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Study on Compressibility and Settlement of a Landfill with Aged Municipal Solid Waste: A Case Study in Taizhou

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Abstract: Capacity expansion of existing landfills is one of the most economical methods of relieving the stress caused by the disposal of local municipal solid waste (MSW) in developing countries. In this paper, the compression characteristics and settlement of the aged MSW in Xiawan landfill were studied. The physical composition, moisture content, volumetric weight, and modified primary compression index of the aged MSW at different depths were tested, and then the settlement of the MSW in the area to be filled with fly ash was calculated. The test results showed that the main components of the aged MSW were muck and textile, indicating that kitchen waste was degraded. The moisture content of the MSW generally increased with depth, and the average moisture content within 5 m of the shallow part of the landfill was 97%. The void ratio of the aged MSW decreased from 4.0 to 2.2 with an increase in vertical load from 1 kPa to 400 kPa. The modified primary compression index of the aged MSW ranged from 0.22 to 0.27, and generally decreased with depth. Under the load generated by the subsequent filling of fly ash, the final strains of the aged MSW was approximately 15% to 20%. The physical composition and compression characteristics of the aged MSW measured in this paper were compared with those reported in previous studies to provide reference for the settlement analysis of landfills with aged MSW.

Keywords: municipal solid waste; compression characteristics; settlement; landfill expansion; waste composition; degradation

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1. Introduction

With the rapid development of urbanization, the annual output of municipal solid waste (MSW) in China has exceeded 240 million tons, and it continuously increased at an annual rate of 8–10% between 1979 and 2013 [1]. The treatment of MSW has become an unavoidable problem in urban management, and the main treatment methods are landfill, incineration, and composting. Sanitary landfill is the most important MSW treatment method in China, accounting for about 60.0% of total MSW disposal. Ministry of Construction documents point out that MSW incineration technology can be developed in cities with the right economic and waste heat value conditions, and a lack of sanitary landfill resources [2,3]. MSW incineration technologies can greatly reduce the volume of MSW, the heat from waste incineration can be used to generate electricity, and the bottom ash from waste incineration may be used as a road base [4,5]. Moreover, the residues (such as fly ash) produced by the incineration of MSW still need to be transported to the landfill for disposal [6]. Thus, a landfill is the ultimate destination for all kinds of MSW.

Due to the limited space available for the construction of landfills, the expansion of existing landfill sites is an effective method of relieving the shortage of landfill storage capacity, extend the service life of the landfill, and buy time for the construction of MSW incineration power plants [7,8]. The settlement of aged waste is a key issue that needs to be addressed in vertically expanded landfills, and is an important consideration in the design of landfill storage capacities and closure systems. A number of experiments and theoretical studies have been carried out on the compression characteristics of MSW and its influencing factors [9–13], which imply that the compression deformation of MSW is composed of the primary compression caused by external force, as well as the secondary compression caused by mechanical creep and organic matter degradation. The settlement deformation of the landfill is directly related to the analysis of the storage capacity of the landfill. The settlement of the MSW landfill after closure generally lasts 20–30 years, and the total settlement is approximately 25–50% of the initial landfill height [14–16].

Several calculation models (e.g., soil mechanics compression and consolidation theoretical model, empirical model, biodegradation model, creep model, and comprehensive models) have been proposed in literature to predict MSW landfill settlement [17–21]. However, the best calculation method of landfill settlement is still debated due to the complexity of the composition of the MSW and the complex factors affecting the settlement of the MSW. The calculation model proposed by Sowers [17] is one of the most commonly used MSW settlement models based on classical soil mechanics theory, which divides the compression deformation of MSW into the primary and secondary compressions. The value range of the primary compression index and secondary compression index of MSW is then analyzed based on the measured data. This model is widely used in landfill settlement estimation due to its few parameters and simple calculation. However, the content of kitchen waste in the MSW in developing countries (e.g., China) generally exceeds 50%, and most of the degradable substances in landfill waste could be degraded within 2 years of disposal due to the MSW with high kitchen waste content [22]. Therefore, when expanding the storage capacity of a landfill with high kitchen waste content MSW, it is necessary to conduct research on the physical composition and compression characteristics of aged MSW.

The reuse of landfill sites (capacity expansion, landscape reconstruction, etc.) after closure is attracting more and more attention. It is necessary to study the compression characteristics of landfilled waste before reusing the sites. MSW in developing countries generally has a high content of kitchen waste, and the degradable substances could be degraded within 2 years after disposal. There are few studies on the composition and compression characteristics of aged MSW in developing countries. The objective of this paper is to study the compression characteristics and settlement of a landfill with aged MSW. In this paper, the fast-degrading materials in the aged waste (such as kitchen waste) have basically been degraded. The variations in physical composition, moisture content, volumetric weight, and modified primary compression index of the aged MSW with depth were tested. The compression characteristics of the aged MSW in Xiawan landfill were analyzed. Then, taking Xiawan landfill as an example, the settlement of the MSW in the area to be filled with fly ash was calculated.

2. Materials and Methods

2.1. Site Description

The Xiawan landfill (Figure 1) is located in Taizhou City, Zhejiang Province, China. The landfill occupies an area of 3.0×10^4 m^2, and has been in operation since 2017. The landfill was designed in accordance with the design specifications of China's municipal solid waste sanitary landfills, with good construction quality control and complete safety facilities (such as the bottom leachate collection and drainage system, horizontal and vertical anti-seepage systems, etc.). Some of the aged waste from a nearby simple MSW landfill (i.e., an old landfill that lacks pollution prevention facilities) was transferred to the Xiawan Landfill. The total storage capacity of the landfill is approximately 7.5×10^5 m^3, and it currently receives 400 t–500 t MSW every day.

Figure 1. Satellite image of the landfill site.

To relieve the stress of landfill storage capacity, the Xiawan landfill plans to build an incineration plant before July 2021 to incinerate MSW and produce electricity and heat. Since fly ash is generated in the incineration process, the fly ash generated from incineration will be buried in a fly ash storage area in the Xiawan landfill, which is marked by the red line in Figure 1. The fly ash storage area covers an area of 6000 m^2, which was selected for ash storage because the amount of waste that has been stored here is less than in other areas. The daily output of fly ash is expected to be 16 t, and the total amount of fly ash that can be disposed of in the fly ash storage area is about 60,000 to 100,000 tons. In addition, about ten meters of MSW has been buried under the fly ash storage area, and the fill age of the waste ranges from 3 to 6 years. The load caused by the subsequent disposal of fly ash will further increase the settlement of the landfill, thereby increasing the risk of instability of the landfill. Therefore, it is urgent to analyze the settlement and deformation of the aged MSW before the construction of the fly ash storage area, and carry out reasonable planning and design for the construction of the fly ash storage area according to the predicted settlement.

2.2. Experimental Materials

The waste samples were all taken from the aged waste under the area to be filled with fly ash, and a total of 5 boreholes (numbered A1–A5) were arranged in the fly ash storage area to take waste samples (Figure 1). To prevent damage to the geomembrane at the bottom of the landfill, the solid waste management office required that the maximum drilling depth not exceed 6 m. A total of 33 waste samples were collected, and the buried depth of the collected waste samples ranged from 1 m to 5 m. The undisturbed waste samples were swiftly sealed after being taken out, and were quickly brought back to the laboratory for testing.

Figure 2 shows the variation of the physical composition of the aged MSW with depth. The analytical tests of the physical composition of MSW were conducted in accordance with the Chinese Technical Specification for Soil Test of Landfilled Municipal Solid Waste (CJJ/T204-2013) [23]. The composition of landfill waste fluctuates with depth, and the content of muck (i.e., waste soils) is the highest and generally increases with depth. The average content of each physical component of the aged MSW at different depths is shown in Figure 3, which shows that the average content of kitchen waste is the lowest (i.e., 0.1%). Wang et al. [24] reported that the proportion of kitchen waste in fresh MSW in Beijing is high (more than 50%), which was different from our results due to the degradation of the landfill waste. According to the test results of the fresh MSW in Taizhou, the proportions of kitchen waste, muck, rubbery plastic, textile, paper, bamboo wood, crushed stone, and other wastes were 54.7%, 14.9%, 12.8%, 5.3%, 4.7%, 4.2%, 2.8%, and 0.6%, respectively. The landfill age of the waste samples used in this paper was generally more than three years, which means that most of the kitchen waste had been degraded [16]. Therefore, the kitchen waste content in the collected waste samples was extremely low.

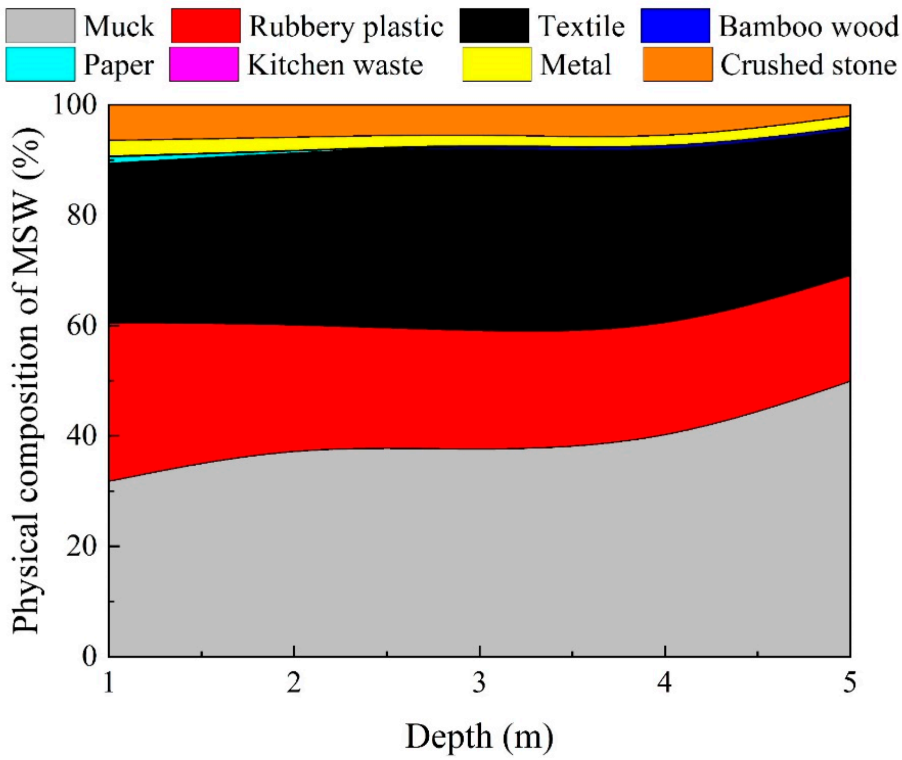

Figure 2. Variation of physical composition of aged municipal solid waste (MSW) with depth.

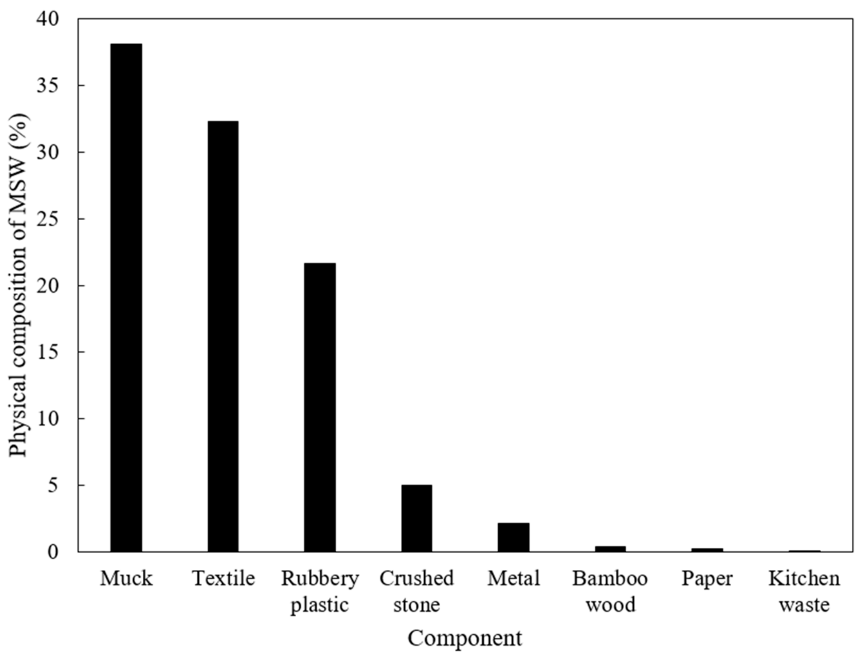

Figure 3. Physical composition of aged MSW samples.

2.3. Experimental Methods

2.3.1. Testing Apparatus

Compression and bulk density related tests were conducted to determine variations in compression index and volumetric weight with depth using a large-scale consolidation and compression apparatus (Figure 4). The sample container was made of plexiglass, and was placed in the center of the loading frame. The diameter and height of the sample container were 200 mm and 250 mm, respectively. The sample container was mainly composed of a cylinder, a base, and a top cap. Permeable plates were arranged at the top and bottom of the sample placed into the sample container, and the top cap was used to load pressure. A leachate outlet pipe was arranged at the base of the sample container, which was controlled by a valve. A loading device was located on the top of the loading frame, which could achieve pressure loading of up to 1600 kPa using a lever. Displacement sensor and measuring cylinder were used to record the amount of compression deformation and the outflow of leachate.

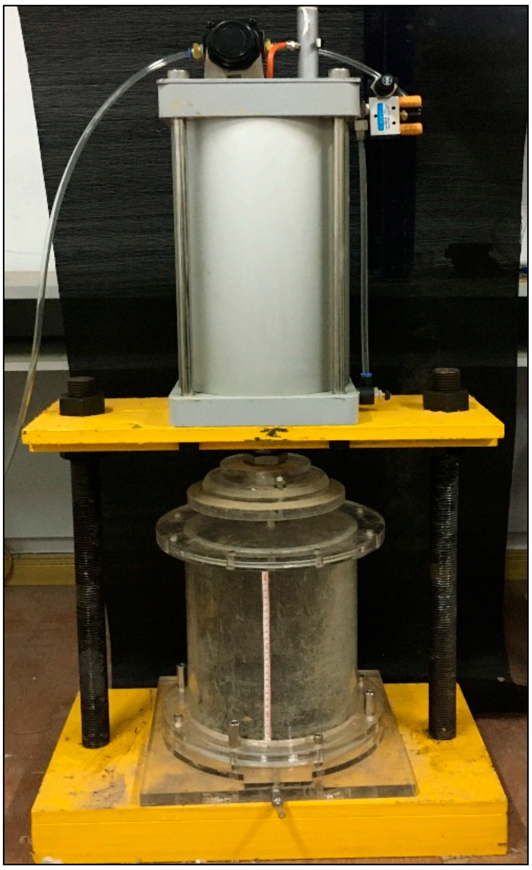

Figure 4. Large-scale consolidation and compression apparatus.

2.3.2. Experimental Procedure

The moisture content tests, volumetric weight tests, and compression index tests were conducted according to the Chinese Technical Specification for Soil Test of Landfilled Municipal Solid Waste (CJJ/T204-2013) [23]. In this paper, a total of 33 sets of moisture content tests, 18 sets of volumetric weight tests, and 18 sets of compression index tests were carried out.

The large-scale consolidation and compression apparatus shown in Figure 4 was used to measure the volumetric weight of waste samples. First, a permeable plate and a filter paper were placed in the bottom of the container in sequence. Then, the waste sample was lightly tapped into the container in layers, after which the weight of the sample was recorded after the filling was completed, and then a piece of filter paper and a permeable plate were put on each sample. After this, the top cap was installed for loading pressure, and the container was placed in the center of the loading frame, the displacement sensor was installed, and the initial height of the waste sample was recorded. In order to simulate the overburden stress of the MSW at different depths, the applied loads of the samples taken at depths of 1 m, 2 m, 3 m, 4 m, and 5 m were 10 kPa, 20 kPa, 30 kPa, 40 kPa, and 50 kPa, respectively. The loads were applied for 24 h, and the compression of each waste sample was recorded at the end of the test. Finally, the natural volumetric weight could be obtained according to the weight of the waste sample and the compressed volume.

The compression index tests were also carried out with the large-scale consolidation and compression apparatus. The preparation process of the waste sample was consistent with the above volumetric weight test. According to the conditions of the landfill site, it was estimated that the thickness of the landfill waste was generally less than 30 m, indicating that the maximum self-weight stress generated by the landfill wastes might be approximately 300 kPa. The applied load levels for each waste sample were 50 kPa, 100 kPa, 200 kPa, and 400 kPa, and the interval between each level of load was 24 h. Once each level of load was applied, the settlement and leachate outflow volume was recorded every 10 min for the first hour. Within 1 h–6 h after loading, the results were recorded once every 30 min. Then, the results were recorded every 1 h until the end of the load. The test conditions were controlled strictly to minimize the influence of external factors on the test.

2.4. Settlement Calculation Method of MSW

According to the Chinese Technical Code for Geotechnical Engineering of Municipal Solid Waste Sanitary Landfill (CJJ 177-2012) [25], the settlement of landfill waste is mainly composed of primary compression and secondary compression, and it is recommended that the layer wise summation method be used for calculation. The settlement of the landfill can be calculated as follows:

$$S = \sum_{i=1}^{n} (S_{pi} + S_{si}) \tag{1}$$

where S is the total settlement of the MSW landfill (m); n is the total number of layers of landfill waste, the thickness of each layer should be 2 m–5 m, and the infiltration surface in the landfill should be used as the layer interface; S_{pi} is the primary compression of each layer of waste (m); and S_{si} is the secondary compression of each layer of waste (m).

The primary compression of each layer of waste can be obtained as follows:

$$S_{pi} = H_i \times C_c' \times \log(\sigma_i / \sigma_0) \tag{2}$$

where H_i is the initial thickness of each layer of waste (m); C_c' is the modified primary compression index of the MSW; σ_i is the effective overburden stress of each waste layer (kPa); σ_0 is the pre-consolidation pressure, and 30 kPa is recommended when there are no test data.

The secondary compression of each layer of waste can be obtained as follows:

$$S_{si} = H_i \times C_\alpha' \times \log(t_i / t_0) \tag{3}$$

where C_α' is the modified secondary compression index of the MSW, which can be determined according to the physical composition of MSW and the empirical value recommended by the specification; t_i is the landfill age of each waste layer (months); and t_0 is the completion time of the primary compression of MSW (months).

3. Results and Discussion

3.1. Moisture Content Distribution

The moisture content (i.e., mass water content) of the MSW at different depths of the landfill is shown in Figure 5. The moisture content of waste samples at different depths ranged from 62% to 153%, and the average moisture content was about 97%. As a whole, the moisture content of MSW showed an increasing trend with depth, but the moisture content of a single borehole did not show an obvious change trend with depth. The variation trend of moisture content along the depth was consistent with that measured by Zhang et al. [26]. In addition, the moisture content of MSW at the same depth measured by different borehole samples varied greatly, indicating that the moisture content of landfilled MSW might change significantly with the change of spatial location. The moisture content of landfill waste exhibited obvious spatial variability. On the one hand, it might be related to the heterogeneity of the MSW. The complex physical composition of the MSW led to extremely poor homogeneity, and the connection of the leachate inside the landfill was restricted. As a consequence, the hydraulic conductivity of MSW might show obvious spatial variability, resulting in an uneven distribution of water content in the landfill. On the other hand, it was also related to the presence of an intermediate cover layer in the landfill waste, which could have caused a perched water table.

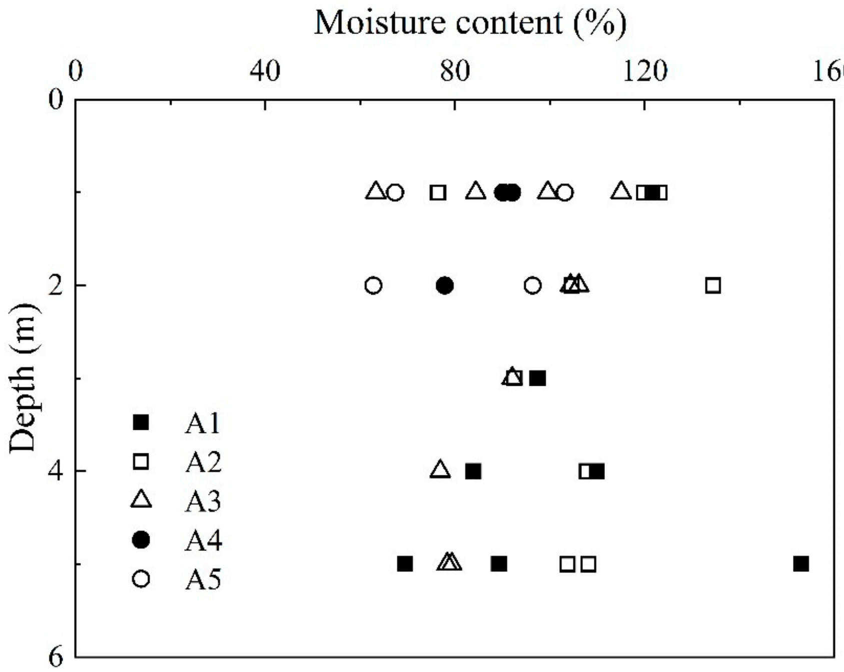

Figure 5. Change of moisture content with embedding depth of MSW samples.

3.2. Volumetric Weight

The relationship between the volumetric weight of MSW samples and the embedding depth is shown in Figure 6. The test results showed that the volumetric weight of waste samples at depths of 1 m to 5 m in the landfill was approximately 5.9 kN/m^3–10.0 kN/m^3, and the average volumetric weight of all waste samples was about 8.0 kN/m^3. Zhang et al. [27] tested the volumetric weight of the MSW at depths of 0 m to 20 m in the Qizishan landfill in Suzhou City, and the results indicated that the volumetric weight of the MSW ranged from 3 kN/m^3 to 15 kN/m^3. The test results of this article were within this range. According to the change curves of the volumetric weight of MSW with depth summarized by Zekkos et al. [28], the variation of the volumetric weight of the MSW with depth in this paper was close to the density curve of MSW with a moderate degree of compaction. Moreover, the degree of compaction of MSW increased with depth due to the fact that the effective overburden stress of the waste increased. As a result, the volumetric weight of MSW generally increased with depth.

3.3. Compression Characteristics

Figure 7 shows the relationship between the pressure and the void ratio of the MSW samples. The results measured from the MSW samples taken from the A3 borehole were selected as the representative data. Under the same load, the void ratio of waste samples showed a decreasing trend with the depth of MSW. When the load was increased from 1 kPa to 400 kPa, the void ratio of the waste samples decreased from about 4.0 to about 2.2, indicating that the degree of compaction of the waste increased. Moreover, the void ratios of the waste samples at different depths were close to each other when the load was 1 kPa, indicating the significant rebound characteristics of MSW [13]. As the load increased, the difference in void ratio of waste samples at different depths first increased and then gradually decreased, which might be related to the different pre-consolidation pressures of the waste samples at different depths.

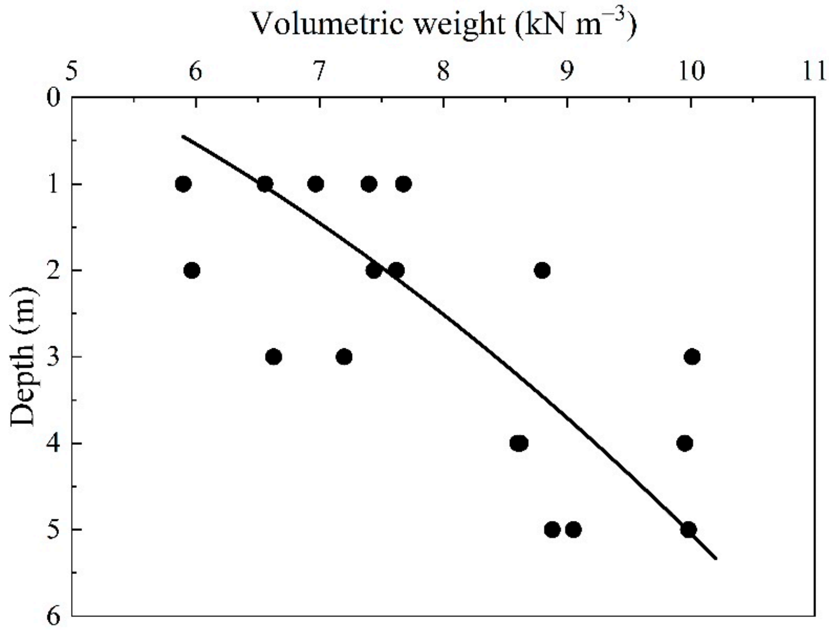

Figure 6. Relationship between volumetric weight and embedding depth of MSW samples.

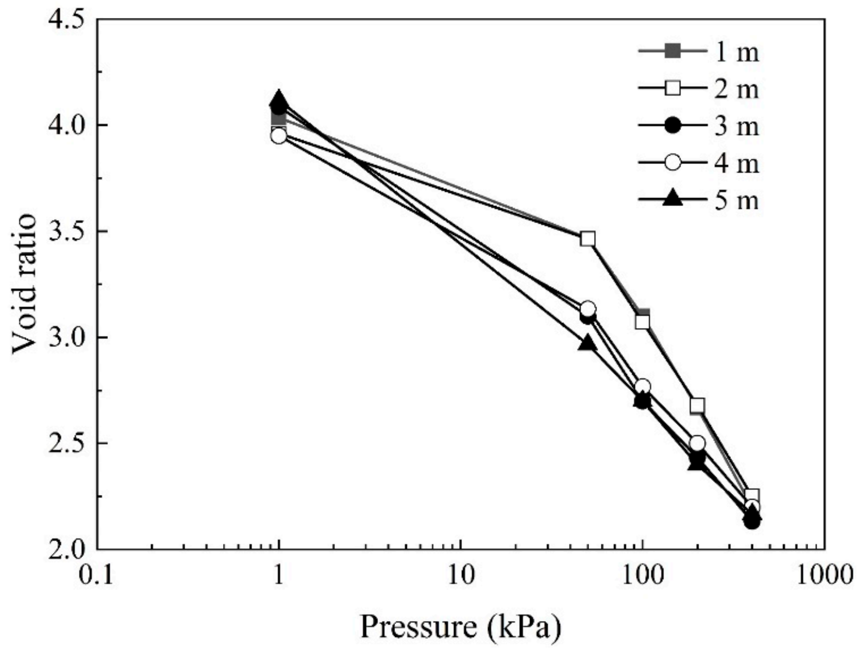

Figure 7. Relationship between the pressure and the void ratio of the MSW samples.

Figure 8 shows the relationship between the modified primary compression index of 18 waste samples and depth. Most of the modified primary compression index values were in the range of 0.22 to 0.27, and the average modified primary compression index was around 0.24. This result was consistent with the test results of Ke et al. [29] on the modified primary compression index of MSW samples at different depths. Although the distribution of the measured modified primary compression index was highly discrete, the value of the modified primary compression index generally decreased as landfill depth increased, which was consistent with the results of Zhan et al. [30]. This might be due to the fact that the content of muck in the waste samples gradually increased with depth (Figure 2), resulting in a higher degree of compaction and homogeneity of the waste sample.

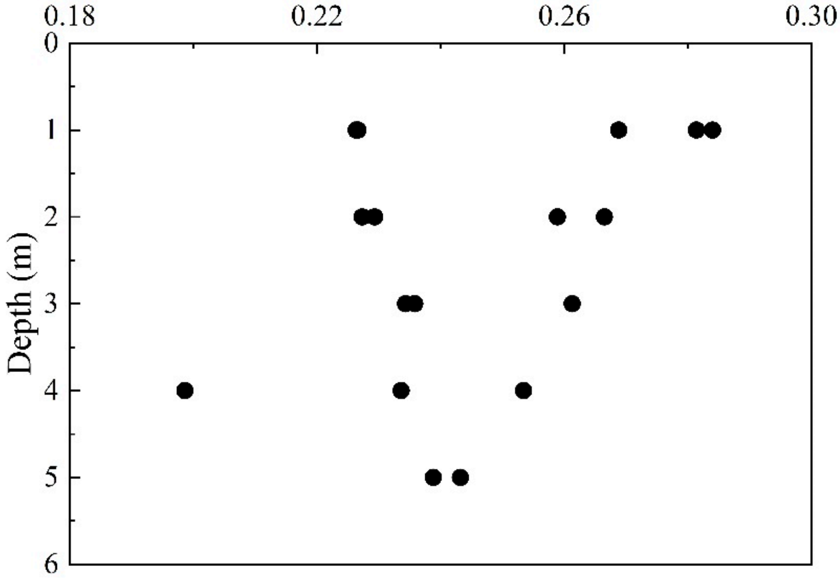

Figure 8. Variation of modified primary compression index with embedding depth of MSW samples.

4. Settlement Prediction of Landfill Waste

In order to evaluate the change in the settlement of the fly ash storage area, the landfill was divided from the plane to facilitate the calculation of the settlement value at different positions in the fly ash storage area. As shown in Figure 9, the entire fly ash storage area was divided into three horizontal (i.e., A1, B1, and C1) and three vertical (i.e., A2, B2, and C2) calculation sections. The settlement of the six settlement calculation sections after filling fly ash was analyzed.

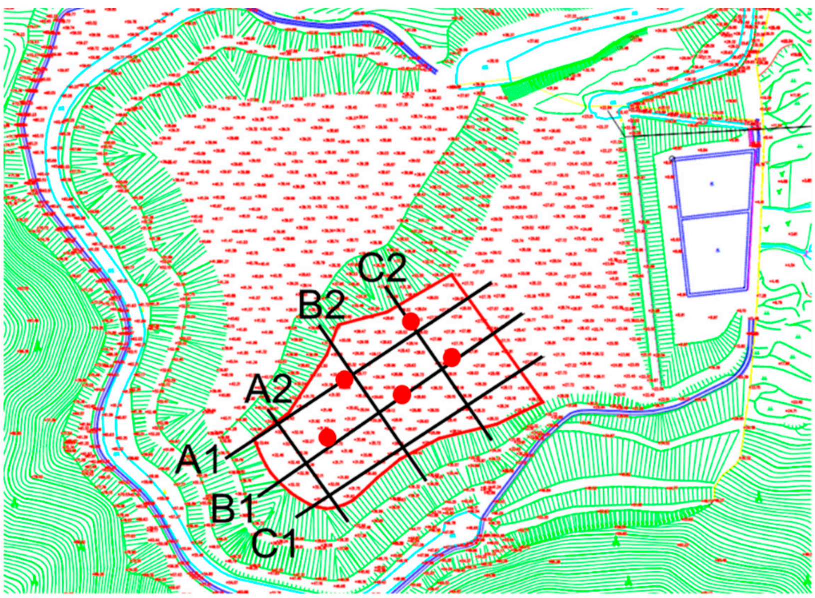

Figure 9. Settlement calculation profiles of waste in fly ash storage area.

The settlement calculation method introduced in Section 2.4 of this paper is adopted to calculate the settlement of the aged MSW under the fly ash storage area. According to the daily output of fly ash and the storage capacity of the Xiawan landfill, it is estimated that the landfill could continue to operate for about 15 years. According to the annual output of MSW, the incineration plant is supposed to produce about 5840 tons of fly ash each year. Based on the location of the fly ash storage area, the stress corresponding to the annual increase of the landfill fly ash is approximately 10 kPa. The compaction density of fly ash is about 1.2 g/cm^3, which indicates that the thickness of fly ash increases by 0.83 m each year. In order to estimate the amount of the settlement of the aged MSW during the fly ash filling process, the settlement values in different years after the start of the fly ash filling are calculated until the closure for this site is completed. A total of 15 time points (i.e., 2021–2035) are selected to calculate the MSW settlement and the corresponding top elevation of the landfill in the six settlement calculation sections. As shown in Table 1, the landfill waste was divided into three layers (i.e., LW1, LW2, and LW3) according to the age of the MSW, and the relevant parameters involved in the calculation were determined according to the indoor test results and the recommended values of the specification [25]. The elevation in the table refer to the height from sea level.

Table 1. Settlement calculation parameters of MSW.

Layer	Elevation	Thickness	Modified Primary Compression Index	Modified Secondary Compression Index
unit	m	m	/	/
LW3	>29	3~5	0.254	0.035
LW2	26~29	3	0.238	
LW1	<26	7~10	0.23	

Figure 10a–c show the elevation prediction results of the three horizontal calculation sections (i.e., A1, B1, and C1) in 2035, where the starting point of the horizontal distance is the end point on the southwest side of the section line (Figure 9). The thickness of the landfill waste gradually increases from west to east. The maximum initial thicknesses of the landfill waste corresponding to sections A1, B1, and C1 are 15.6 m, 16.9 m, and 7.6 m, respectively. The settlement value is positively correlated with the thickness of the landfill waste. The maximum settlement values of the landfill waste corresponding to sections A1, B1, and C1 are 2.5 m, 2.6 m, and 1.58 m, respectively. The thicknesses of the landfill waste corresponding to sections A1, B1, and C1 after settlement are reduced by 15.8%, 15.3%, and 20.8% from the initial thickness, respectively. Figure 10d–f show the elevation prediction results of the three vertical calculation sections (i.e., A2, B2, and C2) in 2035, where the starting point of the horizontal distance is the end point on the north side of the section line. The thickness of the landfill waste generally decreases from north to south. The maximum initial thickness of the landfill waste corresponding to sections A2, B2, and C2 are 3.9 m, 12.2 m, and 15.4 m, respectively. The thicknesses of the landfill wastes corresponding to the sections A2, B2, and C2 after settlement are reduced by 24.7%, 17.5%, and 16.0% from the initial thickness, respectively.

Figure 11 shows the variation curves of the settlement amount corresponding to the maximum settlement point of different profile lines (i.e., A1–C2) with time. As time goes on, the settlement amount of the landfill gradually increases, but the rate of increase gradually decreases over time. In general, the settlement value of the aged MSW increases with the thickness of the landfill waste. Under the load caused by fly ash, the thickness of the landfill waste after settlement is generally reduced by about 15% to 20% compared to the initial thickness. The maximum settlement value of the landfill waste is up to 2.6 m, which indicates that the compaction of landfill waste could increase the landfill capacity of fly ash by about 3 years. The settlement of the existing waste under the load of the newly filled waste cannot be ignored in the design of the capacity expansion of a landfill.

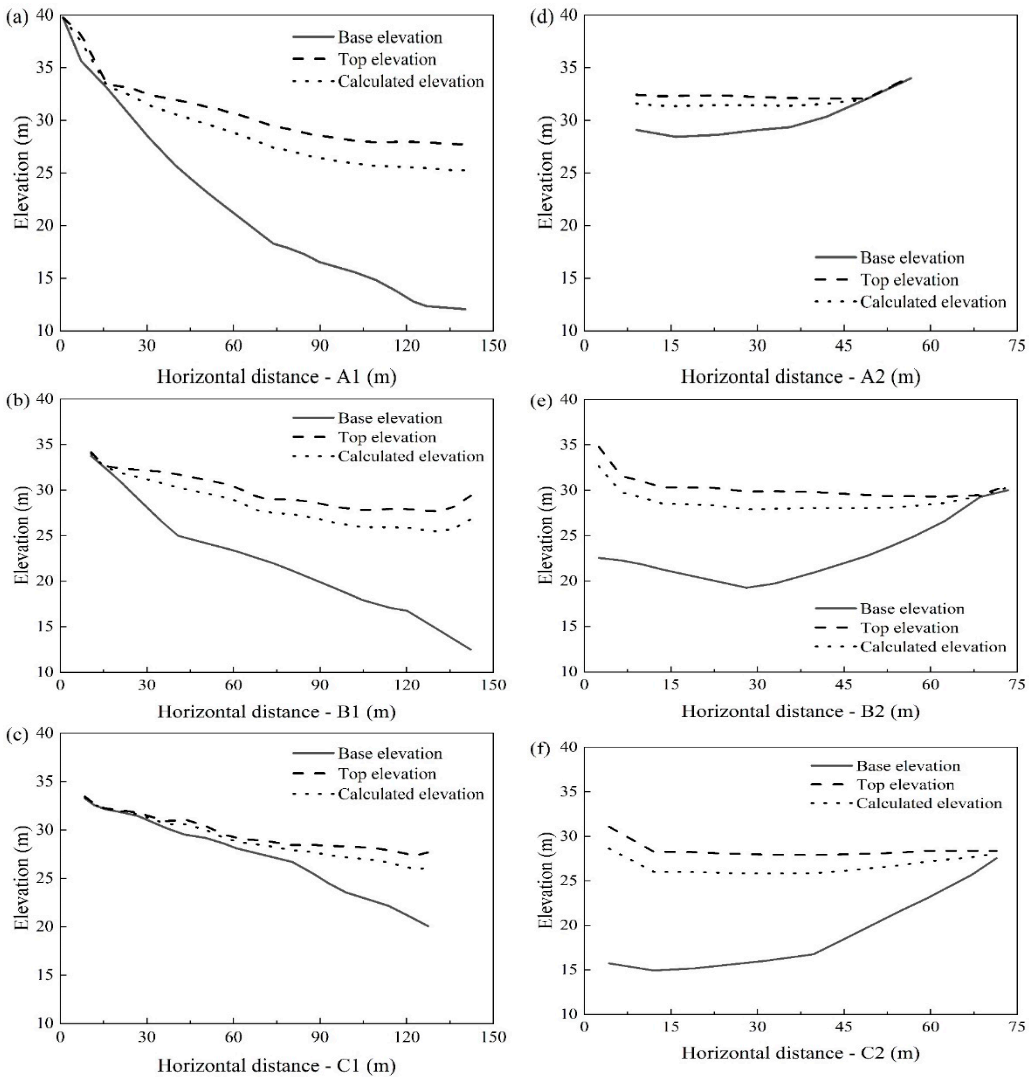

Figure 10. Settlement prediction results of different profiles in 2035: (**a**) section A1; (**b**) section B1; (**c**) section C1; (**d**) section A2; (**e**) section B2; (**f**) section C2.

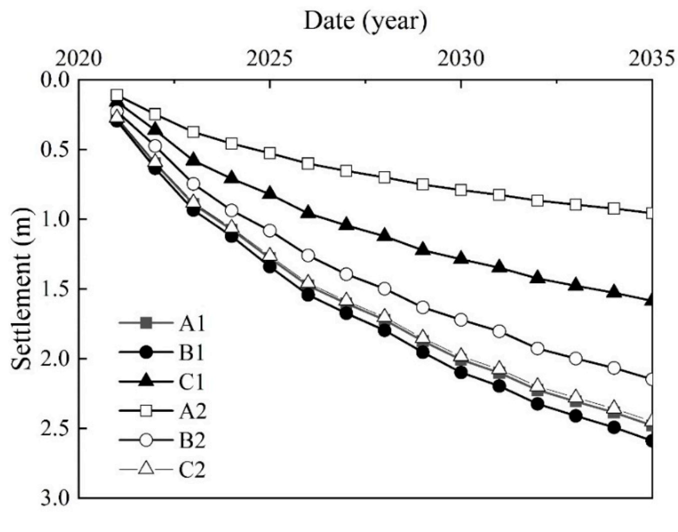

Figure 11. Variation curves of the settlement amount corresponding to the maximum settlement point of different profile lines (i.e., A1–C2) with time.

5. Conclusions

The physical composition, moisture content, volumetric weight, and compression characteristics of aged MSW at different depths in Xiawan landfill were tested, and the settlement of the aged MSW in the area to be filled with fly ash was calculated. The following conclusions can be drawn from the study results:

1. According to the test results, the content of kitchen waste was reduced to 0.1% after more than three years of biochemical degradation of MSW with high kitchen waste content. In developing countries (e.g., China), the content of kitchen waste in fresh MSW is high (generally higher than 50%). The impact of rapid degradation of kitchen waste should be considered in landfill settlement prediction and site reuse design (such as expansion). As for landfills with high-kitchen-waste-content MSW, it is recommended that the reuse project of the landfill sites after the kitchen waste is degraded be considered.
2. The moisture content of the aged MSW generally increased with depth, and the average moisture content at a depth of 5 m was 97%. Moreover, there might be a perched water table in the landfill due to the influence of the intermediate cover layer and the heterogeneity of the MSW, which was not conducive to the collection of leachate.
3. The void ratio of the aged MSW decreased from 4.0 to 2.2 with an increase in vertical load from 1 kPa to 400 kPa. The modified primary compression index of the aged MSW ranged from 0.22 to 0.27, and generally decreased with depth.
4. Under the load caused by fly ash, the thickness of the aged MSW after settlement can be reduced by approximately 15% to 20% compared to the initial thickness. The compaction of landfill waste could increase the landfill capacity of fly ash by about 3 years. The influence of aged MSW settlement must be considered in the capacity expansion design of existing landfills.

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