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A new ternary composition classification method for municipal solid waste and its application

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ABSTRACT

Landfill is the most common waste management method to deal with increasing generation of municipal solid waste (MSW). Around 70% of MSW has been disposed of in landfills, resulting in tens of thousands of closed and operating landfills worldwide. To ensure stability and integrity of a landfill, it is necessary to have a knowledge of the physical and engineering properties of MSW. The properties of MSW may vary widely due to different compositions. Given the significant variation in MSW constituents, a rigorous classification system can facilitate the interpretation and comparison of experimental and testing results among literature, which contributes to the knowledge of the properties of MSW. Therefore, in this study, 14 typical types of MSW constituents were classified using the Hierarchical Cluster Analysis (HCA) based on eight intrinsic properties of materials, including shear modulus(G), elastic modulus (E), Poisson's ratio (v), specific gravity (G_s), thermal conductivity (k), degradable organic content (DOC), methane yield (L_0), and natural water content (w_c). The results showed that the constituents of MSW can be divided into three fractions, namely, biodegradable (B), reinforcing (R), and inert (I) fractions, which is a new ternary MSW composition classification method. The ternary classification method was applied to reanalyze dry unit weight (γ_d) of 150 low-, medium-, and high-compacted MSW specimens from 54 available studies. The MSW types summarized cover waste with B = 1 - 100%, I = 0 - 86.4%, and R = 0 - 59.2%. The γ_d of MSW could be well described by its ternary composition and compaction efforts.

Keywords: Municipal solid waste, waste constituents, classification, dry unit weight

1 INTRODUCTION

A huge amount of municipal solid waste (MSW) is generated worldwide continuously. A significant portion of the MSW is disposed of in landfills, resulting in tens of thousands of closed and operating landfills worldwide. The properties of MSW may vary widely due to different compositions. In order to systematically study the effect of MSW compositions, some classification systems have been proposed in the past few decades. The conventional approach to characterize and report MSW composition is to separate it into as many types of constituents as possible (Geosyntec, 1996). Eleazer (1997) specialized in the biodegradable constituents, separating them into eight fractions. These classification methods may be beneficial to the theoretical studies but tedious and not suitable for engineering applications. Hence, there has been a tendency to categorize the constituents, similar to unified soil classification system (USCS), which is widely-accepted soil classification system used in engineering and geology. Some researchers (Landva and Clark,1990; Zekkos et al., 2005) simplified the waste to a uniform or binary mixture. Landva and Clark (1990) divided the waste constituents into organic and inorganic materials. Zekkos et al. (2005) segregated the waste specimens into the fraction larger than 20 mm and the fraction smaller than 20 mm. However, the binary mixture systems consider either biodegradability (Landva and Clark,1990) or particle size (Zekkos et al., 2005), which is too simplified. Further, some researchers (Grisolia et al., 1995; Dixon and Langer, 2006) attempted to use the ternary classification system, which can incorporate more information than the binary classification system. Grisolia et al. (1995) divided MSW into inert stable elements, highly deformable elements, and readily biodegradable elements. However, some constituents could be undistinguished, for instance, food residues can be divided into both biodegradable and highly deformable fractions. Dixon and Langer (2006) categorized MSW into reinforcing, incompressible, and compressive materials and defined fine fraction as <40mm. However, it focused on the mechanical properties but ignores the bio-chemical properties. The available classification methods all have merits, but none is widely acknowledged nor is validated by a variety of MSW samples with different constituents. Moreover, due to the lack of a standardized waste classification method, the MSW compositions reported in most available studies cannot be directly comparable. This hinders systematic and unbiased comparison of experimental and testing results among studies.

Therefore, in this study, we aim to establish a standardized MSW classification system which incorporates more information of MSW and can be implemented easily in new and available MSW studies. The novel ternary classification method was also applied to reanalyze a variety of MSW samples with different compositions from 54 available studies to correlate systematically the ternary composition and dry unit weight (γ_d) of MSW and investigate the influence of composition and compaction efforts on the γ_d.

2 CLASSIFICATION OF MSW USING HIERARCHICAL CLUSTER ANALYSIS

2.1 Classification method

MSW constituents typically include paper, food, yard, plastics, textile, wood, rubber, leather, ceramic, glass, metal, gravel, concrete, soil-like particles. We gather the values for the physical (specific gravity (G_s)), mechanical (shear modulus (G), elastic modulus (E), poisson's ratio (v)), bio-chemical (degradable organic content (DOC), methane yield (L_0)), thermal (thermal conductivity (k)), and hydraulic (natural water content (w_c)) properties of the 14 typical types of MSW constituents. They are categorized using the hierarchical cluster analysis (HCA), which is a practical and effective method to sort items into groups that share specific properties in common (Revelle, 1979). With the real material data, HCA is executed to group similar objects, so it is possible to classify the mentioned 14 constituents into three types with similar characteristics. To standardize variables, all the property values are normalized to 0-1, using the linear normalization method (Equation 1).

$$\mathrm{x} = \frac{\mathrm{x}_i - \mathrm{x}_{\min}}{\mathrm{x}_{\max} - \mathrm{x}_{\min}} \tag{1}$$

2.2 Property data of MSW

A summary of the 14 typical types of MSW constituents and their corresponding eight intrinsic properties and normalized vlues, including G, E, v, G_s, κ, DOC, L_0, and w_c, are listed in Table 1. These data of properties of individual constituents are obtained from journals, books, or websites (Cruz and Barlaz, 2010; Yesiller et al., 2014; Cardarelli, 2018; Manjunatha et al., 2020; The Engineering ToolBox, 2021). The data in parathesis are linear-normalized data for each intrinsic property using Equation 1. Rationales for selecting these intrinsic properties of constituents of MSW are as follows.

For mechanical properties, shear modulus, elastic modulus, and poisson's ratio can reflect the shear strength, compressibility, lateral stiffness of materials (Dixon and Langer, 2006). For physical properties, specific gravity is a constant for a specific composition and can also affect the dry unit weight of MSW (Yesiller et al., 2014). For bio-chemical properties, methane yield exhibits the degradation potential of the composition and only the degradable organic contents of MSW will be biodegraded (Cruz and Barlaz, 2010). Biodegradation is an important process for the long-term behavior of MSW. For thermal properties, thermal conductivity can affect the transmission of heat within the MSW mass (Manjunatha et al., 2020). Temperature is an important factor in the biodegradable process. For hydraulic properties, natural water content can affect hydraulic conductivity, since the more water a material can hold, the less water can infiltrate (Breitmeyer et al., 2019).

***Table 1.** Eight intrinsic properties of 14 individual composition of MSW*

Composition	Shear modulus (G, GPa)[a,d]	Elastic modulus (E, GPa)[a,d]	Poisson's ratio (v)[a,d]	Specific gravity (G$_s$)[c,d]	Thermal conductivity (κ, W·m^{-1}·K^{-1})[a]	Degradable organic content (DOC, %)[b]	Methane yield (L$_0$, mL of CH4/ dry g)[b]	Natural water content (w$_c$, %)[c]
Paper	4.27 (0.03)	10.5 (0.03)	0.23 (0.33)	1.2 (0.19)	0.095 (0.00)	50 (0.59)	145.8 (0.49)	6 (0.06)
Food	1.32 (0.01)	2.9 (0.01)	0.1 (0.00)	1.22 (0.20)	0.39 (0.001)	85 (1.00)	300.7 (1.00)	70 (1.00)
Yard	1.22 (0.01)	3.05 (0.01)	0.25 (0.39)	0.94 (0.04)	0.036 (0.00)	65 (0.77)	87.5 (0.29)	60 (0.85)
Wood	3.27 (0.02)	8.9 (0.02)	0.359 (0.66)	1.53 (0.36)	0.145 (0.00)	10 (0.19)	0 (0.00)	20 (0.27)
Plastics	0.26 (0.001)	0.69 (0.001)	0.35 (0.64)	0.95 (0.05)	0.425 (0.002)	0 (0.00)	0 (0.00)	2 (0.00)
Textile	1.05 (0.01)	2.91 (0.007)	0.39 (0.74)	1.27 (0.22)	0.25 (0.001)	0 (0.00)	0 (0.00)	10 (0.12)
Leather	0.1 (0.00)	0.3 (0.00)	0.45 (0.90)	0.86 (0.00)	0.185 (0.001)	0 (0.00)	0 (0.00)	10 (0.12)
Rubber	0.7 (0.004)	2.1 (0.01)	0.49 (1.00)	1.1 (0.13)	0.205 (0.001)	0 (0.00)	0 (0.00)	2 (0.00)
Ceramic	154.72 (1.00)	393 (1.00)	0.27 (0.44)	2.7 (1.00)	27.545 (0.12)	0 (0.00)	0 (0.00)	2 (0.00)
Glass	27.05 (0.17)	66 (0.17)	0.22 (0.31)	2.6 (0.95)	1.199 (0.01)	0 (0.00)	0 (0.00)	2 (0.00)
Metal	26.1 (0.17)	70.2 (0.178)	0.345 (0.63)	2.7 (1.00)	237 (1.00)	0 (0.00)	0 (0.00)	4 (0.03)
Gravel	19.2 (0.12)	48 (0.12)	0.25 (0.39)	2.6 (0.95)	3.135 (0.01)	0 (0.00)	0 (0.00)	2 (0.00)
Concrete	12.24 (0.08)	30 (0.08)	0.225 (0.32)	2.6 (0.95)	0.75 (0.003)	0 (0.00)	0 (0.00)	8 (0.09)
Soil-like particles	0.75 (0.004)	2.1 (0.01)	0.41 (0.80)	2.65 (0.97)	1.28 (0.01)	0 (0.00)	0 (0.00)	8 (0.09)
B[f]	2.27	5.48	0.19	1.12	0.17	66.67	178	45.33
R[f]	1.08	2.98	0.41	0.94	0.24	2	0	8.8
I[f]	17.07	43.26	0.29	2.63	48.67	0	0	4.4

[a] Data from Cardarelli (2018)
[b] Data from Cruz and Barlaz (2010)
[c] Data from Yesiller et al. (2014)
[d] Data from The Engineering ToolBox (2021)
[e] Data from Manjunatha et al. (2020)
[f] Average values for biodegradable (B), reinforcing (R), and inert (I) fractions

3.3 Classification result of MSW

The classification result of MSW constituents using HCA is shown in Figure 1. The composition can be clustered into three fractions based on distance. According to their nature, paper, yard, and food are named biodegradable fraction (B), textile, leather, plastics, rubber, and wood are reinforcing fraction (R), and ceramic, metal, gravel, concrete, soil-like particles, and glass are inert fraction (I). Each fraction shares similar physical, mechanical, bio-chemical, thermal, and hydraulic properties, hence are expected to behave similarly during compression, conductivity, and biodegradation processes. Although the classification results are different from those in Grisolia et al. (1995) and Dixon and Langer (2006), they appear to be a combination of the inert stable and readily biodegradable elements in Grisolia et al. (1995) and reinforcing materials in Dixon and Langer (2006). The food belongs to B fraction rather than undistinguished in Grisolia et al. (1995). The average values of each intrinsic property for B, I, and R fractions are also listed in Table 1. The differences of intrinsic properties among B, I, and R fractions can explain the necessity for classification. Overall, the developed classification method is expected to be well-applied to various correlations with crucial properties of MSW.

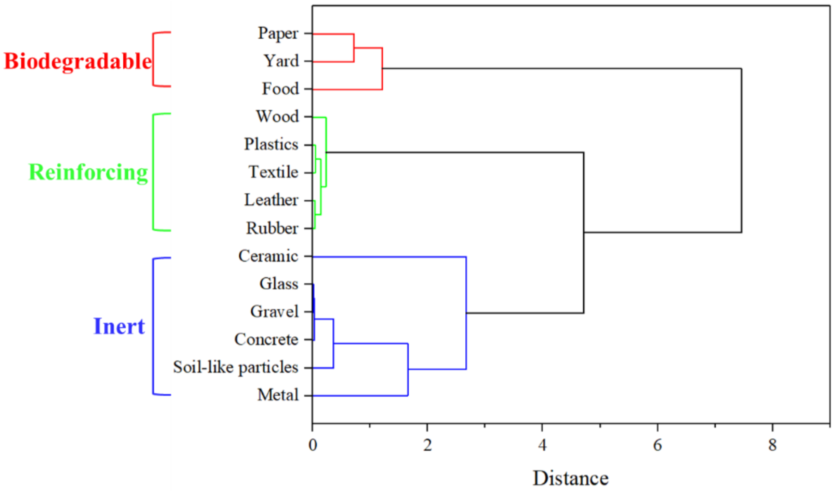


Figure 1. *Classification of MSW constituents using HCA*

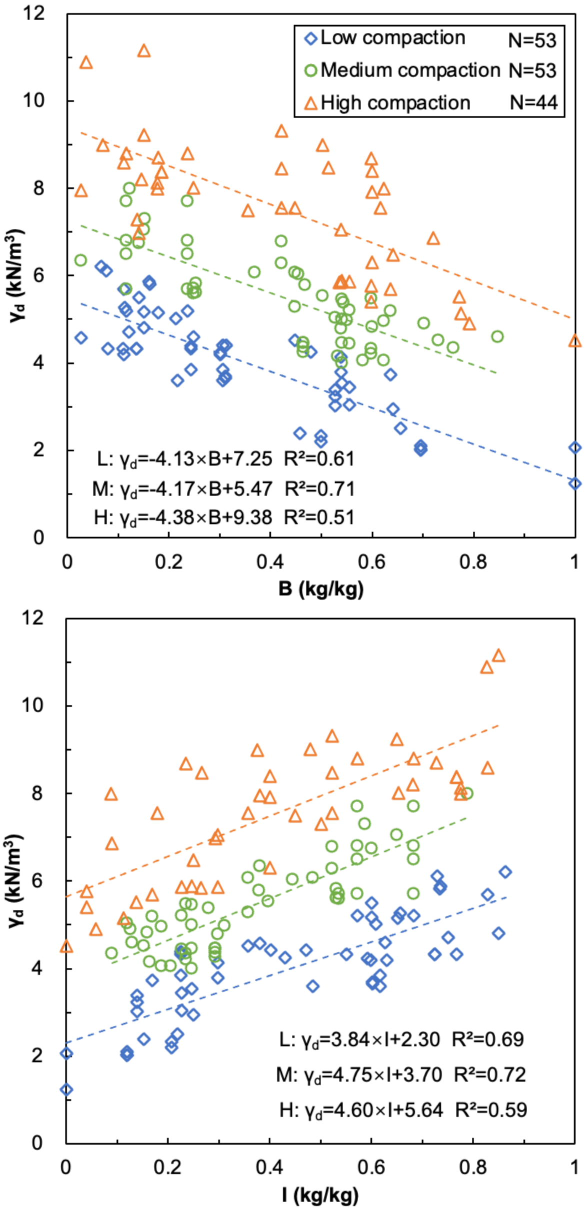
3 CORRELATION OF γ_d AND TERNARY COMPOSITION

3.1 Literature screening and data analysis

Available studies investigating the MSW properties through laboratory experiments were screened for the availability of information on the initial waste composition and dry unit weight (γ_d). A total of 150 MSW specimens with detailed composition characterization results from 54 available studies were summarized and characterized using the ternary composition characterization method (Bareither et al., 2012, 2013; Beaven, 2000; Bhandari and Powrie, 2013; Breitmeyer et al., 2019; Buchanan et al., 2001; Capelo and De Castro, 2007; Chen et al., 2010; Chouksey and Babu, 2015; Dixon et al., 2008; Fei and Zekkos, 2018; Gabr and Valero, 1995; Gomes et al., 2013; Gourc et al., 2010; Han et al., 2011; Hossain and Haque, 2012; Ivanova et al., 2008; Jang et al., 2002; Karimpour-Fard et al., 2011; Lakshmikanthan and Sivakumar Babu, 2017; Landva et al., 2000; Machado et al., 2008; Mali et al., 2012; Olivier et al., 2007; Powrie and Beaven, 1999; Pulat and Yukselen-Aksoy, 2019; Ramaiah et al., 2014; Reddy et al., 2009, 2011; Rosqvist and Bendz, 1999; Salih et al., 2021; Shi et al., 2016; Siddiqui et al., 2013; Singh et al., 2009; Staub et al., 2013; Stoltz et al., 2010, 2012; Suk et al., 2000; Tahmoorian and Khabbaz, 2020; Tinet et al., 2011; Valencia et al., 2009; Vilar and Carvalho, 2004; Wall and Zeiss, 1995; Woodman et al., 2013; Wu et al., 2012; Xie et al., 2006; Xu et al., 2015; Xu et al., 2020; Yuan et al., 2011; Zekkos et al., 2017; Zhang et al., 2018, 2020; Zhang et al., 2021; Zhao et al., 2014).

3.2 γ_d of MSW

The γ_d is a significant physical parameter for the investigation of engineering properties (e.g., compressibility, hydraulic conductivity, and shear strength) of landfilled MSW. It is expected that γ_d wil alter with changes in the ternary composition (B, I, and R) and compaction efforts. The γ_d values are presented with the ternary composition of MSW specimens under low, medium, and high compaction in Figure 2. The MSW types summarized cover waste with B = 1 - 100%, I = 0 - 86.4%, and R = 0 - 59.2%. The γ_d values of the MSW range between 1.25 and 11.16 kN/m^3, which are lower than the values for granular soil (11.9 - 22.9 kN/m^3) and clay (4.2 - 21.0 kN/m^3) (Mitchell and Soga, 2005, Peck et al.; 1974). Generally, γ_d increases significantly with an increase in I and a decrease in B. The R fraction has no obvious effect on the γ_d. The wide range of γ_d for specific composition may result from different compaction efforts. Hence, three compaction efforts (low, medium, and high) are defined based on the description of the specimen preparation process. Three linear regressions are obtained for the correlations of each composition fraction and γ_d for low-, medium-, and high-compacted specimens, respectively. It is apparent that γ_d increases with the increase in compaction efforts. γ_d will increase by ~2 kN/m^3 and ~4 kN/m^3 after medium and high compaction, respectively. The B and I fractions have better correlations with γ_d than R fraction. The correlations are in general better for low- and medium-compacted specimens than high-compacted ones. The correlations of B and I fractions and γ_d have high R^2 from 0.51 to 0.71 and from 0.59 to 0.72, respectively. This indicates that in practice, the γ_d of MSW can be well described by B and I fractions. However, poor correlations are found for R and γ_d with different compaction efforts, which could be attributed to the irregular particle size and shape of R and disturbance of MSW structure.



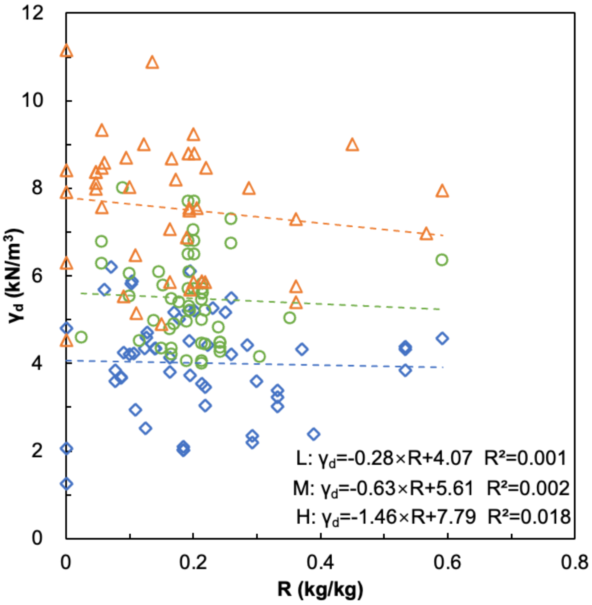


Figure 2. *Correlation between the dry unit weight (γ_d) and ternary composition (B, I, R) of MSW specimens under low, medium, and high compaction*

4 CONCLUSIONS

This study proposed a new ternary MSW classification system based on eight intrinsic properties of MSW, dividing 14 constituents of MSW into three fractions, namely, biodegradable (B), reinforcing (R), and inert (I) fractions. B fraction includes paper, food, and yard, R fraction includes plastics, textile, wood, rubber, and leather, and I fraction includes ceramic, glass, metal, gravel, concrete, and soil-like particles. This classification system was applied to correlate γ_d. The influence of MSW composition and compaction efforts on γ_d was investigated based on data of 150 specimens in the 54 available studies. γ_d increases with the increase in compaction efforts. γ_d increases significantly with an increase in I and a decrease in B. The R fraction has no unique correlation with the γ_d. The correlations of B and I fractions and γ_d have high R^2 from 0.52 to 0.72 and from 0.61 to 0.76, respectively. This indicates that in practice, the γ_d of MSW can be well-described by B and I fractions. The ternary MSW classification system and data synthesis and analysis method can be applied to analyze various properties of MSW, such as void ratio, compressibility, and hydraulic conductivity, in future work.

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REFERENCES

Bareither, C. A., Benson, C. H., Edil, T. B., & Barlaz, M. A. (2012). Abiotic and biotic compression of municipal solid waste. Journal of geotechnical and geoenvironmental engineering, 138(8), 877-888.

Bareither, C. A., Benson, C. H., & Edil, T. B. (2013). Compression of municipal solid waste in bioreactor landfills: Mechanical creep and biocompression. Journal of Geotechnical and Geoenvironmental Engineering, 139(7), 1007-1021.

Beaven, R. P. (2000). The hydrogeological and geotechnical properties of household waste in relation to sustainable landfilling (Doctoral dissertation, Queen Mary University of London).

Bhandari, A. R., & Powrie, W. (2013). Behavior of an MBT waste in monotonic triaxial shear tests. Waste management, 33(4), 881-891.

Breitmeyer, R. J., Benson, C. H., & Edil, T. B. (2019). Effects of compression and decomposition on saturated hydraulic conductivity of municipal solid waste in bioreactor landfills. Journal of Geotechnical and Geoenvironmental Engineering, 145(4), 04019011.

Buchanan, D., Clark, C. F., Ferguson, N. S., & Kenny, M. J. (2001). Hydraulic Characteristics of Wet-Pulverised Municipal Waste. Water and Environment Journal, 15(1), 14-20.

Capelo, J., & De Castro, M. A. H. (2007). Measuring transient water flow in unsaturated municipal solid waste–A new experimental approach. Waste Management, 27(6), 811-819.

Cardarelli, F. (2018). Materials handbook. London: Springer, 2254.

Chen, Y., Ke, H., Fredlund, D. G., Zhan, L., & Xie, Y. (2010). Secondary compression of municipal solid wastes and a compression model for predicting settlement of municipal solid waste landfills. Journal of geotechnical and geoenvironmental engineering, 136(5), 706-717.

Chouksey, S. K., & Babu, G. S. (2015). Constitutive model for strength characteristics of municipal solid waste. International Journal of Geomechanics, 15(2), 04014040.

Cruz, F. B. D. L., and Barlaz, M. A. (2010). Estimation of waste component-specific landfill decay rates using laboratory-scale decomposition data. Environmental science and technology, 44(12), 4722-4728.

Dixon, N., & Langer, U. (2006). Development of a MSW classification system for the evaluation of mechanical properties. Waste management, 26(3), 220-232.

Dixon, N., Langer, U. & Gotteland, P. (2008). Classification and mechanical behaviour relationships for municipal solid waste: study using synthetic wastes. Journal of Geotechnical and Geoenvironmental Engineering, 134 (1), 79-90.

Eleazer, W. E., Odle, W. S., Wang, Y. S., & Barlaz, M. A. (1997). Biodegradability of municipal solid waste components in laboratory-scale landfills. Environmental Science & Technology, 31(3), 911-917.

Fei, X., & Zekkos, D. (2018). Coupled experimental assessment of physico-biochemical characteristics of municipal solid waste undergoing enhanced biodegradation. Géotechnique, 68(12), 1031-1043.

Gabr, M. A., & Valero, S. N. (1995). Geotechnical properties of municipal solid waste. Geotechnical Testing Journal, 18(2), 241-251.

Geosyntec. (1996). Waste mass field investigation, Operating Industries Inc. landfill, Monterey Park, California. Report No. SWP-2.

Gomes, C., Lopes, M. L., & Oliveira, P. J. V. (2013). Municipal solid waste shear strength parameters defined through laboratorial and in situ tests. Journal of the Air & Waste Management Association, 63(11), 1352-1368.

Gourc, J. P., Staub, M. J., & Conte, M. (2010). Decoupling MSW settlement into mechanical and biochemical processes–Modelling and validation on large-scale setups. Waste Management, 30(8-9), 1556-1568.

Grisolia, M., Napoleoni, Q., & Tancredi, G. (1995). Contribution to a technical classification of MSW. In Proceedings Sardinia, 95, 761-767.

Han, B., Scicchitano, V., & Imhoff, P. T. (2011). Measuring fluid flow properties of waste and assessing alternative conceptual models of pore structure. Waste Management, 31(3), 445-456.

Hossain, M. S., & Haque, M. A. (2012). Effects of intermixed soils and decomposition on hydraulic conductivity of municipal solid waste in bioreactor landfills. Journal of materials in civil engineering, 24(10), 1337-1342.

Ivanova, L. K., Richards, D. J., & Smallman, D. J. (2008). The long-term settlement of landfill waste. Proceedings of the Institution of Civil Engineers-Waste and Resource Management, 161 (3), 121-133.

Jang, Y. S., Kim, Y. W., & Lee, S. I. (2002). Hydraulic properties and leachate level analysis of Kimpo metropolitan landfill, Korea. Waste management, 22(3), 261-267.

Karimpour-Fard, M., Machado, S. L., Shariatmadari, N., & Noorzad, A. (2011). A laboratory study on the MSW mechanical behavior in triaxial apparatus. Waste management, 31(8), 1807-1819.

Lakshmikanthan, P., & Sivakumar Babu, G. L. (2017). Performance evaluation of the bioreactor landfill in treatment and stabilisation of mechanically biologically treated municipal solid waste. Waste Management & Research, 35(3), 285-293.

Landva, A.O., & Clark, J.I. (1990). Geotechnics of waste fill. In Geotechnics of waste fills — theory and practice. Edited by A. Landva and G.D. Knowles. American Society for Testing and Materials, Special Technical Publication STP 1070, 86–103.

Landva, A. O., Valsangkar, A. J., & Pelkey, S. G. (2000). Lateral earth pressure at rest and compressibility of municipal solid waste. Canadian Geotechnical Journal, 37(6), 1157-1165.

Machado, S. L., Vilar, O. M., & Carvalho, M. F. (2008). Constitutive model for long term municipal solid waste mechanical behavior. Computers and Geotechnics, 35(5), 775-790.

Mali, S. T., Khare, K. C., & Biradar, A. H. (2012). Estimation of methane gas emission from municipal solid waste landfill: Pune City. India. Environmental Research Journal, 6(1), 71.

Manjunatha, G. S., Chavan, D., Lakshmikanthan, P., Swamy, R., and Kumar, S. (2020). Estimation of heat generation and consequent temperature rise from nutrients like carbohydrates, proteins and fats in municipal solid waste landfills in India. Science of the Total Environment, 707, 135610.

Mitchell J K and Soga K. (2005): Fundamentals of soil behavior. New York: John Wiley & Sons.

Olivier, F., & Gourc, J. P. (2007). Hydro-mechanical behavior of municipal solid waste subject to leachate recirculation in a large-scale compression reactor cell. Waste Management, 27(1), 44-58.

Peck, R.B., Hanson, W.E., and Thornburn, T.H., (1974), "Foundation Engineering", John Wiley and Sons, 514p.

Powrie, W., & Beaven, R. P. (1999). Hydraulic properties of household waste and implications for landfills. Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, 137(4), 235-237.

Pulat, H. F., & Yukselen-Aksoy, Y. (2019). Compressibility and shear strength behaviour of fresh and aged municipal solid wastes. Environmental Geotechnics, 9(1), 55-63.

Ramaiah, B. J., Ramana, G. V., & Kavazanjian, E. (2014). Undrained Response of Municipal Solid Waste Collected from a Waste Site in Delhi, India. Reddy, KR; Shen, S.(2014) Geoenvironmental Engineering. Proceedings Geo-Shangai.

Revelle, W. (1979). Hierarchical cluster analysis and the internal structure of tests. Multivariate Behavioral Research, 14(1), 57-74.

Reddy, K. R., Hettiarachchi, H., Parakalla, N., Gangathulasi, J., Bogner, J., & Lagier, T. (2009). Hydraulic conductivity of MSW in landfills. Journal of Environmental Engineering, 135(8), 677-683.

Reddy, K. R., Hettiarachchi, H., Gangathulasi, J., & Bogner, J. E. (2011). Geotechnical properties of municipal solid waste at different phases of biodegradation. Waste Management, 31(11), 2275-2286.

Rosqvist, H., & Bendz, D. (1999). An experimental evaluation of the solute transport volume in biodegraded municipal solid waste. Hydrology and earth system sciences, 3(3), 429-438.

Salih, B. M. M., Ibrahim, M. A., & Al-Omari, R. R. (2021). Estimation of the Settlement Components of Municipal Solid Waste. Modern Applications of Geotechnical Engineering and Construction: Geotechnical Engineering and Construction, 112, 375.

Shi, J., Qian, X., Liu, X., Sun, L., & Liao, Z. (2016). The behavior of compression and degradation for municipal solid waste and combined settlement calculation method. Waste management, 55, 154-164.

Siddiqui, A. A., Powrie, W., & Richards, D. J. (2013). Settlement characteristics of mechanically biologically treated wastes. Journal of geotechnical and geoenvironmental engineering, 139(10), 1676-1689.

Singh, M. K., Sharma, J. S., & Fleming, I. R. (2009). Shear strength testing of intact and recompacted samples of municipal solid waste. Canadian Geotechnical Journal, 46(10), 1133-1145.

Staub, M. J., Gourc, J. P., Drut, N., Stoltz, G., & Mansour, A. A. (2013). Large-scale bioreactor pilots for monitoring the long-term hydromechanics of MSW. Journal of Hazardous, Toxic, and Radioactive Waste, 17(4), 285-294.

Stoltz, G., Gourc, J. P., & Oxarango, L. (2010). Liquid and gas permeabilities of unsaturated municipal solid waste under compression. Journal of contaminant hydrology, 118(1-2), 27-42.

Stoltz, G., Tinet, A. J., Staub, M. J., Oxarango, L., & Gourc, J. P. (2012). Moisture retention properties of municipal solid waste in relation to compression. Journal of Geotechnical and Geoenvironmental Engineering, 138(4), 535-543.

Suk, H., Lee, K. K., & Lee, C. H. (2000). Biologically reactive multispecies transport in sanitary landfill. Journal of environmental engineering, 126(5), 419-427.

Tahmoorian, F., & Khabbaz, H. (2020). Performance comparison of a MSW settlement prediction model in Tehran landfill. Journal of environmental management, 254, 109809.

The Engineering ToolBox. (2021 January). https://www.engineeringtoolbox.com/

Tinet, A. J., Oxarango, L., Bayard, R., Benbelkacem, H., Stoltz, G., Staub, M. J., & Gourc, J. P. (2011). Experimental and theoretical assessment of the multi-domain flow behaviour in a waste body during leachate infiltration. Waste management, 31(8), 1797-1806.

Valencia, R., Van der Zon, W., Woelders, V. D. H., Lubberding, H. J., & Gijzen, H. J. (2009). The effect of hydraulic conditions on waste stabilisation in bioreactor landfill simulators. Bioresource technology, 100(5), 1754-1761.

Vilar, O. M., & Carvalhod, M. (2004). Mechanical properties of municipal solid waste. Journal of Testing and Evaluation, 32(6), 438-449.

Wall, D. K., & Zeiss, C. (1995). Municipal landfill biodegradation and settlement. Journal of environmental engineering, 121(3), 214-224.

Woodman, N. D., Siddiqui, A. A., Powrie, W., Stringfellow, A., Beaven, R. P., & Richards, D. J. (2013). Quantifying the effect of settlement and gas on solute flow and transport through treated municipal solid waste. Journal of contaminant hydrology, 153, 106-121.

Wu, H., Wang, H., Zhao, Y., Chen, T., & Lu, W. (2012). Evolution of unsaturated hydraulic properties of municipal solid waste with landfill depth and age. Waste Management, 32(3), 463-470.

Xie, M., Aldenkortt, D., Wagner, J. F., & Rettenberger, G. (2006). Effect of plastic fragments on hydraulic characteristics of pretreated municipal solid waste. Canadian geotechnical journal, 43(12), 1333-1343.

Xu, X. B., Zhan, T. L. T., Chen, Y. M., & Guo, Q. G. (2015). Parameter determination of a compression model for landfilled municipal solid waste: an experimental study. Waste Management & Research, 33(2), 199-210.

Xu, H., Wang, J. N., Zhan, L. T., Zhang, Z. Y., Xu, X. B., Chen, Y. M., & Yao, K. (2020). Characterization of compression behaviors of high food waste content (HFWC) MSW and no food waste content (NFWC) MSW in China. Waste Management, 103, 305-313.

Yesiller, N., Hanson, J. L., Cox, J. T., & Noce, D. E. (2014). Determination of specific gravity of municipal solid waste. Waste management, 34(5), 848-858.

Yuan, P., Kavazanjian Jr, E., Chen, W., & Seo, B. (2011). Compositional effects on the dynamic properties of municipal solid waste. Waste management, 31(12), 2380-2390.

Zekkos, D. P. (2005). Evaluation of static and dynamic properties of municipal solid-waste. University of California, Berkeley.

Zekkos, D., Fei, X., Grizi, A., & Athanasopoulos, G. (2017). Response of municipal solid waste to mechanical compression. Journal of Geotechnical and Geoenvironmental Engineering, 143(3).

Zhang, C., Liang, B., Liu, L., Wan, Y., & Zhu, Q. (2021). Determination of Unsaturated Hydraulic Properties of Seepage Flow Process in Municipal Solid Waste. Water, 13(8), 1059.

Zhang, Z., Pan, X., Fang, Y., Wang, Y., Zhang, Y., & Xu, H. (2020). Laboratory study on the hydraulic characteristics of mechanically and biologically treated waste in China. Waste Management, 102, 686-697.

Zhang, Z., Wang, Y., Xu, H., Fang, Y., & Wu, D. (2018). Influence of effective stress and dry density on the permeability of municipal solid waste. Waste Management & Research, 36(5), 471-480.

Zhao, Y. R., Xie, Q., Wang, G. L., Zhang, Y. J., Zhang, Y. X., & Su, W. (2014). A study of shear strength properties of municipal solid waste in Chongqing landfill, China. Environmental Science and Pollution Research, 21(22), 12605-12615.

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