Study on the admixing of recycled C&D waste fine aggregates for partial replacement of sand and ceramic waste tile powder for partial replacement of OPC in foam concrete mixes

फोम कंक्रीट मिश्रण में रेत के आंशिक प्रतिस्थापन के लिए पुनर्चक्रित सी एंड डी अपशिष्ट महीन समुच्चयों और ओपीसी के आंशिक प्रतिस्थापन के लिए सिरेमिक अपशिष्ट टाइल पाउडर के मिश्रण पर अध्ययन

Thesis submitted in partial fulfilment for the
Award of Degree

Doctor of Philosophy

By

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It is certified that the work contained in the thesis titled "**Study on the admixing of recycled C&D waste fine aggregates for partial replacement of sand and ceramic waste tile powder for partial replacement of OPC in foam concrete mixes**" by ***Mr. ROHIT RODHIA*** (Registration No. 19061009) has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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DECLARATION BY THE CANDIDATE

I, ***ROHIT RODHIA***, certify that the work embodied in this thesis is my own bonafide work carried out by me under the supervision of ***Prof. BRIND KUMAR*** from July 2019 to May 2025 at the Department of Civil Engineering of the Indian Institute of Technology (Banaras Hindu University), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I also declare that I have faithfully acknowledged and given credit to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully lifted any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports, dissertations, thesis, etc., or available at websites and included them in this thesis and cited them as my own work.

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ACKNOWLEDGEMENT

Though only my name appears on the cover letter of this dissertation, a lot of wonderful people have contributed to reaching me to my destination. I wish to owe my sincere appreciation to all those people who helped me to accomplish several achievements during this span.

Firstly, I would like to bow my head to this Holy Land of Varanasi, where the combined divine power of ***Kashi Vishwanath***, ***Maa Durga*** and ***Sankat Mochan*** provided me good health, knowledge, strength and capability to work hard at vicious time. Additionally, I would also like to thank "***Shrimad Bhagavad Gita***" who always boosted my moral toward my work on every occasion of negatory time. Medical science has greatly improved their vision about many organs of the human body but study about the MIND, which control other organs of the body, is only taught in "***Shrimad Bhagavad Gita***".

I also bow my head with great respect and gratitude in the pious feet of "***Bharat Ratna Mahamana Pandit Madan Mohan Malaviya Ji***" for establishing this great historical institute for the center of excellence and knowledge, Banaras Hindu University (now Indian Institute of Technology (BHU) Varanasi for engineering studies) who facilitated me the opportunity to enhance and expand the horizon of knowledge.

I express my sincere gratitude to my supervisor ***Prof. Brind Kumar***, Department of Civil Engineering, Indian Institute of Technology (Banaras Hindu University) Varanasi. I am fortunate to have a supervisor who gave me the liberty to express myself and at the same time the valuable guidance to recover when my steps faltered. I also want to acknowledge him for including me in many of the field visits which ultimately enhanced my knowledge and vision. I also learned from him how to take maximum advantages from fewer facilities. Without his support, this dissertation would not have been possible, and I shall always be grateful to him for his guidance, valuable suggestions, and kind encouragement during my entire research work.

I am also grateful to my research committee members and Comprehensive examination members: ***Dr. Tarun Verma (Mining Engineering)*** and ***Dr. Rosalin Sahoo (Civil Engineering)*** for their instructions, valuable suggestions and support throughout the study.

I am much obliged to ***Dr. Surya Kant Sahdeo***, Assistant Professor, Department of Civil Engineer, IIT Ropar, who provide me moral support and inspirations throughout the completion of this degree.

I extend my sincere gratitude to **Dr. Ankit Gupta**, Professor, and **Dr. Abhisek Mudgal**, Assistant Professor, for their constructive comments and valuable insights that greatly enriched my ideas. I am also thankful to **Dr. Agnivesh Pani** and **Dr. Anshuman Sharma**, Assistant Professors, IIT (BHU) Varanasi, for their kind guidance and encouragement. In addition, I acknowledge the valuable support provided by Mr. Roshan Bhandari and Mr. Amit Kumar Singh, the laboratory in-charges, whose assistance was indispensable to the successful completion of this work.

I am obliged to ***Prof. Sasankasekhar Mandal***, Head, Department of Civil Engineering, IIT (BHU) Varanasi, for providing the necessary facilities and a pleasant working atmosphere in the department. I would also like to thank and express my heartfelt thanks and indebtedness to other faculty members of the Department of Civil Engineering, Indian Institute of Technology, Banaras Hindu University, Varanasi, for their support and motivation.

I am sincerely thankful to my M. Tech. Supervisor ***Prof. Kusam Sudhakar Reddy***, Department of Civil Engineering, Indian Institute of Technology, Kharagpur, for encouraging me to do a Ph.D. I am also thankful to him for enhancing my knowledge of Highway Engineering.

I am also grateful to Library In-charge, Civil Engineering Library IIT (BHU) for allowing me to access vast literature resources. I am also grateful to Laboratory In-charge and the technicians of the following labs of our institute, other institutes and the construction company for allowing and helping me in performing laboratory works.

1. Transportation Engineering Laboratory, Civil Engineering Department IIT (BHU)
2. Structural Engineering Laboratory, Civil Engineering Department IIT (BHU)
3. Central Instrument Facility, IIT (BHU)
4. Ministry of Education, India
5. Hem Care Corporation, Rajkot (Gujrat)

I express my appreciation to ***Mr. Sachin Ojha*** (XRD, CIF, IIT (BHU) Varanasi) and Mr. ***Aman Singh*** (FESEM, CIF, IIT (BHU) Varanasi) for their continuous support.

I am deeply grateful to my family for their unwavering support and inspiration. My father, **Sh. Devi Dayal Rodhia**, and my late uncle, **Sh. Satyawan Rodhia**, instilled in me the values of honesty, punctuality, and the importance of physical and mental fitness. My mother, **Smt. Prem Rodhia (Maa)**, and **Smt. Sumitra Rodhia (Mummy)** embody selfless care and sacrifice for the well-being of our family. I am indebted to my elder brothers, **Mr. Ashish Kumar**, **Mr. Maneet Rodhia**, **Mr. Ravinder**, and **Mr. Mohit Rodhia**, as well as my sisters, **Mrs. Preeti** and **Miss Anjali**, for their constant motivation and encouragement. I also acknowledge the joy and strength brought to my life by my nephews, **Jaiaditya (Nona)**, **Lakshyaraj (Kuki)**, **Bantu**, and my niece, **Kiyara (Kiyu)**. Their love and presence have been a source of immense strength throughout my journey.

I sincerely acknowledge the invaluable support, guidance, and encouragement of my seniors Dr. Arunabh Pandey, Dr. Gaurav Verma, and Dr. Jayvant Chaudhary; my colleagues Dr. Amar Deep Pandey, Mrudul Sonar, Dr. Rahul Ranjan, Deepak Rathore, Aakash Singh, Dr. Prabhakar Tripathi, Satyavrat Tripathi, Rohit Ranjan, Ronit Ranjan, Divakar Bhaiya, Gaurav Bhaiya, Utkarsh Mishra, Adarsh, and Dr. Ashish Chouksey; my juniors Khush Goyal, Bittu Kumar, Anshu Saxena, Gaurav Chaurasia, and Taha Ashraf Ansari; as well as my friends Dr. Kapil Malik, Rahul Meena, Utkarsh Naik and Dr. Shiwani, whose contributions have been instrumental during my Ph.D. journey.

Rohit Rodhia

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ABBREVIATIONS and SYMBOLS

FC	Foam concrete
CD-RFA	Recycled fine aggregate from construction and demolition waste
CWTP	Ceramic waste tile powder
SEM	Scanning Electron microscope
XRD	X-ray diffractometer
DI	Durability Index
OPC	Ordinary Portland cement
EMAS	Engineering material arrestor system
XRF	X-ray Fluorescence
ACI	American Concrete Institute
ASTM	American Society of Testing materials
SCM	Supplementary Cementitious Material
HPMC	Hydroxypropyl methyl cellulose
W/C	water to cement ratio
RFA	Recycled fine aggregate
FRFC	Fibre reinforced foamed concrete
E	Modulus of Elasticity
MPa	Mega Pascal
GPa	Giga Pascal
HCl	Hydrochloric acid
H_2SO_4	Sulphuric acid
CSH	Calcium Silicate hydrates
CASH	Calcium Aluminate hydrate
GFC	Geo polymer foam concrete
SAC	Sulfoaluminate cement
MPC	Magnesium phosphate cement (MPC) foam concrete
LC^3	Limestone Calcined Clay Cement
NASH	Sodium-Aluminum-Silicate-Hydrate
FA	Fly ash
BA	Bottom Ash
CBA	Coal bottom ash
UPV	Ultrasonic Pulse Velocity
GBS	Unground blast furnace slag
GGBS	Ground granulated blast furnace slag
SF	Silica fume
FOPA	Fine oil palm ash
OPA	Oil palm ash
LWC	Light weight concrete
RHA	Rice husk ash
QD	Quarry dust

CDWRS	Construction and demolition waste residue soil
CDW	Construction and demolition waste
RA	Recycled aggregates
BIS	Bureau of Indian standard
SSD	Saturated surface dry weight
ITZ	Interfacial transition zone
$Ca(OH)_2$ & (CH)	Calcium hydroxide
CM	Control mix with foam
WRA	waste recycled aggregates
$CaCO_3$	Calcium Carbonate
ANOVA	Analysis of Variance
SAI	Strength Activity Index
SiO_2	Silica oxide
Al_2O_3	Aluminium Oxide
Fe_2O_3	Ferric Oxide
CaO	Calcium Oxide
MgO	Magnese Oxide
SO_3	Sulphur trioxide
C_3S	Tricalcium silicate
C_2S	Dicalcium Silicate
EDX	Energy Dispersive X-ray

ABSTRACT

Solid waste landfills will continue to receive a large amount of waste due to the rapid increase in population worldwide. We can efficiently preserve our finite material resources by transforming a substantial quantity of solid waste into a viable alternative resource. An extensive study has been conducted on using two solid waste materials in concrete due to its widespread application as construction material for roads and buildings.

Foam concrete (FC) is emerging as a novel material. It is gaining good attention amongst academicians due to low self-weight and self-compacting nature. This technology consists of a concrete type in which entrained air is generated through use of foaming agent to a mixture of cement and fine aggregates. Different types of fine aggregate proportions, water-to-cement (w/c) and cement-to-sand ratio, and foam concentration provides an optimum balance for design of FC mixes. Studies in the literature have focused primarily on assessing the properties of the foam concrete. No mention is found on examining the effect of foaming agent dilution ratio, which is expected to play a crucial role in achieving the desired pore structure through optimum air entrainment. Foam concrete is rendered lightweight, and the need is to strike a balance between porosity achieved and the mechanical properties for its infield performance. Identification of appropriate foaming agents is another aspect of framing the technology for broader applications.

Recycled fine aggregates from construction and demolition (CD-RFA) waste processing plants was used for partial replacement of natural river sand below 1.18 size along with OPC. It is expected that the use of CD-RFA in foam concrete mixes would cater to the needs of sustainability. A comprehensive laboratory investigation for utilizing

CD-RFA in FC mixes is made in this research. CD-RFA was utilized in proportions of 0, 10, 30, 50, 70, and 100%, respectively by the mass of sand.

Three dilution ratios of protein based foaming agent viz. 1:20, 1:40 and 1:60 (water: foaming agent) were used to produce FC mixes. The fresh, mechanical, microstructural and durability properties of FC mixtures were studied. An extensive laboratory investigation reveals that the FC mixes at dilution ratio of 1:40 showed the best-balanced relationship between all the aforementioned parameters required for foam concrete. This is a novel finding. Depending on the concentration of the foaming agent, entrained air bubbles of different sixes are formed in FC mixes. These bubbles tend to collapse and merge during the mixing process with the dry ingredients. On drying, these bubbles may leave voids/pores in the FC mass thereby rendering light-weightiness.

Results indicate that the replacement of natural sand up to 50% with CD-RFA is possible by mass of sand. However, the optimum results in terms of fresh, mechanical, microstructural and durability properties were obtained for 10% replacement level. The foam concrete mix prepared using recycled fines will help clearance of a large quantity of CD waste in volume terms, thereby benefiting the environment.

Admixing CD-RFA increases the water absorption of the FC mixes due to the adhered mortar on its surface during processing in the C&D plants. This impacts the porosity and sorptivity of the FC mixes as compared to the control FC mix prepared with sand, OPC and foam. These properties increase considerably as the CD-RFA replacement levels increases. Meanwhile, the incorporation of CD-RFA was found to negatively affect the mechanical properties of the FC mixes. However, the obtained values of compressive strength, flexural strength, and split tensile strength of 10% admixed CD-RFA were 14.17, 4.88 and 2.27 MPa, respectively at 28-day. These results were within the ACI 523R 2014 recommended ranges of 8–22, 3–6.4, and 1–2.2 MPa, thereby rendering CD-RFA admixed foam concrete suitable for semi or non- structural as well as lightweight applications. The control FC mix attained compressive strength, flexural strength, and split tensile strength of 22.35, 4.68 and 2.18 MPa, respectively, which holds promise for its application for structural purposes. Of further interest is the flexural strength achieved by the FC mixes, holding promise for their use in parking lots that would keep the surface dry and help groundwater recharge. The hardened density, abrasion resistance, and resistance to sulphates and chloride attacks showed a perceptible decline for 10% admixed CD-RFA FC mixes.

SEM of FC specimens after 28 days show an irregular distribution of pore-sizes scattered all over the groundmass. The microstructure of foam concrete is influenced by several elements - including the foaming agent, component materials, and mixing technique. Formation of foam bubbles varies noticeably between the control mix and the mix with 100% CD-RFA replacement. This is because the admixing CD- RFA results in large surface area of pores/ voids and is adsorptive. The XRD reveals hydrated products such as portlandite (CH), calcium silicate hydrates (CSH), and unreacted calcite and dicalcium silicate. Samples with higher level of CD-RFA replacement show higher intensity of calcite, which resulted from carbonation of hydrated products as compared to control FC mixes. Also, as the percentage of CD-RFA increases in foam concrete, the concentration of $CaCO_3$ increases in the mix at every dilution ratio along with increase in porosity.

This study uses another waste named ceramic waste tile powder (CWTP) for partial replacement of OPC in foam concrete in different proportions varying from 10%, 30%, 50%, 70%, and 90% by mass of cement. Mixtures of the resulting cementitious material and natural river sand were considered. The development of compressive strength over time (at 7, 28, and 90 days), flexural strength, and split tensile strength at 28 days were examined. The protein-based foaming agent was diluted in the proportion of 1:40 as obtained for CD-RFA.

It was found that with the increase in the proportion of CWTP, the porosity, volume of permeable voids, sorptivity and water absorption of foam concrete mixes increased significantly. At the same time, a downward trend in the mechanical properties were noted. However, the obtained values of compressive strength, flexural strength, and split tensile strength were found to attain peak value at CWTP admixing level of 30% with OPC attaining values of 14.94, 4.86 and 1.65 MPa, respectively. These were found to be well within the ACI 523 R 2014 recommended ranges of 8–22, 3–6.4, and 1–2.2 MPa. The FC mixes were evaluated for durability performance through the abrasion resistance using Cantabro test and exposure to an aggressive environment using 2% sulphuric and hydrochloric acid solution. Hardened density, abrasion resistance, and resistance to sulphates and chloride attacks increase with the increase of replacement level of CWTP in mixes. A durability criterion called *durability index* is introduced in this research to compare the durability of varying replacement levels of CWTP in FC mixes.