

Review

A Review of Characteristics of Landfilled Municipal Solid Waste in Several Countries: Physical Composition, Unit Weight, and Permeability Coefficient

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Abstract

The characteristics of landfilled municipal solid waste have great influence on the design, operation, and management of landfills, affecting settlement, slope stability, and leachate/gas well integrity. Through analysis and study we observed that the landfill method is widely used to dispose of municipal solid waste (MSW), especially in developing countries. The research results of MSW landfill properties are different due to waste inhomogeneity. In this paper, MSW physical composition, unit weight, and permeability coefficient of landfills in several countries were reviewed and discussed. Landfilled MSW has strong regional and temporal characteristics. Landfilled MSW of developing countries has high organic content ranges from 75.00% to 97.15%. The organic contents in landfills of most developed regions are relatively small. The unit weight ranged from 4.9-17.8 kN/m³ and the permeability coefficient ranged from 3.5×10^{-2} cm/sec to 5.0×10^{-8} cm/sec within 60 m. In the process of waste degradation, MSW physical composition, unit weight, and permeability coefficient are changed. Waste classification improves the recovery and utilization of landfill and reduces the amount of waste, which affects the characteristics of landfilled MSW. Thus, strengthening waste classification, recycling, and recovery of MSW is significant and meaningful for construction, operation, and management of landfills.

Keywords: municipal solid waste, MSW disposal method, physical composition, unit weight, permeability coefficient

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Introduction

Municipal solid waste (MSW) mainly includes food and fruit, wood, paper, textiles, plastics, and dust. MSW landfills are made up of MSW formed by layer compaction. With the improvement of economic levels and the increase in urban populations, the production of MSW has increased sharply. In the middle of the 18th century, only 3% of the world’s population lived in the city; in 1950, the proportion of the urban population accounted for 29%; in 1985, the population increased up to 41%; and in 2025, 60% of the world’s population will live in or around cities. According to statistics, the domestic waste production of China increased at a rate of about 9% per year. Waste production increased from 52 million tons in 1986 to 166 million tons in 1996. In the first 50 years of the 21st century, the sustainable urban development in China faced a grim challenge in which the growth rate of MSW production reached peak with the increase of China’s population growth and urbanization level [1-2].

MSW Disposal Methods

The disposal techniques of MSW mainly include 3 kinds of methods: incineration, composting, and landfilling [3-5]. Incineration is often used in developed countries. It has high efficiency in waste disposal. The heat generated by burning can be used to produce electricity and requires a small land area. However, the method presents some difficulties such as large investment and high technical content, and the unclassified collection of waste is a problem for developing countries. Although composting is a good reductive and regenerative MSW disposal method, the high cost, high technical content, and collection of waste is not classified – especially in developing countries. The sanitary landfill method is the most popular waste treatment technology in the world because of its high handing capacity, decreased investment, and low technical content. However, it occupies a large land area and is not effective in reducing waste. Recycling is also a method for disposing of MSW.

Recycling of MSW at the source can reduce the amount of MSW directly disposed by half [6].

Fig. 1 presents the MSW disposal methods in different countries or cities. Others include recycling, untreated, and unclear methods.

Developing countries such as India and China use landfill technology to deal with MSW, as shown in Fig. 1. The landfill method accounted for as much as 91%, and incineration is rarely used by these countries. In India, open dumping of the landfill method is mainly used to dispose of MSW, and it easily caused serious environmental and economic problems [14-20]. In addition to the use of the landfill method, incineration also occupied a very important position in developed countries. The use of incineration is a good choice, especially in Japan, given its small land area requirement. There are some slightly developed countries or cities, such as Denmark, Singapore, and Macao, that use the incineration method. Although the use of incineration technology to deal with MSW is up to 83%, landfill technology is less used. Through analysis, one reason is their small land areas. Nepal is primarily an agricultural country and mainly uses the composting method to deal with MSW. But of course there are exceptions. Waste disposal policy is still an important factor. For instance, Germany was disposing of 69% MSW in landfills in 1993, but this method was banned in 2005.

Based on the above data and analysis, the choice for the main MSW disposal method for a country or a city is mainly based on waste management strategy, economic development, land area, population, and waste classification. Moreover, the main economic source of a country or a city and the technology used for MSW disposal have certain influence on the disposal method.

Landfill technology can deal with almost all the waste in a city and the cost is low relative to other methods [21]. The method was widely used by various countries to deal with MSW, and it was the major disposal method for a long time [22-23]. With the rapid increase of urban population and the rapid development of industry, landfill as the main MSW disposal method gradually tended to

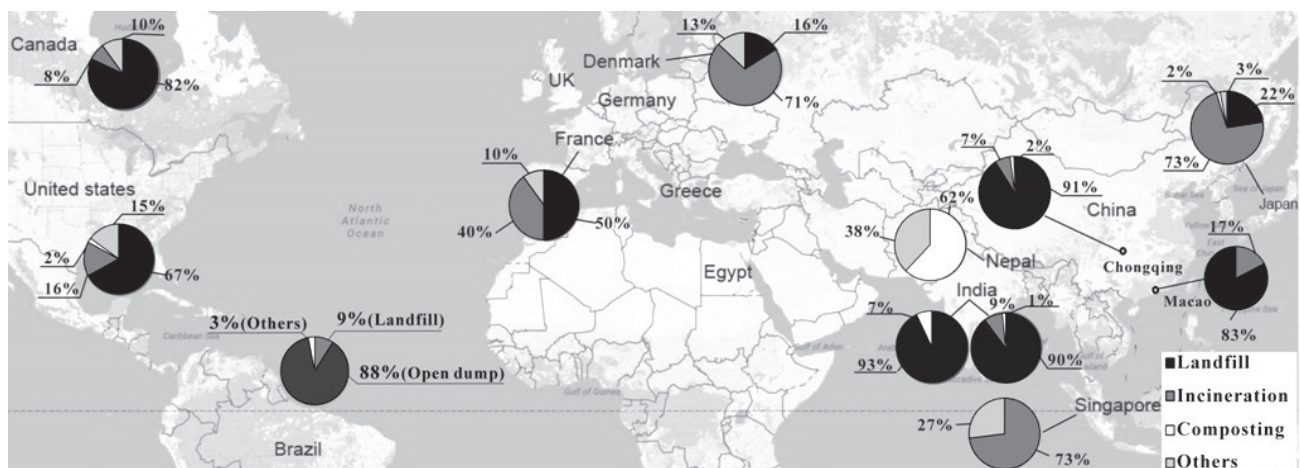


Fig.1. Statistics of MSW disposal methods [7-13].

Table 1. Statistics of failure in various landfills.

MSW Landfill	Year	Accident description	Consequences	Reasons
Landfill in Bandung, Indonesia [24]	2005	Waste pile collapse	2.7 million m ³ of solid waste went down and 147 people were killed	High pore pressures
Chongqing Shapingba Landfill, China [25]	2002	Landslide	About 0.4 million m ³ of solid waste slumped, the 3-layer dormitory of gravel factory mountain was swallowed and 10 people were killed	The composition of waste and heavy rain
Payatas Landfill, Philippines [26]	2000	Landslide	About 278 people were killed and more than 100 people went missing	Uncompacted significant waste and continuous heavy rain
Dona Juana Landfill, Columbia [27]	1997	Waste slope failure	About 1.2 million m ³ of solid waste with a large amount of leachate rapidly slumped in 20 min, rushed out for 1.5 km, and caused serious environmental pollution	High leachate level due to leachate recirculation
The former Yugoslavia, Sarajevo MSW Landfill [28]	1977	Waste pile collapse	2 bridges, 5 houses, and 2 small rivers were completely submerged	

develop in high piles and large capacities. Thus, landfill stabilization problem pose a serious threat to people's life and property safety [2].

How Important and Urgent is it to Study Landfilled MSW Characteristics?

Physical composition, unit weight, and permeability coefficient of MSW are important parameters affecting the stability of a landfill. Several experts have researched these aspects by model test or numerical analysis. So far, no uniform or more mature understanding in engineering characteristic parameters has been drawn all over the world, owing to the complexity of physical composition and degradation. Table 1 shows the statistics of the failure of landfills.

Based on the investigation and research of the above literature, several causes that led to landfill failures were the following:

- 1) Excessively high leachate levels occurring in the landfill due to heavy rain, leachate recirculation, or more waste water content, which caused landslides. The leachate level of MSW landfill was influenced by rain, MSW physical composition, compaction, permeability coefficient, drainage systems, and so on.
- 2) The waste composition and compaction degree had direct influence on the strength characteristics and permeability coefficients of the landfill, which led to the destruction of the landfill.
- 3) Improper design or mismanagement led to the destruction of the landfill. As a result, the composition, unit weight, and permeability coefficient of waste piles were essential for landfill safety. Research on the engineering characteristics of the landfill has not formed a unified understanding due to its anisotropy and complexity. Thus, the engineering characteristics of MSW are an urgent issue worthy of further study.

With the increase in urban populations and the improvement in quality of life, various landfills

are much closer to the saturation point at present. The landfills develop toward high pile bodies and large capacities. In the case of landslides directly threatening lives, property safety, and the surrounding environment, the slope stability of a landfill is an important problem. The engineering properties of MSW directly affect the distribution of leachate and slope stability in a landfill. Because engineering properties of MSW are closely related to the physical compositions, the physical compositions of MSW are analyzed, and the unit weight and permeability coefficient are studied in this paper.

Results and Discussion

Physical Composition of Landfilled MSW

Landfilled MSW has a complicated physical composition, but it is mainly composed of organic and inorganic substances. Organics mainly include food, wood, paper, textiles, plastics, and rubber, etc. Inorganics include metal, glass, tiles, and ash, etc. [29]. MSW compositions differ by times and regions [30-31]. The analysis of landfilled MSW physical compositions can provide the basis for the design of a landfill. To a certain degree, MSW physical compositions can represent the landfilled MSW physical compositions because of an ineffective waste recycling system and the only disposal method of MSW in many countries. Following are analyses of landfilled MSW compositions in spatiotemporal distributions in several countries.

MSW Compositions in Spatial Distribution

The MSW compositions of landfills in several countries are shown in Tables 2 and 3. These countries or landfills are shown in Fig. 2.

Table 2. MSW compositions in spatial distribution (percentage of wet mass).

Locations	Year	Food	Wood	Textiles	Paper	Plastics	Organics	Metal	Glass	Ash and others
Egypt [29]	2016	56.00			10.00	13.00	79.00	2.00	4.00	15.00
Jordan [32–33]	2015	52.70		10.22	9.00	12.85	84.77	4.82	1.25	9.16
China [34]	2015	55.86	2.94	3.16	8.52	11.15	81.63	18.37		
Canada [35]	2012	27.00	2.00	2.00	26.00	8.00	65.00	35.00		
Chihuahua, Mexico [36]	2009	45.00			17.00	13.00	75.00	3.00	5.00	17.00
Beijing, China [37]	2006	63.39	1.78	2.46	11.07	12.70	91.40	2.73		5.87
Philippines [38]	2006	59.10			7.40	10.50	77.00	1.30	1.70	20.00
Grete Island, Greece [39]	2006	39.15	5.24		19.94	16.85	81.18	3.51	5.33	9.98
Chongqing, China [8]	2001	59.20	4.20	6.10	10.10	15.70	95.30	1.10	3.40	0.20
United Kingdom [40]	2000	25.00	0.00	3.00	29.00	7.00	64.00	8.00	10.00	18.00

Table 3. Landfilled MSW compositions in spatial distribution (percentage of wet mass).

Landfill	Year	Food and wood	Paper and textiles	Plastics	Organics	Metal	Dust and others
Xi'an Jiangcungou Landfill, China [41]	2012	53.30	16.30	14.80	84.40	3.31	12.29
Bandeirantes Landfill, Brazil [42]	2010	53.80	18.60	20.90	93.30	5.60	1.10
Suzhou Qizishan Landfill, China [43]	2007	63.49	15.07	18.59	97.15	0.24	2.61
Gokarna Landfill, Nepal [44]	2003	70.00	11.50	9.50	91.00	0.00	9.00
Orchard Hills Landfill, United States [45]	2009	18.60	30.40	11.00	60.00	4.40	35.60
New Jersey Landfill, United States [46]	2005	32.10	26.70	8.90	67.70	4.00	28.30
Spyhill Sanitary Landfill, Canada [47]	2002	29.00	28.00	8.00	65.00	1.50	33.50

Based on statistics, the landfilled MSWs of developing countries have high organic content ranging from 75.00% to 97.15%. The main components were food with contents of 39.15-63.39% (Table 2), and food and wood with

contents of 53.30-70.00% (Table 3). The MSW had high water content and could easily degrade and cause more leachate production because of the increased organics. Therefore, the leachate levels of landfills are higher

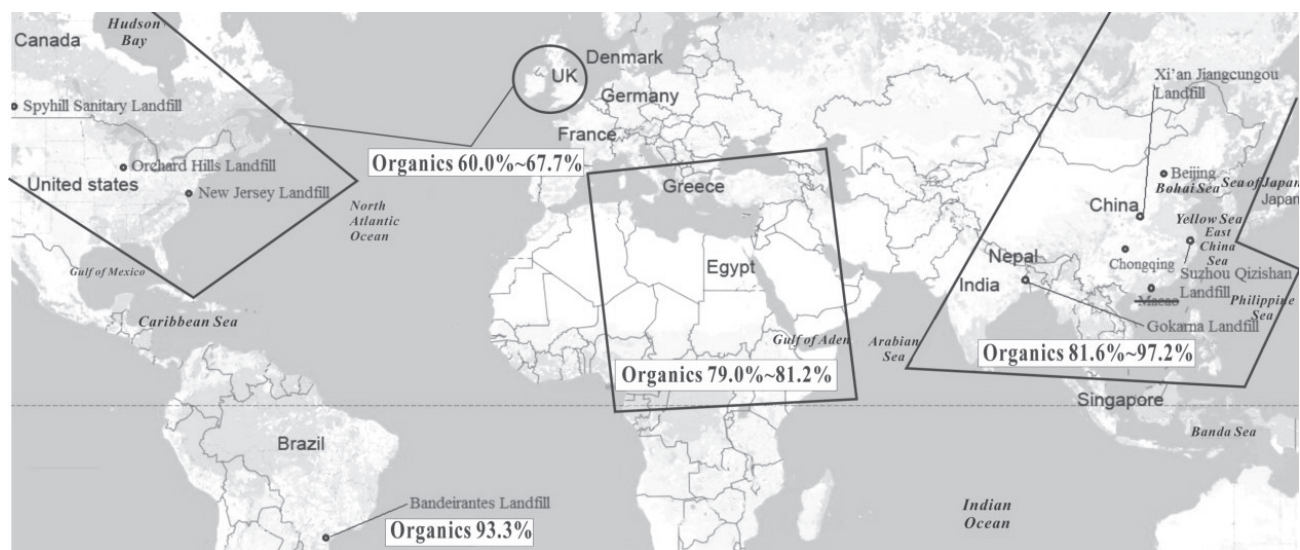


Fig. 2. Organic percentage of landfill waste in several countries.

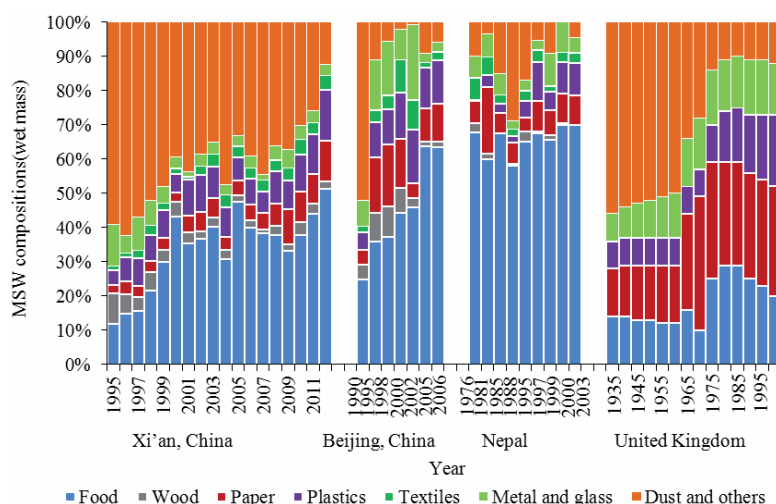


Fig. 3. MSW compositions in temporal distributions [36, 39-40, 43, 47].

and the failure of landfills can occur easily; the organic contents in landfills of developed countries are relatively small on a scale of 60.00-67.70%. The composition content of food and wood ranged from 18.60% to 32.10%. Compared with developing countries, the inorganics had a big value in landfilled MSW, which is good for the stability of a landfill site. MSW disposal technology is related not only to the level of economic development but also to the country's waste classification system, the degree of recycling, and waste utilization.

MSW Compositions in Temporal Distributions

As time goes on, the MSW composition contents are constantly changing in the same region. A few selected developing countries and developed countries have been selected to analyze the differences of MSW physical composition changes over time at different development degrees. The MSW average composition contents of four regions are shown in Fig. 3.

Based on the above figure, China's MSW organic composition was on the rise – especially food. On the contrary, inorganic composition was gradually reduced. Moreover, the main components were food, wood, dust, and others, and paper and textiles, plastics, metal and glass account for only small parts. With economic development and population growth, the production of MSW in Beijing increased from 2.96 million tons in 2000

to 6.20 million tons in 2007 [48]. From 1976 to 2003, the MSW composition components of Nepal changed to a low degree. Food occupied the main part with content of about 65%, and inorganic content initially increased and then decreased. From 1960 to 1985, the MSW organic composition components of the United Kingdom increased rapidly, then the organics became stable in 1985-2000. Inorganics were more than 60% and gradually decreased. Finally, each component's proportions were similar in 2000. In conclusion, food and wood had higher contents in developing Asian countries such as China and Nepal. The United Kingdom belongs to developed European countries, which has similar component proportions.

Given the above, the physical composition of landfilled MSW is affected by MSW management policy, climate, lifestyle, region, times, economic status, and region [49-50]. In addition, developed countries or cities have more paper and less food.

Unit Weight of Landfilled MSW

Influence Factors of Landfilled MSW Unit Weight

MSW unit weight is the weight per unit volume of MSW in landfills, and it has great effect on the landfill settlement and slope stability. International scholars

Table 4. Test methods of landfilled MSW unit weight.

Test methods		Comments
Laboratory test	Average weighting method [41]	Simple, but the average values are rarely used
	Measurement of individual component and weights in waste sample	Inaccurate and time-consuming
Field test	Replacement density measurement in boreholes [42]	Reliable and data obtained for a range of vertical stresses
	Measurement of waste pile vertical stresses	Reliable and shows changes related to vertical stresses

have done much exploration and research in this area. Landfilled MSW unit weight is significantly affected by the environment. In general, as waste ingredients increase, unit weight varies. In view of landfilled MSW, the more the inorganic content, the greater the unit weight. On the contrary, the more the ingredients such as plastics and paper, the smaller the unit weight [51]. In addition, the main components of the landfilled MSW were worked together by regional climate conditions, living habits, religious beliefs, and many other factors. The compaction degree and degradation degree have significant influence on landfilled MSW unit weight, that is the higher the compaction degree or degradation degree, the greater the landfilled MSW unit weight [52-53].

Test Methods

The unit weight of waste pile can be obtained by laboratory or field test. Several test methods of unit weight are shown in Table 4.

Laboratory tests are carried out through field sampling, taking the amount of waste samples, measuring their weights and volumes in the laboratory, and then calculating the unit weight. Alternatively, it is determined by the contents and weights of different components in the samples; however, these results are not accurate and are easily influenced by external factors. Field test is the method used to measure landfill unit weight directly in the borehole. The method is accurate, but it has a higher cost and more difficult operation.

Analysis of Landfilled MSW Unit Weight in Several Countries

MSW unit weight of a landfill is closely related to the buried depth, and the relations have been researched by many scholars [54-55]. Zornberg et al. (1999) [56] determined the MSW unit weight of a southern California landfill by boring test and obtained the unit weight value

range of 10-15 kN/m³ with a depth of 8-50 m. In 2005 Zekkos et al. provided the curves of unit weight and depth of 6 U.S. landfills, and gave the recommended profiles of unit weight, which ranged from 5 to 18 kN/m³ with a depth of 0-60 m. According to the data of Cheery Island Landfill, Zekkos et al. (2010) [57] drew the curve with a unit weight value range of 8-12 kN/m³ and a depth of 0-10 m. Meanwhile, they achieved three curves between unit weight and burying depth of the landfill, and the unit weight was growing with the increase of depth in the landfill. Tu and Qian put forward the 3 new curves for MSW landfill of China, which are presented in Fig. 4 [58]. The change of curve was obvious for the low compaction degree, and the unit weight ranged from 5-12 kN/m³ with a depth of 0-60 m. In the typical compaction and high compaction curves, the increasing rate of unit weight gradually slowed down at 20 and 10 m depths.

Based on the investigation and research of literature, the landfilled MSW unit weight ranged 4.9-12 kN/m³ and their change tendencies were basically the same in China and the USA. The landfills of China were between low compaction degree and typical compaction degree, while those in the USA were relatively high, such as Tri-Cities Landfill and OII Landfill. The major causes of compaction degree were landfilled MSW physical compositions and compaction technology.

Effect of MSW Unit Weight on Landfill Safety

MSW unit weight has a large impact in terms of landfill safety. It affects waste settlement deformation and makes a drain bending and deformation of gas wells. Unit weight affects the estimate of the landfill capacity, and affects the design and operation of the landfill [60]. Thus, MSW unit weight is critical to the basis of landfill stability and integrity, waste slope stability, stable liner system, drainage system integrity, leachate/gas well integrity, and the design and operation of the landfill.

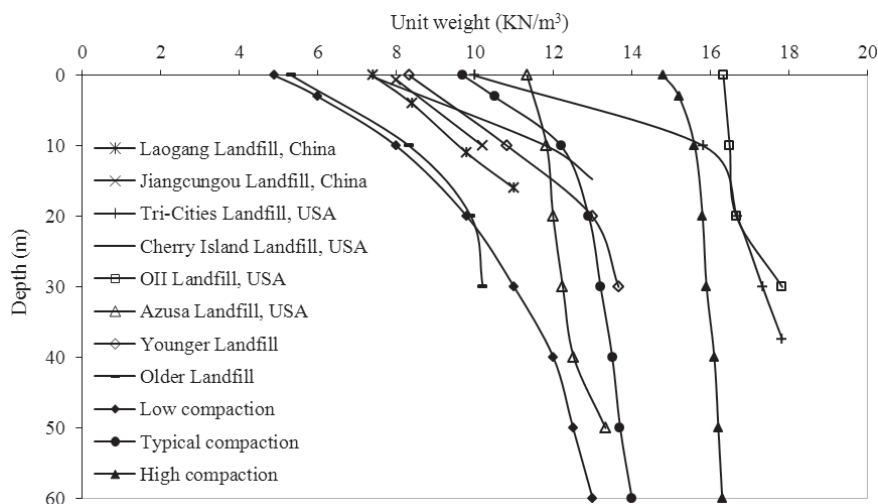


Fig. 4. Comparison of MSW unit weights in different landfills [40, 57-59].

Table 5. Test methods of landfilled MSW permeability coefficients.

Test methods		Comments
Laboratory test	Constant head test [41]	Suitable for large permeability coefficients of shallow waste
	Falling head test	Suitable for small permeability coefficients of deep waste or high content dust of waste
Field test	Surface infiltration pit	Suitable for shallow waste
	Pumping test [42]	Suitable for whole depth profile

Permeability Coefficients of Landfilled MSW

Test Methods

Influence Factors of Landfilled MSW Permeability Coefficient

Leachate distribution of a landfill is determined by permeability coefficient, thus affecting landfill stability. MSW compositions have a great influence on the permeability coefficient. The more plastics, glass, and dust content, the smaller the permeability coefficient. In contrast, the more food, wood, paper, and textiles content, the larger the permeability coefficient. MSW compaction degree of landfill directly affects the permeability coefficient. Considering the function of the upper load, the permeability coefficient is small in deep waste. In addition, in the process of waste degradation, the permeability coefficient changes continuously.

MSW permeability coefficient of a landfill can be obtained by laboratory test or field test. Several test methods are shown in Table 5.

Measuring the permeability coefficient in the laboratory is simple and inexpensive. However, only the permeability coefficient of the surface-landfilled MSW can be measured during the sampling process. It is difficult to reproduce all the landfill conditions in laboratory tests. Field measurements are normally considered the most reliable approach to estimate the landfilled MSW permeability coefficients.

Analysis of Landfilled MSW Permeability Coefficients in Several Countries

Permeability coefficient and other indexes were difficult to determine due to the nonuniformity of the MSW

Table 6. MSW permeability coefficients in landfills.

References	Unit weight (KN/m ³)	Saturated permeability coefficient (m/sec)	Method	Waste
[63]	7.8–11.8	3.0×10^{-5} – 2.9×10^{-6}	Constant head test	Landfill in Korea
[64]	/	1.2×10^{-4} – 4.7×10^{-6}	Falling head test	Landfill in Texas, USA
[65]	/	1.0×10^{-4} – 1.0×10^{-6}	Falling head test	Landfill in France
[66]	6.4–9.3 (dry unit weight)	1.0×10^{-4} – 8.0×10^{-6}	Constant head test	Home-made MSW samples
[67]	3.1–9.4 4.0–13.0 (dry unit weight)	2.0×10^{-3} – 7.8×10^{-7} 2.0×10^{-3} – 4.9×10^{-7}	Steel wall constant head test	Landfill in Illinois, USA
[59]	7.2–12.5	6.7×10^{-5} – 4.6×10^{-6}	Constant head test	Laogang landfill in China
[68]	9.8–16.0	1.8×10^{-3} – 3.1×10^{-8}	Home-made devices	Restructuring waste in China
[69]	/	6.3×10^{-6} – 1.2×10^{-7}	Pumping test	Fresh Kills Landfill in New York, USA
[70]	/	6.9×10^{-4} – 1.2×10^{-4}	/	/
[71]	3.56–5.9 4.8–5.9 (Dry unit weight)	1.6×10^{-3} – 4.9×10^{-6} 1.0×10^{-4} – 1.1×10^{-5}	/	Fresh waste in France
[72]	Not compacted ≥300 kPa	1.0×10^{-5} – 1.0×10^{-6}	/	Tianziling landfill in China

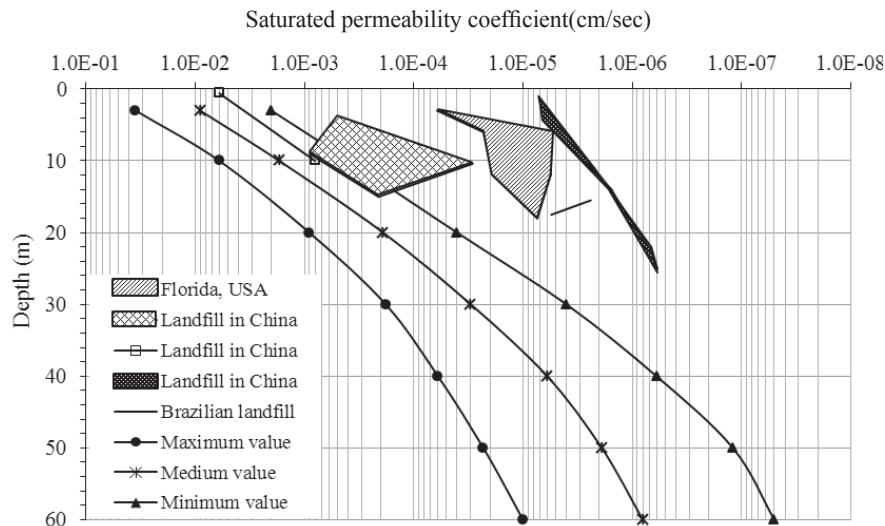


Fig. 5. Comparison of MSW saturated permeability coefficients in several landfills [24, 40–41, 58, 73].

and the limitation of sampling in the landfill. Engineering characteristic parameters, related to landfill safety and stability, were researched and analyzed by Chen and Ke (2005) [61]. The research of permeability coefficient is extremely important to reduce landfill accidents. Landfilled MSW infiltration characteristics directly influence the distribution and level of landfill leachate and greatly influence landfill stability. Gao et al. (2015) [42] counted the variation of permeability coefficient with depth about high kitchen waste content MSW (HKWC MSW) and low kitchen waste content MSW (LKWC MSW). The permeability coefficient of LKWC MSW was larger than that of HKWC MSW at the same depth with a depth of 0–26 m. Li et al. (2014) [62] summarized several factors affecting the permeability coefficient of MSW, including waste density, waste composition, degradation degree, and compaction degree. Two kinds of methods were proposed to adjust the permeability coefficient, namely changing the influence factors and adding inert materials. The research situations of the landfilled MSW saturated permeability coefficients in various countries are shown in Table 6.

According to the survey, the leachate of this landfill reached more than 1,600 tons of every day. Thus, it needs to reduce rainfall infiltration and increase the amount of layer and bottom discharge. According to statistical data, the landfilled MSW permeability coefficient range is very large, at up to 1.0×10^{-8} – 2.0×10^{-3} cm/sec, and the different depth of waste landfill permeability coefficient range is very large. The test method, compaction degree, and composition of the waste is different as well as the permeability coefficient of the landfill of each country.

The relational curves between MSW saturated permeability coefficient and buried depth of landfills are shown in Fig. 5. The range of MSW-saturated permeability coefficients obtained by Jain et al., Wu et al., and Machado et al. was smaller than the minimum value of the standard landfill in China [58, 73–74]. The

compaction degree of landfill is high, and the rainfall infiltration is very little. The leachate is mainly produced by high moisture waste and degradation. The permeability coefficients of Jianguogou Landfill measured by Yang et al. (2016) were between the medium and minimum values, and the compaction degree is relatively low [35]. The leachate is mainly composed of rainfall infiltration, high moisture waste, and degradation.

Effect of MSW Permeability Coefficients on Landfill Safety

Due to the large permeability coefficients and leachate discharge in a timely manner, the landfill has a high leachate level and landfill slope instability will happen. In addition, permeability coefficient would affect the leachate and gas well integrity, leachate discharge, and leachate/gas collection.

Conclusions

According to statistics of the methods in dealing with MSW, the influential factors of the MSW disposal methods were analyzed, and the landfill technology was seen as the main means of dealing with MSW in many countries. The incineration method is often used to deal with MSW in developed countries or cities, whereas landfilling is used in developing countries. The differences of landfilled MSW physical composition in several countries were analyzed, and the causes of these differences were proposed. By analyzing the landfill crashes, MSW physical composition, unit weight, and permeability coefficient of the landfill were important factors affecting landfill safety. Finally, the research situation of landfilled MSW physical composition, unit weight, and permeability coefficient were reviewed, and their relationships were analyzed. The following can be concluded:

- 1) Similar physical compositions emerged in developing countries. Organic matter content was more (as high as 97.15%) and the food as the main ingredients increased over time. The physical compositions of most developed regions were similar. Organic matter content was about 67.7%, and the inorganics had a high value in landfilled MSW compared with developing countries.
- 2) The measurement methods of MSW unit weight and permeability coefficient were given, and the curves between these 2 parameters and depth were drawn. Within 60 m, the unit weight ranged from 4.9-17.8 kN/m³ and the permeability coefficient ranged from 3.5×10⁻² cm/sec to 5.0×10⁻⁸ cm/sec.
- 3) In the process of waste degradation, with increasing buried depth, the organic content decreased gradually and waste residue (waste leftovers after degradation) increased. MSW permeability coefficient of landfill decreased and unit weight increased as buried depth increased. But when the buried depth came to a certain value, the values of organic content, unit weight, and permeability coefficient have little change. In general, landfilled MSW has strong regional and temporal characteristics about the physical composition, unit weight, and permeability coefficient.

The view presented in this paper is that classification improves the recovery and utilization of a landfill and reduces the amount of MSW. At the same time the physical composition, unit weight, and permeability coefficients of landfilled MSW change and affect the stability of the landfill slope. As landfilled MSW composition has great influence in construction, operation, and management of landfills, the recycling and recovery of MSW in a previous step of final disposal is strongly recommended.

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