GEOENVIRONMENTAL AND GEOTECHNICAL CHARACTERIZATION OF PROCESSED AND UNPROCESSED C&D WASTE FOR BULK REUSE IN GEOTECHNICAL APPLICATIONS

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by

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DEDICATED TO

MY MOTHER

CERTIFICATE

This is to certify that the thesis entitled **“GEOENVIRONMENTAL AND GEOTECHNICAL CHARACTERIZATION OF PROCESSED AND UNPROCESSED C&D WASTE FOR BULK REUSE IN GEOTECHNICAL APPLICATIONS”** is being submitted by **Ms Apoorva Agarwal** in the fulfilment for the award of the degree of **Doctor of Philosophy** to the **Indian Institute of Technology Delhi**. This is the record of the research work and is entirely carried out by her under our supervision and guidance. The research report and results resented 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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ABSTRACT

The scarcity of natural materials along with the environmental constraints and prohibition of mining and quarrying demands the exploration of secondary materials as substitutes. Efforts are in progress worldwide to explore the possible use of construction and demolition (C&D) waste for a wide range of applications. The present study assesses the feasibility of using C&D waste for geotechnical applications e.g., structural fill for constructing mechanically stabilized earth (MSE) walls or as an earthfill. The study assessed the following:

i. Feasibility of using processed C&D waste termed sand-sized mixed recycled aggregate (SS_MRA) as structural fill for MSE walls
ii. Feasibility of using unprocessed C&D waste as backfill for embankments.

The first part of the thesis experimentally evaluates the suitability of SS_MRA as structural fill in MSE walls in lieu of conventional fill material (CFM). Detailed physicochemical, geoenvironmental and geotechnical characterization of SS_MRA are carried out, and results are compared with locally available Badarpur sand (BS) and Yamuna sand (YS) (natural reference materials/CFM). The geoenvironmental characterization of SS_MRA shows that heavy metals and total soluble solids are more than the reference materials but are within limits for inert waste and the values reported in the literature. Experimentally determined gradation, physical and shear strength characteristics, and electrochemical properties of SS_MRA met the standard specifications for the structural fill of different guidelines/codes of practice. Pullout tests were conducted to evaluate the soil-geosynthetic peak interface apparent coefficient of friction ($\mu_{S/GSY}$) between geosynthetic reinforcement (geogrids (GG-80 and GG-350) and polymeric strips (PS-25 and PS-50)) and selected structural fill (SS_MRA). The influence of poor compaction on geosynthetic reinforcement – SS_MRA interactions are evaluated, and the results are compared with those of geosynthetic

reinforcement in natural reference materials. Poor compaction significantly lowers $\mu_{S/GSY}$ particularly in polymeric strips. $\mu_{S/GSY}$ of geosynthetic reinforcement embedded in MRA is comparable with the reference materials and the values reported in the literature.

The second part examines the suitability of using (-4.75 mm) unprocessed C&D waste in earthfill applications. The detailed physicochemical, geoenvironmental and geotechnical characterization was carried out, and the results are compared with the local available soil (Delhi silt (DS)). The geoenvironmental characterization reveals that (-4.75 mm) unprocessed C&D waste has elevated heavy metals and total soluble solids compared to local soil but is within limits for inert waste criteria. From the geotechnical characterization, it can be concluded that (-4.75 mm) unprocessed C&D waste has properties similar to local soil and, thus, can be used in earthfills.

In addition, geoenvironmental characterization of fines obtained during processing C&D waste, termed recycled aggregate sludge (RA_S), has been carried out. The experimental results reveal that RA_S has a very high total soluble solids concentration and is within limits for non-hazardous waste. Thus, it is unsuitable for reusing without prior treatment.

Thus, the results of the present study encourage the construction industry in bulk utilization of SS_MRA as structural fill in MSE walls and (-4.75 mm) unprocessed C&D waste for earthfills.

सार

पर्यावरणीय बाधाओं और खनन और उत्खनन पर रोक के साथ-साथ प्राकृतिक सामग्रियों की कमी विकल्प के रूप में माध्यमिक सामग्रियों की खोज की मांग करती है। अनुप्रयोगों की एक विस्तृत श्रृंखला के लिए निर्माण और विध्वंस (सी एंड डी) कचरे के संभावित उपयोग का पता लगाने के लिए दुनिया भर में प्रयास जारी हैं। वर्तमान अध्ययन भू-तकनीकी अनुप्रयोगों के लिए सी एंड डी कचरे का उपयोग करने की व्यवहार्यता का आकलन करता है, जैसे यांत्रिक रूप से स्थिर पृथ्वी (एमएसई) की दीवारों के निर्माण के लिए संरचनात्मक भराव या मिट्टी के भराव के रूप में। अध्ययन ने निम्नलिखित का आकलन किया:

i. एमएसई की दीवारों के लिए संरचनात्मक भराव के रूप में प्रसंस्कृत सी एंड डी कचरे को रेत के आकार के मिश्रित पुनर्नवीनीकरण कुल (एसएस_एमआरए) का उपयोग करने की व्यवहार्यता
ii. तटबंधों के लिए बैकफ़िल के रूप में असंसाधित सी एंड डी कचरे का उपयोग करने की व्यवहार्यता।

थीसिस का पहला भाग प्रयोगात्मक रूप से SS_MRA की उपयुक्तता का मूल्यांकन करता है क्योंकि पारंपरिक भरण सामग्री (CFM) के बदले MSE की दीवारों में संरचनात्मक भरण होता है। SS_MRA का विस्तृत भौतिक रासायनिक, भू-पर्यावरण और भू-तकनीकी लक्षण वर्णन किया जाता है, और परिणामों की तुलना स्थानीय रूप से उपलब्ध बदरपुर रेत (BS) और यमुना रेत (YS) (प्राकृतिक संदर्भ सामग्री / CFM) से की जाती है। SS_MRA के भू-पर्यावरणीय लक्षण वर्णन से पता चलता है कि भारी धातु और कुल घुलनशील ठोस संदर्भ सामग्री से अधिक हैं लेकिन निष्क्रिय अपशिष्ट और साहित्य में बताए गए मूल्यों की सीमा के भीतर हैं। प्रयोगात्मक रूप से निर्धारित ग्रेडेशन, भौतिक और कतरनी ताकत विशेषताओं, और एसएस_एमआरए के इलेक्ट्रोकेमिकल गुणों ने विभिन्न दिशानिर्देशों/अभ्यास के कोडों के संरचनात्मक भरने के लिए मानक विनिर्देशों को पूरा किया। भू-संश्लेषक सुदृढीकरण (जियोग्रिड्स (GG-80 और GG-350) और बहुलक स्ट्रिप्स (PS-25 और PS-50)) के बीच घर्षण ($\mu_{S/GSY}$) के मृदा-भू-संश्लेषण शिखर

इंटरफ़ेस स्पष्ट गुणांक का मूल्यांकन करने के लिए पुलआउट परीक्षण किए गए थे और चयनित संरचनात्मक भरण (SS_MRA)। जियोसिंथेटिक सुदृढीकरण पर खराब संघनन का प्रभाव - SS_MRA इंटरैक्शन का मूल्यांकन किया जाता है, और परिणामों की तुलना प्राकृतिक संदर्भ सामग्री में जियोसिंथेटिक सुदृढीकरण के साथ की जाती है। विशेष रूप से पॉलीमेरिक स्ट्रिप्स में खराब संघनन $\mu_{S/GSY}$ को काफी कम करता है। MRA में सन्निहित जियोसिंथेटिक रीइन्फोर्समेंट का $\mu_{S/GSY}$ संदर्भ सामग्री और साहित्य में रिपोर्ट किए गए मूल्यों के साथ तुलनीय है।

दूसरा भाग अर्थफिल अनुप्रयोगों में (-4.75 मिमी) असंसाधित सी एंड डी कचरे के उपयोग की उपयुक्तता की जांच करता है। विस्तृत भौतिक-रासायनिक, भू-पर्यावरण और भू-तकनीकी लक्षण वर्णन किया गया था, और परिणामों की तुलना स्थानीय उपलब्ध मिट्टी (दिल्ली गाद (डीएस)) से की गई है। भू-पर्यावरण लक्षण वर्णन से पता चलता है कि (-4.75 मिमी) असंसाधित सी एंड डी कचरे में स्थानीय मिट्टी की तुलना में भारी धातु और कुल घुलनशील ठोस पदार्थ हैं, लेकिन निष्क्रिय अपशिष्ट मानदंड की सीमा के भीतर है। भू-तकनीकी लक्षण वर्णन से, यह निष्कर्ष निकाला जा सकता है कि (-4.75 मिमी) असंसाधित सी एंड डी कचरे में स्थानीय मिट्टी के समान गुण होते हैं और इस प्रकार, मिट्टी के भराव में इस्तेमाल किया जा सकता है।

इसके अलावा, सी एंड डी कचरे के प्रसंस्करण के दौरान प्राप्त महीन कणों का भू-पर्यावरणीय लक्षण वर्णन किया गया है, जिसे पुनर्नवीनीकरण कुल कीचड़ (RA_S) कहा जाता है। प्रायोगिक परिणामों से पता चलता है कि RA_S में बहुत अधिक कुल घुलनशील ठोस सांद्रता है और यह गैर-खतरनाक कचरे की सीमा के भीतर है। इस प्रकार, यह पूर्व उपचार के बिना पुन: उपयोग के लिए अनुपयुक्त है।

इस प्रकार, वर्तमान अध्ययन के परिणाम एमएसई दीवारों में संरचनात्मक भराव के रूप में एसएस_एमआरए के थोक उपयोग में निर्माण उद्योग को प्रोत्साहित करते हैं और (-4.75 मिमी) अर्थफिल के लिए असंसाधित सी एंड डी अपशिष्ट।

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AASHTO	**:**	American Association of State Highway and Transportation Officials
APHA	**:**	American Public Health Association
ASTM	**:**	American Society of Testing and Materials
BDL	**:**	Below Detection Limit
BMTPC	**:**	Building Material and Technology Promotion Council
BS	**:**	Badarpur Sand
C&D	**:**	Construction & Demolition
CBR	**:**	California Bearing Ratio
CC	**:**	Consolidation Characteristics
CCA	**:**	Chromated Cooper Arsenate
CD	**:**	Consolidated Drained Triaxial Test
CFM	**:**	Conventional Fill Material
CMD	**:**	Cross Machine Direction
CoV	**:**	Coefficient of Variation
DC	**:**	Degree of Compaction
DI	**:**	Deionised Water
DOC	**:**	Dissolved Organic Carbon
DOT	**:**	Department of Transportation
DS	**:**	Delhi Silt
DST	**:**	Direct Shear Test
EC	**:**	Electrical Conductivity
ECDGE	**:**	European Commission Director General Environment
ED-XRF	**:**	Energy Dispersive X-Ray Fluorescence
EU	**:**	European Union
FDOT	**:**	Florida Department of Transportation
FHWA	**:**	Federal Highway Administration
GG	**:**	Geogrid
GSD	**:**	Grain Size Distribution
HW	**:**	Hazardous Waste
HDPE	**:**	High-Density Polyethylene
IW	**:**	Inert Waste
ICP-MS	**:**	Inductive Coupled Plasma Mass Spectrometry
IDOT	**:**	Illinois Department of Transportation
INDOT	**:**	Indiana Department of Transportation
IRC	**:**	Indian Road Congress
IS	**:**	Indian Standards
LaDOT	**:**	Louisiana Department of Transportation
LA	**:**	Los Angeles value
LL	**:**	Liquid Limit
LLDPE	**:**	Linear Low-Density Polyethylene
LOI	**:**	Loss on Ignition

LVDT	:	Linear Variable Differential Transducers
MD	:	Machine Direction
MDD	:	Maximum Dry Density
MDOT	:	Michigan Department of Transportation
MODOT	:	Missouri Department of Transportation
MoRTH	:	Ministry of Road Transport and Highways
MNDOT	:	Minnesota Department of Transportation
MP	:	Modified Proctor
MRA	:	Mixed Recycled Aggregate
MSDOT	:	Mississippi Department of Transportation
MSE	:	Mechanically Stabilized Earth
NCDOT	:	North Carolina Department of Transportation
NHW	:	Non-Hazardous Waste
NJDOT	:	New Jersey Department of Transportation
NP	:	Non-Plastic
NR	:	Not Reported
NVDOT	:	Nevada Department of Transportation
ODOT	:	Oregon Department of Transportation
OMC	:	Optimum Moisture Content
PCB	:	Polychlorinated Biphenyls
PET	:	Polyethylene Terephthalate
PI	:	Plasticity Index
PLI	:	Pollution Load Index
PS	:	Polymeric Strips
RA	:	Recycled Aggregate
RAP	:	Reclaimed Asphalt Pavement
RA_S	:	Recycled Aggregate Sludge
RCA	:	Recycled Concrete Aggregate
RMA	:	Recycled Masonry Aggregate
RIDOT	:	Rhode Islands Department of Transportation
RMA	:	Recycled Masonry Aggregate
SDOT	:	Seattle Department of Transportation
SP	:	Standard Proctor
SS_MRA	:	Sand-Sized Mixed Recycled Aggregate
SS	:	Shear Strength
SSD	:	Saturated Surface Density
TDS	:	Total Dissolved Salts
TOC	:	Total Organic Carbon
TNDOT	:	Tennessee Department of Transportation
TSS	:	Total Soluble Solids
UHMI	:	Ultra-High Matrix Introduction
USCS	:	Unified Soil Classification System
XRD	:	X-Ray Diffraction

WA	**:**	Water Absorption
WVDOT	**:**	West Virginia Department of Transportation
YS	**:**	Yamuna Sand
ZAV	**:**	Zero Air Void

LIST OF ANNOTATIONS

Al	:	Aluminium
Al_2O_3	:	Aluminium oxide
Ag	:	Silver
As	:	Arsenic
Ba	:	Barium
Be	:	Beryllium
C	:	Cost of the MSE wall
$CaCO_3$	:	Calcite
CaO	:	Calcium oxide
C_c	:	Compression index
C_s	:	Swell index
Cd	:	Cadmium
C_f	:	Contamination factor
Cl^-	:	Water-soluble chlorides
Co	:	Cobalt
Comp.	:	Composition
Cr (VI)	:	Hexavalent chromium
Cr	:	Chromium
Cr_2O_3	:	Chromium (III) oxide
Cu	:	Copper
d	:	Rate of transportation of fill material
D_{max}	:	Maximum particle size
D_r	:	Relative density
d_{t1}	:	Transportation cost for an initial 5 km
d_{t2}	:	Transportation cost per km beyond 5 km to 10 km
d_{t3}	:	Transportation cost per km beyond 10 km to 20 km
d_{t4}	:	Transportation cost per km beyond 20 km
e	:	Voids ratio
e_{max}	:	Maximum void ratio
e_{min}	:	Minimum void ratio
F	:	Fluoride
Fe_2O_3	:	Ferric oxide
G_s	:	Specific gravity
H	:	Height of wall
Hg	:	Mercury
I_{geo}	:	Geoaccumulation index
k	:	Permeability
K_2O	:	Potassium oxide
L	:	Total length of reinforcement
L_e	:	Effective length/length of the reinforcement in the resistant zone/ embedment length
L_R	:	Rankine length
L/S	:	Liquid to Solid ratio
mC_d	:	Modified degree of contamination
MgO	:	Magnesium oxide
Mo	:	Molybdenum
Mn	:	Manganese
MnO	:	Manganese oxide

Mt	:	Million tonnes
n	:	Number of layers of reinforcement
Na	:	Sodium
Na_2O	:	Sodium oxide
Ni	:	Nickel
P_2O_5	:	Phosphorus pentoxide
Pb	:	Lead
P_R	:	Peak pullout resistance
PTFE	:	Polytetrafluoroethylene
R	:	Cost of the fill material
r	:	Cost of reinforcing element
R_b	:	Bricks
Rep.	:	Reported
R_c	:	Concrete
R_u	:	Unbound aggregate
R_a	:	Asphalt
r_{GG}	:	Rate for GG
r_{PS}	:	Rate for PS
R_{SS_MRA}	:	Cost for SS_MRA
R_{YS}	:	Cost for YS
Sb	:	Antimony
Se	:	Selenium
SiO_2	:	Silicon dioxide
Sn	:	Tin
SO_3	:	Sulphur trioxide
SO_4^{2-}	:	Water-soluble sulphates
S_v	:	Vertical spacing of reinforcement
SrO	:	Strontium oxide
t	:	tonnes
T_{allow}	:	Allowable tensile strength
Ti	:	Titanium
TiO_2	:	Titanium oxide
T_{ult}	:	Ultimate tensile strength
V	:	Vanadium
Vol.	:	Volume
X	:	Others
Zn	:	Zinc
ZnO	:	Zinc oxide
γ_{dmax}	:	Maximum dry density
#N	:	Number of samples
α_h	:	Horizontal acceleration
γ_{dmin}	:	Minimum dry density
ϕ_p	:	Peak angle of shearing resistance
ε_v	:	Volumetric strain
ϕ_r	:	Residual angle of shearing resistance
$\Delta\sigma_n$	:	Net effective stress
ν	:	Poisson’s ratio of sand
k_o	:	Coefficient of lateral earth pressure at rest
τ	:	Maximum shear stress
ψ	:	Dilation angle

f_b	**:**	Bond coefficient/interaction coefficient
$\mu_{S/GSY}$	**:**	Soil-geosynthetic interface apparent coefficient of friction
RF_{ID}	**:**	Reduction factor for installation damage
RF_{CR}	**:**	Reduction factor for creep
RF_D	**:**	Reduction factor for degradation
T_{allow}	**:**	Allowable tensile strength