - 0.260	0.043 - 0.083		
[34]			3.9 – 5.1 (fresh MSW) 4.5 – 5.5 (Landfill MSW)					
[35]	51 to 64	93.9-145.1 (Dry weight basis)) 48.4-59.2 (Wet weight basis)	4.7 – 6.0	1.2 x 10^{-7} to 7.62 x 10^{-10}				

5.1 Physical properties of municipal solid waste (MSW)

5.1.1 Organic content

Engineering characteristics of MSW vary with waste degradation. MSW degradation can be known as the converting of organic matter in MSW into biogas. The MSW degradation occurs in five stages. Stage I is defined as aerobic stage due to the existence of oxygen, that is initially trapped in the voids. During this stage, which persists for a brief time, primarily nitrogen and carbon dioxide are generated. In stage I, no methane production is observed. Stage II is defined as transition stage, during which all of the oxygen is used by bacteria and carbon dioxide is produced. During stage III, short chain carboxylic acids, carbon dioxide, alcohols, and hydrogen are produced by acid-forming bacteria. During the stages IV and V, acetogenic and methanogenic bacteria generate methane either by converting acids into carbon dioxide and methane or by decreasing carbon dioxide with hydrogen. In this stage, methane concentration is between 50% to 60%, and the enormous amount of gas generated implies a high rate of methane generation [30,31,40]. Reddy et al., [30] studied influences of degradation on MSW geotechnical characteristics at Orchard Hills landfill, USA. The study revealed that organic content of fresh MSW was 84.1 %, which steadily reduced to 58.0 % in the highly degraded stage. It was also indicated that the percent reduction in organic content was 11, 12, 16, 17 and 31 % for degradation stages I, II, II, IV and V, respectively. Also, Reddy et al., [31] obtained the equivalent result, the organic content of fresh MSW was 57.5 %, and it subsequently decreased to 15.5 % after degradation stages. Figure 1 shows alteration of MSW organic content with degradation. Therefore, organic content reduces with the degradation of MSW.

Ramaiah et al., [36] investigated physical and mechanical characterizations of MSW from two dumpsites in Delhi, India. They reported that the total organic content (TOC) ranged from 15 % to 33 % and from 20 % to 29 % at the Okhla and Ghazipur dumpsites, respectively. Because of the existence of higher proportions of inert materials, such as soil-like and gravel-sized portions, and lower proportions of paper, plastics, textiles, rubber, and organic waste, the MSW TOC at these two landfills was comparatively low. In contrast, Chen et al., [37] indicated that the MSW organic content of a landfill in China reduced from 28 % to 16 %. This decrease in organic materials is caused by changing the depth for the top 10 m of fill, and the waste composition changes with depth. Therefore, MSW organic content is highly dependent on the MSW composition.

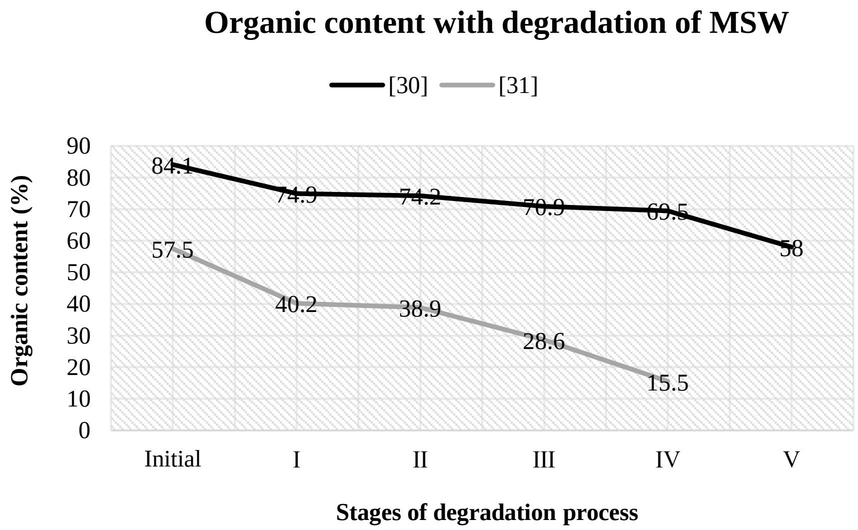

Figure 1. Variation of MSW organic content with degradation

5.1.2 Moisture content (MC)

The initial waste composition, regional meteorological conditions, operational circumstances, rate of decomposition, and organic content all affect the moisture content of waste [41]. Generally, the MSW moisture content increases with degradation of the waste [30]. Reddy et al., [30] indicated that MC of fresh MSW was 44 % on the basis of a dry weight based. Further, the MC of MSW during degradation process increased significantly from 100 to 285 % on dry weight based (proportion of the moisture mass to the dry MSW mass) or from 50 to 74 % on wet weight based (proportion of the moisture mass to the wet MSW mass). Because of particle disintegration, a rise in moisture content may also have increased MSW's field capacity. Machado et al., [21] evaluated geotechnical characteristics of MSW in two Brazilian landfills. They demonstrated that the MC of fresh MSW samples is distinctly higher than that of the aged waste. Thus, the MC of MSW decreases with age of the landfills. Feng et al., [6] mentioned that the MC of MSW at Laogang Landfill, China, ranged between 30.0 % and 68.9 %. The primary cause of low alteration in MC was the low range of MSW age. Also, Reddy, Hettiarachchi, Gangathulasi, et al., [35] investigated the geotechnical characteristics of synthetic MSW. Synthetic MSW consists of selected components in specific proportions. Most types of the components present in real waste can be utilized in the synthetic waste immediately [35,42,43]. Reddy, Hettiarachchi, Gangathulasi, et al., [35] revealed that the MC of synthetic MSW in the United States varied between 93.9-145.1 % on a dry weight based, similar to 48.4-59.2 % on a wet weight based. Figure 2 shows the MC of MSW in studied literature.

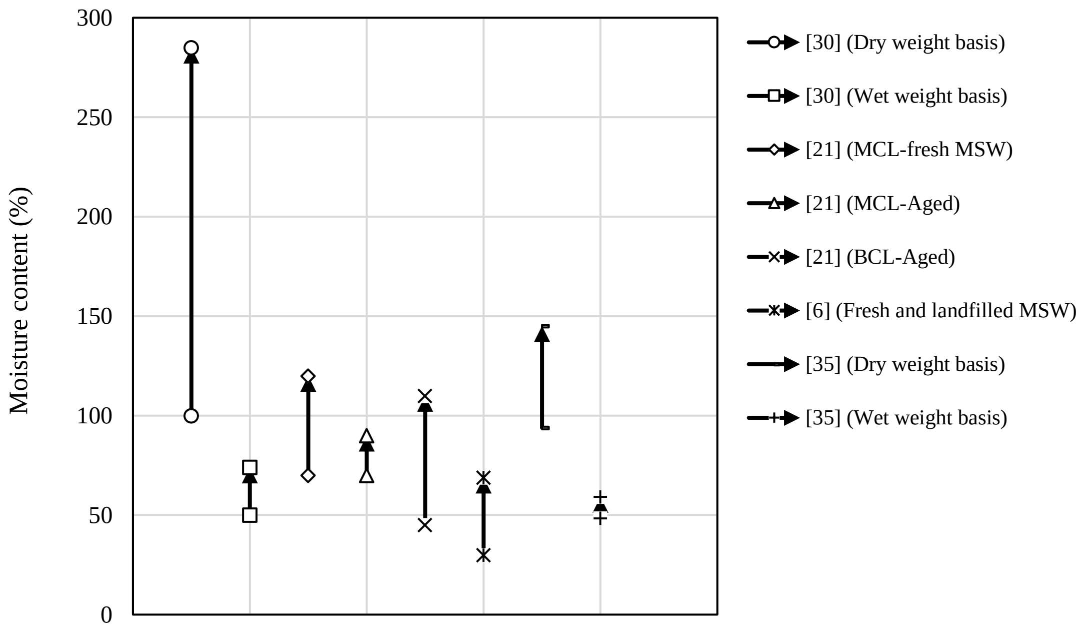

Figure 2. Moisture content of MSW in different landfills

5.1.3 Unit weight

Unit weight of MSW is an important factor in engineering evaluations of landfill operations [41,44]. Feng et al., [6] demonstrated that the total unit weight of MSW at Laogang Landfill in China changed in a small range between 7.2 to 12.5 kN/m^3. They noticed that the unit weight increased with the increase in depth from 0 to 16 m. Machado et al., [21] indicated the MSW unit weight in two landfills varied from 13 to 17.5 kN/m^3. Reddy, Hettiarachchi, Parakalla, et al., [34] studied that the dry unit weight of a fresh MSW changed in a small range which was 3.9 – 5.1 kN/m^3, and that of landfilled MSW varied between 4.5 – 5.5 kN/m^3. Also, Reddy, Hettiarachchi, Gangathulasi, et al., [35] found the equivalent result for dry unit weight of synthetic MSW in the United States that ranged between 4.7 to 6.0 kN/m^3. Generally, according to the reviewed studies, the important aspects that affect the MSW unit weight are waste composition and landfill operations techniques. [44].

5.2 Mechanical properties of municipal solid waste (MSW)

5.2.1 Hydraulic conductivity

Hydraulic conductivity of MSW materials is an essential factor for design of landfill systems. This parameter is significant because it affects the distributions of leachate pressure in the waste body [41]. Degradation due to variations in unit weight and particle size distribution has a substantial effect on hydraulic conductivity of MSW [31]. Machado et al., [21] revealed that the hydraulic conductivity of MSW varied from 10^{-5} to 10^{-8} m/s. Machado et al., [21] stated that this decrease in hydraulic conductivity was due to the rising depth and overburden stress. Reddy et al., [31] obtained consistent outcomes under various degradation levels. They observed that hydraulic conductivity reduced from 10^{-5} to 10^{-10} m/s from fresh MSW to highly degraded state. The degradation process was the cause of reduction in hydraulic conductivity. Degradation generated higher unit weight and more fines, leading to lower hydraulic conductivity of the degraded MSW. Also, Reddy, Hettiarachchi, Gangathulasi, et al., [35] indicated that hydraulic conductivity of synthetic MSW samples varied from 1.20×10^{-7} to 7.62×10^{-10} m/s that was lower than that of field MSW due to the presence of 40% fines in the synthetic MSW.

5.2.2 Compressibility

Compressibility parameter includes primary compression ratio and secondary compression ratio [30]. Durmusoglu et al., [33] investigated that values of MSW's primary compression ratio were within a comparatively small range (0.128–0.260). Consistently, values of MSW's secondary compression ratio were also within a small range (0.043–0.083). Generally, it was noticed that the compressibility of specimens with lower moisture contents was higher than that of specimens with higher moisture contents. Ramaiah et al., [36] obtained a similar result, and they revealed that the compression ratio of MSW at Okhla and Ghazipur dumpsites in Delhi, India, ranged between 0.11 and 0.17. The relatively low proportions of compressible constituents like paper, plastics, textiles combined with the comparatively high proportions of inert materials like soil-like and gravel-sized portions were the leading causes of the low compression ratio of MSW. Reddy et al., [31] found an inverse result, and they reported that compression ratio of synthetic MSW altered in range of 0.34–0.15. Therefore, when waste degraded, the compression ratio declined. Secondary compression ratio of synthetic MSW altered in range of 0.015 – 0.011. Reddy et al., [31] noticed a reduction in the secondary compression ratio with an increase in the MSW degradation. The secondary compression ratio exhibited similar trends to the primary compression ratio in its alteration with the level of degradation [31]. According to that research, degradation led to lower compressibility than fresh samples. In addition, Chen et al., [37] reported that the primary compression index of MSW reduced from 1.0 to 0.3 with an increase in depth from 0 to 37 m. MSW composition changed with embedment depth, which caused variations in compressibility. The MSW sample became denser and more homogeneous with depth, containing more cinder materials and less compressible elements, thus demonstrating lower compressibility.

5.2.3 Shear strength

One of the mechanical characteristics of MSW is shear strength parameters [36]. Reddy et al., [30] indicated that the friction angle of waste samples reduced from 30◦ to 12◦ for the initial and highly degraded stages. However, cohesion values did not present any consistent trend with degradation but ranged from 29 kPa to 65 kPa. Another study reported that the friction angle of MSW at Laogang Landfill, China changed from 15.7◦ to 21.9◦, and cohesion varied from 29.1 kPa to 18.3 kPa [6]. Furthermore, Vilar & Carvalho, [32] investigated the mechanical characteristics of MSW from Bandeirantes Sanitary Landfill in Brazil. They revealed that the friction angle of MSW ranged between 17° and 27°, and the cohesion ranged between 39 and 53 kPa.

6. Review of geotechnical properties of the soil beneath and surrounding municipal solid waste (MSW)

This section presents the research outcomes associated with the geotechnical characteristics of the soil influenced by MSW. The most important practical experiments for evaluating physical and mechanical properties of a soil affected by MSW are reviewed and discussed in detail.

6.1 Physical properties

6.1.1 pH

Soil pH is vital in regulating accumulation, bioavailability, and trace element mobility [27]. Ali et al., [9] investigated the physicochemical features of soil at the control and waste dumping sites in Islamabad city in Pakistan. They reported that the mean pH value at the control site was 8.65 whereas the mean pH value at the dump site was 8.75. The pH of dump sites was comparatively high compared to control sites. This high pH value at disposal sites is because the quantity of the dumped waste highly influences soil pH in open dump sites. High pH values cause heavy nutrients immobile, particularly in semi-arid ecosystems, which promote plant growth [9]. Mohammed et al., [27] indicated that the mean soil pH value at the waste disposal site of Halabja province, Kurdistan Region, Iraq, varied from 7.9 to 8.3. There was no discernible variation in the sampled points' pH values due to the soil's alkaline and calcareous nature of the soil in the area of the research (Halabja province). Also, Azeez et al., [10] studied the implications of soil heavy metal distributions in the MSW disposal scheme at Abeokuta in Southwestern Nigeria. They demonstrated that the soil pH value at the control site was 6.9 and 7.4 at the MSW disposal site. However, it was found that the soil pH value rises with the depth of the soil. The pH value of the soils at different depths varied from 8.39 in 0 – 0.2 m to 8.48 in 0.8 – 1 m depth. Frempong & Yanful, [25] studied the influence of MSW landfill leachate on geotechnical characteristics of three types of soil (K, A, and H), as described in Table 5. They obtained that the pH value of the soils K, A, and H in a natural condition were 6.9, 4.9, and 4.7, respectively, while the pH value of soils K, A, and H in MSW landfill leachate-permeated condition were 8.2, 7.2, and 7.3 respectively. It can be seen that soil pH value rises in MSW landfill leachate-permeated soil state.

On the other hand, in some other studies, it has been observed that soil pH value at dumping sites is less than that of control sites. For example, Emeka et al., [11] reported that the mean pH value of soil from the MSW dumpsite at Ugwuokwenu was 6.5 in the contaminated soil and 6.98 in the uncontaminated soil. This result shows that the pH of contaminated soil is more acidic than that of uncontaminated soil. Consequently, Raman & Sathiya Narayanan, [2] revealed that soil pH ranged between 6.3 to 7.0 at Pallavaram solid waste landfill site in Chennai. These observations are shown in Table 5. Thereby it can conclude that the MSW affects the pH values of the surrounding soil and that effect is based on the composition of the MSW.

Table 5: Impact of MSW on pH value of soil

Reference	Landfill site	Soil type	pH value	
			Natural soil	Contaminated soil
[9]	Dumping sites of Islamabad city	Sandy load at control site Loamy sand at disposal site	8.65	8.75
[27]	Waste disposal site in Halabja			7.9 – 8.3
[10]	MSW Dumpsite in Abeokuta, Nigeria		6.9	7.4
[25]	MSW landfill in Ghana, West Africa	Soil K (a grayish brown, silty clay with gravel traces, from a depth of 0.1– 0.3 m).	6.9	8.2
		Soil A (a yellowish brown, sandy silty clay, from a depth of 0.2 – 1.4 m).	4.9	7.2
		Soil H (a reddish brown, sandy clayey silt, from a depth of 0.8–1.6 m).	4.7	7.3
[11]	Dumpsite in Nnewi		6.98	6.5
[2]	Pallavaram solid waste dumpsite			6.3 – 7.0

6.1.2 Organic content

Mohammed et al., [27] evaluated the influence of waste disposal on the surrounding soil and water quality in Halabja province, Kurdistan Region, Iraq. The soil samples' organic content varied from 6.6 % to 11 %, with a mean of 9.2 %. The impact of MSW disposal on soil characteristics was the cause of the high organic content. Anikwe & Nwobodo, [18] reported a consistent result, and recorded high organic content in the dumpsite compared to the control site. Emeka et al., [11] indicated that the soil samples' organic content gathered from the dumpsite was an average of 17.85 % whereas that of the control samples gathered at different distances was an average of 2.92 %. Sujatha et al., [24] also demonstrated that the soil samples' organic content at the dumping site varied from 40.88 % to 60.17 % and that of the control sample gathered from a distance of 1 km was 23.84 %. Azeez et al., [10] also revealed that the soil samples' organic content at the dumpsite was 18.6 %, whereas that for the control samples was 8.1 %. Generally, these results infer that compared to the control samples, the soil beneath the dumpsite has a high organic content because of leachate seepage. On the other hand, Ali et al., [9] obtained inverse results, as shown in Table 6; they reported that the organic content of control site (1.64 %) was higher as compared to that of the disposal site (1.54 %) from Islamabad city in Pakistan because of more abundance of vegetation at the control site. Therefore, it can be concluded that MSW in open damping sites greatly affects the organic content of the surrounding soil.

Table 6: Impact of MSW on organic content of soil

Reference	Landfill site	Soil type	Organic content (%)	
			Natural soil	Contaminated soil
[27]	Waste disposal site in Halabja			9.2
[11]	Dumpsite in Nnewi		2.92	17.85
[24]	MSW dumping yard in Ariyamangalam, Trichy, India		23.84	40.88 to 60.17
[10]	MSW Dumpsite in Abeokuta, Nigeria		8.1	18.6
[9]	Dumping sites of Islamabad city	Sandy loam at control site Loamy sand at disposal site	1.64	1.54

6.1.3 Specific gravity

Specific gravity is a significant property since it contributes to the computation of other soil-related characteristics [11]. Thakur et al., [23] demonstrated that specific gravity of contaminated soil in a non-engineered landfill site in India ranged from 1.95 to 2.08 that increased with depth while specific gravity for natural soil to be 2.46. Because the dumping effect tends to diminish with depth, soil-specific gravity increases. Thus, it can be observed that contaminated soil has the lowest specific gravity when compared to uncontaminated soil [23]. Additionally, Sujatha et al., [24] studied that the dumpsite samples' specific gravity in Ariyamangalam, Trichy, India varied between 1.84-2.38 and that of control sample was 2.65. Soil specific gravity in the dumpsite was comparatively low and highly discrete due to higher organic content as compared to the control sample. Another study was presented by Sharma et al., [14] on the influence of open dumping of MSW on soil properties in four towns of Himachal Pradesh in India. They indicated that specific gravity of soil at the four town dumpsites ranged from 1.19 to 2.24 at 0.5-1.5 m depth, while specific gravity of soil at non-dump sites ranged between 2.55 and 2.57. Thus, it reveals that waste components negatively influence soil-specific gravity. The findings of the studies mentioned above are presented in Table 7.

Table 7: Impact of MSW on specific gravity of soil

Reference	Landfill site	Specific gravity		
		Natural soil	Contaminated soil	
			Depth (m)	SG
[23]	Non-engineered landfill site in Una Town in India	2.46		1.95-2.08
[24]	MSW dumping site in Ariyamangalam, Trichy, India	2.22		2.145
[14]	Baddi town dumpsite in Himachal Pradesh, India	2.57	0.5	2
			1	2.2
			1.5	2.24
	Mandi town dumpsite in Himachal Pradesh, India	2.56	0.5	2
			1	2
			1.5	2.1
	Sundernagar town dumpsite in Himachal Pradesh, India	2.55	0.5	2
			1	2.1
			1.5	2.1
	Solan town dumpsite in Himachal Pradesh, India	2.56	0.5	1.19
			1	2
			1.5	2.1

6.1.4 Atterberg limits

Harun et al., [17] evaluated the influences of leachate on Atterberg limit parameters of sandy clay soil. They observed that the reduction in liquid limit and plastic limit values with an increase in leachate content revealed the influences of leachate on Atterberg limit. Liquid limit of leachate-contaminated soil reduced from 59.7 % to 40.5 % by increasing leachate contents between 0 % and 20 %. When the leachate content was increased, a consistent trend was presented to the plastic limit. The variations in reduction in liquid limit were higher than plastic limit. Plasticity index reduced from 18.4 % to 6.54 % with increased leachate contents. Frempong & Yanful, [25] also found a similar result, and indicated that permeation with leachate of the landfill did not cause to essential variations in soils' plastic limit. In contrary, the soils' liquid limit and plasticity index reduced, with the most significant reduction of 17 %. Inverse results were obtained in some other past investigations. For instance, Sujatha et al., [24] evaluated impact of MSW dumping on soil characteristics in Ariyamangalam, Trichy, India. The dumpsite samples' liquid limit ranged between 20 % and 30 %, with an average of 25.5 %. Liquid limit of control sample was 15 % presenting less compressibility than those obtained from dumpsite. The dumpsite samples' plastic limit ranged between 13.4 % and 18.3 % with an average of 16.4 % whereas the plastic limit of control sample was 25 %. Plasticity index also presented a consistent trend, dumpsite samples' plasticity index ranged between 3.33 % and 13.4 % with an average of 9.01 % whereas the plasticity index of control sample was 10 %. The control sample was low plastic, whereas samples obtained from the dumpsite fell in moderate plastic range. This result showed that dumping has increased the soil plasticity. These findings are shown in Table 8.

Table 8: Impact of MSW on Atterberg limit parameters of soil

Reference	**Landfill site**	**Soil type**		**Atterberg limits**					
				Natural soil			**Contaminated soil**		
				LL (%)	**PL (%)**	**PI (%)**	**LL (%)**	**PL (%)**	**PI (%)**
[17]		Sandy clay soil		59.7	41.3	18.4	40.5	33.96	6.54
[25]	MSW landfill in Ghana, West Africa	Inorganic clays of high plasticity (CH)	Soil K	87		61	70		44
			Soil A	54		26	50		24
			Soil H	56		30	54		28
[24]	MSW dumping site in Ariyamangalam, Trichy, India	Silty sand (SM)		15	25	10	25.5	16.4	9.01

6.2 Mechanical properties

6.2.1 Compaction characteristics

The compaction test presents a relationship between dry density and moisture content of soil. Nayak et al., [26] studied determining the compaction characteristics of clean and contaminated soil from dumpsites on the southwest coast of India. They demonstrated that the MDD of soil was 15.47 kN/m^3 at OMC of 19.52 %. With 10 % leachate, MDD and OMC became 14.98 kN/m^3 and 25.01 %. Furthermore, with 20 % leachate, the MDD reduced gradually. Also, the same result was obtained by Thakur et al., [23]. The research findings presented that MDD reduced from 17.18 kN/m^3 to 16.5 kN/m^3 and OMC increased from 15.8 % to 17.5 % for contaminated soil compared to natural soil, which MDD was 17.1 kN/m^3 and OMC was 15.7 %. This decrease in MDD was because of the degradation of organic materials available in waste. Harun et al., [17] also performed an investigation on the leachate influences on compaction characteristics of leachate-contaminated soil, and observed similar results.

Moreover, Sujatha et al., [24] studied the effect of MSW dumping on soil geotechnical characteristics in Ariyamangalam, Trichy, India, and obtained that the MDD of the MSW dumpsite samples varied from 17.5 kN/m^3 to 19.5 kN/m^3 and OMC varied from 14.28 % to 16.66 % while MDD of control sample was 19.8 kN/m^3 and OMC was 13.95 %. Also, Sharma et al., [14] investigated the influence of open dumping of MSW on soil properties in four dumpsites. It was noticed that soil collected at 0.5 m depth in the dumping sites presented lower values of MDD compared to soil collected at 1.5 m depth. The soil MDD for all four dumpsites ranged from 17.8 kN/m^3 to 18.7 kN/m^3, whereas it varied from 21 kN/m^3 to 22 kN/m^3 for the natural soil. Thus, the dumpsite soils presented a smaller dry density. In addition, the OMC of the dumpsite soils was also higher compared to the natural soil. These indications are presented in Table 9, as shown below.

Table 9: Impact of MSW on compaction characteristics of soil

Reference	Landfill site	Soil type	Compaction characteristics					
			Natural soil			Contaminated soil		
			Depth (m)	MDD (kN/m3)	OMC (%)	Depth (m)	MDD (kN/m3)	OMC (%)
[26]	Dumpsites in the southwest coast of India	Lateritic soil		15.47	19.52		14.98	25.01
[23]	Non-engineered landfill site in India	Sandy soil	0.5-1.5	17.1	15.7	0.5-1.5	16.5 to 17.18	17.5 to 15.8
[17]	MSW dumping site in Ariyamangalam, Trichy, India	Sandy clay soil		16.75	14		14.70	23
[24]				19.8	13.95		17.5 to 19.5	14.28 to 16.66
[14]	Baddi town dumpsite in Himachal Pradesh, India			22	12	0.5	17.8	12
						1	18.5	12
						1.5	18.7	12
	Mandi town dumpsite in Himachal Pradesh, India			21	13	0.5	17.8	13.5
						1	17.9	13
						1.5	18.7	13
	Sundernagar town dumpsite in Himachal Pradesh, India			22	13	0.5	18.4	10.5
						1	18.6	10
						1.5	18.4	10
	Solan town dumpsite in Himachal Pradesh, India			22	12	0.5	17.8	12
						1	18.5	12
						1.5	18.7	12

6.2.2 Hydraulic conductivity

Hydraulic conductivity defines the capability of a porous medium to convey a particular fluid, and it depends on both the medium and the fluid [45]. Emeka et al., [11] revealed that the natural soil had greater hydraulic conductivity than that of contaminated soil. This outcome was due to a greater proportion of sand in the natural soil in the study. Their findings agree that the contaminated soil, which has fewer fine soil particles, is loosely arranged, making the soil more permeable. Sujatha et al., [24] reported the equivalent results. The research reported that the hydraulic conductivity of contaminated samples varied from 2.11 x 10^{-7} m/s to 3.15 x 10^{-7} m/s and that of natural soil was 4.44 x 10^{-6} m/s. There was a markable reduction in hydraulic conductivity of contaminated soil compared to natural soil. Also, Frempong & Yanful, [25] revealed a reduction in soil's hydraulic conductivity with leachate permeating into the soil. Additionally, Thakur et al., [23] demonstrated that the hydraulic conductivity of contaminated soil was less when compared to natural soil. Hydraulic conductivity of dumpsite soil changed with depth from 2.57 x 10^{-7} to 2.32 x 10^{-6} m/s for contaminated soil and 5.8 x 10^{-6} to 6.7 x 10^{-6} m/s for natural soil. The alteration in hydraulic conductivity could be because of the accretion of heavy metals that migrate with leachate through soil [24]. These heavy metals, which sedimented in soil matrix, restrict water movement through soil, reducing soil hydraulic conductivity [23]. Essienubong et al., [28] also indicated that the soil sample gathered from each of the Uselu Market and New Benin dumpsites presented lower hydraulic conductivity than the samples collected away from the dumpsites. This outcome might be because of clogging impact by organic waste that could happen because of the biological material build-up and growth of microorganisms during waste degradation. Most of the time, clogging leads to very low hydraulic conductivity because of interactions with leachate. Leachate can impair drainage layer of the underlying soil by oversaturating soil pore spaces due to the biological waste materials and microorganism buildup in the waste stream.

Some researchers reported different results. For instance, Sharma et al., [14] evaluated the influence of open dumping of MSW on soil properties. They reported that hydraulic conductivity of contaminated soils, between 3.2×10^{-5} and 4×10^{-5} m/s, was higher than that of the natural soil, which varied from 3.2×10^{-6} m/s to 4×10^{-6} m/s. Nayak et al., [26] also investigated that increasing of leachate content increased soil's hydraulic conductivity, as shown in Table 10. This increase in soil's hydraulic conductivity was because of chemical interaction between clay particles and leachate [26].

Table 10: Impact of MSW on hydraulic conductivity of soil

Reference	Landfill site	Soil type	Hydraulic conductivity results			
			Natural soil		Contaminated soil	
			Depth (m)	Hydraulic conductivity (m/s)	Depth (m)	Hydraulic conductivity (m/s)
[11]	Dumpsite in Nnewi			0.89		0.072
[24]	MSW dumping site in Ariyamangalam, Trichy, India			4.44×10^{-6}		2.11×10^{-7} to 3.15×10^{-7}
[25]	MSW landfill in Ghana, West Africa	Soil K		1.6×10^{-14}		9.5×10^{-15}
		Soil A		7.8×10^{-13}		9.0×10^{-13}
		Soil H		4.7×10^{-13}		3.1×10^{-13}
[23]	Non-engineered landfill site in India		0.5-1.5	5.8×10^{-6} – 6.7×10^{-6}	0.5-1.5	2.57×10^{-7} – 2.32×10^{-6}
[28]	Uselu Market Dumpsite			2.42×10^{-5}		1.0×10^{-8}
	New Benin Dumpsite			2.14×10^{-4}		1.45×10^{-8}
[14]	Baddi town dumpsite in Himachal Pradesh, India			3.0×10^{-6}	0.5	3.4×10^{-5}
					1	3.2×10^{-5}
					1.5	2.7×10^{-5}
	Mandi town dumpsite in			3.16×10^{-6}	0.5	3.8×10^{-5}
					1	3.1×10^{-5}
					1.5	2.7×10^{-5}

	Himachal Pradesh, India				
	Sundernagar town dumpsite in Himachal Pradesh, India		4 x 10^{-6}	0.5	3.6 x 10^{-5}
				1	3 x 10^{-5}
				1.5	3.2 x 10^{-5}
	Solan town dumpsite in Himachal Pradesh, India		3 x 10^{-6}	0.5	4 x 10^{-5}
				1	3.4 x 10^{-5}
				1.5	2 x 10^{-5}
[26]	Dumpsites in the southwest coast of India	Lateritic soil	3.06 x 10^{-7}		5.79 x 10^{-7}

6.2.3 California Bearing Ratio (CBR)

Thakur et al., [23] studied the influence of MSW dumping on the soil engineering features from a non-engineered landfill site. They indicated that CBR value of dumpsite soil changed in the range of 4.63 % to 5.62 % for the unsoaked condition and 1.52 % to 2.07 % for the soaked condition. The CBR value of natural soil ranged from 5.45 % to 5.81 % for unsoaked condition and 1.77 % to 2.03 % for soaked condition. Compared with natural soil, CBR value of the dumpsite soil is reduced by 12 % to 17 % and 20 % to 25 % for unsoaked and soaked conditions, respectively. Similar outcomes were noticed by Sharma et al., [14]. They reported that the dumpsite soils presented a smaller CBR value than the natural soil. CBR value of dump soil changed in the ranges of 12.3 % to 16.8 % in the unsoaked condition and 4 % to 5 % in the soaked condition, while for natural soil, the value is 18 % (unsoaked) and 6 % (soaked), respectively. Compared to the natural soil, CBR value of dump soils in unsoaked and soaked conditions reduced by 19.16 % and 25 %, respectively, which presents that for CBR experiments in both states, natural soil has more strength than contaminated soil. This change might be due to organic matter decomposition and leachate percolation through voids into the soil, that alters the soil engineering characteristics. These findings of CBR tests (unsoaked and soaked conditions) are shown in Table 11 and Figure (3,4).

Table 11: Impact of MSW on CBR of soil

Reference	**Landfill site**	**CBR value**					
		Natural soil			**Contaminated soil**		
		Depth (m)	**CBR (unsoaked)**	**CBR (soaked)**	**Depth (m)**	**CBR (unsoaked)**	**CBR (soaked)**
[23]	Non-engineered landfill site in India	0.5-1.5	5.45-5.81	1.77-2.03	0.5-1.5	4.63-5.62	1.52-2.07
[14]	Baddi town dumpsite in Himachal Pradesh, India		17.5	5.9	0.5	12.34	4.52
					1	16.69	5.35
					1.5	17.42	6.7
			18.44	6.42	0.5	16.71	5.7

	Mandi town dumpsite in Himachal Pradesh, India			1	16.78	5.8
				1.5	17.12	6.13
	Sundernagar town dumpsite in Himachal Pradesh, India	17.51	7.2	0.5	16.13	4.52
				1	16.2	4.9
				1.5	16.8	6.5
	Solan town dumpsite in Himachal Pradesh, India	17.88	6.2	0.5	12.34	4.52
				1	16.69	5.35
				1.5	17.42	5.9

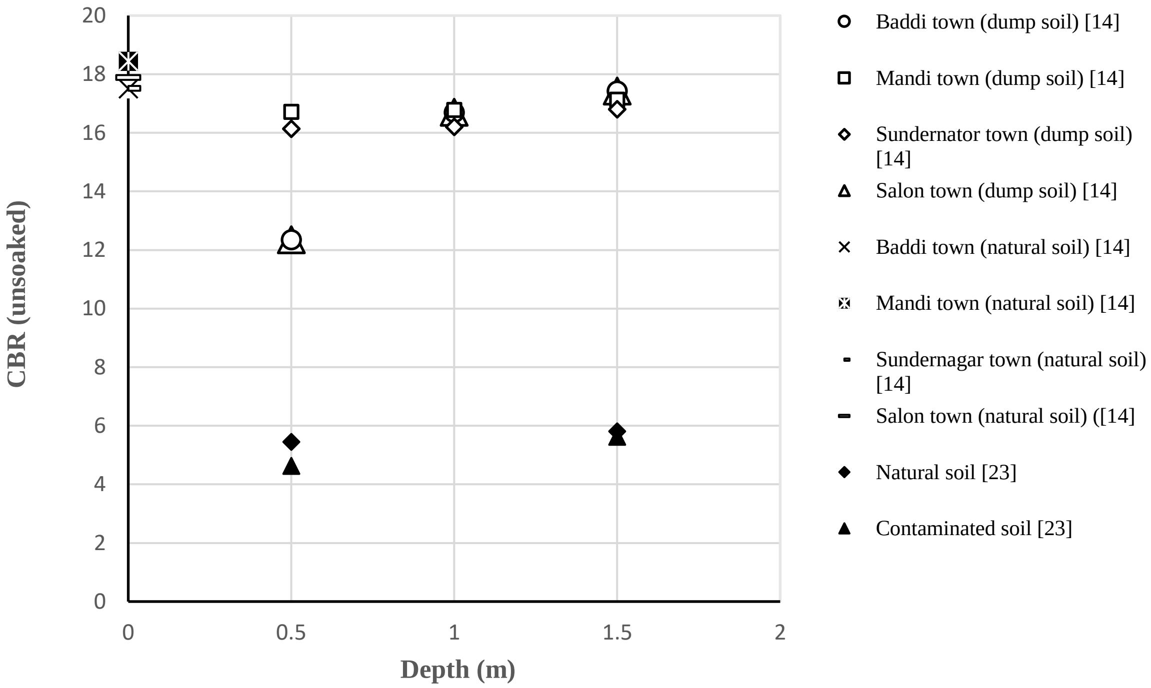

Figure 3. CBR values of soil (unsoaked condition)

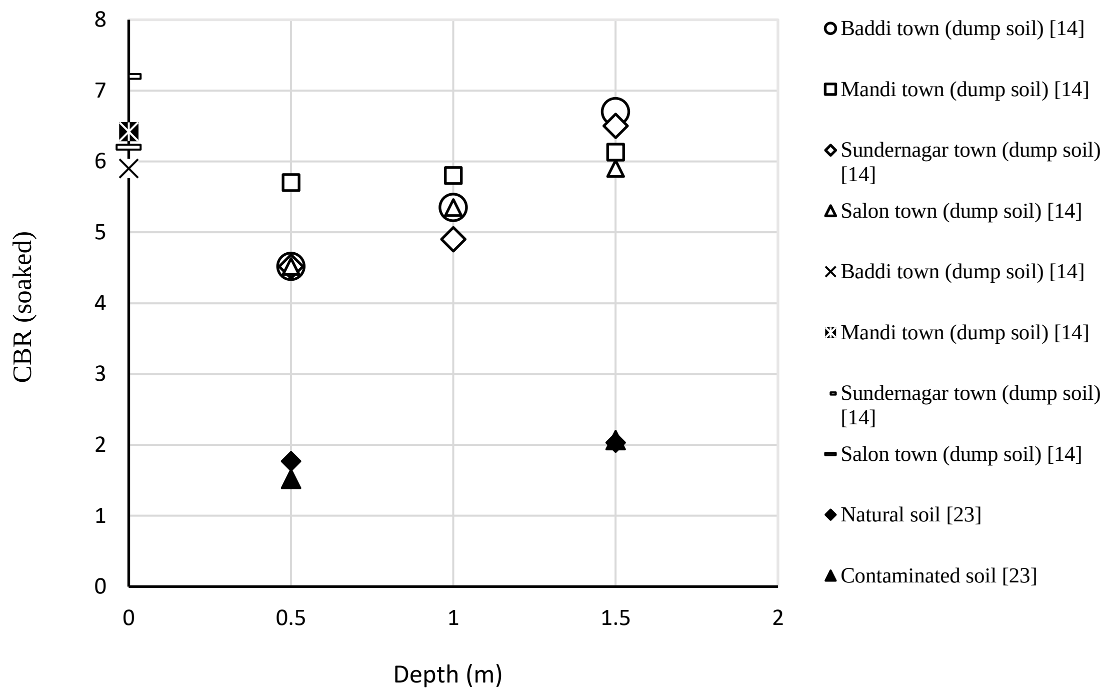

Figure 4. CBR values of soil (soaked condition)

6.2.4 Shear strength

Evaluation of the strength parameters is essential for determining the stability of landfills [24]. Sujatha et al., [24] observed that the cohesion of the dumping site samples varied from 25 kPa to 75 kPa and that of the control sample was 15 kPa. The internal friction angle of samples collected from dumping site varied between 11˚ and 30˚ and that of control sample was 38˚. The internal friction angle of soil sample obtained from the site (i.e., the Ariyamangalam dumpsite) was lower than that for the control sample collected outside MSW dumpsite. However, the cohesion of the dumpsite samples was also greater than that of the control sample. Sunil et al., [39] indicated a similar result; they found a slight increase in the cohesion of contaminated soil from 18.46 to 20.22 kPa with 20 % of leachate and a decrease in internal friction angle from 30.4° to 25.8°. The increase in cohesion and reduction in internal friction angle in the above studies was because of an increase in clay particles in the soil after interacting with leachate. Therefore, it could be indicated that the shear strength parameters are substantially changed due to the impact of dumping. There is an increase in cohesion and a reduction in internal friction angle, demonstrating the increase in the plasticity of soils. However, Sharma et al., [14] presented low cohesion values and internal friction angle of dumpsite soils, which indicate less shear strength compared to natural soil. According to this study, contaminated soil has decomposing organic material continually. Hence, shear strength of contaminated soil reduces compared to soil collected from the natural site. These indications are shown in Table 12.

Table 12: Impact of MSW on shear strength parameters of soil

Reference	Landfill site	Shear strength parameters					
		Natural soil			Contaminated soil		
		Depth (m)	Cohesion (kN/m²)	Friction angle (°)	Depth (m)	Cohesion (kPa)	Friction angle (°)
[24]	MSW dumpsite in Ariyamangalam, Trichy, India	0.5-1.5	15	38	0.5-1.5	25 to 75	11 to 30
[39]			17.4 to 19.1	31 to 30		18.46 to 20.22	30.4 to 25.8
[14]	Baddi town dumpsite in Himachal Pradesh, India		6	34.9	0.5	1.67	35.79
					1	2.67	35.75
					1.5	3	34.6
	Mandi town dumpsite in Himachal Pradesh, India		4.33	34.22	0.5	1	36.12
					1	2	35.37
					1.5	3.33	34.21
	Sundernagar town dumpsite in Himachal Pradesh, India		5	35.7	0.5	1.33	34.21
					1	3.33	32.62
					1.5	1.67	34.21
	Solan town dumpsite in Himachal Pradesh, India		6	34.99	0.5	1.67	35.79
					1	2.67	35.75
					1.5	3	34.6

7. Conclusion

The main aim of this article was to review the literature on the geotechnical properties of municipal solid waste (MSW) and effect of MSW disposal sites on the geotechnical properties of underlain and surrounding soil, which presented the following conclusions:

1. Due to the existence of the extensive diversity of materials and the impact of waste structure, assessing the engineering characteristics and consequently the behavior of MSW is extremely difficult. The waste components and degradation levels of MSW materials caused an increase in moisture content and unit weight, and a decrease in organic content, hydraulic conductivity and compressibility of the MSW.
2. The composition of MSW changes with embedment depth. MSW sample becomes denser and more homogeneous with depth, containing more inert materials and less compressible elements, thus demonstrating lower compressibility.
3. Degradation generates higher unit weight and more fines, which leads to the lower hydraulic conductivity of

degraded MSW, especially in deeper layers.

4. The quantity of the dumpsite, the seepage of landfill leachate through the soil, the evaporation of moisture from the contaminated soil, and the degradation of organic materials available in waste all influence the geotechnical properties of soil. So, variations in MSW components significantly impact the waste's engineering properties and can change the geotechnical properties of underlying and surrounding soil.
5. MSW causes an increase in pH and organic content and a decrease in the specific gravity, LL, and PI of the soil.
6. MSW causes an increase in OMC and a decrease in MDD, internal friction angle, hydraulic conductivity, and CBR values of the soil from the dumping sites.
7. The impact of dumping on soil is reduced with depth due to less interaction with waste.
8. The MSW substantially influences the physical and mechanical properties of soil. However, further investigations are necessary to evaluate the observed variations associated with geotechnical features of soil influenced by MSW

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List of Symbols and Abbreviations

Symbol and Abbreviation	Full Name of Symbols and Abbreviations
MSW	Municipal Solid Waste
TOC	Total Organic Content
MC	Moisture Content
LL	Liquid Limit
PL	Plastic Limit
PI	Plasticity Index
MDD	Maximum Dry Density
OMC	Optimum Moisture Content
CBR	California Bearing Ratio