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Geoenvironmental Considerations for Bulk Reuse of MSW Residues from Old Dumps and WTE Plants in Geotechnical Applications

Manoj Datta , Garima Gupta and Mohit Somani

Indian Institute of Technology Delhi, New Delhi 110016, India
`mdatta@civil.iitd.ac.in`

Abstract. For achieving sustainability in management of municipal solid waste (MSW), it is important to ensure that residues, remaining after processing of waste in various plants (composting, waste to energy (WTE), landfilling etc.), are reutilized in a safe and useful manner. Such residues constitute more than 25 to 35% of the total MSW generated in urban areas. This paper examines the feasibility of using soil-sized residues from landfill mining operations as well as from WTE plants in large quantities (bulk) in geotechnical applications relating to earthworks and structural fills. The geotechnical properties of the residues as well as the contaminants of concern in these residues from two waste dumps and three waste-to-energy plants of Delhi have been evaluated and the critical parameters inhibiting their un-restricted bulk reuse have been identified. The role of high soluble solids, high organic content, elevated heavy metals, release of color and variable pH has been brought out. The design measures and treatment methods that need to be adopted when using these residues in surface fills, shallow fills, deep fills and structural fills have been highlighted.

Keywords: Reuse, Aged MSW, Bottom Ash, Waste-To-Energy, Contaminants, Earth Fills.

1 MSW Residues and Bulk Reuse

Solid Waste Management Rules [1] of India stipulate that all municipal solid waste (MSW) be processed in composting plants, waste-to-energy plants or other processing plants prior to being sent to landfills. This helps in reducing the footprint of landfills. Residual materials which are left-over after processing and recovery of resources from the fresh or old municipal waste have been referred to as MSW residues in this paper. They include : (a) soil and gravel-like mixed material left after mining & screening aged MSW from old landfills / waste dumps from which useful material such as combustibles (paper, plastics, cloth and wood), metals, large sized stones, concrete and other building materials, have been removed; (b) bottom ash from Waste to Energy (WTE) plants after combustion / incineration of MSW; (c) rejects from composting plants (both pre-process and post-process components); and (d) rejects of other processing plants such as building materials recycling plants etc. In this paper, the focus is on the first two types of MSW residues only since rejects from composting plants and other processing plants reach the MSW landfill / waste dump.

Reuse of MSW residues is an important area of research towards achieving sustainability in MSW management since more than 25-35% of the total MSW generated remains in the form of residues after all resource recovery and these accumulate in landfills if not re-utilized.

Bulk reuse refers to re-utilization of MSW residues in 'large quantities'. The benchmark for 'large quantity' is not defined. For MSW residues this quantity should be large enough to absorb the annual production from a city. India has 5 mega-cities with populations exceeding 10 million, each producing more than 2-4 million tons of MSW annually, which in turn yield MSW residues of the order of a million tons per annum if the entire quantity of waste which is generated undergoes complete processing in an efficient manner. Bulk reuse covers applications in which MSW residues can be consumed in quantities of the order of 0.05 to 0.1 million tons or more (0.5 to 1.0 lakh tons) annually.

In the area of geotechnical engineering, earth fills and structural fills offer attractive options for consumption in bulk quantities in (i) embankments for roads, railway, water-retaining structures, (iii) structural-fills behind mechanically stabilised earth (MSE) walls of flyovers & bridges, (v) compacted fills for low-lying areas, (v) compacted fills for deep open pits and (vi) surface fills in large-area projects involving re-vegetation/ soil-conditioning/eco-forestry. MSW residues also find applications in building materials industry as well as in pavement construction industry but these applications are beyond the scope of the present study.

2 Earlier Studies on Reuse

A brief summary of the reuse of aged MSW from landfills and bottom ash from WTE plants in geotechnical engineering as reported in literature is presented in Tables 1 and 2.

From Table 1 it is evident that reuse of soil-like material (SLM) derived from aged MSW by landfill mining has mostly been confined to using it as soil cover at the landfill site itself. Offsite applications of SLM in earthwork projects in large quantities have not been reported from overseas. In India, a MSW dump at Indore [2] was recently reported to have been remediated through landfill mining and reuse / relocation of SLM segregated from the excavated aged waste. The details of material balance of recovered and reused / relocated components are not available. More recently, in Delhi, the National Green Tribunal (NGT) has directed that bio-mining of old dumps should be undertaken to reduce the height of these 50-60m high dumps [3].

The ash generated from WTE plants comprises of two components, namely, bottom ash (80%) and flyash (20%). Flyash is not reused as it is observed to be hazardous with high level of heavy metals [4–6] but bottom ash has lower level of contaminants and Table 2 lists the reported reuse of MSW bottom ash from WTE plants. Significant reuse has been reported from Netherlands in embankments. Data from other

Table 1. Reuse of aged MSW recovered by landfill mining reported in literature

Source/Reference	Name of landfill	Reuse of component
Nelson [20], Joseph et al. [21]	Frey Farm Landfill USA	219,500 m^3 of MSW; 56% of the reclaimed waste was used as a fuel and 41% of the reclaimed soil-like material was used as a cover material on-site itself, 3% of was reclaimed waste was reburied in landfill.
IWCS [22]	Shawano County Landfill, USA	267,600 m^3 of soil-like material from mined MSW was stockpiled and categorized as ‘clean’, ‘mildly contaminated’, and ‘contaminated’ based on concentrations of contaminants.
IWCS [22]	Perdido landfill, USA	344050 m^3 of MSW was mined, 60% of mined MSW consist of soil-like material (<75 mm) was reused as a cover material at the site itself.
Dhar [23]	Central Disposal Systems landfill, USA	191138 m^3 of MSW was relocated, only the well-decomposed mined waste was used as a daily cover.
Dhar [23]; Joseph et al. [21]	Maung Pathum Dumpsite, Thailand	Bulk of the mined MSW was used as a landfill cover material and some portion was used as compost after supplying P & K.

Table 2. Reuse of bottom ash from WTE plants reported in literature

Source	Place of application	Reuse
Lentz [24], Wiles and Shepherd [25]	Connecticut, USA	732 m^3 of bottom ash used as structural fill in access road to Shelton landfill
IEA Bioenergy [26]	Caland Wind Barrier, The Netherlands	650,000 tons of bottom ash utilized in embankment (length 700 m, height 15 m)
	Highway A-15 Rotterdam, The Netherlands	400,000 tons of BA utilized in embankment for roadway construction
	Netherland lane, England	base course layer for half a mile road stretch in residential area
Rogbeck and Hartlén [27], Olsson et al. [28], Arm et al. [29]	Torringevagen road, Malmö, Sweden	1350 m^3 of bottom ash used as road subbase

countries is limited. In India, bulk reuse of WTE ash has not been reported and such ash may be finally stockpiled within the plant boundary or at earmarked locations in the municipal area or sent to landfills.

3 Objective and Scope

The objective of the present study is to assess the feasibility of substituting local soils in earthwork projects by using MSW residues, in part or in full.

This has been achieved by assessing the geoenvironmental properties of MSW residues obtained from landfill mining operations from two waste dumps of Delhi as well as from three WTE plants of Delhi. The study is confined to soil-like fraction (minus 4.75mm) from landfill mining as well as minus 4.75mm fraction obtained by screening of bottom ash generated by WTE plants. The results presented herein are early findings of research work which is currently in progress at IIT Delhi [7–12] and more data is expected in the near future. The focus is on geotechnical properties and on geochemical studies for contaminants of concern in these materials which can impact the subsurface environment. The scope of the work covers investigating the composition, grain size distribution, mineralogy, plasticity, compaction characteristics and engineering properties of the materials obtained through laboratory studies. Studies to assess contaminants of concern included assessment of heavy metals (total and leachable), soluble salts, organic content, pH and release of colour.

Finally, the possibility of bulk reuse is addressed through assessment of appropriate precautions, design measures and treatment options.

4 Methodology

For the experimental studies, large-quantity disturbed representative samples were collected from the field. At MSW dumps, pits of 1m x 1m x 1m were excavated using a backhoe (Fig. 1) and at WTE plants the samples were obtained from stockpiles of bottom ash (Fig. 2). The excavated material was sun-dried in the field in the open. Compositional analysis was done by manually separating the visible components of the materials (Figs. 3 and 4). Grain size distribution was carried out by manual sieving on large sized screens at the site (Fig. 5 and 6).

Detailed tests were conducted on total residue and minus 4.75mm fraction as per the following protocols. The compositional analysis was carried out following ASTM D5231-92 [13]. Geotechnical properties including grain size distribution, plasticity, compaction characteristics, and engineering properties were determined by using Indian Standards [14]. Organic content was determined by heating the oven dried material at 550 (±50 °C) following Monkare et al. [15]. Total soluble solids, soluble sulphates, and soluble chlorides were determined following APHA [16]. EN 12457-2 [17] was used to determine leachable heavy metals using deionized water. Toxicity characteristics leaching procedure (TCLP) was performed following USEPA method 1311 [18]. Total heavy metals were determined by ICP-MS after acid digestion of solid samples by aqua regia in accordance with Quaghebeur et al. [19]

Fig. 1. Collection of samples of aged MSW from a pit at dump site

Fig.2. Stock Pile of Bottom ash

Fig. 3. Compositional analysis of aged MSW

Fig. 4. Compositional analysis of bottom ash from WTE plants

Fig. 5. Large size screens used at the site for the manual screening

Fig. 6. On-site screening

5 Results of Studies on MSW Residues from Old Dumps of Delhi

5.1 Composition and grain size distribution of total excavated waste

Fig 3 shows the components of total MSW recovered by excavation and segregation at two aged waste dumps of Delhi and Table 3 lists the relative quantities of the components. Also listed in Table 3 are data reported by other researchers. The table highlights that in Delhi waste dumps, the minus 20mm material (fine gravel and below) constitutes 72 to 77% of the total excavated material and that bulk of the balance is C&D waste fragments over 20mm in size. Combustibles & other components are only 4 to 7% by weight. This in stark contrast to data reported by Kaartinen et.al [30] (Table 3) where the combustibles & others are as high as 48%.

The grain size distribution of aged MSW from two waste dumps of Delhi is listed in Table 4 which highlights the fact that soil sized fraction in these dumps (i.e. sand + silt + clay) is as high as 65 to 75% in the aged waste. This points to the fact that significant quantities of local soils, drain silt and street sweepings have reached the waste dumps of Delhi in the past on account of the absence of other streams of waste management. Such grain size distribution is also reported by CRRI [31] but other researchers have reported lower percentages of soil-sized fraction in overseas landfills (Table 4).

Table 3. Composition of aged MSW recovered by landfill mining

Source	Age (years)	Compositional analysis (%)			
		Fine fraction	Combustibles[a]	C&D waste	Others
Previous studies					
Kurian et al. [32] (India)	~10	68 (< 20 mm)	2.5	28	3.5
Hogland et al. [33] (Sweden)	23-25	72 (< 18 mm)	6	20	2
Kaartinen et al. [30] (Finland)	-	43 (< 20 mm)	44	-	3.8
Rong et al. [34] (China)	-	70 (< 5mm)	14	9	7
Singh & Chandel [35] (India)	8-10	50 (< 4 mm)	14	30	6
Present IITD study[b]					
Aged MSW (Delhi)	10-20	72-77 (< 20 mm)	3.2-4	18-24	0.9-3

[a] *Combustibles includes paper, plastic, wood, and textiles;*
[b] *Somani et al.* [8]+*recent results*

Table 4. Grain size distribution of aged MSW (wt. %)

Source	Age (years)	Size (in mm)				
		> 80[a]	80-20[b]	20-4.75[c]	4.75-.075[d]	< 0.075[e]
Previous studies						
Kaartinen et al. [30] (Finland)	5-10	20-25	25-50	15-20	← 15-30 →	
CRRI [31] (India)	5-25	5-10	15-20	18-20	30-37	28.5-32
Wanka et al. [36] (Germany)	15-30	28-45	15-28	14-16	← 15-32 →	
Lopez et al. [37] (Austria)	20-25	14	26	← 60 →		
Present IITD study[f]						
Aged MSW (Delhi)	10-20	2-8	8-15	12-20	45-50	20-25

[a]*cobbles+boulders;* [b]*coarse gravel;* [c]*fine gravel;* [d]*sand;* [e]*silt+clay;*
[f]*Somani et al.* [8] + *recent results*

5.2 Geotechnical properties and mineralogy of soil-sized fraction

Soil sized fraction of aged MSW waste is usually referred to as soil-like-material (SLM). Table 5 lists the geotechnical properties of SLM from Delhi waste dumps. It also summarises the properties available in literature of SLM from other landfills. The specific gravity is lower than that of soils as is the maximum dry density in compaction tests and this is attributable to presence of organic matter. SLM from Indian waste dumps [31, 38] is non-plastic and exhibits angle of shearing resistance in the range of 28 to 36 degrees. The small value of cohesion intercept (10 to 24 kPa) could be related to the presence of small amount of fine fibrous material in the SLM.

The permeability of SLM from Delhi waste dumps lies in the range of 10^{-7} to 10^{-9} m/sec which is attributable to presence of significant fine-grained material. The primary compression index is reported to lie in the range of 0.1 to 0.19 (with the exception of Song et. al. [39]) but the secondary compression index, which is important for estimating long-term time-dependent settlement due to degradation of organic matter, has not been reported by any of the investigators.

Tables 6 and 7 present the results of XRD and XRF studies on SLM from Delhi waste dumps. One notes from Table 6 that quartz, calcite and feldspars are the predominant minerals. This is also borne out by the XRF results listed in Table 7 in which the elements have been reported as oxides. Si, Ca, Al and Fe are the main elements with silica constituting more than 50% of the total. These observations are supported by the results of Kemeklyte et. al. [40] and Vollprecht et.al. [41].

Table 5. Geotechnical properties of SLM

Parameters	*Previous studies*			*Present IITD study*[d]
	Song et al. [39] (Korea)	Oettle et al. [42] (USA)	CRRI [31] (India)	SLM (Delhi)
Size (mm)	-	-	< 4.0	< 4.75
% fines	-	29-36	-	40-50
G_s	2.44-2.58	-	1.93	2.20-2.52
PI	-	19-32	NP	NP
MDD[a] (kN/m^3)	6.8-15.6	15.2-18.5	16	13.5-15.2
OMC[a] (%)	-	19-32	14	20-30
k (m/s)	-	-	10^{-8}-10^{-9}	10^{-7}
C_c	0.1-0.2	0.04	0.14-0.19	-
Shear strength testing	DST[b] dry	-	DST dry	DST saturated
c' (kPa)	5-25[c]		10-25	20-24
ϕ' (°)	12-35[c]		28-38	34-36

G_s: specific gravity; PI: plasticity index; NP: non-plastic; MDD: maximum dry density; OMC: optimum moisture content; k: coefficient of permeability; C_c: compression index; DST: direct shear test; c':effective cohesion intercept; φ':effective angle of shearing resistance;

[a] *Proctor compaction;*

[b] *large DST (300mm x 300 mm);*

[c] *lower values were found corresponding to high organic content and vice versa;*

[d] *Somani et al.* [9] + *recent results*

Table 6. Major minerals in SLM: Results of XRD

Source	Major minerals
Previous studies	
Kemeklytė et al. [40] (Estonia)	quartz, calcite, albite, dolomite
Vollprecht et al. [41] (Belgium)	quartz, calcite, feldspars, kaolinite, illite, siderite, gypsum
Present IITD study	
SLM (Delhi)	quartz, calcite, feldspars
Delhi silt	quartz, illite, kaolinite, feldspars
Yamuna sand	quartz, feldspars, mica

Table 7. Results of XRF analysis of SLM expressed as oxides

Source	Size	SiO_2	CaO	Al_2O_3	Fe_2O_3	Others
Previous study						
Vollprecht et al. [41] (Belgium)	< 4.5	69-70	4.7-4.9	3.9-4.0	4.4-4.5	15-16
Present IITD study						
SLM (Delhi)	< 4.75	55-57	10-10.5	9-11	4.8-5.2	16-18
Delhi silt	< 4.75	57-62	5-6	15-16.5	4-5	10-12
Yamuna sand	< 4.75	74	4	11	3	8

5.3 Contaminants of concern in soil-sized fraction

The most important aspect concerning reuse of MSW residues is whether the material is hazardous or not. The TCLP test is universally adopted to assess the possibility of release of heavy metals from wastes and residues. For SLM from old MSW landfills, results of previous studies have indicated that release of heavy metals in TCLP test lie within the prescribed levels for SLM from aged MSW landfills (Table 8). These findings are also observed to be applicable to SLM of Delhi from old waste dumps in the present study as shown in Table 8. Hence these residues can be considered as 'non-hazardous' and thus need not be confined in hazardous waste landfills. However, it is important to assess that reuse of these 'non-hazardous' residues does not have a harmful impact on the subsurface environment - soil and ground water - at the location of their reuse because these residues are not inert. In addition, these contaminants should not have harmful effect on metallic, concrete or polymeric materials buried in such residues when they are used in earth-fills.

Table 8. Leaching of heavy metals from SLM by TCLP method and regulatory levels of USEPA (in mg/kg)

Metals	*Previous studies*[a]	*Present IITD study*[b]	TCLP levels[c]
		SLM (Delhi)	(USEPA)
Ag	-	0.02-0.48	100
As	0-6.5	0.1-0.2	100
Ba	6-6.5	6.4-11.2	2000
Cd	1-36	0.1-0.15	20
Cr	1-7	2.1-2.5	40
Cu	1-6.5	4.2-5.7	-
Hg	-	0.01-0.1	4
Ni	0.43-10	1.6-2.3	-
Pb	0-6	0.3-0.7	100
Se	-	0.02-0.03	20
Zn	2.9-28	19-40	-

[a] *Esakku et al.* [43]; *Prechthai et al.* [44], *Masi et al.* [45]; *Rong et al.* [34];
[b] *conducted at pH 4.93 at liquid-to-solid (L/S) ratio 20;* [c] *regulatory levels by USEPA*

Table 9. Organic content (OC), total soluble solids (TSS), color and pH of SLM

Source		OC[h]	TSS		Soluble Cl^-	Soluble SO_4^{2-}	Color	pH
		%	mg/kg	%	mg/kg	mg/kg	Pt-Co	
Previous studies								
Kurian et al. [32][a] (India)		11.7	-		-	-	-	7.6-8.6
Kurian et al. [32][b] (India)		13.8	-		-	-		6.9-8.1
Prechthai et al., [44] (Thailand)		22	17000	1.7	-	-		7.7
Kaartinen et al. [30] (Finland)		-	10000-13000	1.0-1.3	800-1200	7000-15000		8-8.3
Masi et al. [45] (Italy)		9.0	-	-	-	-		6.7
Burlakovs et al. [50] (Estonia)		18-20	13000-20000	1.3-2.0	-	-		7.6-8.0
Wanka et al. [36] (Germany)		-	-	-	70-160	4000-16000		7.6-8.4
Present IITD study[c]								
SLM (Delhi)		6.0-18.0	14000-20000	1.4-2.0	3000-8000	4000-9000	325-580	7.1-8.5
Delhi silt[d]		1.2	2000	0.2	400	400	30	7.0-7.2
Yamuna sand[d]		0.4	600	0.06	70	60	-	7.6-7.7
Regulatory levels								
Organic content[e]		1-5	-	-	-	-	-	-
LAGA 2012 levels[f] (Germany)	A	-	-	-	100	500	-	-
	B	-	-	-	200	1500	-	-
	C	-	-	-	400	3000	-	-
	D	-	-	-	1500	6000	-	-
Dutch levels[g]	C1	-	-	-	616	1730	-	-
	C2	-	-	-	8800	20000	-	-

[a]*Perungudi landfill;* [b]*Kodingayur landfill;* [c]*Somani et al.* [7]*+recent results;* [d]*background levels (maximum values observed);*[e]*MORTH* [46], *TxDOT* [47], *El Howayek et al.* [48]*;*
[f]*LAGA 2012* [36] *where A permits reuse without any restriction, B permits reuse without providing any sealing to avoid groundwater contamination, C permits reuse if a cohesive soil layer between reclaimed material and groundwater is provided, and D permits reuse if the surface layer is sealed;*
[g]*Soil quality decree* [51] *where C1 and C2 refers to open and isolated reuse, respectively*
[h]*OC determined as LOI 550±50°C;*
Note: underlined values exceed regulatory levels for unrestricted reuse

Tables 9 to 11 depict the contaminants of concern identified in the present study on SLM from waste dumps of Delhi. These include (a) total soluble solids, (b) release of colour, (c) heavy metals (total and leachable) and (d) organic content. Soluble solids, colour and heavy metals can cause a harmful impact on the subsoil and ground water if they leach out due to infiltration of precipitation. Organic content is considered as a contaminant only from the perspective of causing long-term settlements in structural fills which can affect the performance of structures founded on such fills. In addition, pH values for SLM are also tabulated in Table 9.

Total soluble solids in Table 9 are observed to be as high as 2% by weight which is ten times or more than the background levels observed in Delhi silt and Yamuna sand. Soluble chlorides and sulphates significantly exceed the background levels as well as regulatory levels for unrestricted reuse (Dutch and German standards). Further one notes that dark yellowish-brown leachate is released by SLM when water percolates through it. The intensity of colour is 325-580 units in comparison to 30 units released by Delhi silt. Both, total soluble solids and colour, can deteriorate the quality of sub-soil and ground water at shallow depth in pervious formations.

From Table 9 it is evident that SLM contains 6 to 18% organic content which is far in excess when compared to the background level of 1.2% observed in Delhi silt and 0.4% observed in Yamuna sand. It also exceeds the regulatory levels for earth-fills specified by MORTH [46], TxDOT [47] and El Howayek et al. [48]. This implies that one can expect significant secondary settlement if SLM is used in structural fills (to replace local soil) due to slow degradation of the organic matter. Table 9 shows that SLM from Delhi waste dumps exhibits pH in the range of 7.1 to 8.5 which is similar to the values for Delhi silt and Yamuna sand as well as results of other studies.

Table 10. Total heavy metals in SLM (in mg/kg)

Source	As	Cd	Cr	Cu	Ni	Pb	Zn
Previous studies[a]	0.1-11 (68)	0.8-4 (55)	54-657	75-968 (2245)	21-247	53-477	167-2000
Present IITD study[b,c]							
SLM (Delhi)	3-8	0.3-4	89-230	140-501	26-53	27-333	153-571
Delhi silt[d]	2.2	n.d.	28	45	8	4	65
Yamuna sand[d]	0.4	0.05	10	11	28	6	55
Regulatory levels							
Screening level[e,f]	12	10	64	63	50	140	200
Response level[e,g]	50	13	-	190	100	530	720

[a] *Kurian et al.* [32]*; Prechthai et al.* [44]*; Masi et al.* [45]*; Burlakovs et al.* [50]*;* [b] *Somani et al.* [9]*;* [c] *using aqua regia acid digestion;* [d] *background levels (maximum values observed);* [e] *COWI* [49]*;* [f] *screening level indicates contamination level in soil beyond which it is probably contaminated and more investigations are required;* [g] *response level indicates contamination level in soil beyond which further characterization and remedial action is required; underlined values exceed regulatory levels; the values in parenthesis ( ) are the outliers*

Tables 10 and 11 show the quantities of total heavy metals and leachable heavy metals observed in SLM from Delhi waste dumps along with the levels in local soil (Delhi silt & Yamuna sand). Total content of many of the heavy metals, except As and Cd, is found higher than the screening or response levels for contaminants in soils of India recommended by COWI [49] to Ministry of Environment, Forest & Climate Change. The leachable heavy metals in SLM (Table 11) are a small percentage of the total heavy metals (Table 10). The levels of leachable heavy metals such as As, Cu, Ni, Pb, and Zn in some cases exceed the German and Dutch regulatory levels for unrestricted reuse. Nevertheless, the levels of both total and leachable constituents are several times higher than those of the local soil. This implies that the heavy metal levels in the soil and ground water beneath a thick earth-fill of SLM can rise if percolation of precipitation occurs through the body of the fill.

Table 11. Leachable heavy metals extracted using DI water (EN 12457-2) in SLM, background soils and regulatory levels (in mg/kg)

Source		As	Cd	Cr	Cu	Ni	Pb	Zn
Previous studies[a]		< 0.02	0.006-0.095	0.03-0.17	0.2-2	0.05-1	0.01-1.4	0.2-11
Present IITD study[b,c]								
SLM (Delhi)		0.01-0.2	0.001-0.003	0.004-0.1	0.08-2.0	0.01-0.46	0.01-0.4	0.2-1.5
Delhi silt[d]		0.001	0.0003	0.001	0.008	0.002	0.002	0.27
Yamuna sand[d]		0.01	0.01	0.02	0.11	0.02	0.03	0.6
Regulatory levels								
LAGA 2012 levels[e]	A	0.1	0.02	0.15	0.5	0.4	0.2	1
	B	0.1	0.02	0.3	0.5	0.5	0.4	1
	C	0.4	0.05	0.75	1.5	1	1	3
	D	0.5	0.05	1	2	1	1	4
Dutch levels[f]	C1	0.9	0.04	0.63	0.9	0.44	2.3	4.5
	C2	2	0.06	7	1	2.1	8.3	14

[a] *Kurian et al.* [32], *Kaartinen et al.* [30], *Wanka et al.* [36];

[b] *Somani et al.* [9] + *recent results;*

[c] *EN 12457-2 test was conducted at L/S 10;*

[d] *background levels (maximum values observed);*

[e] *LAGA 2012* [36] *where A permits reuse without any restriction, B permits reuse without providing any sealing to avoid groundwater contamination, C permits reuse if a cohesive soil layer between reclaimed material and groundwater is provided, and D permits reuse if the surface layer is sealed;*

[f] *Soil quality decree* [51] *where C1 and C2 refers to open and isolated reuse, respectively; DI: deionized; underlined values exceed regulatory levels for unrestricted reuse.*

6 Results of Studies on MSW Residues from Waste-to-Energy (WTE) Plants of Delhi

The residue from MSW WTE plants comprises of two components, namely, bottom ash (80%) and flyash (20%). As indicated in Section 2.0 on earlier studies, flyash is not reused as it is observed to be hazardous with high level of heavy metals. Hence only bottom ash is discussed hereafter.

6.1 Composition and grain size distribution of total bottom ash

Fig. 4 shows the components of the total bottom ash obtained from WTE plants in Delhi and Table 12 lists the relative quantities of the components. The main components are soil -sized material (sand + silt + clay) and slag (fused material) + stones + C&D material (gravel sized). Ceramics, glass, metals and unburnt organics are the minor constituents. These results are similar to the findings of other investigators listed in Table 12.

The grain size distribution of bottom ash from Delhi plants is presented in Table 13 which shows that soil-sized fraction of bottom ash varies from 54 to 76% of the total material in Delhi WTE plants and this range is similar to findings of other researchers.

Table 12. Composition of bottom ash from WTE plants

Source	Composition
Previous studies	
Arm [52] (Sweden)	slag, glass, ceramics, metals, unburned substances (paper, plastic, textile, wood)
Yu et al. [6] (China)	fused material particles, ceramics, concrete, glass, metals, brick
Inkaew et al. [53] (Japan)	ceramics, glass, relic metal, unburned organic matter, slag
Šyc et al. [54] (Czech Republic)	fraction < 2 mm (30-37), residual fraction (20-29), glass (9-23), magnetic fraction (11-16), ceramics and porcelain (1.8-5.1), ferrous scrap (6-11), NFe metals (1-3), unburned organic material (0.2-1)
Zhu et al. [55] (China)	slag, ceramics, glass, Fe and NFe metals, unburned or non-combustible substances
Present IITD study[a]	
Bottom ash (Delhi)	soil-like[b] (58-63), slag (fused material) + stones + C&D material[c] (21-29), ceramics (1.8-3.0), glass (0.4-2.7), Fe metals (0.6-1.8), unburned organics (0.4-16)

[a]*Gupta et al.* [12]; [b]*fraction passing 4.75 mm;*
[c]*fraction above 4.75 mm (gravel-sized) which constitutes slag, stones, C&D waste etc.*

Table 13. Grain-size distribution of bottom ash from WTE plants (wt. %)

Source	Size (in mm)				
	> 80[a]	80-20[b]	20-4.75[c]	4.75-.075[d]	< 0.075[e]
Previous studies					
Forteza et al. [56] (Spain)	0	0-5	36-47	46-59	2-5
Hjelmar et al. [57] (Denmark)	0	21-33	33-34	31-37	4-9
Lin et al. [58] (Taiwan)	0	3-5	22-33	60-73	1.5-3
Puma et al. [59] (Italy)	0	4	32	64	0.4
Nikravan et al. [60] (Iran)	2.5	15	32.5	48.5	1.5
Present IITD study[f]					
Bottom ash (Delhi)	0-2	4-33	10-30	46-63	8-13

[a]*cobbles+boulders;* [b]*coarse gravel;* [c]*fine gravel;* [d]*sand;* [e]*silt+clay;*
[f]*Gupta et al.* [12]

6.2 Geotechnical properties and mineralogy of soil-sized fraction

Soil-sized fraction (SSF) of bottom ash (BA) is referred to as SSF-BA hereafter in this paper. Geotechnical properties of SSF-BA have been studied with a view to assess suitability of using it to replace local soil in earthworks. Table 14 lists the geotechnical properties of SSF-BA from Delhi WTE plants and other plants around the world from which it is noted that the ash is non-plastic, has specific gravity in the range of 2.03 to 2.79 and exhibits maximum dry density in the range of 13.0 to 18.7 kN/cu.m. The engineering properties of SSF-BA from all studies summarised in Table 14 are akin to granular soils. The angle of shearing resistance lies in the range of 38 to 51 deg. The permeability values are observed to be in the range of 10^{-5} to 10^{-7} m/sec and the compression index in the range of 0.04 to 0.08. The high values of angle of shearing resistance are attributed to the irregular shape and the highly uneven surface of the individual particles.

Tables 15 and 16 present the results of XRD and XRF studies on SSD-BA from Delhi WTE plants. One notes from Table 15 that quartz, calcite and feldspars are the predominant minerals. This is also borne out by the XRF results listed in Table 16 in which the elements have been reported as oxides. Si, Ca, Al and Fe are the main elements with silica constituting more than 50% of the total. These observations are supported by the results of other investigators in Table 16, with the exception that in some cases silica is less than 40%.

Table 14. Geotechnical properties of SSF-BA

Parameter	*Previous studies*					*Present IITD study*[d]
	Tay and Goh [61]	Pandeline et al. [62]	Muhunthan et al. [63]	Puma et al. [59]	Le et al. [64]	SSF-BA
	Singapore	USA	USA	Italy	France	Delhi
Size (mm)	0.074-5	< 4.75	-	< 9.5	< 20	< 4.75
% fines	0	-	-	0.1	5.7	10-20
G_s	2.67	2.55-2.79	2.03	-	-	2.56-2.63
PI		-	-	NP	-	NP
MDD[a] (kN/m^3)	-	15.4-18.1	15.4	15.6	18.7[b]	13-15
OMC[a] (%)	-	15.5-18.3	26.8	n.d.	12.5[b]	19-23
k (m/s)	10^{-6}-10^{-5}		10^{-5}	10^{-7}	-	10^{-6}-10^{-5}
C_c	-	-	-	-	0.04-0.05	0.04-0.08
Shear strength testing	CD saturated	CD saturated	DST at OMC	DST[c] dry	- -	DST dry
c' (kPa)	0	14-28	8	0	-	0
φ' (°)	46.5	38-50	51	45	-	45-50

G_s: specific gravity; PI: plasticity index; NP: non-plastic; MDD: maximum dry density; OMC: optimum moisture content; k: coefficient of permeability; C_c: compression index; c'- effective cohesion intercept; φ'- effective angle of shearing resistance; DST: direct shear test; CD: consolidated drained triaxial test; n.d.: not detected;
[a]Proctor compaction; [b]modified Proctor; [c]particle size < 2.8 mm; [d]Gupta et al. [12]

Table 15. Major minerals in SSF-BA: Results of XRD

Source	Major minerals
Previous studies	
Gori et al. [65] (Germany)	quartz, calcite, gehlenite, anhydrite, kalifelspar, akermanite, hematite, magnetite, apatite
Yang et al. [66] (Japan)	quartz, calcite, gehlenite, anorthite
Wang et al. [67] (Singapore)	quartz, calcite, anorthite, gehlenite, andradite
Loginova et al. [68] (The Netherlands)	quartz, feldspar, magnesium ferrite, melilite, spinel, pyroxene, sylvite, zeolite, calcite, anhydrite, halite, mica
Present IITD study[a]	
SSF-BA (Delhi)	quartz, calcite, feldspars
Delhi silt	quartz, illite, kaolinite, feldspars
Yamuna sand	quartz, feldspars, mica

Table 16. Results of XRF analysis for SSF-BA expressed as oxides

Source	Size	SiO_2	CaO	Al_2O_3	Fe_2O_3	Others
Previous studies						
Alam et al. [69] (The Netherlands)	1-4	37	19	12	14	18
Yang et al. [70] (China)	-	54	14	9	4	19
Funari et al. [71] (Italy)	< 20	33	23	9	10	25
Qiao et al. [72] (UK)	< 14	36	20	8	6	30
Present IITD study[a]						
SSF-BA (Delhi)	< 4.75	50-57	12-15	8-11	5-7	16-20
Delhi silt	< 4.75	57-62	5-6	15-16.5	4-5	10-12
Yamuna sand	< 4.75	74	4	11	3	8

[a]*Gupta et al. [11]*

6.3 Contaminants of concern in soil-sized fraction

Similar to the concern in SLM, the most important aspect concerning reuse of SSF-BA is whether the material is hazardous or not. Results of TCLP tests in previous studies have indicated that release of heavy metals from bottom SSF-BA (Table 17) lie below the levels prescribed by USEPA. These findings are also observed to be applicable to SSF-BA from Delhi WTE plants as shown for the present study in Table 17. Hence these residues can be considered as ‘non-hazardous’ and thus need not be confined in hazardous waste landfills. However, it is important to confirm that reuse of these ‘non-hazardous’ residues does not have a harmful impact on the subsurface environment - soil and ground water - at the location of their reuse as these residues are not ‘inert’. In addition, these contaminants should not have harmful effect on metallic, concrete or polymeric materials buried in such residues when they are used in earth-fills.

Table 17. Leaching of heavy metals from SSF-BA by TCLP method and regulatory levels of USEPA (in mg/kg)

Source	*Previous studies*[a]	*Present IITD study*[b,c]	TCLP levels[d] (USEPA)
		SSF-BA (Delhi)	
Ag	n.d.	0.1-0.2	100
As	n.d.	0.1- 0.3	100
Ba	12-101	8-14	2000
Cd	0.2-5	0.2-0.6	20
Cr	4-20	1-5	20
Cu	31-512	1-10	-
Hg	n.d.	< 0.005	4
Ni	-	1-3	-
Pb	2-79	0.1-0.3	100
Se	< 0.2	< 0.1	20
Zn	360-1082	19-44	-

[a]*Lin et al.* [73], *Lin and Chang* [75], *Lin et al.* [58], *Kuo et al.* [76], *Nikravan et al.* [60]*;* [b]*Gupta et al.* [11]*;* [c]*TCLP test was conducted at pH 4.93 at liquid-to-solid (L/S) ratio of 20;* [d]*regulatory levels by USEPA; n.d.: not detected.*

Tables 18 to 20 depict the contaminants of concern identified in the present study on SSF-BA from Delhi WTE plants. These include (a) total soluble solids, (b) heavy metals (total and leachable), and (c) organic content, as was the case for SLM. In addition, pH – a parameter that has important bearing on reuse as backfill for MSE walls (as will be discussed later) has also been included.

Total soluble solids (TSS) in Table 18 are observed to be as high as 3.5% by weight which is 10 to 60 times the background levels observed in Delhi silt and Yamuna sand. Total soluble solids can deteriorate the quality of subsoil and ground water at shallow depth in pervious formations. It may be noted from Table 18 that soluble chlorides and sulphates (major constituents of TSS) significantly exceed the Dutch regulatory levels for unrestricted reuse. They also exceed the FHWA levels for use as structural fill in MSE walls having steel reinforcement.

SSF-BA from Delhi WTE plants contains organic material in the range of 3 to 6.5% (Table 18) which is similar to that reported by earlier investigators [56, 73, 74] and significantly in excess of the background level of 1.2% observed in Delhi silt and 0.4% observed in Yamuna sand. This implies that the combustion process in the WTE furnaces is not complete and strict control on combustion efficiency is desirable to bring down the organic content below regulatory levels of 3 to 5% for use in earthworks.

Table 18. Organic content (OC), total soluble solids (TSS), and pH of SSF-BA

Source		OC^g	TSS		Soluble Cl$^-$	Soluble SO$_4^{2-}$	pH
		wt. %	mg/kg	wt. %	mg/kg	mg/kg	
Previous studies							
Abbas et al. [77] (Sweden)		-	24000-42000	2.4-4.2	-	-	-
Forteza et al. [56] (Spain)		4.1	-	-	-	11000	10.7-12.6
Lin et al. [73] (Taiwan)		3.1-6.1	-	-	-	-	10.5-11.0
Santos et al. [78] (Belgium)		0.7-5.3	-	-	-	-	10.5-12.4
Tang et al. [74] (The Netherlands)		7.4	-	-	3800	18100	7.8
Yang et al. [79] (Japan)		-	-	-	5000	-	-
Present IITD study[a]							
SSF-BA (Delhi)		3.0-6.5	25000-35000	2.5-3.5	2500-8000	5000-10000	8.3-10.3
Delhi silt[b]		1.2	2000	0.2	400	400	7.0-7.2
Yamuna sand[b]		0.4	600	0.06	70	60	7.6-7.7
Regulatory levels							
Organic content[c]		1-5					-
Austrian levels[d]					3000	5000	
Dutch levels[e]	C1		-		616	1730	-
	C2				8800	20000	-
FHWA levels[f] (USA)	I	-	-	-	100	200	5-10
	II	-	-	-	-	-	3-9
	III	-	-	-	-	-	> 3

[a] *Gupta et al.* [11]*;* [b] *background levels (maximum values observed;*

[c] *MORTH* [46], *TxDOT* [47] *and El Howayek et al.* [48]*;*

[d] *Austrian levels for reuse in roads* [80]*;*

[e] *Soil quality decree* [51] *where C1 and C2 refers to open and isolated reuse, respectively*

[f] *FHWA* [81] *levels for reuse in MSE walls where I refers to reuse with steel reinforcement, II refers to reuse with PET geogrids and III refers to reuse with PP/HDPE geogrids;*

[g] *OC determined as LOI 550 ± 50°C;*

Note: underlined values exceed regulatory levels for unrestricted reuse.

Table 19. Total heavy metals in SSF-BA (in mg/kg)

Source	As	Cd	Cr	Cu	Ni	Pb	Zn
Previous studies[a]	3-94	3-24	169-900	500-3116	35-286	683-2700	600-5230
Present IITD study[b,c]							
SSF-BA (Delhi)	6-7	3-5	108 - 511	311 - 497	48 - 91	133 - 224	890 - 1267
Delhi silt[d]	2.2	n.d.	28	45	8	4	65
Yamuna sand[d]	0.4	0.05	10	11	28	6	55
Regulatory levels							
Austrian levels[e]	-	10	800	-	200	900	-

[a] *Forteza et al.* [56], *Gori et al.* [65], *Sorlini et al.* [82], *Santos et al.* [78], *Alam et al.* [83];
[b] *Gupta et al.* [11]; [c] *using aqua-regia acid digestion;*
[d] *background levels (maximum values observed);*
[e] *Austrian levels for reuse in roads* [80]; *n.d.: not detected.*

Table 20. Leachable heavy metals extracted using DI water (EN 12457-2) in SSF-BA, background soils and regulatory levels (in mg/kg)

Source	As	Cd	Cr	Cu	Ni	Pb	Zn
Previous studies[a]	< 0.2	< 0.04	0.3-1.2	2-9	0.01-0.55	1-34 (0.03)	0.5-5 (0.01)
Present IITD study[b,c]							
SSF-BA (Delhi)	0.01-0.02	0.003-0.02	0.1-0.8	0.4-3	0.1-0.5	0.3-0.4	0.2-1.1
Delhi silt[d]	0.001	0.0003	0.001	0.008	0.002	0.002	0.27
Yamuna sand[d]	0.01	0.01	0.02	0.11	0.02	0.03	0.6
Regulatory levels							
Austrian levels[e]	0.5	-	0.5	4	0.4	0.5	-
Dutch levels[f] C1	0.9	0.04	0.63	0.9	0.44	2.3	4.5
C2	2	0.06	7	1	2.1	8.3	14

[a] *Forteza et al.* [56], *Gori et al.* [65], *Sorlini et al.* [82], *Santos et al.* [78], *Alam et al.* [83];
[b] *Gupta et al.* [11]; [c] *EN 12457-2 test was conducted at L/S 10;*
[d] *background levels (maximum values observed);* [e] *Austrian levels for reuse in roads* [80];
[f] *Soil quality decree* [51] *where C1 and C2 refers to open and isolated reuse, respectively; DI: deionized; underlined values exceed regulatory levels for unrestricted reuse; values in parenthesis ( ) represent outliers.*

Table 18 also highlights that SSF-BA from Delhi WTE plants exhibits pH in the range of 8.3 to 10.3. Other researchers have reported values between 7.8 and 12.6. Freshly produced BA has high pH and this reduces slowly with time when ash is stored in the open due to the process of carbonation / weathering [78]. High pH is not acceptable for structural fills in MSE walls as it impacts the performance of some polymeric geosynthetics as well as metallic reinforcement. Hence FWHA guidelines restrict the pH within a narrow range between 3 to 9 for polyester and 5 to 10 for metallic reinforcement (Table 18). High pH does not affect performance of HDPE and polypropylene geosynthetics.

Tables 19 and 20 show the quantities of total heavy metals and leachable heavy metals observed in SSF-BA from Delhi WTE plants along with the levels in local soil (Delhi silt & Yamuna sand) and results of earlier studies reported by other investigators. The leachable heavy metals in Table 20 are a small percentage of the total heavy metals (Table 19). Nevertheless, the levels of both total and leachable constituents are several times higher than those of the local soil. Total content of the heavy metals is within the regulatory levels specified by Austria for reuse in roads. However, few leachable heavy metals such as Cr, Cu and Ni sometimes exceed the Dutch regulatory levels for unrestricted reuse (Table 20). This implies that the heavy metal levels in the soil and ground water beneath a thick earth-fill of SSF-BA can rise if percolation of precipitation occurs through the body of the fill.

7 Bulk Reuse – Design Measures and Treatment Options

It is clear from the above discussions that reuse of both SLM and SSF-BA is affected by contaminants of concern. These residues have high soluble salts which can leach into the subsoil and the ground water. The level of heavy metals is elevated in comparison to background levels but mostly below or in some cases above regulatory levels. SLM has two additional factors which have to be considered for reuse, namely, release of colour as well as presence of significant organic content. On the other hand, SSF-BA exhibits an unusual characteristic - high pH at the time of production which reduces slowly with time on account of weathering / carbonation.

The following design measures and treatment options (Tables 21 and 22) can be considered, depending upon the intended end-use, the thickness / height of the total fill and the characteristics of the site at which the residue is being placed. (The cost of application increases from option (i) to (iv)).

1. Unrestricted use: This option implies that the residue can be directly utilised for the application without any design measures or treatment.
2. Reuse with sealing layers / isolation layers: In this option (Table 21), design measures in the form of low-permeability soil layers and / or geomembranes are used to prevent ingress of water into the body of the residue to eliminate formation and emission of leachate.

3. Reuse with sealing / isolation layers and leachate management system: In addition to design measures in option(ii), additional design measures in the form of drainage layers at the base of the fill along with leachate extraction & treatment systems are implemented to handle the leachate which is generated.
4. Treatment and then reuse: Treatment of residues prior to reuse is an expensive option. Various alternatives have been suggested by researchers (Table 22) and their viability has to be established in each specific case – treatment options include (a) blending; (b) immobilization / solidification using binders; (c) size separation; (d) washing; (e) carbonation; (f) thermal treatment and (g) biological stabilization

Table 21. Design measures for reuse of residues

Country	Source	Levels of reuse[a]	Design measures for reuse
Germany	LAGA levels [36]	A	unrestricted use
		B	no sealing required to avoid groundwater contamination (site restrictions)
		C	cohesive soil layer between the recycled material and groundwater necessary
		D	sealing of the surface required
The Netherlands	Soil Quality Decree [51]	C1	Open reuse: material can be reused as such with allowed infiltration of 300 mm/year (upto 15 m height)
		C2	Isolated reuse: material can be reused with allowed infiltration of 6 mm/year (upto 15 m height); distance from highest GWL > 0.5 m
Austria	BMNT [80]	Single level	Reuse in roads; essential to provide low-seepage capping (either hydraulic or bituminous stabilisation); use prohibited in protected and conservation areas or within bounds of discharge of a 30-year flood; distance from GWL > 2 m

[a] *Levels of reuse given in Table 9, 11, 18, 19, 20.*

Table 22. Treatment techniques for reuse of aged waste and BA from WTE plants investigated by previous researchers

Source	Method	Applicable for	Description
Wanka et al. [36]	Wet mechanical treatment	Aged waste	Washing of aged MSW was suggested before reuse. Fraction of aged MSW (10-60 mm) was separated into lightweight, fine, and inert fraction after treatment. Inert fraction and fine fraction can be used under the criteria 'C' as per LAGA 2012 shown in Table 11 and 21
Monkare et al. [15]	Biological stabilization	Aged waste	Fraction less than 20 mm was anaerobically stabilized with the addition of water, inoculum (sewage sludge). The treatment resulted in the reduction of biological methane potential of fine fraction
Oettle et al. [42]	Blending	Aged waste	Fraction passing 76 mm of aged MSW was mixed with locally available soil and its use as an engineered fill in applications with moderate settlement tolerances were suggested
Polettini and Pomi [84]	Carbonation	BA	Chemical transformations induced by natural or artificial carbonation of BA results in reduction of pH
Sorlini et al. [82]	Washing	BA	Removal of soluble salts as well as heavy metals due by washing
Loginova et al. [68]	Size separation	BA	Finer fractions (rich in contaminants) are removed from the BA which result in reduction of soluble salts and heavy metals
Hyks et al. [85]	Thermal treatment	BA	BA when heated (temperature range 930-1080°C) resulted in reduced leaching of some contaminants due to chemical transformations and/or encapsulation
Cioffi et al. [86], Chen et al. [87]	Immobilization/Solidification	MSWI BA	Use of binders (such as cement, asphalt etc.) immobilizes heavy metals in BA

The strategies for bulk reuse of SLM and SSF-BA which can be considered in specific application areas are discussed below.

1. Large-area surface application for re-vegetation / soil conditioning / eco-forestry: Unrestricted reuse of SLM can be considered for applications such as soil conditioning, re-vegetation or ecoforestry at sites which are remote and distant from urban areas, where ground water is deep below, thickness of surface layer to be applied is nominal (say 0.25 to 0.5 m thick) and non-edible vegetation is grown to avoid cross contamination by plant root uptake. The well-graded grain size distribution and availability of organic carbon & other nutrients in SLM [88] would enhance vegetative growth. Release of metals, salts and dark coloured leachate would not be significant as long as thickness of application is low. If such sites are to be accessible for human activity, a covering of local soil or in-place blending/mixing with local soil is considered important.
2. SSF-BA is not suitable for surface applications because of its granular nature and susceptibility to erosion, and such residues are unlikely to support vegetation.

3. Shallow earth-fills for raising low-lying areas or for landscaping: In areas where elevation of low-lying ground has to be raised by a few metres to a level equal to or above the adjacent ground level or high flood level or for landscaping of an area for non-load bearing applications such as parks, golf courses, playing fields, car parking areas etc., both compacted SLM and SSF-BA can be considered for filling the low-lying area with provision of sealing layers at top and base of the earth-fill.

4. Deep earth-fills in open pits: In urban settings one often encounters open pits, tens of metres deep, where some local mining operations have been conducted in the past. These pits usually exist as abandoned pits with their base close to ground water table. Such pits can be filled with compacted SLM or SSF-BA to reclaim the area. However basal liners should be provided with active leachate drainage and collection systems akin to those used in non-hazardous MSW landfills along with a final cover system at the top of the filled-up area, which can then be used for non-load bearing activities.

5. Embankments for roads, railways and water retaining structures: Unrestricted reuse of SLM in embankments is not feasible because the presence of high organics will lead to excessive long-term secondary settlements. This issue along with possibility of release of soluble salts and dark coloured leachate suggests that some pre-treatment in the form of blending with local soils [42] and immobilization with binders has to be attempted. Alternatively, thermal treatment (heating till 550 deg. Celsius) can help remove the organic matter and colour. Further studies are required.
6. SSF-BA can be used in embankments with strict control on combustion efficiency at WTE plants to keep organics within regulatory levels (less than 3 to 5%). To minimise leaching of soluble salts, sealing layers can be designed

for the top surface, sides and base. A bottom drainage layer to discharge the leachate into lined toe drains / surface water drains is desirable in areas where high infiltration into the embankment is expected to occur.

7. For water retaining embankments, such as those around lakes, reservoirs & canals, SSF-BA can be reused in conjunction with a clay core. Additional attention would have to be paid to the quality of seepage water and its treatment for the initial years (if the level of contaminants is above permissible levels) before discharge to surface water drains. With passage of time, the excessive soluble solids will be washed out.

8. Structural fills for MSE walls: With rapid development of transportation infrastructure, mechanically stabilized earth walls (MSE walls) are finding extensive usage in construction of approach roads of flyovers, bridges, rail overbridges etc. In such applications, structural fill is required in large quantities for construction of MSE walls. The percentage of fines, high organic content and soluble salts in SLM are far too excessive to permit its usage as structural fill in such applications. SSF-BA has lower organic content and less percentage fines and is thus better suited for this application. However, its high initial pH and variable organic content hampers its unrestricted reuse. Better control at the WTE plant can reduce the organic content and percent fines to acceptable level. HDPE / PP geogrids can be used in the pH range and soluble salts exhibited by SSF-BA. However, accelerated carbonation is required to lower the pH of the ash to the required level if polyester or metallic reinforcements are used. Excessive salts have to be reduced (by washing or other means) when metallic reinforcement is used. Prevention of migration of soluble salts to the subsoil / ground water is to be ensured by providing a low-permeability sealing layer at the base.

8 Note of Caution

The results presented in this paper pertain to residues from waste dumps and WTE plants of Delhi and only a limited number of contaminants were examined; others, such as persistent organic pollutants, pharmaceutical chemicals, microbial pathogens etc. were not studied. In old MSW dumps, the sources of waste, other than household waste, can be as diverse as industrial waste, biomedical waste etc. since separate facilities for such waste may not have been set up in the past. Hence a comprehensive site-specific assessment should be made for other contaminants as well when examining the use of residues from old landfills in earthwork projects.

9 Conclusions

The study reported in this paper reveals that the level of heavy metals in MSW residues is not high enough to classify them as hazardous. However, these exist at elevated levels in comparison to the background soils of the location. Further, presence of high soluble salts, high organic content, high pH and release of dark coloured leachate due to ingress of water affect the feasibility of unrestricted use of these residues. For bulk reuse, design measures in the form of covering with local soil or sealing top and bottom of earth-fills with low-permeability layers as well as effective drainage and collection of leachate can be adopted for different applications. Treatment methods such as separation, blending, immobilization / solidification, washing, carbonation, thermal and biological stabilization are under development and their feasibility can be assessed on case-to-case basis.

Conflict of Interest: None

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