Chapter: 4

Depth-Wise Assessment of Engineering Properties of Legacy-Waste/Municipal Solid Waste Fines

4.1. Introduction of the Chapter:

Previous chapters discussed in details about the background, previous studies aligned to the present study and the methodology and material used in the study. In the chapter investigation the various physical and engineering properties of MSW & MSWF from depth i.e. 0, 2, 5, & 10 meters at a legacy waste site near the Varuna River in Varanasi, India is caried. This chapter aims to determine depth wise MSW and MSWF profile. The importance of this in-depth characterization is underscored by the potential of their suitable utilization and environmental impacts of leachate leakage from dumpsites, especially those in proximity to water bodies (Naveen et al. 2018; Singh 2022b).

Through a comprehensive set of tests, including particle size distribution, specific gravity, consistency limits, compaction characteristics, California Bearing Ratio (CBR), and shear strength characteristics, the potential of MSWF is assessed in civil engineering applications, such as pavement subgrades (Donato et al. 2022; Sadek et al. 2022). Additionally, the use of Landfill Mined Soil-like Fraction (LMSF) in mitigating expansive soil cracks indicates the broader utility of these materials in civil engineering (Patil et al. 2023).

Findings of present chapter can contribute significantly to the understanding of MSWF's geotechnical properties and demonstrate its potential for beneficial reuse in civil engineering applications. By stabilizing MSWF below impermeable pavement layers, its exposure to the open environment and groundwater is minimized, offering an environmentally friendly solution to waste management. This chapter not only sheds light on optimizing civil engineering structures using MSWF but also aligns with CPCB guidelines, presenting a sustainable pathway for the reclamation of legacy waste sites and their conversion into usable urban land (R. Singh, 2022).

4.2. Material and Method

The methodology involves material collection, assessment of basic properties, experimental evaluation of materials treated with selected biopolymers, and the demonstration of various civil engineering applications for both treated and non-treated materials. Detailed material collection and processing are discussed in Chapter 3. Specifically, legacy waste samples were collected from an old dumpsite in Sarriya, Varanasi, India, at depths of 0, 2, 5, and 10 meters. These samples were then dried, homogenized, and sieved. The experimental investigation included microstructure, chemical, and geotechnical analyses to assess property variations with depth. Key tests, following ASTM standards, involved specific gravity, particle size distribution, consistency limits, pH, compaction characteristics, CBR, UCS, and shear strength. SEM and EDX analyses were also conducted for microstructural and elemental characterization.

For strength determination, cylindrical samples with a diameter of 50 mm and a length of 100 mm were prepared at the respective Maximum Dry Density (MDD) and Optimum Moisture Content (OMC). These samples were tested after 24 hours of preparation and desiccated in a desiccator to ensure homogenization and prevent moisture loss. Three replicas of each sample were made, and the average value of these three replicas was taken to ensure accuracy. The methodology for simplification is shown in the flowchart below Figure 16.

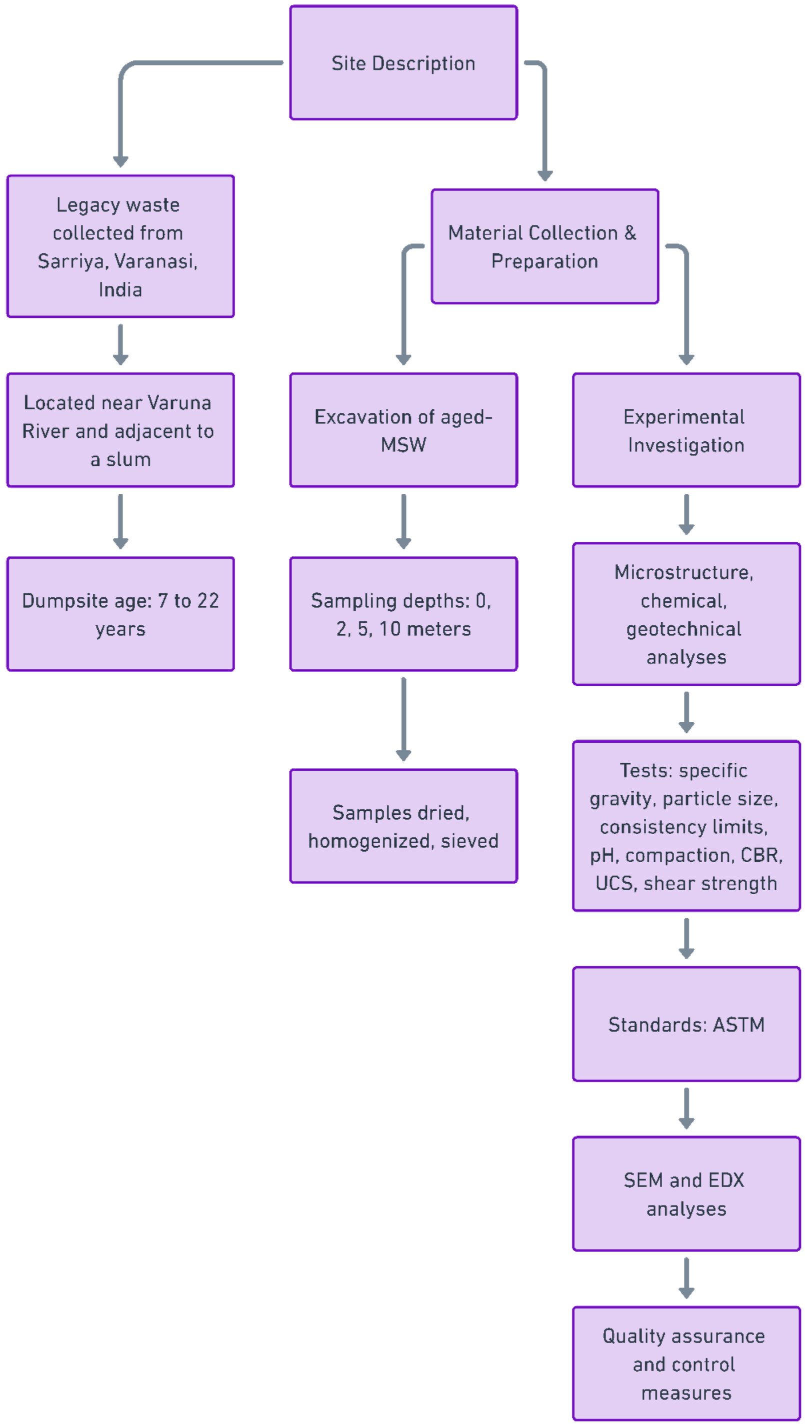

Figure 16: Flow chart of the investigation plan.

4.3. Results of Experimental Investigation:

4.3.1. Composition Analysis of MSW at Varying Dumpsite Depths:

The stratification of municipal solid waste (MSW) within the landfill reveals a notable shift in composition with increasing depth. As depicted in Figure 17: Composition Breakdown of Legacy Waste Materials

, the legacy waste, post-sieving through a No. 4 sieve (4.75mm), bifurcates into various waste components, with the finer fraction, termed Municipal solid waste fines (MSWF), earmarked for extensive experimental scrutiny. Table 6 enumerates the proportionate distribution of these fractions across different landfill strata.

Figure 17: Composition Breakdown of Legacy Waste Materials

The composition analysis, adhering to ASTM standards, indicates a pronounced increment in fines content as one delves deeper into the dumpsite. This trend is likely attributable to the advanced decomposition of biological waste, which, over time, disintegrates into smaller, soil-like particles al. 8. Non-biological waste, though less susceptible to decomposition, also contributes to the fines fraction due to material degradation under the influence of prolonged pressure and the landfill's own weight. This results in a denser fines composition at greater depths, corroborating with other research findings that suggest approximately 60% of legacy waste by weight is constituted by particles smaller than 4.75mm (refer to Table 9).

Table 6: The fractions of MSW, collected from varying depths.

Fractional components	**MSW collection depth**			
	0 m	**2 m**	**5 m**	**10 m**
Plastic waste (%)	3.5	3.8	2.2	1.5
Textile waste (%)	3.9	2.8	3.0	1.8
Glass, ceramic, and granite (%)	4.0	3.7	2.7	2.5
Aggregate (%)	22.7	19.0	17.5	15.1
MSWF (< 4.75mm) (%)	62.2	68.4	71.8	77.2
Other waste (%)	3.7	2.3	2.8	1.9

4.3.1. Effect of Depth on Organic Content of MSWF

The organic content within Municipal solid waste fines (MSWF) is a critical parameter that reflects the degree of waste decomposition and is indicative of the landfill's age and the environmental conditions within. The methodology involved sieving legacy waste to isolate particles under 4.75 mm, predominantly composed of decomposed organic matter such as paper, foliage, and wood. The quantification of organic content was conducted through thermogravimetric analysis, where MSWF samples were incinerated at 440°C, and the mean value from three random samples was calculated for each specified depth (Gerassimidou et al. 2020). Figure 18 a illustrates a clear inverse relationship between organic content and dumpsite depth. The highest concentration of organic material, 7.2%, is observed at the surface level (0 m), where recent biodegradable deposits are most abundant. Conversely, at a depth of 10 m, the organic content markedly diminishes to 2.6%, indicative of the advanced stage of decomposition or the absence of biodegradable material. Intermediate depths of 3 m and 5 m exhibit organic contents of 5% and 4.2%, respectively. These observations are in line with the patterns reported in the literature, where organic content is seen to decrease with depth as microbial activity and compaction reduce the volume of decomposable matter (Somani et al. 2022).

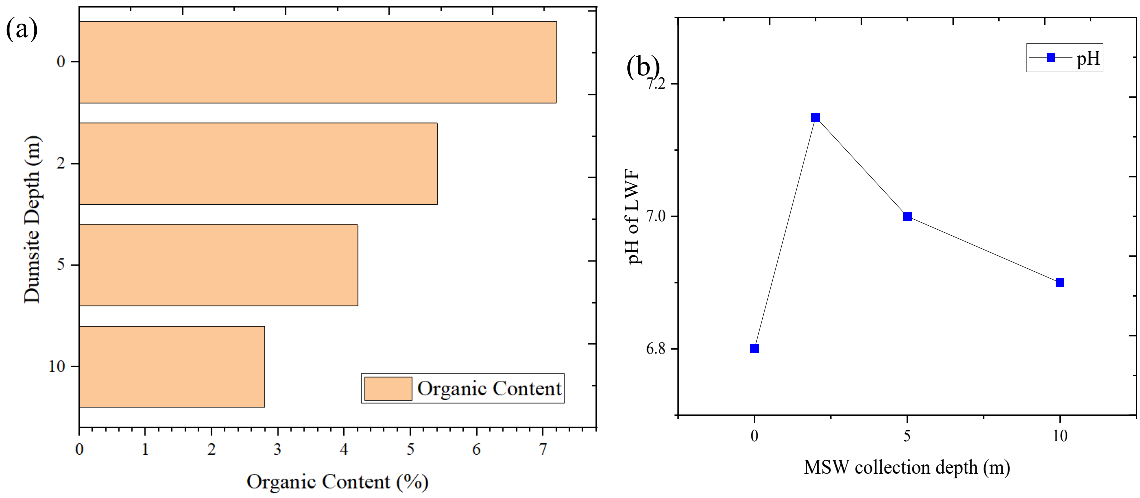

Figure 18:(a) Organic content of MSWF with depth (b) pH variation of MSWF with the depth of dumpsite.

4.3.2. Variation of pH of MSW of Varying Dumpsite Depth

The pH levels of municipal solid waste (MSW) at various depths of the dumpsite present a nuanced picture of the underlying biodegradation processes, as depicted in Figure 18 b. At the surface, the pH is measured at 6.8, indicative of active aerobic degradation where the presence of oxygen facilitates the breakdown of organic matter. At 2-meter depth, the pH slightly increases to 7.15. This elevation could be attributed to the infiltration of alkaline substances or the onset of anaerobic conditions, where the absence of oxygen leads to the production of alkaline byproducts such as methane and carbon dioxide, thus raising the pH.

Further into the dumpsite at 5 and 10 meters, the pH shows a declining trend, registering at 7 and 6.9, respectively. This reduction could be reflective of the diminishing biodegradation activity due to the age of the waste and the consequent decrease in the generation and entrapment of alkaline gases. At the substantial depth of 10 meters, it is plausible that the waste has undergone extensive stabilization over time, leading to a more neutral pH environment as the biodegradation process reaches a state of equilibrium. The observed pH variations align with other research findings on synthetic and various landfill wastes, where pH values have ranged from 6.47 to 8.5, as summarized in Table 9. These pH dynamics are crucial for understanding the chemical stability of the waste and its potential impact on the surrounding environment, particularly in the context of Municipal solid waste fines (MSWF) and their suitability for reuse in civil engineering applications.

4.3.3. Variation in Specific Gravity of MSWF with Depth

The investigation into the specific gravity of Municipal solid waste fines (MSWF) reveals a discernible increment with the depth of the legacy waste site. Initial measurements at the surface (0 m depth) show a specific gravity of 2.21, which is indicative of a higher concentration of organic materials, typically characterized by their lower density. As it was probed deeper into the legacy waste site, at a depth of 10m, the specific gravity notably increases to 2.35 (Ref. Figure 19 a) This trend suggests a gradual transition to a denser material composition, likely due to the increased presence of inorganic fines such as silts and clays, which are known to have higher specific gravities (Patwa et al. 2021). Furthermore, the compaction of these fines under the weight of overlying waste could lead to a denser arrangement of particles, thus contributing to the higher specific gravity readings observed at greater depths.

The specific gravity of soil is a critical parameter in geotechnical engineering as it influences the mechanical behaviour of the soil, including its shear strength and compressibility. In the context of landfill mining, understanding the variation in specific gravity is essential for predicting the load-bearing capacity of the reclaimed soil and for designing appropriate foundation systems (Das 2009). This comparison not only validates present findings but also underscores the potential of MSWF as a substitute material in geotechnical applications, provided that its handling and placement are managed according to its unique properties. By integrating these detailed geotechnical insights into the characterization of MSWF, present study aims to bridge the knowledge gap in the sustainable reuse of materials excavated from landfill mining projects.

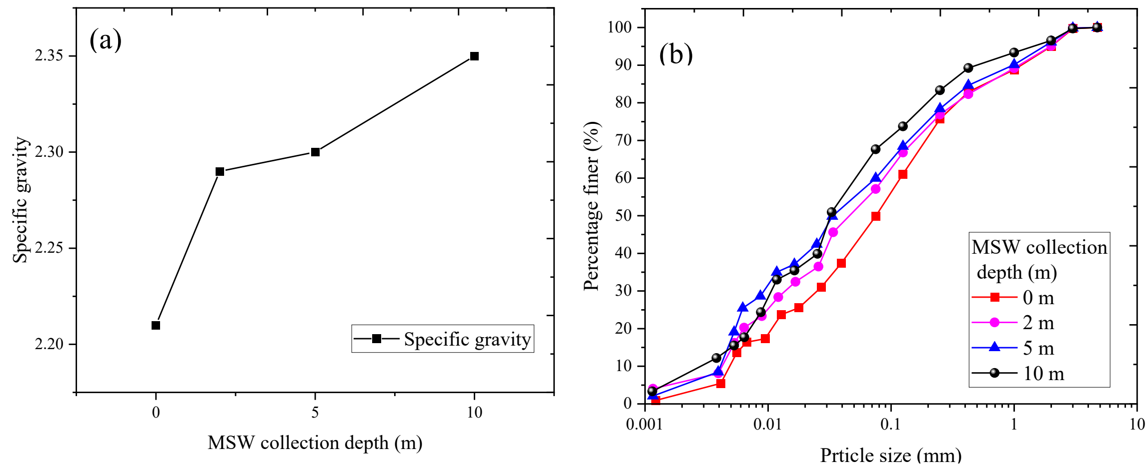

Figure 19: (a) Variation of specific gravity of MSWF (b) Particle size distribution of MSWF

4.3.4. Particle Size Distribution of MSWF

The particle size distribution of Municipal solid waste fines (MSWF) at varying depths, as shown in Figure 19 b, indicates a trend towards finer particles with increased depth. This observation is consistent with the expected outcomes of prolonged biodegradation and compaction within the landfill, which are key factors in the transformation of waste material into finer, soil-like particles. The distribution metrics, including D10, D30, D60, and the coefficients of uniformity (CU) and curvature (CC), are detailed in Table 8. A decrease in CU with depth suggests a more uniform particle size distribution, which is critical for evaluating the material's suitability for engineering applications, such as landfill cover layers or as fill material in construction.

Conversely, the increase in CC with depth could indicate a more well-graded composition, potentially offering better stability when used in geotechnical applications. This correlation suggests that an increase in CC results in improved particle interlocking and densification, thereby enhancing shear strength and overall geotechnical stability in applications such as landfill covers and fill material. These findings, while aligning with those of (Rawat and Mohanty 2021) for similar materials, also provide a direct correlation to the practical aspects of landfill mining, addressing the study's aim to characterize MSWF for sustainable reuse. The particle size distribution is a fundamental property that influences the behavior of MSWF in terms of its drainage, compaction, and shear strength, which are essential parameters for the design and implementation of civil engineering projects utilizing these materials. Granulometric insights into the broader context of legacy waste site rehabilitation, study contributes to the strategic objectives of biomining.

Table 7: Particle Size Distribution of Municipal solid waste fines (MSWF) at Various Depths

Parameters	**MSW collection depth**			
	0 m	**2 m**	**5 m**	**10 m**
D_{10} (mm)	0.005	0.0043	0.0041	0.0029
D_{30} (mm)	0.026	0.015	0.0091	0.012
D_{60} (mm)	0.25	0.086	0.072	0.05
C_U	50	20	17.56	17.24
Cc	0.54	0.61	0.28	0.99

D_{10}, D_{30}, D_{60}, are the particle sizes corresponding to 10%, 30%, and 60% finer materials on the cumulative particle size distribution curve, respectively, Cu- Coefficient of uniformity, Cc- Coefficient of curvature,

4.3.5. Compaction Characteristics of MSWF with Depth

Municipal solid waste fines (MSWF) compaction characteristics are integral to understanding their potential reuse in civil engineering applications. The data depicted in Figure 20 reveals a distinct correlation between the depth of MSWF extraction from the dumpsite and their compaction properties. Notably, the Maximum Dry Density (MDD) tends to increase with depth, while the Optimum Moisture Content (OMC) conversely decreases. At the surface level (0 m depth), the OMC is at its highest (16.5%), which is likely due to the abundance of organic material that is characteristically less dense and has a higher water absorption capacity. This results in a lower MDD at the surface. In contrast, at a depth of 10 meters, the MDD reaches a peak of 1.72 Mg/m^3, suggesting a denser material composition, possibly due to a higher concentration of clay particles, as indicated in Table 7. These particles, when subjected to compaction efforts, tend to slide over each other, creating a more compact and dense structure. This phenomenon is consistent with the findings of 94, who observed similar behavior in compacted soil samples. The study's findings are contextualized with existing literature in Table 9, providing a benchmark for comparison and further emphasizing the unique contributions of this research in understanding the compaction behavior of MSWF at varying depths. This understanding is crucial for the design and implementation of landfill mining projects, ensuring that the materials extracted are utilized optimally in a manner that is both environmentally sustainable and technically sound.

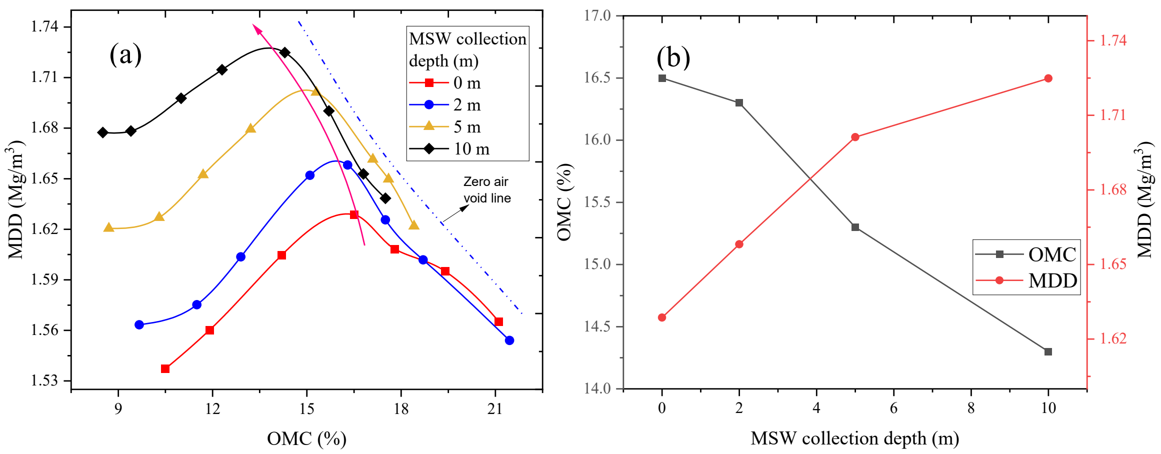

Figure 20: (a) Compaction curves of MSWF of different depths (b) Variation of OMC and MDD of MSWF

4.3.6. Variations in Consistency Limits of MSWF

The consistency limits of Municipal solid waste fines (MSWF) provide essential insights into their behaviour and potential for reuse in various engineering applications. As depicted in Figure 21 a, the liquid limit (LL), plastic limit (PL), and plasticity index (PI) of MSWF all exhibit an upward trend with increasing depth of the dumpsite. This pattern is likely a consequence of the accumulation of finer particles at greater depths, which is a result of the intense pressure and advanced degradation processes occurring within the landfill over time.

The observed increase in LL, PL, and PI with depth suggests that the fines have a higher specific surface area, necessitating a greater volume of water to achieve hydration. Additionally, the elevated interparticle cohesion among these fines requires more water to transition the MSWF matrix to a plastic state. At the maximum depth studied, 10 meters, the LL, PL, and PI values reached their zenith at 36.7%, 24.2%, and 12.5%, respectively. Conversely, at the surface level (0 m depth), the values were at their lowest, with LL at 30.5%, PL at 22.9%, and PI at 8.6%. These findings align with the patterns observed in other studies, such as 95, which reported similar increases in consistency limits with a rise in fine particle content in sand. Understanding the variations in consistency limits is critical for predicting the behavior of MSWF when used as a construction material, particularly in terms of stability and durability.

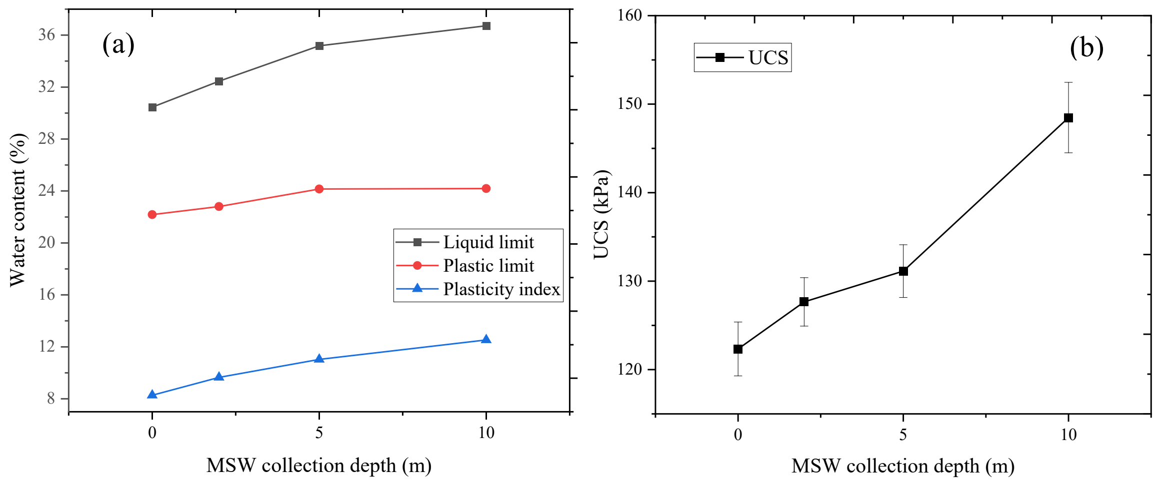

Figure 21: (a) Variation of consistency limits of MSWF (b) Variation of UCS with depth.

4.3.7. Compressive Strength of MSWF with Depth

The compressive strength of Municipal solid waste fines (MSWF), as determined by the unconfined compressive strength (UCS) test, is a critical parameter for assessing their suitability for various civil engineering applications. The UCS is indicative of the material's ability to withstand loads without experiencing failure. Present findings, illustrated in Figure 21 b, reveal that the UCS of MSWF escalates with an increase in dumpsite depth. This trend is attributable to the enhanced interparticle cohesion found within the fines collected from greater depths, where the fines are more densely packed due to the prolonged pressure and decomposition processes.

The peak UCS value, averaging 148.5 kPa, was observed at a depth of 10 meters, while the lowest UCS of 122.3 kPa was recorded at the surface level of the dumpsite. These measurements were taken from samples prepared at their respective optimum moisture content (OMC) and maximum dry density (MDD), which were then cured for 24 hours at room temperature within a desiccator prior to testing.

When compare with other materials detailed in Table 9, such as Municipal Solid Waste bottom ash, which exhibits a UCS range of 1000-1100 kPa in saturated conditions and 900-1000 kPa in unsaturated conditions at a density of 1.6 g/cc, it is evident that MSWF has a comparatively lower UCS. However, the relevance of this comparison lies in the context of the material's application. While MSWF may not match the compressive strength of more traditional materials, its increasing strength with depth provides valuable information for its potential use in scenarios where lower compressive strength is permissible or can be engineered to meet the requirements.

4.3.8. California Bearing Ratio (CBR) of MSWF with Depth

The California Bearing Ratio (CBR) is a pivotal measure in the design of pavements and other surfaces that bear loads. It assesses the strength of subgrade soil and its suitability for use in road and airfield pavements. This study, as depicted in Figure 22 a, has meticulously analyzed the CBR of Municipal solid waste fines (MSWF) at varying depths of a legacy waste site. The results indicate a discernible increase in both soaked and unsoaked CBR values as the depth of MSW collection augments. This is primarily due to the denser soil profile created by the finer particles at greater depths, which resists penetration by the CBR plunger more effectively. Consequently, the CBR values are higher for MSWF collected from these depths. Specifically, the soaked CBR values ranged from a minimum of 7.5% to a maximum of 9.8%, while the unsoaked CBR values were between 15.4% and 17.2%.

When contextualized with other studies, such as the CBR values reported for the Varanasi landfill by 93 and a Himachal Landfill by Sharma et al. (2018), these findings present a nuanced understanding of the geotechnical properties of MSWF. The soaked CBR values for the Varanasi landfill were found to be between 10.6–12.6%, slightly higher than present study, while the Himachal Landfill presented lower values of 4.52-6.7%. The unsoaked CBR values from these studies ranged from 14.21–19.74 and 12.34-17.42%, which are also higher than those observed in present research. This variability underscores the importance of site-specific analysis for the accurate assessment and utilization of MSWF in civil engineering applications.

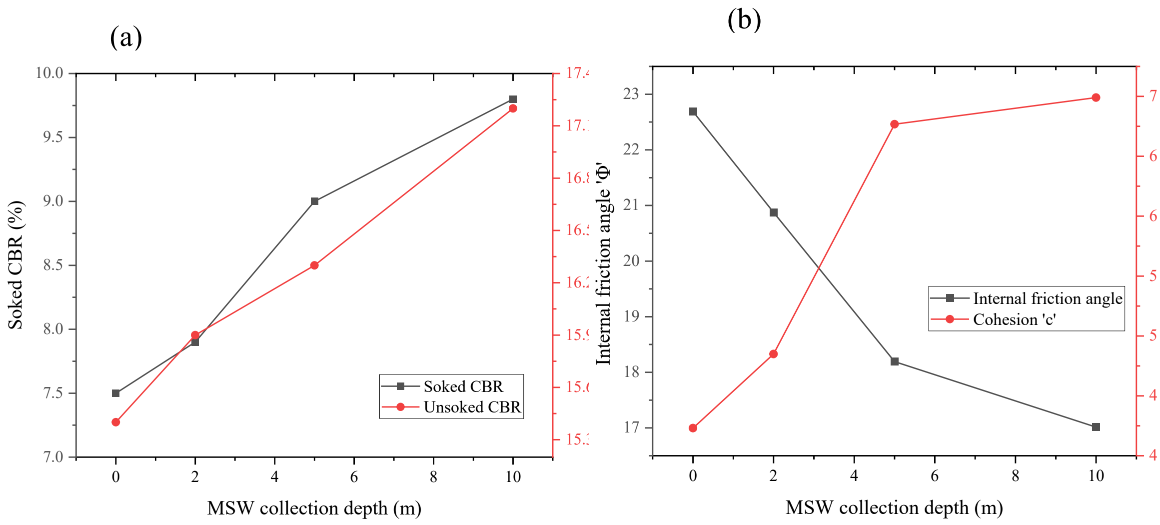

Figure 22: (a) Compaction curves of MSWF (b) Variation of cohesion and angle of internal friction

4.3.9. Shear Strength Characteristics of MSWF with Depth

The shear strength parameters of Municipal solid waste fines (MSWF) were determined using unconsolidated undrained (UU) triaxial tests, with confining pressures set at 50, 100, and 150 kPa. The tests revealed a discernible pattern: as the depth increased, so did the cohesion of the MSWF, indicating a more compact material composition in the deeper layers of the waste. Specifically, the cohesion values ranged from 42.3 kPa at the surface to 69.9 kPa at a depth of 10 meters. In contrast, the angle of internal friction showed a decrease with depth, from 22.7° at the surface to 17° at the deepest point measured. These variations are illustrated in Figure 22 b, which plots the deviator stress against axial strain for different confining pressures, showing the highest deviator stress at an average axial strain of 6 to 8%.

This nuanced understanding of the shear strength characteristics of MSWF is essential for the study's aim to thoroughly characterize the geotechnical properties of legacy waste. It provides a clear indication of the material's behavior under stress and its potential suitability for engineering applications, such as landfill reclamation and the construction of embankments. The data also contribute to the broader goal of sustainable waste management by offering insights into the structural integrity of materials recovered from legacy waste sites. This aligns with the research objectives by highlighting the potential for the civil engineering reuse of MSWF, thereby addressing the identified research gap. The comparative analysis with other forms of MSW, as referenced in the literature 96–98, further underscores the unique properties of MSWF and its distinct behaviour compared to more conventional materials.

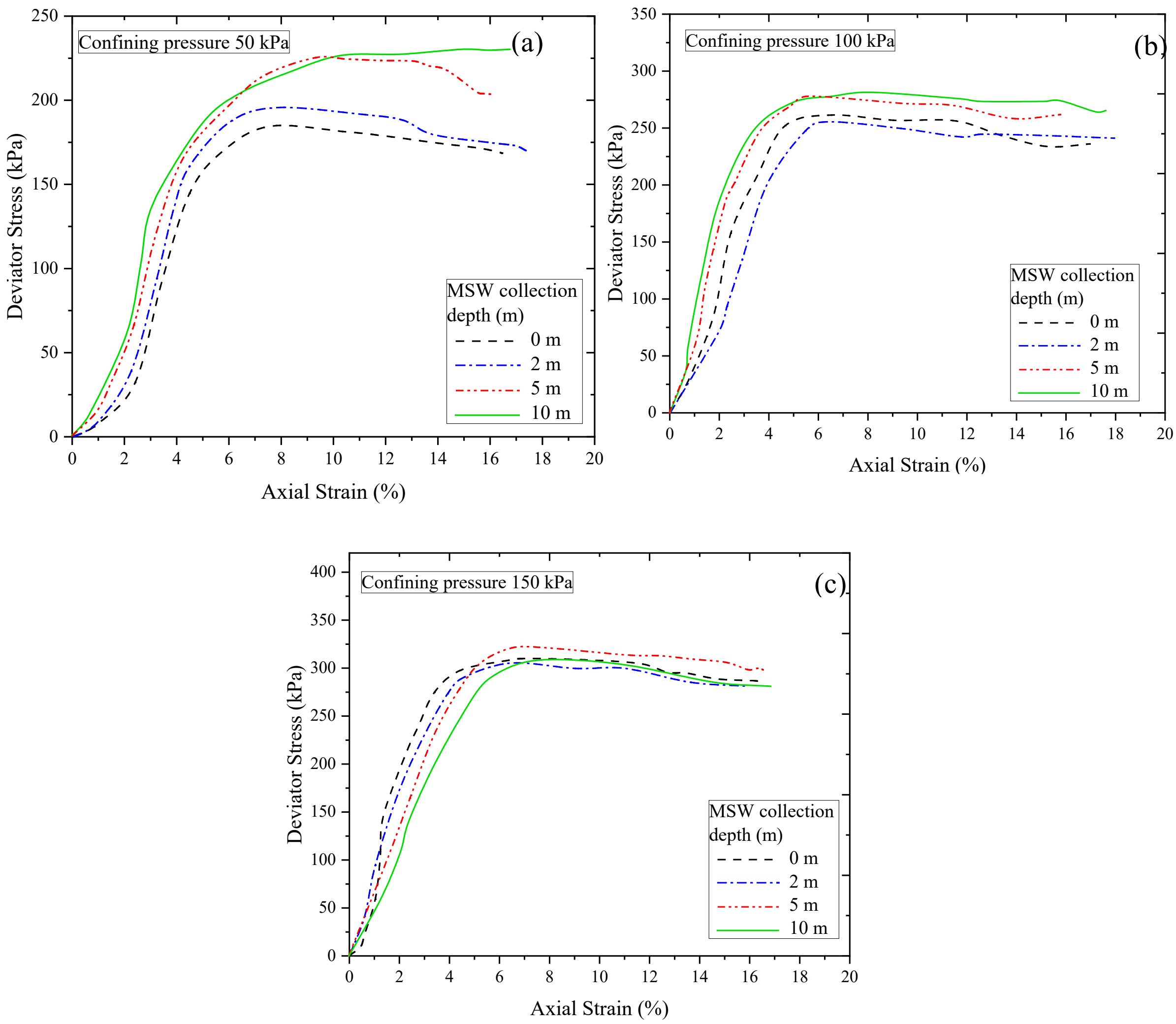

Figure 23: Deviator stress vs. axial strain of MSWF for different depths of MSW collection at confining stress of (a) 50 kPa, (b) 100 kPa, (c) 150 kPa

4.3.10. Microstructural and Elemental Analysis of MSWF with Depth

The microstructural and elemental composition of Municipal solid waste fines (MSWF) was scrutinized using scanning electron microscopy (SEM) and energy dispersive X-ray analysis (EDX), with the findings depicted in Figure 24 and summarized in Table 8. SEM imagery revealed a denser aggregation of fines in samples from 5 to 10 meters depth compared to those from shallower depths of 0 and 2 meters. The EDX analysis identified the presence of various metals within the MSWF, including aluminium (Al), magnesium (Mg), titanium (Ti), iron (Fe), niobium (Nb), and tantalum (Ta), with Ti, Fe, Nb, and Ta being recognized as heavy metals.

Interestingly, while other studies have detected hazardous heavy metals like lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) in MSW, these were found in negligible quantities or were below detectable levels in the current study (Huang et al., 2022; A. Singh & Chandel, 2022). This suggests a distinct composition of the MSWF in the studied dumpsite, which may have implications for its handling and potential reuse. The highest weight percentage of carbon was recorded at a depth of 10 meters (45.52%), which aligns with the expectation of increased carbonic compound formation due to more extensive decomposition at greater landfill depths. Conversely, the highest weight percentage of oxygen (48.97%) was found in samples from the surface, likely due to more direct interaction with the atmospheric oxygen.

This microstructural and elemental characterization is pivotal to the study's objectives, as it provides a granular view of the material's composition, which is essential for assessing its suitability for various applications. The absence of certain hazardous heavy metals in significant quantities could potentially broaden the scope for the safe reuse of MSWF in civil engineering projects, thus contributing to the research's aim of promoting sustainable waste management practices. Moreover, the findings offer a nuanced understanding of the changes in MSWF composition with depth, which is critical for the strategic planning of biomining operations and the subsequent application of the excavated materials.

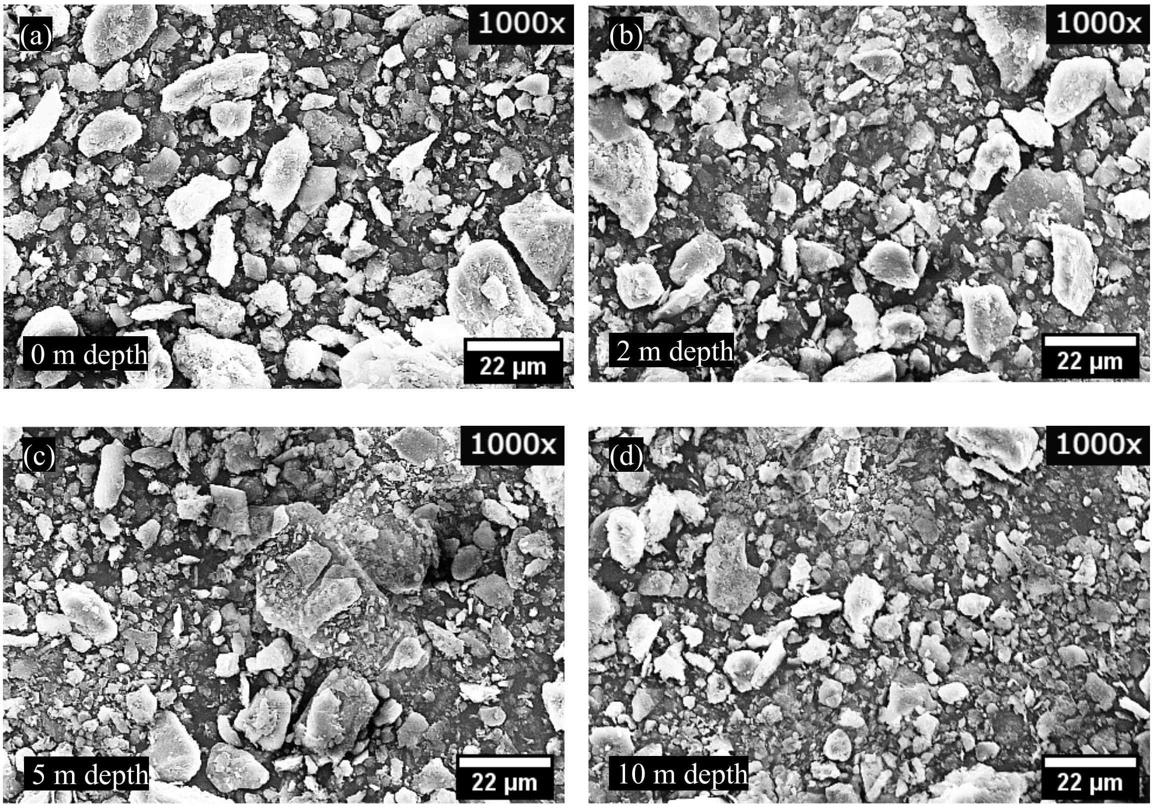

Figure 24: Scanning Electron Microscopy Depictions of Municipal Solid Waste Fines at Varied Dumpsite Depths

Table 8: Elemental Composition and Spectrum Analysis of Municipal Solid Waste Fines (MSWF)

Spectrum Label	C	O	Na	Mg	Al	Si	K	Ca	Ti	Fe	Nb	Ta
Weight % 0 m	15.58	48.97	3.59	0.48	8.57	18.34	0.63	1.79	0.03	1.47	0.37	0.19
Weight % 2 m	25.51	26.79	--	0.18	1.72	40.26	0.79	0.63	0.14	2.57	1.15	0.26

Weight % 5 m	21.12	36.99	--	1.03	9.11	19.43	6.63	0.57	0.23	4.55	0.24	0.12
Weight % 10 m	45.52	31.06	--	0.65	6.34	9.61	2.94	0.37	0.31	2.92	0.28	0

4.4. Significance of Geotechnical Findings

The geotechnical analysis conducted in this study reveals a clear stratification of Municipal solid waste fines (MSWF) properties with depth, which is of particular relevance given the dumpsite's proximity to the Varuna River. The results demonstrate that as it is probed deeper into the landfill, the MSWF becomes more homogenous and stable, with a notable increase in fines and a corresponding decrease in organic content. These changes suggest a reduced influence of the adjacent water body on the waste material, leading to a more consistent and predictable behavior of the MSWF.

The improved geotechnical properties at greater depths, such as higher Maximum Dry Density (MDD), Unconfined Compressive Strength (UCS), shear strength, and California Bearing Ratio (CBR), indicate that the deeper MSWF is less susceptible to water-induced degradation. This is particularly significant for civil engineering applications where the integrity of the material is paramount, and the risk of leachate migration into the water body must be carefully managed. Furthermore, the study underscores the need for careful consideration of the environmental impact of landfill reclamation projects, especially when situated near water bodies. The findings suggest that sourcing MSWF from deeper layers can yield a material that is not only more suitable for construction purposes but also poses a lower environmental risk due to its reduced organic content and higher stability.

Table 9: Comparative Analysis of Geotechnical Properties of MSWF and Various MSW Sources

Parameters	MSWF Properties (In Study)	Properties of different MSW forms
Fines percentage	77.2-62.2% (<4.75 mm)	70% (< 5mm) 101; 43% (< 20 mm) 102; 50 (< 4 mm) 103; 60% (<4.75 mm)
Heavy Metals	Ti, Fe, Nb, Ta	As, Cd, Cu, Cr, Co, Fe, Hg, Ni, Pb, Ti, Zn
pH Value	6.8-7.15	Synthetic MSW- 7.5; Gazipur Landfill 7.4-7.6 ; Mulund dumpsite Mumbai 6.47-7.87 ; Delhi Landfill - 7.1-8.5
Specific gravity	2.21-2.35	Synthetic- 1.09-2.47; Varanasi- 2.32; MSW MSWI Ash - 2.10-2.61
Particle size distribution Cu, Cc	17.24-50 0.28-0.99	Varanasi Landfill Cu, Cc - 25.76 and 0.88
Optimum moisture content	15.9-17.8 %	SLM Delhi Landfill – 20-30 % 98; MSW Varanasi- 18.40% ; MSWI Ash- 18.9%–28.4% ; Ghazipur landfill- 17-19%
Maximum dry density	1.64-1.69 Mg/m2	SLM Delhi Landfill – 13.5-15.2 kN/m³, Synthetic MSW - 4.7 – 6.0 kN/m³, MSW Varanasi- 1510 kg/m³, MSWI Ash- 11.65–16.4 kN/m³, Ghazipur landfill- 16.7-15.5 kN/m³.
Plasticity Index PI	8.3 - 12.5 %	Sixty-year-old MSW- 19-32 %; SLM Delhi Landfill – NP ; Ghazipur landfill- NP ; MSWI Ash- 6-14
Unconfined compressive strength (UCS)	119.2 - 152.9 kPa	MSWI bottom ash (1600 kg/m³), Saturated- 1000-1100 kPa, Unsaturated- 900-1000 kPa, MSWIFA ~200-1000 kPa.
California bearing ratio	Soaked- 9.1 - 10.2, Unsoaked- 15.4 - 17.2	Varanasi Landfill- (Unsoaked) 14.21–19.74 (Soaked) 10.6–12.6; Himachal Pradesh Landfill- (Unsoaked) 12.34-17.42, (Soaked) 4.52-6.7
Cohesion (c)	42.3 - 69.9 kPa	Synthetic MSW- 16–19 kPa, Shredded fresh MSW- 31–64 kPa, SLM Delhi Landfill- 20–24 kPa, Ghazipur landfill- 10–25 kPa.
The angle of internal friction (φ)	17.0 - 22.7 °	Synthetic MSW- 27-29 °; Shredded fresh MSW 26-30 °; SLM Delhi Landfill - 34-36 °; Ghazipur landfill- 28-38°

MSWIA- *Municipal solid waste incineration ash,* ***SLM***- *Soil-like material,* ***MSWIFA***- *Municipal solid waste incineration fly ash,* ***MSWI bottom ash*** *- Municipal solid waste incineration bottom ash,* ***Cc***- *Coefficient of curvature,* ***Cu***- *Coefficient of uniformity,* ***PI***- *Plasticity index,* ***UCS***- *Unconfined compressive strength*

Reference: *(Rawat and Mohanty 2021); (Mondelli et al. 2022; Singh and Chandel 2022); (Reddy et al. 2011); (CRRI Geotechnical Engineering Division 2016); (Singh and Chandel 2020); (Datta et al. 2020); (Oettle et al. 2010); (Reddy et al. 2009b); (Liang et al. 2020); (Xu 2019); (Reddy et al. 2009a); (Sharma et al. 2018); (Zekkos et al. 2013)*

4.5. Key takeaways and Way Forward

- Organic content decreases with depth, becoming more consistent and less influenced by external factors, suggesting better stability at greater depths.
- UCS of LWF increases with depth, from 120 kPa at shallow depths to 140 kPa at 10 meters depth, indicating suitability for civil engineering applications.
- Specific gravity increases from 2.21 at the surface to 2.35 at 10 meters depth, indicating denser material compositions such as silts and clays.
- Both soaked and unsoaked California Bearing Ratio (CBR) values increase with depth, with soaked CBR values rising from 15.3% at the surface to 17.4% at 10 meters depth, indicating a denser soil profile suitable for road and airfield pavements.
- SEM imagery shows denser aggregation of fines in samples from 5 to 10 meters depth, indicating more compact material composition and enhanced stability at greater depths.
- EDX analysis identified metals such as Al, Mg, Ti, Fe, Nb, and Ta in LWF, with concentrations varying by depth, affecting material reactivity and application suitability.

- Elemental composition at 10 meters depth: 48.97% O, 8.57% Al, 18.34% Si, 1.79% Ca, and 1.47% Fe, indicating significant quantities of heavy metals.
- Particle size distribution shows finer particles at greater depths, with D10 decreasing from 0.005 mm at the surface to 0.0029 mm at 10 meters depth.
- Consistency limits (LL, PL, PI) of LWF increase with depth, indicating higher water retention capacity and specific surface area of finer particles.

In the next chapter, the properties of the **biopolymer-treated MSWF** analysed, focusing on samples cured in dry conditions. This analysis will also represent the effects of surface treatment.