

**WASTE TO RESOURCE: ASSESSING THE REUSE POTENTIAL OF  
MSW INCINERATION BOTTOM ASH IN FLEXIBLE PAVEMENTS,  
EMBANKMENTS AND REINFORCED SOIL STRUCTURES**

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EMBANKMENTS AND REINFORCED SOIL STRUCTURES**

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**Submitted**

*in fulfilment of the requirements of the degree of*

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**MARCH 2024**

**DEDICATED TO  
MY FAMILY**

## **CERTIFICATE**

This is to certify that the thesis entitled “Waste to Resource: Assessing the Reuse Potential of MSW Incineration Bottom Ash in Flexible Pavements, Embankments and Reinforced Soil Structures” being submitted by Mr. Deepesh Bansal to the Indian Institute of Technology Delhi is a record of bonafide research work carried out by him 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.

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If there is an omission of someone's explicit mention, it is more due to the limitations or shortcomings of my memory than anything else, and I sincerely apologize for that. Lastly, I express my thanks to the almighty for providing me with the strength, patience, and sensibility to complete this work.

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## **ABSTRACT**

The efforts to reduce the consumption of natural aggregates to meet sustainable development goals have necessitated the use of secondary materials in civil engineering applications. The experimental data in the literature suggests that municipal solid waste (MSW) incineration bottom ash (IBA) can potentially replace natural aggregates in field applications. However, IBA is currently disposed of in open dumps or sanitary landfills in India. An extensive literature review indicated that a comprehensive study characterizing bottom ash as fill material in pavements and reinforced soil structure (RSS) is missing. Additionally, IBA properties vary based on waste composition, pre-processing of waste, and plant operating conditions worldwide. Hence, a detailed study is undertaken investigating the geoenvironmental, geotechnical and mechanical characterization of IBA from Delhi for reusing as an alternative to natural aggregates in pavement subbase, subgrade, and embankments, and RSS. The incineration ash samples were collected from two MSW incineration facilities in New Delhi, India.

The physicochemical characteristics (like mineralogy, major and minor elements, total heavy metals) and leaching characteristics of ash samples were studied within the geoenvironmental characterization of incineration ashes. The influence of particle size, pH, and L/S on the leaching characteristics of IBA was studied in detail. Finally, leaching characteristics were compared with international reuse and disposal standards to determine their fate.

Grain size distribution, plasticity, compaction characteristics, hydraulic conductivity, abrasion, impact, soundness, shear strength, dynamic characteristics, pullout characteristics, etc., were studied within the geotechnical and mechanical characterization of IBA. The obtained properties were compared with regulatory standards to evaluate the reuse of IBA in pavement layers, embankments, and RSS.

The experimental results revealed that the leaching concentration of contaminants and organic content of IBA decreases with an increase in particle size. pH significantly influences the leaching of all inorganic constituents in IBA except chlorides, sulfates, and antimony. The results further indicate that IBA is suitable for disposal in non-hazardous waste landfills regardless of particle size at its intrinsic pH. However, it is recommended to dispose of IBA in monofills as co-disposal with MSW in sanitary landfills can cause the pH of IBA to shift towards the acidic range, which may exacerbate the contaminant leaching from IBA. The comparison of leaching test results with international regulatory standards for reuse demonstrates that using IBA in unbound applications is feasible in paved roads and earthworks subjected to minimal water infiltration.

The geotechnical investigation shows that IBA is a well-graded, non-plastic, lightweight material with adequate drainage characteristics. IBA offers high bearing (soaked CBR values of 40-48%) and shear strength (angle of shearing resistance of 46.3°-47.9°). The secant and resilient moduli of IBA are comparable to conventional material, suggesting its ability to withstand deformation under static and cyclic loading. Higher water absorption and abrasion values preclude its application in subbases of highways and urban roads. However, high strength, stiffness, hydraulic conductivity, durability, and leaching characteristics make IBA suitable for rural roads. IBA also fulfills the standard guidelines for use as fill material in road embankments and subgrades. The pullout test results demonstrate that the interaction coefficient of polymeric strips and geogrid in IBA (0.73-1.53 and 0.79-1.91, respectively) is comparable or higher to materials conventionally used as structural fill in RSS, indicating adequate bondage between IBA and geosynthetic reinforcement.

Based on comprehensive laboratory testing, constraints associated with reusing IBA in field applications were identified, and treatment processes like carbonation, blending, and washing were performed to improve the required properties of IBA. Two steps of washing

and screening with treated wastewater for a total liquid-to-solid ratio of 6 L/kg and a total washing time of 15 min were found to improve the properties of fresh and carbonated IBA for open reuse.

Finally, the sustainability and economic feasibility of reusing IBA compared to natural aggregates was also assessed through life cycle assessment (LCA) and cost analysis. Among the three discussed scenarios with reference to the baseline condition, the reuse of treated IBA in road layers emerges as the most sustainable alternative till a distance of  $d+15$  km (where  $d$  is the transportation distance for natural materials). It can be inferred from cost analysis that the reuse of treated IBA in pavement layers and RSS is also an economically viable option, irrespective of the transportation distance of the material.



## सारांश

प्राकृतिक एग्रीगेट के उपभोग को कम करने के प्रयासों ने सतत विकास लक्ष्यों को पूरा करने के लिए सिविल अभियांत्रिकी अनुप्रयोगों में पुनर्निर्माण सामग्रियों का उपयोग आवश्यक बना दिया है। साहित्य में प्रयुक्त प्रयोगात्मक आंकड़े इस सुझाव को देते हैं कि नगर निगम सॉलिड वेस्ट (एमएसडब्ल्यू) दहन अशेष (आईबा) आधारभूत सामग्रियों की भूमि अनुप्रयोगों में प्राकृतिक एग्रीगेट की जगह ले सकता है। हालांकि, वर्तमान में आईबा को भारत में खुले भूमि या स्वच्छता से भरे भूमिगत ठोस कचरे के साथ डाला जा रहा है। एक व्यापक साहित्य समीक्षा ने इसे सड़क, एम्बैंकमेंट्स, और रिइनफोर्स्ड सॉइल स्ट्रक्चर्स (आरएसएस) के रूप में ऐश की विस्तृत अध्ययन की कमी बताई। इसके अतिरिक्त आईबा की कैरेक्टरिस्टिक्स विभिन्न कचरे की संरचना, कचरे की पूर्व-प्रसंस्करण, और प्लांट के संचालन शर्तों के आधार पर बदलती रहती है। इसलिए, दिल्ली से आईबा की जीओएनवायरमेंटल, जियोटेक्निकल और मैकेनिकल विशेषताओं का विस्तृत अध्ययन किया गया है, जिसका उद्देश्य इसे पैवमेंट सबबेस, सबग्रेड, और इम्बैंकमेंट्स, और आरएसएस में प्राकृतिक एग्रीगेट के एक विकल्प के रूप में पुनःप्रयोग के लिए जांचना है। इस अध्ययन के लिए आईबा सैंपल्स न्यू दिल्ली, भारत के दो नगर निगम सॉलिड वेस्ट इंसिनेरेशन सुविधाओं से एकत्र किए गए थे।

जीओएनवायरमेंटल विश्लेषण के अंदर, एश सैंपल्स की भौतिक-रासायनिक विशेषताएँ (मिनरलॉजी, प्रमुख और अल्प तत्व, कुल भारी धातु) और एश सैंपल्स की लीचिंग विशेषताएँ अध्ययन की गईं। आईबा की लीचिंग कैरेक्टरिस्टिक्स पर कण आकार, पीएच, और एल/एस के प्रभाव का विस्तृत अध्ययन किया गया। अंत में, लीचिंग कैरेक्टरिस्टिक्स को अंतरराष्ट्रीय पुनःप्रयोग और निस्तारण मानकों के साथ तुलना की गई थी ताकि इसका भविष्य तय किया जा सके।

आईबा की जीओटेक्निकल और मैकेनिकल विशेषता के अंदर ग्रेन साइज वितरण, प्लास्टिसिटी, संपीड़न विशेषताएँ, पारगणता, घिसाई, संघटन, इम्पैक्ट, साउंडनेस, शियर स्ट्रेंथ, गतिक विशेषताएँ,

पुलआउट विशेषताएँ आदि का अध्ययन किया गया। प्राप्त गुणधर्मों की तुलना विनियामक मानकों के साथ की गई थी ताकि आईबीए का पुनःप्रयोग पैवमेंट लेयर, इम्बैंकमेंट्स, और आरएसएस में मूल्यांकन किया जा सके।

प्रयोगशाला परिणाम से पता लगता है की आईबा की लीचिंग और आर्गेनिक कंटेंट कण का साइज बढ़ने पर काम हो जाती है। पीएच की वजह से आईबा में सभी अप्राकृतिक घटकों की लीचिंग पर प्रभाव पड़ता है सिर्फ क्लोराइड सल्फेट और अनितमोनी को छोड़ कर। परिणाम से यह भी पता चलता है की आईबा को नॉन-हजारड़ौस वैस्ट लैंडफिल्स में डाल सकते है उसके आंतरिक पीएच पर और किसी भी कण के साइज पर। इसके अतिरिक्त परिणाम से यह पता लगता है कि आईबा को मोनोफिल्स में डालना चाहिए ना कि एमएसडब्ल्यू के साथ सेनेटरी लैंडफिल्स में, क्योंकि इससे आईबा का पीएच एसिडिक रेंज में चला जायेगा जिससे कंटामिनेंट की लीचिंग बढ़ जाएगी। पुनःप्रयोग के लिए अंतरराष्ट्रीय नियामक मानकों के साथ लीचिंग परीक्षण के परिणामों की तुलना यह साबित करती है कि अप्रतिबंधित अनुप्रयोगों में आईबा का उपयोग सड़को और पृथ्वीकरण में संवेदनशील जल प्रवाह के परिचार में संभव है।

जीओटेक्निकल और मैकेनिकल शैली में आईबा की जाँच ने दिखाया कि यह एक वेल ग्रेडेड, नॉन-प्लास्टिक, हल्के भौतिक लक्षणों वाला पदार्थ है जिसमें पर्याप्त ड्रेनेज लक्षण हैं। आईबा ने उच्च बेयरिंग (40-48% की सोकड़ सिबिआर मूल्य) और शियर स्ट्रेंथ (46.3°-47.9° की शीरिंग रेसिस्टेन्स का कोण) प्रदान किया है। आईबा का सेकंट और रेजिलिएंट मॉड्यूल सामान्य पदार्थ के समान है, जिससे स्थिर और साइक्लिक लोडिंग के तहत उसकी उत्कृष्टता का सुझाव है। उच्च जल अवशोषण और मलिनता मूल्य ने इसका अनुप्रयोग हाईवे और शहरी सड़कों के सबबेस में बाधित कर दिया है। हालांकि, उच्च स्ट्रेंथ, स्तिफनेस, परमाबिलिटी, स्थायिता, और लीचिंग विशेषताएं आईबा को गाँवी सड़कों के लिए उपयुक्त बनाती हैं। आईबा रोड एम्बैंकमेंट्स और सबग्रेड में पदार्थ के रूप में उपयोग के लिए मानक दिशा में है। पुलआउट परीक्षण के परिणाम दिखाते हैं कि आईबा और जीओसिंथेटिक पुनर्निर्माण

में पॉलीमेर स्ट्रिप्स और जीओग्रिड के बीच इंटरएक्शन कोइफिशिएंट (0.73-1.53 और 0.79-1.91, क्रमशः) सामग्रियों के बीच संरचनात्मक भंडारण की अद्यतित संकेत करती हैं।

व्यापक प्रयोगशाला परीक्षण के आधार पर, फ़्रील्ड में आईबा का पुनर्उपयोग करने के संबंधित बाधाएँ पहचानी गईं और आईबा की आवश्यक गुणधर्मों को सुधारने के लिए कार्बोनेशन, मिश्रण, और धुलाई जैसी उपचार प्रक्रियाएं की गईं। ओपन पुनःप्रयोग के लिए प्रोसेसिंग के बाद फ्रेश और कार्बोनेटेड आईबा की गुणधर्मों को सुधारने के लिए 6 लीटर/किलोग्राम की कुल तरलता-स्थूल अनुपात और कुल धोने का समय 15 मिनट के साथ संरचित जल से स्क्रीनिंग के दो कदमों को उपयुक्त पाया गया।

अंत में, आईबा की पुनर्उपयोग की स्थायिता और आर्थिक योजना की तुलना में सतती और आर्थिक वाणिज्यिकता का मूल्यांकन भी लाइफ साइकिल असेसमेंट (एलसीए) और लागत विश्लेषण के माध्यम से किया गया। बेसलाइन स्थिति के संदर्भ में तीन चरणों के साथ तुलना करते समय, सड़क पर संशोधित आईबा का पुनःप्रयोग  $d+15$  किमी की दूरी तक (जहां  $d$  प्राकृतिक एग्रीगेट के परिवहन की दूरी है) सबसे दक्ष विकल्प के रूप में प्रकट होता है। लागत विश्लेषण से सिद्ध होता है कि सड़क पर संशोधित आईबा का पुनःप्रयोग करना एग्रीगेट की दूरी के बिना एक आर्थिक विकल्प भी है।





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## LIST OF ABBREVIATIONS

|      |   |                                           |
|------|---|-------------------------------------------|
| MSW  | : | Municipal Solid Waste                     |
| IBA  | : | Incineration Bottom Ash                   |
| IFA  | : | Incineration Fly Ash                      |
| RSS  | : | Reinforced Soil Structures                |
| UBA  | : | Unsegregated Bottom Ash                   |
| OM   | : | Overall Material                          |
| GSM  | : | Gravel-sized Material                     |
| SLM  | : | Soil-like Material                        |
| CA   | : | Combined Incineration Ash                 |
| L/S  | : | Liquid-to-solid                           |
| WtE  | : | Waste-to-energy                           |
| MG   | : | Moving Grate                              |
| RDF  | : | Refused Derived Fuel                      |
| MDD  | : | Maximum Dry Density                       |
| OMC  | : | Optimum Moisture Content                  |
| MPT  | : | Modified Proctor Test                     |
| CBR  | : | California Bearing Ratio                  |
| CD   | : | Consolidated Drained                      |
| CU   | : | Consolidated Undrained                    |
| CS   | : | Confining Stress                          |
| NS   | : | Normal Stress                             |
| DS   | : | Direct Shear                              |
| BS   | : | Bulk Stress                               |
| LVDT | : | Linear Variable Differential Transformers |
| LOI  | : | Loss on Ignition                          |
| DI   | : | De-ionized                                |
| XRD  | : | X-ray Diffraction                         |
| DBL  | : | De-ionized water Batch Leaching           |
| DCL  | : | De-ionized water Column Leaching          |
| HW   | : | Hazardous Waste                           |
| NHW  | : | Non-hazardous Waste                       |

|        |   |                                              |
|--------|---|----------------------------------------------|
| IW     | : | Inert Waste                                  |
| TCLP   | : | Toxicity Characteristics Leaching Procedure  |
| EU     | : | European Union                               |
| LCA    | : | Life Cycle Assessment                        |
| PS     | : | Polymeric Strips                             |
| GG     | : | Geogrid                                      |
| PET    | : | Polyester                                    |
| C&D    | : | Construction and Demolition                  |
| SM     | : | Sintered Material                            |
| F&NF   | : | Ferrous and Non-ferrous                      |
| PBL    | : | pH-dependent Batch Leaching                  |
| ICDD   | : | International Centre for Diffraction Data    |
| XRF    | : | X-ray Fluorescence                           |
| ICP-MS | : | Inductively Coupled Plasma Mass Spectrometry |
| DOC    | : | Dissolved Organic Carbon                     |
| LA     | : | Los Angeles                                  |
| AIV    | : | Aggregate Impact Value                       |
| NMA    | : | Natural Mineral Aggregates                   |
| TWW    | : | Treated Wastewater                           |
| WT     | : | Washing with varying time                    |
| WL     | : | Washing with varying L/S                     |
| SW     | : | Step Washing                                 |
| SWS    | : | Single step Washing and Screening            |
| TWS    | : | Two steps Washing and Screening              |
| GSD    | : | Grain Size Distribution                      |
| DOC    | : | Dissolved Organic Carbon                     |
| BDL    | : | Below Detection Limit                        |
| YS     | : | Yamuna Sand                                  |
| BS     | : | Badarpur Sand                                |
| SB     | : | Single Batching                              |
| MB     | : | Multiple Batching                            |
| MD     | : | Machine Direction                            |
| CMD    | : | Cross Machine Direction                      |
| GSB    | : | Granular Subbase                             |



|                   |   |                                         |
|-------------------|---|-----------------------------------------|
| WMM               | : | Wet Mix Macadam                         |
| C-OM              | : | Carbonated Incineration Ash             |
| WF                | : | Washed Fines                            |
| WW                | : | Washed Water                            |
| ETP               | : | Effluent Treatment Plant                |
| FU                | : | Functional Unit                         |
| GW                | : | Global Warming                          |
| SOD               | : | Stratospheric Ozone Depletion           |
| IR                | : | Ionizing Radiation                      |
| OFH               | : | Ozone Formation, Human Health           |
| FPM               | : | Fine Particulate Matter                 |
| OFT               | : | Ozone Formation, Terrestrial Ecosystems |
| TA                | : | Terrestrial Acidification               |
| FE <sub>u</sub>   | : | Freshwater Eutrophication               |
| ME <sub>u</sub>   | : | Marine Eutrophication                   |
| TE                | : | Terrestrial Ecotoxicity                 |
| FE                | : | Freshwater Ecotoxicity                  |
| ME                | : | Marine Ecotoxicity                      |
| HCT               | : | Human Carcinogenic Toxicity             |
| H <sub>n</sub> CT | : | Human Non-carcinogenic Toxicity         |
| LU                | : | Land Use                                |
| MRS               | : | Mineral Resource Scarcity               |
| FRS               | : | Fossil Resource Scarcity                |
| WC                | : | Water Consumption                       |
| CM                | : | Conventional Material                   |
| MSE               | : | Mechanically Stabilized Earth           |



## LIST OF ANNOTATIONS

|                         |   |                                                        |
|-------------------------|---|--------------------------------------------------------|
| $\text{SiO}_2$          | : | Silica oxide                                           |
| $\text{CaO}$            | : | Calcium oxide                                          |
| $\text{Al}_2\text{O}_3$ | : | Aluminum oxide                                         |
| $\text{Fe}_2\text{O}_3$ | : | Ferric oxide                                           |
| $\text{MgO}$            | : | Magnesium oxide                                        |
| $\text{K}_2\text{O}$    | : | Potassium oxide                                        |
| $\text{Na}_2\text{O}$   | : | Sodium oxide                                           |
| $\text{SO}_3$           | : | Sulfur trioxide                                        |
| $\text{P}_2\text{O}_5$  | : | Phosphorus oxide                                       |
| $\text{TiO}_2$          | : | Titanium oxide                                         |
| $\text{CO}_2$           | : | Carbon dioxide                                         |
| $\text{Cl}$             | : | Chlorite                                               |
| $I_d$                   | : | Relative density                                       |
| $\phi'_p$               | : | Effective angle of internal friction at peak stress    |
| $\phi'_c$               | : | Effective angle of internal friction at critical state |
| $c'$                    | : | Cohesion intercept                                     |
| $E_{50}$                | : | Secant elastic modulus                                 |
| $\nu$                   | : | Poisson ratio                                          |
| $\psi$                  | : | Dilation angle                                         |
| $\gamma_d$              | : | Dry unit weight                                        |
| $M_r$                   | : | Resilient modulus                                      |
| $\Theta$                | : | Bulk stress                                            |
| $\sigma_d$              | : | Deviatoric stress                                      |
| $\sigma_c$              | : | Confining stress                                       |
| $P_a$                   | : | Atmospheric pressure                                   |
| $\tau_{\text{oct}}$     | : | Octahedral shear stress                                |
| $k_1$ - $k_{10}$        | : | Model coefficients,                                    |
| $R^2$                   | : | Regression coefficient                                 |
| $V_s$                   | : | Shear wave velocity                                    |
| $G_{\text{max}}$        | : | Maximum shear modulus                                  |
| $\text{As}$             | : | Arsenic                                                |
| $\text{B}$              | : | Boron                                                  |

|                               |   |                                            |
|-------------------------------|---|--------------------------------------------|
| Ba                            | : | Barium                                     |
| Co                            | : | Cobalt                                     |
| Cd                            | : | Cadmium                                    |
| Cr                            | : | Chromium                                   |
| Cu                            | : | Copper                                     |
| Mo                            | : | Molybdenum                                 |
| Pb                            | : | Lead                                       |
| Ni                            | : | Nickel                                     |
| Sb                            | : | Antimony                                   |
| Se                            | : | Selenium                                   |
| Sn                            | : | Tin                                        |
| V                             | : | Vanadium                                   |
| Zn                            | : | Zinc                                       |
| Cl <sup>-</sup>               | : | Chlorides                                  |
| SO <sub>4</sub> <sup>2-</sup> | : | Sulfates                                   |
| Avg                           | : | average                                    |
| P <sub>r</sub>                | : | Peak pullout resistance                    |
| C <sub>i</sub>                | : | Soil reinforcement interaction coefficient |
| L <sub>e</sub>                | : | Embedment length of reinforcement          |
| B                             | : | Width of reinforcement                     |
| σ <sub>n</sub>                | : | Normal stress                              |
| Δσ <sub>n</sub>               | : | Increase in normal stress                  |
| b <sub>w</sub>                | : | Width of polymeric strip                   |
| b <sub>s</sub>                | : | Spacing between polymeric strip            |
| H                             | : | Height                                     |
| i                             | : | Infiltration coefficient                   |
| T                             | : | Time period                                |
| C <sub>R</sub>                | : | Cost of road section                       |
| R <sub>m</sub>                | : | Rate of fill material                      |
| V                             | : | Volume of fill material per unit length    |
| R <sub>t</sub>                | : | Freight rate of transportation             |
| d                             | : | Transportation distance                    |
| CW                            | : | Cost of MSE Wall                           |

|       |   |                                          |
|-------|---|------------------------------------------|
| $R_g$ | : | Rate of geogrid                          |
| $n$   | : | Number of reinforcement layers           |
| $S_v$ | : | Vertical spacing of reinforcement layers |