CHARACTERIZATION OF MSW INCINERATION ASH FROM THREE PLANTS IN DELHI: OPTIONS FOR DISPOSAL AND REUSE AND COMPARISON WITH DATA FROM OTHER COUNTRIES

GARIMA GUPTA

DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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Characterization of MSW Incineration Ash from Three Plants in Delhi: Options for Disposal and Reuse and Comparison with Data from Other Countries

by

GARIMA GUPTA

Department of Civil Engineering

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Dedicated to my Dear

Amma

(Late Smt. Sushila Kumari)

&

Baba

(Mr. Ram Prasad Gupta)

CERTIFICATE

This is to certify that the thesis entitled "Characterization of MSW Incineration Ash from Three Plants in Delhi: Options for Disposal and Reuse and Comparison with Data from Other Countries" being submitted by Ms. Garima Gupta to the Indian Institute of Technology Delhi is a record of bonafide research work carried out by her under our supervision and guidance. The thesis work, in our opinion, has reached the standard fulfilling the requirements for DOCTOR OF PHILOSOPHY degree. The research report and results presented in this thesis have not been submitted, in part or full, to any University or Institute for the award of any degree or diploma.

Prof. Manoj Datta Professor Department of Civil Engineering Indian Institute of Technology Delhi, New Delhi-110016, India	Prof. B.J. Alappat Professor Department of Civil Engineering Indian Institute of Technology Delhi, New Delhi-110016, India	Prof. Shashank Bishnoi Professor Department of Civil Engineering Indian Institute of Technology Delhi, New Delhi-110016, India

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ABSTRACT

India is witnessing the rise of municipal solid waste (MSW) incineration (MSWI) plants wherein MSW is burnt, and energy is recovered as a by-product. Incineration process is accompanied by generation of solid residues, namely, bottom ash (200-300 kg/ton of MSW) and fly ash (10-50 kg/ton of MSW). Disposal and reuse of the incineration residues is regulated in most of the developed nations to minimize their impact on the environment. MSWI fly ash (MIFA) has mostly been deemed hazardous whereas MSWI bottom ash (MIBA) is classified non-hazardous and holds a potential for bulk reuse in civil engineering applications. Previous studies have revealed the variability in characteristics of MSWI ash attributable to differences in composition of MSW, pre-processing of waste, operating conditions of the incinerator etc. The composition of MSW in India being significantly different from higher-income nations like European countries, Singapore, Japan etc. necessitate detailed characterization of Indian MSWI ash prior to determining its fate.

Present study is the first and fundamental for laying a scientific foundation for disposal and reuse of MSWI ash in the country. At present, MIBA and MIFA are co-disposed in MSW landfills, open dumpsites, or mining pits with no prior assessment of its contamination potential to the sub-surface environment. Due to dearth of scientific studies on MSWI ash in India and absence of national legislations to regulate its reuse, recycling of MSWI ash in field applications remains uncharted and requires exhaustive investigation. While India is facing shortage of sand and has regulated its mining due to the consequential environmental impact, recycling of MIBA as its substitute would substantially contribute

towards sustainable development by reducing the onus on natural resources and plummeting the space requirement for its disposal.

MSWI ash was sampled from the three incineration plants operational in Delhi over a period of one and half years in different seasons, i.e., monsoons, winters, summers. MIBA was processed to obtain soil-sized fraction (passing 4.75 mm) for laboratory testing while MIFA was characterized as-received. Unprocessed-unscreened Delhi MIBA (or UDBA) was characterized for physical properties such as visual composition, grain size distribution and moisture content. Soil-sized fraction of Delhi MIBA (SDBA) was studied in conjunction with coal bottom ash, Badarpur sand and Yamuna sand for physicochemical and geotechnical characteristics whereas Delhi MIFA (or DFA) was studied in conjunction with Delhi silt and coal fly ash for physicochemical characteristics. A detailed comparison of the assessed characteristics with global experimental data was undertaken to trace the peculiarities of Indian MSWI ash in comparison to the MSWI ash from higher-income nations. Leaching studies which are deemed mandatory for assessing the fate of MSWI ash were undertaken to determine their options for disposal and reuse. Furthermore, the study addressed the need to investigate the right set of contaminants for the leaching studies. Lastly, treatment studies were undertaken on SDBA to facilitate its reuse in bound and unbound applications.

Soil-sized fraction of Delhi MIBA (or SDBA), though a lookalike of silty sand with analogous mechanical behaviour, is not as innocuous as it may appear. The concentration of total soluble solids and most of the trace metal(loid)s in SDBA is highly elevated in comparison to the conventionally used granular materials. Apart from soluble salts and trace metal(loid)s, presence of organics and percentage fines (passing 0.075 mm) were found concerning for variety of reuse alternatives. Leaching studies revealed that reuse of SDBA is adjudged feasible only in a restricted manner in applications like fill material for embankments, road construction, floor structures of industrial or storage building, foundations, levelling of terrain and embankments, development and rehabilitation of landfills, and restoration of degraded areas from mining activities. In absence of reuse of SDBA, it can safely be disposed in MSW landfills.

The study also delineated 3-step wet-screening treatment for SDBA to attenuate leaching of contaminants and meet most of the international regulatory criteria for reuse. The method of treatment devised in the present study is simple, sustainable, economical, and practically feasible in comparison to washing treatment methods proposed earlier with regard to choice of washing agent, quantity of washing agent and duration of the treatment. The study further developed M25 concrete mix using SDBA as a replacement of fine aggregates which satisfy the requirements of compressive strength and leaching criteria for bound reuse.

DFA, though a lookalike of silt, has distinctive physiochemical characteristics in comparison to Delhi silt or coal fly ash. DFA carries substantial load of soluble salts and toxic heavy metal(loid)s causing it to be classified as extremely hazardous. Reuse of DFA in bound or unbound applications is strictly prohibited. DFA should necessarily be disposed in hazardous waste landfills after pre-treatment. Co-disposal of bottom ash and fly ash is not recommended as mixing of the two residues would transfer contaminants from highly contaminated fly ash to less contaminated bottom ash and hence, deter any future utility of bottom ash.

The comprehensive compilation of previous studies revealed wide variation in the characteristics of MIBA as well as MIFA. However, the physicochemical and geotechnical characteristics of SDBA as well as physicochemical characteristics of DFA assessed in the present study were observed to fit within the domain of the global experimental data reported from higher-income nations. The work further demonstrates that despite wide variation in MSW composition and MSWI ash characteristics globally, MSWI ash mostly meets the similar fate.

The study put forth a list of contaminants of concern (or CoCs) for MSWI ash which are consistently found to exceed various regulatory criteria across the countries. The study recommends mandatory inclusion of these CoCs in the future investigations as exclusion of any of the CoCs may present a fragmented picture of leaching from MSWI ash and further result in non-consideration of the same CoCs in the treatment studies undertaken thereafter.

With new MSWI plants emerging worldwide, the study is relevant for policymakers, MSWI plant operators, and researchers to manage MSWI residues and cope with the associated problems more effectively.

सारांश

भारत में नगरपालिका ठोस अपशिष्ट (एमएसडब्ल्यू) भस्मीकरण (एमएसडब्ल्यूआई) संयंत्रों में वृद्धि देखी जा रही है, जहां एमएसडब्ल्यू को जलाया जाता है, और ऊर्जा को उप-उत्पाद के रूप में पुनर्प्राप्त किया जाता है। भस्मीकरण प्रक्रिया के साथ-साथ ठोस अवशेष, अर्थात् तलहटी राख (200-300 किग्रा/टन एमएसडब्ल्यू) और उड़न राख (10-50 किग्रा/टन एमएसडब्ल्यू) उत्पन्न होते हैं। पर्यावरण पर उनके प्रभाव को कम करने के लिए अधिकांश विकसित देशों में भस्मीकरण अवशेषों के निपटान और पुन: उपयोग को विनियमित किया जाता है। एमएसडब्ल्यूआई उड़न राख (एमआईएफए) को ज्यादातर परिसंकटमय माना गया है जबकि एमएसडब्ल्यूआई तलहटी राख (एमआईबीए) को गैर-परिसंकटमय वर्गीकृत किया गया है और सिविल इंजीनियरिंग अनुप्रयोगों में बड़े पैमाने पर पुन: उपयोग की संभावना है। पिछले अध्ययनों से एमएसडब्ल्यूआई राख के गुणों में अंतर का पता चला है, जिसका कारण एमएसडब्ल्यू की संरचना में बदलाव, कचरे का पूर्व-प्रसंस्करण, भस्मक की परिचालन स्थितियों आदि को बताया गया है। भारत में एमएसडब्ल्यू की संरचना यूरोप, सिंगापुर, जापान आदि उच्च आय वाले देशों से काफी भिन्न है, इसलिए इसके भाग्य का निर्धारण करने से पहले भारतीय एमएसडब्ल्यूआई राख के विस्तृत लक्षण वर्णन की आवश्यकता है।

वर्तमान अध्ययन देश में एमएसडब्ल्यूआई राख के निपटान और पुन: उपयोग के लिए वैज्ञानिक आधार रखने वाला पहला और इसलिए सबसे महत्वपूर्ण अध्ययन है। वर्तमान में, एमआईबीए और एमआईएफए को पर्यावरण में संभावित संदूषण के किसी भी आकलन के बिना एमएसडब्ल्यू लैंडफिल, खुले डंपसाइट्स या खनन गड्ढों में सह-निपटान किया जाता है। भारत में,

एमएसडब्ल्यूआई राख पर वैज्ञानिक अध्ययन की कमी और नियामक कानूनों की अनुपस्थिति के कारण क्षेत्रीय अनुप्रयोगों में एमएसडब्ल्यूआई राख का उपयोग अज्ञात बना हुआ है और इसके लिए विस्तृत जांच की आवश्यकता है। भारत रेत की कमी का सामना कर रहा है और परिणामी पर्यावरणीय प्रभाव के कारण रेत खनन को नियंत्रित किया है। रेत के विकल्प के रूप में एमआईबीए का पुनर्चक्रण प्राकृतिक संसाधनों पर बोझ को घटाके और एमआईबीए के निपटान के लिए स्थान की आवश्यकताओं को कम करके सतत विकास में महत्वपूर्ण योगदान देगा।

एमएसडब्ल्यूआई राख का नमूना दिल्ली में चालू तीन भस्मक संयंत्रों से डेढ़ साल की अवधि में विभिन्न मौसमों, यानी, मानसून, सर्दी, गर्मी में लिया गया था। प्रयोगशाला परीक्षण के लिए एमआईबीए से मिट्टी बराबर कणों (4.75 मिमी से छोटे) को छलनी का उपयोग करके अलग किया गया, जबकि एमआईएफए का परीक्षण बिना किसी प्रसंस्करण के किया गया था। असंसाधित दिल्ली एमआईबीए (या यूडीबीए) का दृश्य संरचना, कण आकार वितरण और नमी सामग्री जैसे भौतिक गुणों के लिए परीक्षण किया गया था। छनी हुई दिल्ली एमआईबीए (एसडीबीए) का अध्ययन भौतिक रासायनिक और भू-तकनीकी विशेषताओं के लिए कोयला तली राख, बदरपुर रेत और यमुना रेत के साथ संयोजन में किया गया था, जबकि दिल्ली एमआईएफए (या डीएफए) का अध्ययन भौतिक रासायनिक विशेषताओं के लिए दिल्ली गाद और कोयला उड़न राख के संयोजन में किया गया था। उच्च आय वाले देशों की एमएसडब्ल्यूआई राख की तुलना में भारतीय एमएसडब्ल्यूआई राख की विशिष्टताओं का पता लगाने के लिए वैश्विक प्रायोगिक डेटा के साथ एक विस्तृत तुलना की गई। एमएसडब्ल्यूआई राख के भाग्य का आकलन करने के लिए लीचिंग अध्ययन उनके निपटान और पुन: उपयोग के विकल्पों को निर्धारित करने के लिए किए गए थे। इसके अलावा, लीचिंग अध्ययन के लिए सही संदूषकों की जांच करने की आवश्यकता पर भी ध्यान दिया

गया। अंत में, क्षेत्रीय अनुप्रयोगों में इसके पुनः उपयोग की सुविधा के लिए एसडीबीए पर उपचार अध्ययन किया गया।

एसडीबीए, यद्यपि समान यांत्रिक व्यवहार के साथ गादयुक्त रेत जैसा दिखता है, लेकिन उतना अहानिकर नहीं है जितना दिखता है। एसडीबीए में कुल घुलनशील ठोस पदार्थों और अल्प मात्रा में मौजूद अधिकांश धातुओं की सांद्रता पारंपरिक रूप से उपयोग किए जाने वाली मिट्टी की तुलना में अत्यधिक बढ़ी हुई है। विभिन्न प्रकार के पुन: उपयोग विकल्पों के लिए कार्बनिक सामग्री और सूक्ष्म कणों (0.075 मिमी से छोटा) की उपस्थिति अधिक पाई गई। लीचिंग अध्ययनों से पता चला है कि एसडीबीए का पुनः उपयोग तटबंधों के लिए सामग्री भरने में, सड़क निर्माण में, औद्योगिक या भंडारण भवन की फर्श संरचनाओं में, नींव, इलाके और तटबंधों को समतल करने में, एमएसडब्ल्यू भरण स्थल का विकास और पुनर्वास करने में, और खनन गतिविधियों से खराब हुए क्षेत्रों की बहाली करने जैसे अनुप्रयोगों में प्रतिबंधित तरीके से किया जा सकता है। यदि एसडीबीए का पुन: उपयोग नहीं किया जाता है, तो इसे एमएसडब्ल्यू लैंडफिल में सुरक्षित रूप से निपटाया जा सकता है।

अध्ययन में दूषित पदार्थों की लीचिंग को कम करने और पुनः उपयोग के लिए अधिकांश अंतरराष्ट्रीय नियामक मानदंडों को पूरा करने के लिए एसडीबीए के लिए 3-चरणीय धुलाई-छनाई उपचार की भी रूपरेखा तैयार की गई है। यह उपचार विधि धुलाई एजेंट की पसंद, धुलाई एजेंट की मात्रा और उपचार की अवधि के संबंध में पहले प्रस्तावित धुलाई उपचार विधियों की तुलना में सरल, टिकाऊ, किफायती और व्यावहारिक रूप से व्यवहार्य है। इसके अलावा, रेत के प्रतिस्थापन के रूप में एसडीबीए का उपयोग करके एम25 कंक्रीट मिश्रण विकसित किया गया था जो संपीड़न शक्ति और लीचिंग नियमों की आवश्यकताओं को पूरा करता है।

डीएफए, हालांकि गाद जैसा दिखता है, इसमें दिल्ली गाद या कोयला उड़न राख की तुलना में विशिष्ट भौतिक रासायनिक विशेषताएं हैं। डीएफए में उच्च मात्रा में घुलनशील लवण और जहरीली धातुएं होती हैं, जिसके कारण इसे बेहद परिसंकटमय के रूप में वर्गीकृत किया जाता है। भू-तकनीकी अनुप्रयोगों में डीएफए का पुन: उपयोग सख्त वर्जित है। पूर्व-उपचार के बाद डीएफए को आवश्यक रूप से परिसंकटमय अपशिष्ट भरण स्थल में निपटाया जाना चाहिए। तलहटी राख और उड़न राख के सह-निपटान की अनुशंसा नहीं की जाती है। ऐसा इसलिए है क्योंकि दोनों अवशेषों के मिश्रण से प्रदूषक तत्व उड़न राख से तलहटी राख में स्थानांतरित हो जाएंगे और इसलिए, तलहटी राख की भविष्य में कोई उपयोगिता नहीं रह जाएगी।

पिछले अध्ययनों के व्यापक संकलन से एमआईबीए के साथ-साथ एमआईएफए की विशेषताओं में व्यापक भिन्नता का पता चला। हालाँकि, वर्तमान अध्ययन में मूल्यांकित प्रायोगिक गुण उच्च आय वाले देशों से रिपोर्ट किए गए वैश्विक प्रायोगिक डेटा के क्षेत्र में फिट होते देखे गए। यह कार्य आगे प्रदर्शित करता है कि विश्व स्तर पर एमएसडब्ल्यू संरचना और एमएसडब्ल्यूआई राख विशेषताओं में व्यापक भिन्नता के बावजूद, एमएसडब्ल्यूआई राख का अधिकांशतः समान भाग्य होता है।

अध्ययन ने एमएसडब्ल्यूआई राख के लिए महत्वपूर्ण प्रदूषकों (या सीओसी) की एक सूची सामने रखी है जो लगातार देश भर में विभिन्न नियामक मानदंडों से अधिक पाए जाते हैं। अध्ययन भविष्य की जांच में इन सीओसी को अनिवार्य रूप से शामिल करने की सिफारिश करता है। ऐसा इसलिए है क्योंकि किसी भी सीओसी को शामिल न करने से एमएसडब्ल्यूआई राख से लीचिंग की गलत तस्वीर पेश हो सकती है। परिणामस्वरूप, भविष्य के उपचार अध्ययन इन सीओसी को शामिल करना भूल सकते हैं।

दुनिया भर में उभर रहे नए एमएसडब्ल्यू भस्मीकरण संयंत्रों के साथ, अध्ययन नीति निर्माताओं, एमएसडब्ल्यूआई संयंत्र संचालकों और शोधकर्ताओं के लिए एमएसडब्ल्यूआई अवशेषों का प्रबंधन करने और संबंधित समस्याओं से अधिक प्रभावी ढंग से निपटने के लिए प्रासंगिक है।

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LIST OF NOTATIONS AND ABBREVIATIONS

AC	Accelerated carbonation
APC	Air pollution control
APHA	American Public Health Association
ASTM	American Society for Testing and Materials
b.d.l.	Below detection limit
BF	Bag filter
BS	Badarpur sand
BT	Batch leaching test
BTEX	Benzene, Toluene, Ethylbenzene, and Xylene
C&D	Construction and demolition
CBA	Coal bottom ash
CDT	Consolidated drained triaxial test
CFA	Coal fly ash
CLSM	Controlled low strength material
CNS	Chinese National Standard
CoC(s)	Contaminant(s) of concern
COD	Chemical oxygen demand
CT	Column leaching test
CU	Consolidated undrained triaxial test
CV	Coefficient of variation (%)
DBA	Delhi MSW incineration bottom ash
DCA	Delhi combined ash
DFA	Delhi MSW incineration fly ash
DI	Deionized
DOC	Dissolved organic carbon
DR	Dilution ratio
DS	Delhi silt
DST	Direct shear test

EC	Electrical conductivity
XRF	X-ray fluorescence
EPA	Environmental Protection Agency
ESP	Electrostatic precipitator
EU	European Union
FDoT	Florida Department of Transportation
Fe	Ferrous
FHWA	Federal Highway Administration
GLF	Gravel-like fraction
GSD	Grain-size distribution
GWL	Ground water level
HDPE	High density polyethylene
HW	Hazardous waste
ICP-MS	Inductively coupled plasma mass spectrometry
INDOT	Indiana Department of Transportation
IRC	Indian Road Congress
IS	Indian Standard
IW	Inert waste
JLT	Japanese leaching test
KSLT	Korean standard leaching test
L/S	Liquid to solid ratio
LDOTD	Louisiana Department of Transportation and Development
LOI	Loss on ignition
MDD	Maximum dry density
MIBA	MSW incineration bottom ash
MIFA	MSW incineration fly ash
MNRE	The Ministry of New and Renewable Energy
MoRTH	The Ministry of Road Transport and Highways
MPC	Modified Proctor compaction
MPS	Maximum particle size
MSE	Mechanically stabilized earth

MSW	Municipal solid waste
MSWI	MSW incineration
NEA	National Environmental Agency
NHW	Non-hazardous waste
non-Fe	Non-ferrous
NW	Natural weathering
OMC	Optimum moisture content
PAC	Powdered activated carbon
PAHs	Polycyclic aromatic hydrocarbons
PCDDs	Polychlorinated dibenzodioxins
PCDFs	Polychlorinated dibenzofurans
PET	Polyester
PI	Phenol index
PP	Polypropylene
PVA	Polyvinyl alcohol
R.O.	Remaining oxides
RD	Relative density
RDF	Refuse derived fuel
RSS	Reinforced soil slope
RTLs	Regulatory threshold limit(s)
SBT	Serial batch leaching test
SDBA	Soil-sized fraction of Delhi MSW incineration bottom ash
SDS	Semi-dry scrubber
SEM	Scanning electron microscope
SLF	Sanitary landfill
SLF	Soil-like fraction
SPC	Standard Proctor compaction
SS	Total soluble solids
STP	Sewage treatment plant
T0	Untreated sample
TA	Treatment by ageing or weathering

TB	Treatment by blending with uncontaminated material
TCLP	Toxicity characteristic leaching procedure
TDS	Total dissolved solids
TEPA	Taiwan Environmental Protection Agency
TH	Treatment by heat or thermal treatment
TKN	Total Kjeldahl Nitrogen
TOC	Total organic carbon
TS	Treatment by dry size screening using 0.15 mm sieve
TW	Treatment by washing
TWS	Treatment by wet screening
UDBA	Unprocessed-Unscreened Delhi MSW incineration bottom ash
USCS	United soil classification system
USEPA	United States Environmental Protection Agency
VC	Vibratory compaction
WHO	World Health Organization
XRD	X-ray diffraction
XRF	X-ray fluorescence
YS	Yamuna sand
$c^{'}$	Effective cohesion (kPa)
C_b^i	Contamination factor calculated for contaminant i with respect to background soil b
D_{50}	Mean particle diameter or particle size at which 50% of the particles are finer (mm)
D_{90}	Particle size at which 90% of the particles are finer (mm)
D_{10}	Particle size at which 10% of the particles are finer (mm)
ε_a	Axial strain (%)
ε_{v}	Volumetric strain (%)
ε_z^i	Exceedance factor or modified contamination factor calculated for contaminant i with respect to legislation z
E_{50}	Secant Young’s modulus at 50 % of the peak deviatoric stress (MPa)
$E_{0.2}$	Secant Young’s modulus at 0.2% axial strain (MPa)

k	Coefficient of permeability (m/s)
η	Removal efficiency of contaminants (%)
ν	Poisson's ratio
σ_n'	Applied normal stress (kPa)
φ_p'	Effective angle of shearing resistance at peak stress (°)
φ_c'	Effective angle of shearing resistance at critical stress (°)
ψ	Dilation angle (°)
R_L	Relevance level (%)
TR_{BA}	Transfer ratio of the trace metal(loid)s to bottom ash (%)
$\gamma_{d\,min}$	Minimum dry unit weight (kN/m^3)
$\gamma_{d\,max}$	Maximum dry unit weight (kN/m^3)