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GEOTECHNICAL CHARACTERIZATION AND POTENTIAL ECOLOGICAL RISK ASSESSMENT FROM SOIL-LIKE MATERIAL OBTAINED FROM LANDFILL MINING

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Landfill mining targets the issue of legacy waste at municipal solid waste (MSW) dump sites, and the soil-like material or fine fraction is one of the four primary residues of landfill mining. This fine fraction constitutes around 45-80% of the overall landfill-mined residues, hence its utilization is of the utmost significance. However, due to the distinct waste composition and heterogeneity of the fine fraction, its valorization becomes challenging. This study investigates the geotechnical characterization, heavy metal analysis, as well as the assessment of potential ecological risks caused by fine fraction from landfill mining at the Boragaon dump site in Guwahati, India. The findings indicated that soil-like material is classified as well-graded, non-plastic sand with low specific gravity and bulk density values of 2.15 and 1.01 g/cc, respectively, and high porosity of 69% owing to organic matter. The OMC and MDD values were reported to be 28.75% and 1.32 g/cc, respectively, and the shear strength parameters were determined to be 10.7 kPa and 40.3°, indicating characteristics typical of organic soil. The permeability of the fine fraction was 4.7E10-8 m/s showing medium to low permeability. The fine fraction also demonstrated elevated measures of total heavy metals. Based on the potential ecological risk assessments, Pb had high risk, followed by Cu and Ni contributing to moderate risk, and Cr and Zn contributing to low risks. Given the evident ability of the soil-like material to cause pollution within the geoenvironment, appropriate treatment methods have been suggested.

Keywords: Landfill mining, fine fraction, soil-like material, municipal solid waste, geotechnical characterization, potential ecological risk assessment, heavy metal pollution.

1. Introduction

Numerous developing nationsface significant challenges in managing substantial quantities of municipal solid waste (MSW) deposited over time through open dumping practices. Legacy waste is defined as aged MSW ditched in dump sites and non-sanitary landfills for more than two decades (Peter et al., 2019). Landfill mining involves the systematic excavation, screening, sorting, and segregation of legacy MSW in order to reclaim urban spaces and obtain landfill-mined residues. These residues possess the capability to replace essential resources, thus enhancing the prospect of a circular economy(Jones et al., 2013). Besides this, the landfill mining operation also contributes to the restoration and remediation of urban land space. The utilization of the fine fraction, which makes up approximately 45-80% of the total landfill-mined residues, is of the utmost significance. However, the peculiar characterization of the fine fraction also poses challenges to its overall application. The study byGoli et al. (2022) indicated that the fine fraction contains an exceptionally high concentration of heavy metals, posing challenges for its practical application. Moreover, the composition of the MSW has a great influence on the representation of the fine fraction because of the unique waste composition and the improper practices of dumping mixed MSW.

Over the years, the unscientific landfill site in Boragaon has been the primary location for the disposal of the majority of MSW generated in Guwahati, India. Guwahati’surban local body has initiated the reclamation process of the legacy MSW through landfill mining. The main objective of this study is to investigate the landfill-mined fine fraction (hereafter LMFF) obtained through landfill mining at the Boragaon dump site in Guwahati, India. The analysis shall include a geotechnical assessment, an evaluation of the total heavy metals, and the potential ecological risk assessment.This study aims to provide crucial insights into the environmental impact of the LMFF and also shed light on the potential risks posed by heavy metal contamination. This study will also address the assessment of potential treatment and off-site applications for the LMFF.

2. Materials and Methodology

2.1. *Sampling of LMFF*

At the time of sampling, the LMFF was obtained from the trommel which had a screening size of 30mm. Based on the observation on site, the legacy waste was excavated in parts and stored in different heaps. The representative samples of LMFF (< 30mm in size) weighing approximately 1 tonne were initially collected from all these heaps using coning and quartering method such that the homogeneity was maintained.

2.2. *Geotechnical characterization of LMFF*

The porosity (*n*) of the LMFF, was evaluated based on the empirical relations that exist between bulk density (${}^{3}{}_{b}$), dry density (${}^{3}{}_{d}$), moisture content (*w*), voids ratio (*e*), and porosity (*n*).The grain size distributionwas conducted using both dry and wet sieve analysis, whereas the liquid limit and plastic limitwere measured using the cone penetration method and the thread rolling method respectively, as specified in the IS: 2720- Part 4 and Part 5(Bureau of Indian Standards, 1985). The Standard Proctor Test, as outlined in IS: 2720- Part 7(Bureau of Indian Standards, 1980b),was used to determine the optimum moisture content (OMC) and maximum dry density(MDD) of the LMFF.The unconfined compressive strength test,the direct shear test, and the falling head method as outlined in IS: 2720- Part 10 (Bureau of Indian Standards, 1991),Part 13 (Bureau of Indian Standards, 1986a), andPart 17 (Bureau of Indian Standards, 1986b) were conducted to determine the compressive strength, shear strength and the permeability of the LMFF respectively.For the sake of comparison, all these parameters were also evaluated forthe local soil for reference values.

2.3. *Analysis of total heavy metals and potential ecological risk assessment*

The analysis of total heavy metals in the LMFF, followed by their bioavailability, leachability, and sequential extraction was conducted based on the method outlined in the study by (Singh & Kalamdhad, 2019), and employing the Inductively Coupled Plasma Mass Spectrometry (LC-ICPMS).The study documented the heavy metals which predominantly occur in five distinct fractions, specifically: the exchangeable fraction (F1), the carbonate fraction (F2), the reducible fraction (F3), the oxidizable fraction (F4), and the residual fraction (F5). Gibson and Farmer (1986) reported that the fractions exhibit the following trend with respect to mobility: F1> F2> F3> F4> F5.The potential ecological risk index (R_I) was developed as a means of evaluating the extent of heavy metal contamination in sediments, considering the toxicity of heavy metals and the impact on the environment (Maanan et al., 2015). Based on this, $R_I$is evaluated for LMFF wherein,it is the addition of all risk factors for individual heavy metals and is evaluated as follows:

$$R_I = \sum E_r^i \cdots (1)$$

Where, $E_r^i = T_r^i \times C_f^i$ and $C_f^i = C_n/C_{nr}$

Where,E_r^i denotes the monomial potential ecological risk factor, i.e. for individual heavy metals, C_f^i is the contamination factor, which is determined by the ratio of the quantity of a given heavy metal in the sample (C_n), and the reference/ background concentration value of that TM (C_{nr}). T_r^i is the toxic response factor, that indicates the possible hazard and toxicity of specific metals and the environment's vulnerability to pollution. Based on Hakanson (1980)standardized toxic response factor, T_r^i values for Cd, Cr, Cu, Ni, Pb, and Zn are 30, 2, 5, 5, 5, and 1, respectively.

3. Results & Discussion

3.1.*Geotechnical characterization of LMFF*

The percentages of gravel-like, sand-like, and fine-like particles in the LMFF were determined to be 9.1%, 89.1%, and 1.8% respectively, based on the results obtained from both dry and wet sieve analyses. The particles retained by the 4.75 mm sieve are comprised of glass fragments, textiles, plastics, and other miscellaneous materials, in addition to the presence of gravel whereas the particles passing the 2µ sieve were almost insignificant. The coefficient of uniformity (C_u) and coefficient of curvature (C_c) were determined to be 6.12 and 1.17, respectively. Thus, LMFF may be categorized as well-graded sand (SW) whereas the background local soil is predominantly silty. Additionally, because of the inability to ascertain the plastic limit, it was determined thatLMFF was non-plastic.The measured values for the bulk density, specific gravity, and porosity of the LMFFwere determined to be 1.01 g/cc, 2.11, and 0.69, respectively, and for the local soil samples, were 1.52 g/cc, 2.68, and 0.53 respectively. It can be noted that the bulk density and specific gravity of the LMFF are lower than those of the local soil, whereas the porosity of LMFF is higher than the local soil.This could be owing to the fact that LMFF contains organic content because of the decomposition of MSW over the years. Moreover, the OMC and MDD of the LMFF and local soil were determined to be 28% and 21.5%, and 1.33 and 1.68 g/cc respectively. The LMFF curveis flatter in comparison to the local soil curve, and its higher OMC and lower MDD values can be attributed to the presence of humic substances.The unconfined compressive strength for LMFF and local soil were determined to be 0.37 MPa and 0.40 MPa. The directshear test gave cohesion as 10.67 kPa and angle of internal friction as 40.3° because of the heterogeneity nature of the LMFF. The high angle of internal friction could be because of the presence of plastic, fibres, and other miscellaneous materials in LMFF. Finally, the falling head permeability test gave the value of permeability, $k = 4.7\text{x}10^{-8}$ m/sec showing medium to low permeability. Based on this, it is evident that the organic matter present in LMFF influences its geotechnical properties. Moreover,based on the compressive and shear strength of the LMFF, it has the potential to serve as a viable alternative to local soil in earthwork and geotechnical applications, subject to the presence of contaminants.

3.2.*Total heavy metal analysis and potential ecological risk assessment*

Table 1 presents the comprehensive analysis of total heavy metals (Cd, Cr, Co, Cu, Fe, Mn, Ni, Pb, Zn) conducted for the LMFF, regulatory standards for application as a construction material,the bioavailability, and leachability of the LMFF.Based on bioavailability, Zn, Cu, Mn, and Fe are available for plant uptake and have the potential to enter the food chain. Based on leachability, Zn was the most leachable, although the heavy metals in the leachate did not exceed the regulatory values byEPA (1992), and hence LMFF and its leachate are classified as non-hazardous.However, these leachable heavy metals still have the potential to contaminate the groundwater and geoenvironment. The sequential extraction demonstrated that Fe, Cu, and Zn exist in F3 and F4 fractions associated with organic matter thereby indicating their potential for mobility, whereas both Pb and Ni predominantly exist in F5 fractions, indicating their resistance to mobility. However, Mn demonstrated the potential to be easily mobilized because of its presence in F2 and F3 fractions.

Table 1. Total heavy metals in the fine fraction

Sources	**Heavy Metals in LMFF**								
	Cr	Mn	Fe	Co	Ni	Cu	Zn	Cd	Pb
Total Heavy Metals (current study)- Guwahati, India (mg/kg)	124.35 ± 9.7	577.95 ± 59.6	16430.3 ± 990.7	58.25 ± 6.4	508.5 ± 74	697.25 ± 31.3	705.65 ± 30.5	Not detected	797.45 ± 93.6
Regulatory Standards for Use as Construction Material (mg/kg)	**5**	**-**	**-**	**-**	**2.1**	**10**	**14**	**0.06**	**8.3**
Total Heavy Metals (Belgium, Europe)Quaghebeur et al. (2013)(mg/kg)	113 ± 6	Not reported	Not reported	Not reported	46 ± 2	107 ± 37	463 ± 329	3.3 ± 2	172 ± 89
Total Heavy Metals (Estonia, Europe)Kaczala et al. (2015)(mg/kg)	54-123	313-383	29600-53900	5.6-8.1	29-44	191-362	1300-2000	1.12-1.21	128-477
Bioavailability(current study) (mg/L)	Not detected	0.24 ± 0.01	0.18 ± 0.01	Not detected	Not detected	0.83 ± 0.03	1.0 ± 0.1	Not detected	0.004 ± 0.00
Leachability(current study) (mg/L)	Not detected	3.3 ± 0.15	1.9 ± 0.2	Not detected	0.4 ± 0.00	1.02 ± 0.01	8.87 ± 0.04	Not detected	0.5 ± 0.04

The potential ecological risks due to heavy metals have been evaluated for the local soil and LMFF. Table 2 illustrates the monomial potential ecological risk factor, E_r^i calculated for individual trace elements like Cr, Cu, Ni, Pb, and Zn along with the potential ecological risk index, R_I. Based on the classification of potential ecological risks, it is evident that the degree of pollution caused by Cr and Zn is low for both soil and LMFF and for Cu – it is low for soil and has a moderate degree of pollution for LMFF. Ni causes moderate degree of pollution and Pb made the most dominant contribution with a high degree of potential ecological risk for soil as well asLMFF. Soil andLMFF posed a considerable ecological risk, withthe $R_I$of LMFF being 1.3 times more than that of soil. These results are alarming for LMFF which poses a considerable risk to the ecology. Jiang et al. (2014)presented similar results for risk indices for a coal mine and reported soil pollution near the coal mining site due to Cd. The ecological harms are reduced with increasing distance from the mining site.

Table 2. Potential Ecological Risk factors (E_r^i) and Potential Ecological Risk Index (R_I)

Samples	**Potential Ecological Risk Factors (E_r^i)**					**Ecological Risk Index, R_I**	**Degree of Ecological Risk**
	Cr	Cu	Ni	Pb	Zn		
Soil	3.98	23.73	51.09	188.76	2.28	269.8	Considerable risk
LMFF	4.11	76.79	52.24	204.47	7.93	345.5	Considerable risk

4. Conclusions & Way Forward

In conclusion, this study provides valuable insights into the characteristics of LMFF as well as its potential to cause ecological risks.Based on the geotechnical characterization, LMFF has the potential to serve as a viable alternative to local soil in earthwork and geotechnical applications. However, its suitability for construction purposes is limited due to the presence of organic matter and total heavy metals. This study highlights several key findings, such as the LMFF is classified as a well-graded sand and non-plastic. It exhibits a high porosity of 69% and low specific gravity and bulk density values of 2.15 and 1.01 g/cc respectively.LMFF also exhibited good shear strength properties and medium permeability because of the heterogeneity of the MSW. LMFF also has the potential to cause considerable ecological risk due to heavy metals like Cu, Ni, and Pb. Based on these findings, it is evident that theLMFF needs to be utilized only with proper treatment. The treatment of LMFF followed by its utilization should be prioritized such that the ecological risk caused due to heavy metals is reduced.The treatment methods might include,

- Immobilization of heavy metals by the application of lime, biochar, or zeolite reduces the potential ecological risks. Various studies like Gray et al. (2006), Malik et al. (2018), and Haghighatjou and Shirvani (2020) have shown the treatment of metal-contaminated soils or acidic soils employing the application of lime or biochar that aid in the increase in pH along with its ability to retain heavy metals.
- Phytoextraction and phytoremediation techniques to reduce theheavy metals in the LMFF.These hyperaccumulator plants either absorb the heavy metals in their tissues or promote chemical reactions to immobilize them (Yang et al., 2022).
- Geopolymerization of the LMFF for immobilization of heavy metals and obtaining value-added products and aid in the prospect of a circular economy.The alkaline environment required for the formation of a geopolymer matrix helps to bind heavy metals, thereby reducing their mobility and bioavailability (Bah et al., 2022).
- Bioremediation techniques- employing microbial and enzymatic treatment of the LMFF to encapsulate the heavy metals by microbe-metal interactions.These mechanisms entail biosorption, bioaccumulation, or biomineralization, all of which result in stable complexes that effectively sequester heavy metals (Ayangbenro and Babalola, 2017).

However, after the treatment of LMFF, further studies need to be conducted to ascertain the readiness of LMFF to be utilized as a fill or construction material, along with the feasibility, techno-economic assessments, and life cycle assessments.

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