OPTIMIZATION OF SUSTAINABLE CONSTRUCTION MATERIALS FOR INDUSTRIAL APPLICATIONS

Ph.D. Thesis

By

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INDIAN INSTITUTE OF TECHNOLOGY INDORE

OCTOBER 2023

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A THESIS

Submitted in partial fulfilment of the requirements for the award of the degree
of
DOCTOR OF PHILOSOPHY

by
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I hereby certify that the work which is being presented in the thesis entitled **OPTIMIZATION OF SUSTAINABLE CONSTRUCTION MATERIALS FOR INDUSTRIAL APPLICATIONS** in the partial fulfilment of the requirements for the award of the degree of **DOCTOR OF PHILOSOPHY** and submitted in the **DEPARTMENT OF CIVIL ENGINEERING, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from December 2018 to October 2023 under the supervision of **Prof. SANDEEP CHAUDHARY**, Professor, Department of Civil Engineering.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

13.05.2024

Signature of the student with date

(SANCHIT GUPTA)

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

13.05.2024

Signature of Thesis Supervisor with date

Prof. SANDEEP CHAUDHARY

SANCHIT GUPTA has successfully given his Ph.D. Oral Examination held on **May 10, 2024**.

13.05.2024

Signature of Thesis Supervisor with date

Prof. SANDEEP CHAUDHARY

“My work is dedicated to my family, who have always supported and encouraged my passion for research.”

ACKNOWLEDGEMENTS

At the time when I was completing my doctoral thesis, I remembered the old African proverb, “it takes a village to raise a child”. The proverb reminds us of the efforts that people around us have made for us to succeed. So, before I share what I have learned in my path towards this doctoral thesis, I will like to express my gratitude to my village or those who have been there on my journey. This is my deepest gratitude to my family, supervisor, mentors, colleagues and friends for their continuous support during the ups and down of this journey.

First and foremost, I would like to thank my thesis supervisor and mentor, Prof. Sandeep Chaudhary, whose constant support, guidance and encouragement has helped me grow as a researcher. Since I started my academic journey, he has encouraged me to explore new research ideas, anchored me when I strayed off topic, shared his wisdom when I needed to learn, and showed patience when I needed time. His firm but compassionate approach has been invaluable in shaping my thesis and myself as researcher. I am profoundly grateful to the knowledge, time, opportunity and resources, he has given to me this journey.

I would like to express my gratitude to my progress committee (PSPC) members: Dr. Guru Prakash, Dr. Kaustav Bakshi and Dr. Indrasen Singh. Their periodic assessments and insights helped me keep my doctoral thesis on track and enrich the quality of my work. I will also like to thank the head of the department Dr. Abhishek Rajput, for the guidance and resources shared by him during my journey. I will also like to acknowledge the efforts of the discipline post graduate committee (DPGC) thank Dr. Priyansh Singh for his role as Convener, DPGC. I am also grateful to Dr. Debasis Nayak, Dr. Hem C Jha, Dr. Vinod Kumar, Dr. Surya Prakash and Prof. Neelima Satyam for sharing their knowledge and laboratory resources during my experimental works.

I want to thank my father, Mr. Raj Kumar Gupta, my mother, Mrs. Sandhya Gupta, my brother, Mr. Shubham Gupta, and my sister-in-law, Mrs. Rupali Gupta for their faith in me and for teaching me a lot to grow myself. Their patience during the pandemic helped me to focus on my work. I am also thankful to my cousins Mr. Aman Gupta, Mrs. Shweta Gupta, Mr. Ritesh Gupta, Mrs. Neha Gupta and Mr. Atul Gupta who never let me feel that I am away from my home.

I am also fortunate to receive support from Dr. Akshay Anil Thakare, Dr. Vivek Gupta, Dr. Amardeep Singh, Dr. Salman Siddique, Dr. Trilok Gupta, and Dr. Abhishek Jain. They not only shared their knowledge and mentorship, but also allowed me to participate in their research activities. Their knowledge and experience, allowed me to explore various research domains and find my strength as a researcher. I am grateful to my colleagues and friends, Dr. Ashita Singh, Ms. Astha Sharma, Mr. Harshit Agrawal, Mr. Dheerendra Singh and Mr. Dhruv Narayan Lal who both helped and encouraged me in this journey. I am thankful to Mr. Sapan Gaur and Mr. Suresh Waskle for their assistance during the experimental works. I acknowledge the support received from Mr. Ghanshyam, Ms. Rinki Kukreja, Mr. Sandeep Patil, Mr. Amit Jadhav, Mr. Pranjal Shrimali, Mr. Ajay Malviya and Mr. Shivcharan Patel. I am also grateful to some of my colleagues, who were not involved my doctoral thesis, but working with them has helped me grow as a researcher. And for this I will like to thank Dr. Harsha Upadhyay, Mr. Sumer Thakur, Mr. Shivam Rajpoot, Ms. Niyati Totala, Mr. Sumit Meena, Mr. Chetan Shakti Pandey, Mr. Abhishek Ojha, Mr. Ayush, Mr. Parth Dwivedi, Mr. Himanshu Gupta, Mr. Himanshu Khati, Mr. Bejamin Basumatary, Mr. Tarun Soni, Mr. Anshu Ratan, Mr. Ravi Kumar and Ms. Aishwarya Agrawal.

I will like to specially thank my friends, who not only supported and encouraged me in my research, but were an integral part of my journey outside the laboratory. I am grateful to Dr. Nitin Tiwari and Dr. Subhash Yadav, who have been like brothers to me. I am also grateful to Dr. Akshay Anil Thakare, Ms. Saika Manzoor, Dr. Meghna Sharma, Dr. Moirangthem Johnson Singh, Dr. Nikhil Kumar, Ms. Astha Sharma and Mr. Aman Patel (aka AP) for always being there for me. In addition to my closest friends, I am also grateful to AAINA for always lifting my spirits on campus (hail AAINA).

I sincerely express my gratitude to Director, IIT Indore, for his support during my journey and extending the resources of the institute. I am also thankful to DOAA, associate DOAA, assistant registrar, junior superintendent, and other academic affairs office staff for their help during my Ph. D. program. I am also thankful to all academic and non-academic staff which directly or indirectly helped during my stary at IIT Indore.

Last but not the least, I am thankful to the Ministry of Education, Govt. of India, for providing the financial assistance, which allowed me to pursue this journey.

Sanchit Gupta

SYNOPSIS

1. Introduction

The last century has witnessed an unprecedented growth in infrastructure. This growth in infrastructure consumed a significant volume of natural resources. The construction industry became the highest consumer of natural resources at the beginning of the 21st century (>35.9%) [1]. High resource consumption presents several environmental challenges, including the depletion of natural resources. Recognising the environmental threat, there is a growing interest towards introducing resource sustainability[1] in the construction industry. The United Nations Sustainable Development Goals (SDG) in 2015 also emphasised the need to ensure sustainable consumption and production of natural resources.

Resource sustainability can be typically achieved by reducing natural resource consumption. The consumption of natural resources can be lowered by reducing material use, recirculating waste, and using alternative resources. The construction industry consumes a wide range of natural resources. Understanding the factors associated with different resources can help design solutions for resource sustainability and help in developing sustainable construction materials[2]. Among several materials, concrete is the highest consumed resource in the construction industry. Concrete (itself) is designed using cement, water, aggregates, fibres, chemical admixtures and mineral additives. Considering a large number of resources, the present work focuses on raw materials of concrete with a high threat towards resource sustainability.

Threat towards resource sustainability is defined as the rate at which natural resource reserves are depleting. An extensive review has been carried out on the consumption pattern, regeneration rate, recirculation

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[1] Resource sustainability implies sustainable production, consumption and management of natural resources.

[2] Sustainable construction material here refers to any construction material, i.e., cement, water, etc., with higher resource sustainability.

ratio and available reserves of various raw materials. Fig. 1 presents a linear visualisation of the threat towards resource sustainability. As shown in Fig. 1, cement and coarse aggregates have the highest threat towards resource sustainability. In the case of cement, limestone shortage governs the threat to resource sustainability. Limestone has high consumption, low regeneration, lack of viable alternatives and limited reserves. Based on the present consumption rate, the viable limestone reserves in India are expected to last 34 years of cement manufacturing. Recognising the threats, the present work focuses on the resource sustainability of cement and coarse aggregates to develop sustainable construction materials.

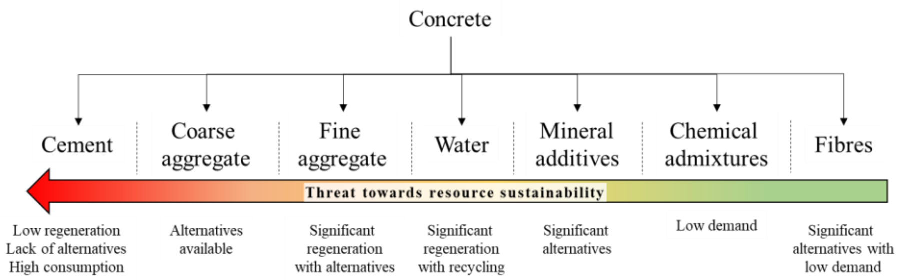

Fig. 1. Threat towards resource sustainability for various raw materials of concrete

Literature shows that the threat towards resource sustainability has been recognised for over 30 years [2]. During this time, several studies have been conducted to improve resource sustainability. However, only limited studies go for industrial applications, highlighting the presence of barriers [3]. A barrier indicates that construction material costs (economic, environmental and social costs) are higher than what the stakeholder can afford. Understanding these barriers can help select an existing or develop a new solution with a higher likelihood of industrial application.

The present work focuses on the resource sustainability of cement and coarse aggregates in the Indian construction industry. An extensive review has been carried out on the existing solutions of resource sustainability and factors affecting their application in the Indian construction industry. Based on the reviewed factors, the present work identifies two possible strategies for optimising sustainable construction materials. For cement, the study focuses on maximising clinker substitution by optimising the selection of supplementary cementitious materials (SCMs). For coarse aggregates, the study focuses on developing a treatment strategy for improving the technical properties of mixed recycled aggregates (MRA). After identifying a solution for maximising resource sustainability, the study focuses on optimising the industrial application of sustainable construction materials. The present work investigates the industrial application of limestone calcined clay cement (LC^3), which is a low-clinker cement with improved resource sustainability over commercially used ordinary Portland cement (OPC) and Portland pozzolana cement (PPC). The present work utilises experimental investigations and Monte Carlo simulation to assess the fire risk associated with the industrial application of LC^3. Monte Carlo simulation is then used for developing the safety guidelines for robust[3] industrial application of LC^3. Overall, the present work develops solutions for improving resource sustainability and demonstrates the application of Monte Carlo simulation for optimising the industrial application of sustainable construction materials.

The detailed objectives and key results are summarised in subsequent sections.

2. Objectives

The overall scope of this study has been divided into four research objectives:

- To review the factors influencing the field translation of supplementary cementitious materials and alternative aggregates in the Indian construction industry.

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[3] Robust implies sturdy or a structure which can survive the accidental loads (like fire)

- Formulation of a systematic framework for optimising the selection and field application of supplementary cementitious materials.
- Development of sustainable aggregates through process optimisation of upcycling construction and demolition waste.
- To demonstrate the potential of Monte Carlo simulation in designing safety guidelines for robust field application of sustainable construction materials.

3. Major work reported in the thesis

A. Alternative materials and factors affecting the industrial application of SCMs and aggregates in India

Limestone shortage threatens the resource sustainability of cement manufacturing in India. Clinker substitution using SCMs can lower dependency on limestone and improve the resource sustainability of cement. Analysis of the Indian construction industry shows that many waste and locally available resources can be used as SCMs. The present legal framework permits the increased utilisation of SCMs, but only after necessary experimental investigations. In regions with high SCM availability, stakeholders must select an SCM that can meet all performance requirements at high replacement levels. Similarly, stakeholders need to identify alternative resources as potential SCMs in regions with low SCM availability. A suitable selection strategy will lower the cost of local optimisation and help stakeholders maximise SCM utilisation.

Resource sustainability of aggregates can be improved by the use of alternative construction materials. Most alternative aggregates identified in the literature have either limited availability (e.g., slags) in India or show poor performance in concrete (e.g., plastic). C&D waste has significant availability, and their recycling as alternative aggregates can partly solve the problem of resource sustainability. The legal provision favours the use of alternative aggregates after they have satisfied the necessary codal provisions. Therefore, resource sustainability for aggregates requires the development of alternative aggregates using C&D wastes which satisfies relevant codal provisions.

B. Characterisation-based approach for SCM selection

Selection of SCMs based on their source of origin has become challenging. SCMs with similar origins can show widely different characteristics and effects on the properties of concrete. For example, Silpozz, a variation of rice husk ash, behaves similarly to silica fume and not rice husk ash. Alternative classification systems like characterisation-based classification can present a viable alternative to source-based classification. The present study explores the potential for characterisation-based classification by investigating the correlation between SCM characteristics and their effect on the properties of concrete. Over 20 different SCMs have been investigated for their physical, mineral, chemical and morphological characteristics and their effect on the various properties of concrete. The SCMs are then grouped using the characterisation-based classification. A meta-heuristic analysis has been carried out to observe the correlation between the SCM characteristics and their effect on the properties of concrete.

Results show that SCMs with similar characteristics have similar effects on the properties of concrete. The morphology and particle size of SCMs influence concrete workability. The particle size and chemical composition of SCMs influence the mechanical strengths of concrete. Carbonation-based corrosion is influenced by particle size and chemical composition of SCMs. Chloride-based corrosion, wetting and drying cycles and permeability improve with pozzolanic activity and not other SCM characteristics. In terms of SCM characteristics, particle size (through specific surface area), chemical composition (through XRF) and morphology (through SEM) can be used for predicting the effect of SCM addition on concrete properties. Based on characterisation-based classification, the present work also proposes a heuristic approach for optimising the selection of SCMs.

C. *Development of alternative aggregates using thermo-mechanical treatment of MRA*

Coarse aggregates present a case where resource consumption greatly exceeds the available alternatives. The simplistic strategy for resource sustainability requires manufacturing alternative aggregates, which is also favoured in the existing legal provisions [4]. Upcycling C&D waste presents the most viable alternative based on resource availability and technical viability. MRA prepared by unsorted recycling of C&D waste is the most common form of recycled aggregate in India. A significant gap observed in the literature is that the use of MRA significantly lowers the mechanical properties of concrete [5]. Treatment of MRA can improve the mechanical properties of concrete and improve its application [5]. The various treatment techniques, except thermo-mechanical treatment, require additional resources for treatment and lower the resource sustainability associated with aggregates [5]. Thermo-mechanical treatment can improve resource sustainability but has not been demonstrated for MRA.

The present study focuses on developing alternative aggregates using thermos-mechanical treatment of MRA. By varying the exposure temperature (300 °C – 800 °C), six different protocols have been adopted for the thermo-mechanical treatment of MRA. The treated MRA has been compared with untreated MRA and mechanically treated MRA in terms of adhered mortar removal and various aggregate characteristics, as per IS 383: 2016 [4]. The optimum treatment protocol is further investigated for its effect on the properties of concrete and compared with both NA and untreated MRA. The study also evaluates the carbon emission and cost associated with production of alternative aggregate.

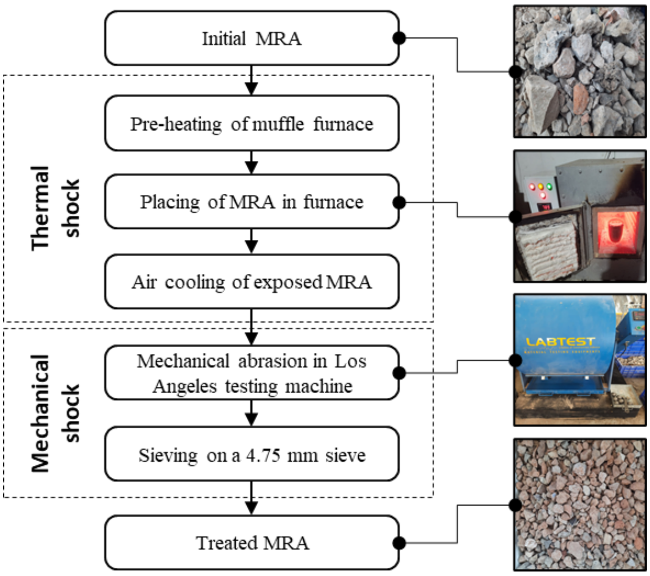


Fig. 2. Thermo-mechanical treatment of MRA

Results show that the aggregates prepared by thermo-mechanical treatment of MRA at 700 °C show the best aggregate characteristics. Exposure temperature up to 700 °C helps remove adhered mortar and improves the properties of treated aggregate. Above 800 °C, the treated aggregate develops internal weakness and shows poor properties. Aggregate treated at 700 °C satisfies the relevant codal provision of IS 383: 2016 and can be used as concrete aggregate for all practical applications. Concrete prepared with 100% MRA treated at 700 °C shows a comparable mechanical performance and higher slump than concrete prepared with natural aggregates. Life cycle assessment (LCA) shows that the carbon emission of treated aggregates can be lower or higher based on the fuel source for electricity. Further analysis shows that thermo-mechanical treatment using solar energy as the source of treatment can lower both the cost and carbon emissions of the alternative aggregates.

D. Use of Monte Carlo simulation for robust industrial application of alternative construction materials

Using alternative construction materials can lower one or more strength or durability characteristics of the developed concrete and prevent the industrial application of sustainable construction materials. The present study investigates the robust industrial application of LC^3 concrete. LC^3

is a low-clinker, resource-sustainable alternative to conventionally used cement. Literature shows that for most strength and durability characteristics, LC^3 is more sustainable than OPC and PPC [6]. However, LC^3 was investigated for fire performance in the previously reported literature.

The present experimental investigation compares the fire performance of LC^3 concrete with concrete prepared using OPC and PPC. Concrete prepared with LC^3, OPC and PPC were exposed to 16 elevated temperature scenarios with elevated temperatures of 400°C, 600°C, 800°C, and 1000°C for different exposure durations of 0.5 h, 1 h, 2 h, and 4 h. Residual properties of concrete, in terms of mass loss, residual ultrasonic pulse velocity (rUPV) and residual compressive strength (rCS) have been evaluated. XRD and TGA have been performed to understand the mineral composition and thermal degradation of LC^3, OPC and PPC cement pastes.

Results show that hardened LC^3 paste has a higher thermal degradation (as per TGA) than OPC and PPC pastes. TGA shows that thermal degradation is mainly affected by physically absorbed water (≤120 °C), portlandite (400 °C – 460°C) and calcite (600 °C – 750°C). The thermal degradation pattern in LC^3 is also supported by XRD, which shows a higher concentration of calcite and a lower concentration of portlandite. In terms of concrete, LC^3 concrete shows higher mass loss, lower rUPV and lower rCS. The mass loss in concrete resembles the mass loss in TGA. The loss in rUPV and rCS of concrete resembles the thermal degradation of cement pastes up to 600 °C. Above 800 °C, the rUPV and rCS of concrete with all three cement types and different exposure durations become similar. Above 800 °C, cement type has limited impact on the mechanical properties of concrete.

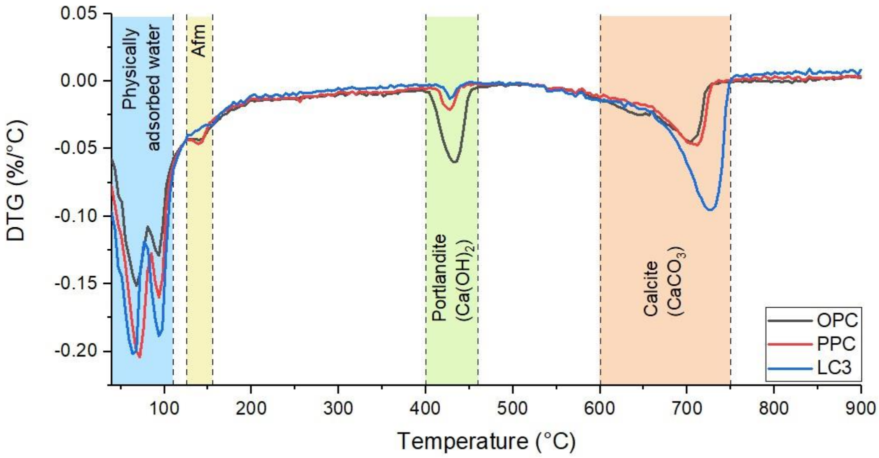


Fig. 3. TGA using DTG curve for OPC, PPC, and LC^3 pastes

The significance of the study parameters, i.e., change in cement type, exposure temperature and exposure duration, has also been analysed using three-factor ANOVA. ANOVA shows that exposure temperature has the highest effect on the properties of concrete, followed by exposure duration and change in cement type. Although the effect of change in cement type on the fire performance of concrete is low, the effect remains statistically significant. Adopting LC^3, a low-clinker cement, can increase the fire risk of concrete structures.

Resource sustainability requires the use of low-clinker cement, like LC^3, which in turn requires a robust industrial application. In the present work, Monte Carlo simulation has also been used to evaluate the fire risk of LC^3 concrete structures and develop suitable risk mitigation strategies. Monte Carlo simulation uses parameters from the Indian construction industry, fire curves defined in the literature and experimental results on LC^3, OPC and PPC to identify the probability (or risk) of failure in concrete structures. The simulation parameters are then adjusted to identify the scenarios where the risk of failure in LC^3 concrete is similar to the industry-accepted risks for OPC and PPC concrete.

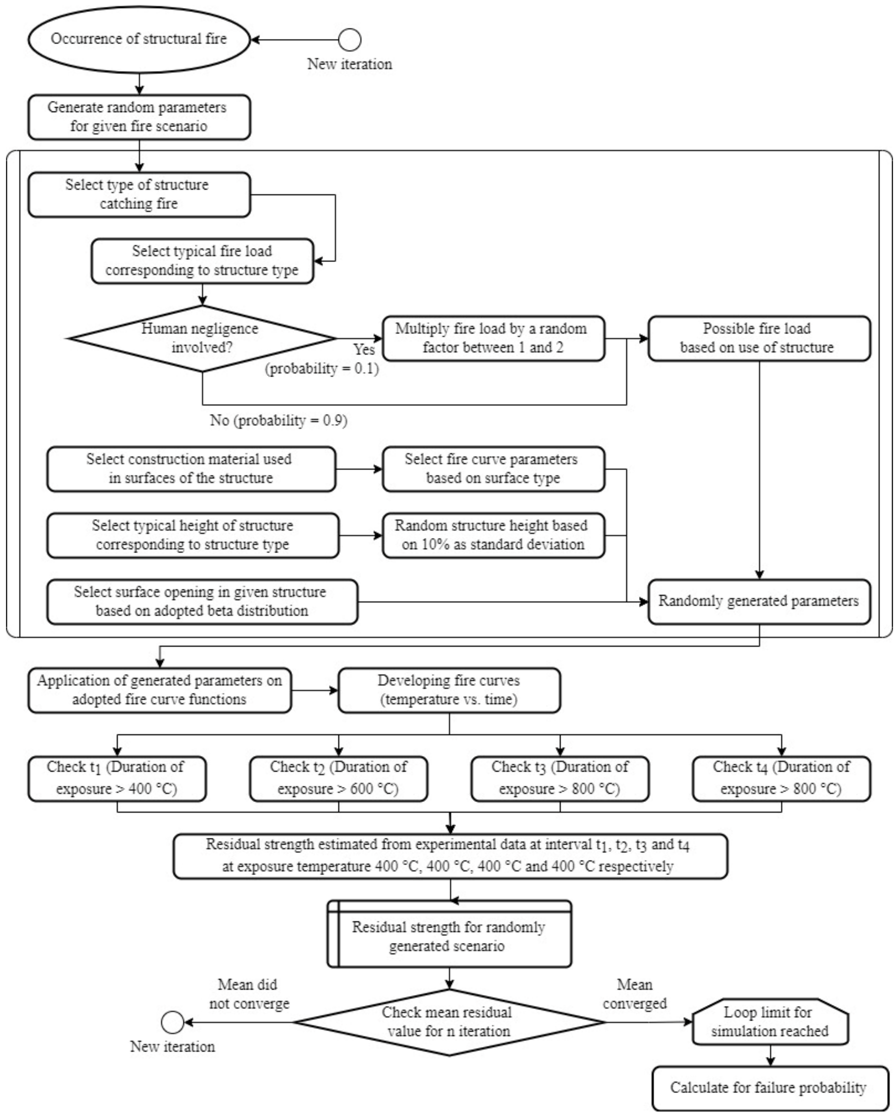


Fig. 4. Outline for Monte Carlo simulation

Results show that the probability of failure in LC^3 concrete (2.22%) is higher than OPC concrete (0.22%) and PPC concrete (1.14%). The risk can be lowered by restricting LC^3 to residential applications (risk 0.42%) or by adopting a factor of safety between 1.08 (risk 1.14%) and 1.19 (risk 0.22%).

4. New findings in thesis work

- Among the various raw materials of concrete, cement and coarse aggregate have the highest threat towards resource sustainability, based on their present consumption rate, recirculation and regeneration.

- A comprehensive review of the factors (barriers and facilitators) influencing the field translation of SCMs and aggregates in the Indian construction industry.
- SCMs with similar physical, chemical and morphological characteristics have similar effects on the properties on the properties of concrete. The effect on the properties of concrete does not correlate with the source of origin of SCMs.
- Characterisation of SCMs can be used to estimate the effect on the properties of concrete and for the systematic selection of new and alternative SCMs.
- Aggregates prepared by thermo-mechanical treatment of MRA at 700 °C show good aggregate characteristics, satisfy the relevant codal provision of IS 383: 2016, and can be used for complete (100%) replacement of natural aggregates.
- Thermo-mechanical treatment using solar energy as the source of treatment can upcycle construction and demolition waste as low-cost, low-carbon alternative aggregates.
- LC^3 concrete at elevated temperatures shows a higher loss in mechanical and physical characteristics than OPC and PPC concrete.
- Monte Carlo simulation can evaluate the fire risk of concrete structures prepared using alternative construction materials and develop risk mitigation strategies for their robust industrial application.

LIST OF PUBLICATIONS

(A) Outcomes from Ph.D. thesis work:

A1. In refereed journals

Published: 04

1. **Gupta, S.**, and Chaudhary, S. (2020). "State of the art review on Supplementary Cementitious Materials in India – I: An overview of legal perspective, governing organizations, and development patterns." Journal of Cleaner Production, 261, 121203. DOI:10.1016/j.jclepro.2020.121203 (I.F. 11.1)
2. **Gupta, S.**, and Chaudhary, S. (2022). "State of the art review on supplementary cementitious materials in India – II: Characteristics of SCMs, effect on concrete and environmental impact". Journal of Cleaner Production, 357, 131945. DOI: 10.1016/j.jclepro.2022.131945 . (I.F. 11.1)
3. **Gupta, S.**, Singh, D., Gupta, T., and Chaudhary, S. (2022). "Effect of limestone calcined clay cement (LC3) on the fire safety of concrete structures". Computers and Concrete, 27(4), 263-278. DOI: 10.12989/cac.2022.29.4.263 . (I.F. 4.1)
4. **Gupta, S.**, Agrawal, H., and Chaudhary, S. (2023). "Thermo-mechanical treatment as an upcycling strategy for mixed recycled aggregate", Construction and Building Materials, 398, 132471. DOI: 10.2139/ssrn.4269956 (I.F. 7.4)

A2. In refereed conferences

Presented: 02

1. **Gupta, S.**, and Chaudhary, S. (2023), Resource sustainability and the bubble of carbon neutrality in cement manufacturing industry, 2023 International Conference on Resource Sustainability (icRS 2023), August 7-9, Guildford, Surrey, the United Kingdom
2. **Gupta, S.**, and Chaudhary, S. (2023), Recirculation strategy for end-of-life concrete structures as low carbon construction materials,

International Symposium on Life Cycle Maintenance of Concrete Infrastructure (LCMCI2023), September 25-26, Hong Kong, China

A3. Book chapters

Published: 02

1. **Gupta, S.**, and Chaudhary, S. (2021), Large Scale Waste Utilisation in Sustainable Composite Materials for Structural Applications, in: Emerging Trends of Advance Composite Materials in Structural Applications, Composites Science and Technology. Springer, 2021. DOI: 10.1007/978-981-16-1688-4_7.
2. **Gupta, S.**, and Chaudhary, S. (2020), Use of fly ash for the development of sustainable construction materials, in: New Mater. Civ. Eng., Elsevier, 2020: pp. 677–689. DOI: 10.1016/B978-0-12-818961-0.00021-1.

A4. Analysis note

Accepted for publication: 02

1. **Gupta, S.**, Chaudhary, S., and Gupta T. (**Accepted for publication**), Variability in the Properties of Recycled Aggregate in different countries and its effect on the Properties of the concrete, in: Structural behaviour and innovation of recycled aggregate concrete - State-of-the-Art Report of the RILEM Technical Committee 273-RAC, RILEM.
2. **Gupta, S.**, Chaudhary, S., and Gupta T. (**Accepted for publication**), Codal Provisions, Standards, and Guidelines in India for the use of Recycled Aggregate in Concrete, in: Structural behaviour and innovation of recycled aggregate concrete - State-of-the-Art Report of the RILEM Technical Committee 273-RAC, RILEM.

(B) Other outcomes outside of the Ph.D. thesis work:

B1. In refereed journals

Papers published: 02

1. Thakare, A. A., Siddique, S., Sarode, S. N., Deewan, R., Gupta, V., **Gupta, S.**, and Chaudhary, S. (2020). "A study on rheological properties of rubber fiber dosed self-compacting mortar." Construction and Building Materials, 262, 120745. DOI: 10.1016/j.conbuildmat.2020.120745 (I.F. 7.4)
2. Jain, A., Gupta, R., **Gupta, S.**, and Chaudhary, S. (2023). "Evaluation of real time fire performance of eco-efficient fly ash blended self-consolidating concrete including granite waste." Journal of Building Engineering, 77, 107553. DOI: 10.1016/j.jobe.2023.107553 (I.F. 6.4)

B2. In refereed conferences

Presented: 06

1. Agrawal, H., Modhe, S., **Gupta, S.**, and Chaudhary, S. (2019), "Porosity based design - An improved design approach for pervious concrete", Proc., Ninth Asia-Pacific Young Researchers & Graduates Symposium, December 19-20, Shanghai, China.
2. Gandhi, S., **Gupta, S.**, and Chaudhary, S. (2019), "Segregation studies on light weight aggregate concrete", Proc., Ninth Asia-Pacific Young Researchers & Graduates Symposium, December 19-20, Shanghai, China.
3. **Gupta, S.**, Sharma, A., and Chaudhary, S. (2023), "Advancing 3D printing of concrete using heat-cured geopolymer", Proc., Materials Science, Form-Building Technologies and Equipment 2023 (ICMSTE 2023), May 16-19, Yalta, Russia.
4. **Gupta, S.**, Lal, D. N., Sharma, A., and Chaudhary, S. (2023) "A novel mathematical model for temporal effect of buildup and breakdown on cement rheology", Proc., International Conference

on Applied Mathematics and Mechanics (ICAMM 2023), October 18-20, Indore, India.

5. **Gupta, S.**, and Chaudhary, S. (2023) “Understanding the significance of quality control on the life cycle of concrete structures under corrosion”, Proc., 10th Asia-Pacific Young Researchers and Graduates Symposium (YRGS 2023), December 06-08, Perth, Australia.
6. **Gupta, S.**, Patra, S. K., and Chaudhary, S. (2023) “Upcycling Waste Tyre Rubber as Innovative Slip and Fall Event Reducing (SAFER) Concrete Flooring”, Proc., Recent Advances in Waste Minimization & Utilization-2024 (RAWMU 2024), April 23-24, Jalandhar, India.

B3. Book chapters

Published: 01

1. **Gupta, S.**, and Chaudhary, S. (under review), Conventional and emerging materials used in FRP-Concrete Composites for earthquake resistance, in: RC Structures Strengthened with FRP for Earthquake Resistance. Springer, 2024. DOI: 10.1007/978-981-97-0102-5_8.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

Afm	Mono-sulfo-aluminate
BOF	Basic oxygen furnace slag
C_3S	Alite
C_2S	Belite
C_4AF	Tetra calcium alumino ferrite
CC	Calcined clay
CS	Copper Slag
CWP	Ceramic waste powder
C&D	Construction and demolition
DOE	De-oiled earth
EAF	Electric arc furnace slag
eq. kg CO_2	Equivalent kg of CO_2
ESP	Egg shell powder
FA	Fly ash
FeA	Ferrochrome ash
GGBS	Ground granulated blast furnace slag
GP	Glass powder
$GtCO_2$	Giga tonnes of carbon dioxide
IF	Induction furnace slag
INR	Indian national rupee
IS	Indian standard
JS	Jarosite slurry
LC^3	Limestone calcined clay cement
LS	Lime sludge
MBS	Micronized biomass silica
MK	Metakaolin
MP	Marble powder
MRA	Mixed-recycled aggregates
Mt	Million tonne
Mtpa	Million tonne per annum
NA	Natural aggregate
OPC	Ordinary Portland cement

PPC	Portland pozzolana cement
RA	Recycled aggregates
RAP	Reclaimed asphalt pavement aggregates
RBA	Recycled brick aggregates
RCA	Recycled concrete aggregate
rCS	Residual compressive strength
RHA	Rice husk ash
RM	Red mud
rUPV	Residual ultrasonic pulse velocity
SBE	Spent bleach earth
SCBA	Sugarcane bagasse ash
SCM	Supplementary cementitious material
SDG	Sustainable development goals
SSA	Sewage sludge ash
SF	Silica fume
TGA	Thermogravimetric analysis
UPV	Ultrasonic pulse velocity
USD	United States dollar
WS	Wollastonite

NOTATIONS

a	Fire curve coefficient
A_v/A_t	Surface opening
b	Fire curve coefficient
β	Assured minimum success of value
c	Fire curve coefficient
C_{cem}	Landed costs of cement
C_i	Landed costs of SCM at i^{th} iteration
$C_{savings}$	Cost savings
C_{test_j}	Cost of j^{th} type of test
C_{total}	Total testing charges
d	Fire curve coefficient
f_{ae}	Compressive strength of concrete after exposure to elevated temperature
f_{be}	Compressive strength of concrete before exposure to elevated temperature
h_{eq}	Height of structure
i	Iteration of SCM selection
j	Type of test
k_T	Correction factor based on the fraction of volume procured at various time intervals
m	Fire curve coefficient
m_1	Weight of the coarse aggregate before exposure to acid
m_2	Weight of the coarse aggregate after exposure to acid
n	Fire curve coefficient
O	Opening factor
$p\ (\phi_p)$	Probability of an optimum level selection
ϕ_i	Fraction of cement replaced by SCM
ϕ_p	Optimum level of replacement
q	Fire load
r	Expected rate of returns
$r(\phi)$	Probability of successful exploration

$r_n(\phi)$	Probability of successful exploration after n trials
$r_n(\phi)_\alpha$	Probability of successful exploration after n trials for α savings
T	Exploitation duration
$T_g(t)$	Temperature as a function of time
$t^{i,j}$	Time of conducting the respective tests
T_{max}	Maximum temperature of fire
t_{max}	Time required to attain T_{max}
t_{V_f}	Time of material procurement
V	volume of cement expected to be used in construction
V_f	Volume procured at various time intervals
W	Weight of concrete specimen

Chapter 1
Introduction

The last century has witnessed an unprecedented growth in infrastructure. The infrastructural development, while essential for civilization, presents an increasing threat to the environment. The construction industry became the highest consumer of natural resources at the beginning of the 21st century (>35.9%) [1]. The construction industry is also responsible for 6% of global energy use and 11% of global carbon emissions [7]. Recognizing the associated environmental concerns, there has been a growing interest towards introducing sustainability in the construction industry.

1.1. Understanding sustainability

The interpretation of the word 'sustainability' has evolved over the years. The 1987 United Nations report titled "Report of the World Commission on Environment and Development: Our Common Future" defined sustainable development as a state that "meets the needs of the present without compromising the ability of future generations to meet their own needs" [8]. This definition of sustainable development served as the foundation for modern interpretations of sustainability. Initially, sustainability was defined in terms of environment and technical dimensions[4] [8]. The interpretation of 'sustainability' further changed with the introduction of 'social indicators' in the United Nations Sustainable Development Goals (SDG) in 2015. The 2015 resolution titled "Transforming our world: the 2030 Agenda for Sustainable Development", as agreed by 193 nations, defined three dimensions of sustainable development – economic, social and environmental [9]. In some texts, one may also see a fourth dimension of sustainability, which can be politics, human well-being, culture or technology [10, 11]. These dimensions can be covered under the 'social' dimension of

[4] Dimension: one or more aspect or element of sustainability

sustainability. In its modern form, sustainability can be interpreted as a state that meets present and future needs without causing further damage to economic, environmental and social dimensions.

The three dimensions of sustainability are measured in terms of various indicators or cost indices[5] [12]. The cost index (plural: indices) is used to define the cost or negative changes caused by any activity on the dimensions of sustainability or their subsets. Some of the commonly used cost indices are carbon emissions (environment), embodied energy (environment), financial costs (economy), training and education (social) and legal aspects (social) [12]. In simplistic terms, sustainability is a state which is achieved by selecting the set of activities with the lowest cost indices. The process of selecting and implementing the lowest-cost activities is known as managing sustainability.

Simple economics suggest that one should also be able to afford the cost of sustainability. This introduces three additional terms to the cost indices, i.e., regenerative capacity, deficit and exchange. Regenerative capacity is the maximum recovery of cost indices in a given period of time. It defines the maximum limit up to which the costs can be considered sustainable. Deficit is the additional costs for any activity over the regenerative capacity in a given period of time. It defines the additional damage caused to any dimension of sustainability in a given period of time. Exchange is defined as the recovery of one cost index at the expense of other cost indices. Let us review carbon emissions as an example. The global annual regenerative capacity for CO_2 emissions is 21.9 $GtCO_2$, and the excess carbon emission has created a deficit of 19.5 $GtCO_2$ [13]. These excess carbon emissions can be reduced through carbon capture, which will exchange carbon emissions with other cost indicators.

[5] Cost index, cost, indicator, sustainability indicator and sustainability parameter are some of the words used interchangeably in the literature. For the purpose of uniformity, the word cost index has been used in further discussions.

Sustainability, in its true sense, is achieved when, after accounting for all exchanges, the deficit is zero for all cost indices across the three dimensions. However, this version of sustainability is far from reality [13]. In practice, a slightly compromised definition of sustainability is used in the literature. Sustainability can, therefore, be interpreted as a state in which any activity, process or product has both the lowest cost indices and deficits.

1.2. Concept of sustainability in construction

The construction industry is one of the major players responsible for creating offsets in the environment dimension of sustainability. Fig. 1.1 shows the contribution of the construction industry towards global environmental offsets [1, 7]. The offset figure (Fig. 1.1) includes both construction and post-construction operational contributions [1, 7]. Other cost indices are gaining recognition but lack a global dataset in the literature and, therefore not included in further discussion.

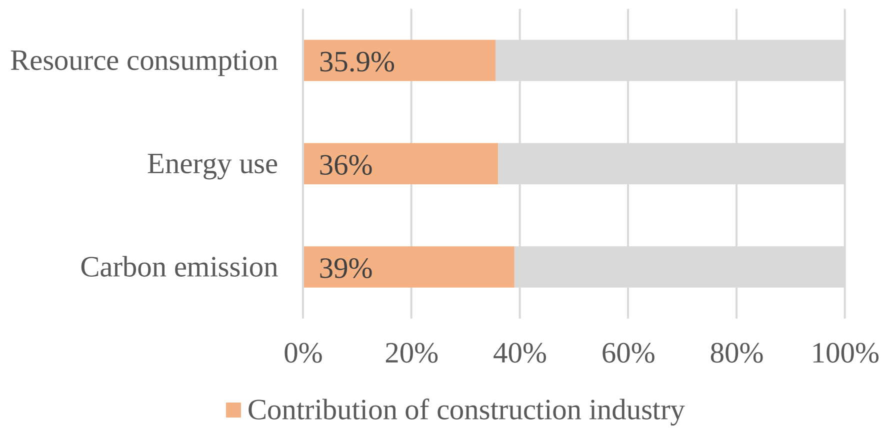


Fig. 1.1 Contribution of the construction industry towards environmental offset

The sustainability of the construction industry can be analysed in terms of the regenerative capacities of the three cost indices. The carbon and energy regeneration capacities of the earth are significantly higher as compared to the offsets created by the construction industry [7, 13]. Furthermore, there has been a rapid shift towards renewable energy, which can compensate for the carbon and energy offsets [14]. On the other hand, the regeneration capacities of most natural resources are much lower, which presents a long-term threat to the construction industry. For example, calcium carbonate or limestone used in construction industry has a low regeneration capacity. In case of construction, over 4 billion tonnes of limestone is excavated (as terrestrial limestone) to meet the annual cement manufacturing needs. A fraction of this calcium then travels through various sources to reach the ocean, where it absorbs carbon dioxide to form calcium carbonate and bicarbonate [13]. Finally, about 50 Mt of limestone is subducted as terrestrial limestone [15]. The case of calcium regeneration shows that the regeneration capacity of natural resources can be as low as 1% of their annual consumption, which creates pressure on their reserves. In India, the known reserves of limestone are expected to last for 22 years, with identified feasible reserves for an additional 12 years of cement manufacturing[6] [16]. The rapidly depleting limestone reserves and low regeneration capacity threaten the raw material availability for cement manufacturing.

The critical impact on the environment from the offsets of resource consumption has also been reported for sand [17], timber [18] and clay [19]. Regenerative capacity highlights that high volume resource consumption, as compared to other cost indices, is a greater threat to the sustainability of the construction industry. There should be a greater emphasis on reducing resource consumption until the point when it matches the regenerative capacity. Recognizing the significance of resource sustainability, the present study focuses on the same.

1.3. Approaching sustainability in resource consumption

The threat of offset created by resource consumption has also been recognized within the United Nations SDG 12, which suggests that to achieve sustainability for construction, we need to "ensure sustainable

[6] The total limestone availability with current rate of cement manufacturing is expect to last for about 350 years, but beyond next 34 years the limestone mining may lose its feasibility and affect the economic dimension of sustainability

consumption and production patterns" [9]. The widely adopted strategies for ensuring sustainable consumption/production patterns focus on reducing material use, redirecting wastes as a substitute for natural resources or redesigning the materials to have a lower offset on cost indices. The various strategies for approaching sustainability in resource consumption follow one of the three principles, i.e., 7R's, circular economy and value addition.

1.3.1. 7R's

The concept of 7R's can be defined as a process where resource consumption is reduced by waste minimization. 7R's represent seven steps occurring in the order of material flow – Rethink, Refuse, Reduce, Reuse, Repurpose, Recycle and Recover. Fig. 1.2 shows a typical application for the concept of 7R's on the material flow process.

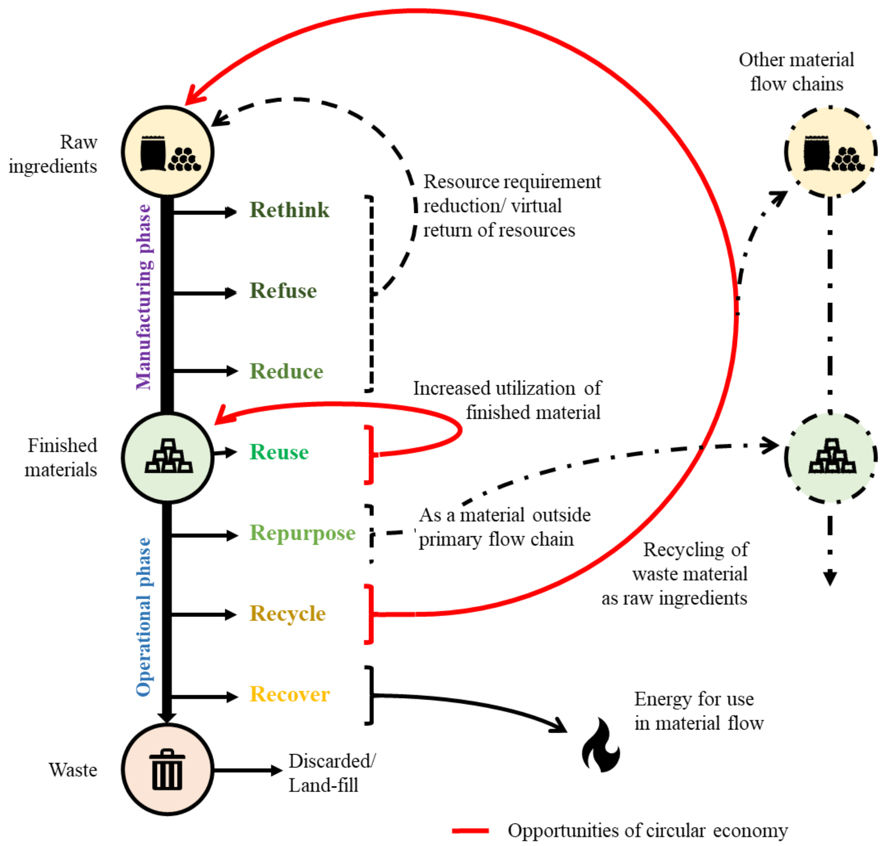
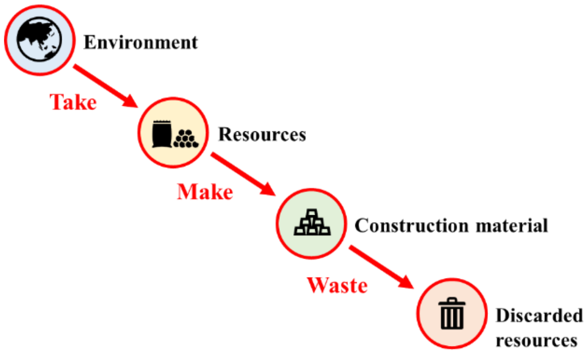


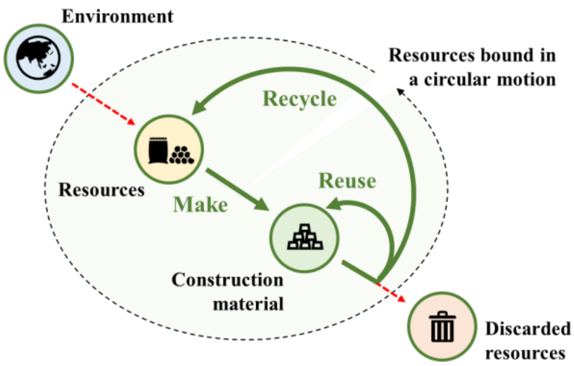
Fig. 1.2 Application of 7R's

1.3.2. Circular economy

Circular economy is a specific scenario of 7R's, which focuses on reusing materials as long as possible. A circular economy reduces dependency on the extraction of natural resources, thus lowering the environmental offset with each subsequent material use. The recirculation of resources in the manufacturing process gives the name of circular economy. A circular economy presents the ideal scenario for resources with low regeneration capacities.



(a) Linear economy
(Take-make-waste approach)



(b) Circular economy
(Minimization of take and waste)

Fig. 1.3 Comparison of circular economy with linear economy

Compared to the concept of 7R's, the circular economy focuses on closing the material loop. In other words, the circular economy focuses on increasing reuse, while 7R's focus on reducing the overall use of materials (both natural and reused resources). The efficiency of the circular economy is measured in terms of circular material use rate.

$$\text{Circular material use rate} = \frac{\text{Circular use of materials}}{\text{Overall use of materials}} \quad \text{Eq. 1.1}$$

1.3.3. Value addition

Value addition is the concept of identifying a more sustainable application for a given resource and reallocating the resource for the said application. It is possible to identify value-added applications for any given resource without reducing any waste or recirculation of resources. This differentiates value addition from 7R's and circular economy. Value addition focuses on improving the utilization of a given resource within the material process.

1.4. Resource sustainability of concrete

Concrete is the largest consumed artificial material on earth, with an annual consumption of over 30 billion tonnes [20]. It is one of the most consumed resources in the construction industry. In terms of resources, concrete consists of six construction materials, i.e., cement (binder), aggregates (fine and coarse), water, fibres, chemical admixtures and mineral additives. The approaches for resource sustainability may lower the consumption of some resources but not necessarily all. For example, the addition of silica fume (mineral additive) can lower cement (binder) requirements while increasing water requirements [21]. This presents a challenge in identifying a solution with optimum resource sustainability. A possible method for comparing the sustainability of different resources is through resource regeneration and offset.

1.4.1. Recognizing the threats to resource sustainability

Among the different components of concrete, water has the highest regeneration capacity, with a global surface runoff of 1700 km^3 [22]. The estimated global water consumption of concrete is about 40 km^3, which includes batching water (2 km^3), virtual water (16 km^3) and curing water (22 km^3) [23, 24]. Literature shows that the water consumption of concrete is much lower than the regeneration capacity [23, 24]. Furthermore, concrete production can be carried out using recycled water or sea water [25, 26]. This shows that water can potentially have zero offsets and may not be a critical factor in resource sustainability.

On the other spectrum of resource sustainability is cement. The global cement production exceeds 3746 Mtpa [27]. With a clinker factor of 0.72 and a limestone factor of 1.5, the limestone requirement for cement manufacturing exceeds 4000 Mtpa [28]. The regenerative capacity for limestone is significantly lower, about 50 Mtpa. Furthermore, available literature lacks any alternative source of limestone that can feasibly meet the needs of cement manufacturing [29, 30]. The low regeneration capacity and high consumption rates create offsets, which lead to the depletion of limestone reserves. Resource sustainability of limestone is a critical factor that can significantly affect the future of cement manufacturing [31].

Aggregate presents a different scenario of resource sustainability. The global consumption of aggregate (for concrete use) can be estimated in the range of 30 billion tonnes per annum (~24 to 32) [32]. Fine aggregates are regenerated in the form of silts in rivers, reservoirs/dams and oceans and can be safely used within the regenerative capacity [33]. Although specific data is not available for all regions, the regeneration capacity of fine aggregates is significantly high. Consider the case of India; the aggregate demand in India can be estimated as 2600 Mtpa (~2400 to 2800), of which about 1000 Mtpa (~800 to 1200) is for fine aggregates. This need for fine aggregate can be largely met through annual sedimentation in dams (~3500 Mtpa) [34, 35]. The requirement for fine aggregates can also be met from recycled wastes like construction and demolition (C&D) wastes, slags, mining waste, etc. [36]. In this scenario of fine aggregates, an offset will occur if material utilization is not diversified to different sources. The scenario of resource sustainability is different for coarse aggregates on account of very low regeneration capacity. Typically, strategies like recycling and repurposing are used to lower the resource consumption of coarse aggregates [37]. However, the substitutes of coarse aggregates are not available in significant volume to have a major impact on resource sustainability. Coarse aggregate is also a critical resource which requires sustainable interventions.

Among other resources, mineral additives and fibres can be either manufactured or recycled from waste [38, 39]. Over the years, several waste streams have been identified which can be used as fibres and mineral additives, which can meet the need for concrete. For example, in India, about 380 Mtpa of mineral additives are generated against the 105 Mtpa requirement for clinker substitution [38]. However, the disparity in regional availability and lack of awareness limits their field application [3, 38]. Observed literature shows that material utilization should be diversified to different sources in the case of fibres and mineral additives [38, 39]. If the resource consumption is not diversified to different sources, the materials will require manufacturing and create offsets.

Fig. 1.4 shows a linear visualization of the threat of resource sustainability for the constituents of concrete. It can be observed from the figure that cement has the highest threat, followed by coarse aggregate, fine aggregate, water, mineral additives, chemical admixtures and fibres. Cement has the highest threat of sustainability on account of low regeneration capacity, limited reserve and high consumption rate. On the other spectrum, chemical admixtures and fibres have the lowest threat because of the limited demand and availability of waste-based alternatives.

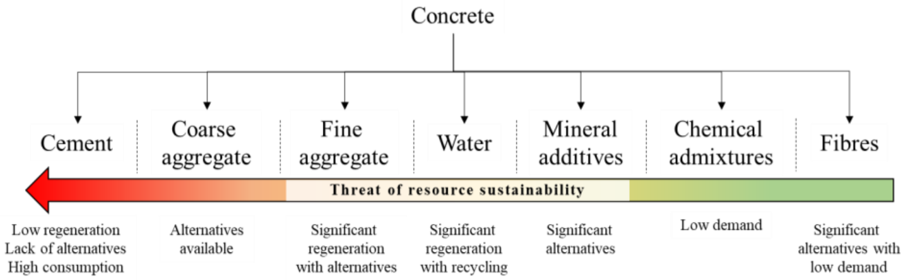


Fig. 1.4 Linear visualization for the threat of resource sustainability for the constituents of concrete

1.4.2. Integration of resource sustainability in concrete

The concrete construction industry, for a long time, was focused on alternative resources with the aim of reducing one of the four factors – economic cost, embodied energy, equivalent carbon emission and hazardous wastes. As late as 1984, published articles on sand substitution focused on waste minimization and high transportation costs [40]. Resource shortage was recognized way later in the early 1990s with river sand and limestone shortage in Taiwan [2]. Since then, several investigations have been carried out to ensure resource sustainability.

Literature shows that numerous studies have been conducted over the years for the identification, assessment and field application of sustainable resources [3]. Despite the sheer volume of literature, very limited solutions are actually implemented in the industry [3]. For example, over two dozen SCMs have been identified in India alone, of which four are primarily used in the construction industry [3]. The factors limiting the field application of sustainable resources have been reported in the literature as barriers [3].

1.4.3. Barriers to industry translation

Barriers can be defined as the cost requirements for industrial applications which are not affordable to the stakeholders. The barriers are similar to cost indices and include economic, environmental and social barriers. In addition to this, the barriers are classified as technological and legal barriers [41]. Although legal barriers can be covered under social barriers, they are often discussed separately due to their significance in industrial translation [3].

Several researchers have emphasized the significance of legal barriers [3, 42, 43]. Scrivener et al. [42] and John et al. [44] identified the lack of suitable standards as a barrier to commercial utilization of sustainable resources. John et al. [45], Martirena and Monzo [46] and Hemalatha and Ramaswamy [47] highlighted the importance of technical standards towards the utilization of various SCMs. Similarly, Juenger et al. [48]

emphasized on need for further improving the relevant standards. Fig. 1.5 shows a visual representation of how legal barriers limit the application of SCMs in cement substitution [3].

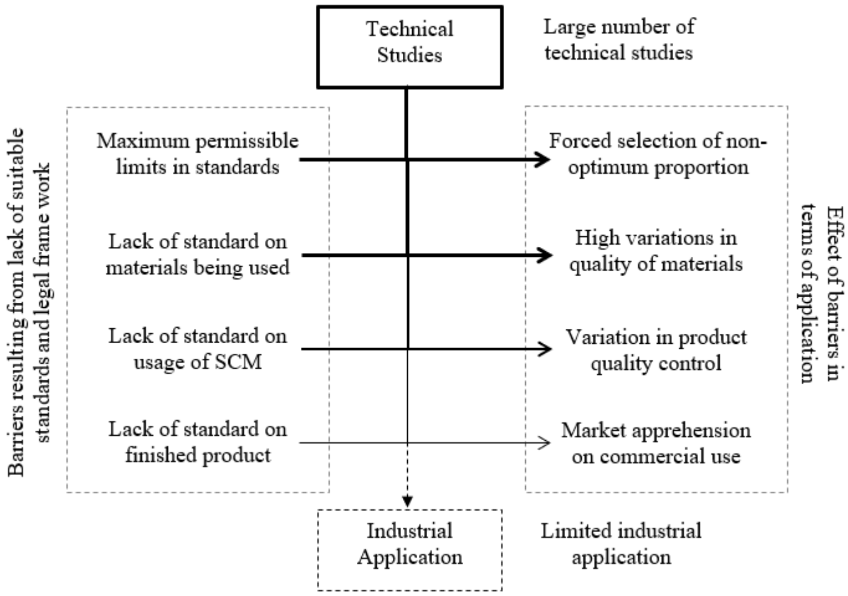


Fig. 1.5 Effect of barriers resulting from lack of suitable standards and legal framework

The reviewed literature suggests that legal modifications are needed for the industrial translation of sustainable resources. However, in the case of the Indian construction industry, provisions exist that can be used to overcome legal barriers posed by technical standards [3]. These provisions allow for the use of alternative resources if they either have the desired material properties or meet all necessary performance requirements. For example, technical standards IS 383: 2016 and IS 9103: 1999 state that any alternative resource can be processed to manufacture aggregates and chemical admixtures, respectively [4, 49]. The core difference between the two provisions is that aggregates need to have desired material properties while admixture is required to meet necessary performance requirements [4, 49]. In the case of concrete, non-standard resources may be used in the design mix if the final product meets all technical specifications and is approved by the engineer-in-charge [50]. The alternative provisions typically require additional testing and increase the cost of industrial translation.

Although the cost of industrial translation remains the same, the net sustainability gains remain uncertain. There is often a possibility that the use of alternative resources may not recover the cost of industrial translation, which often creates a barrier to alternative provisions.

1.4.4. Need for optimization of sustainable construction materials

The stakeholders can be willing to introduce resource sustainability only if there is a degree of certainty in the recovery of costs. To ensure recovery of costs, there is a need for optimization of sustainable construction materials. Optimization of sustainable construction materials should not be considered the same as maximizing resource sustainability. Optimization focuses on all cost indices and not just minimizing natural resource utilization. For example, blending SCMs as per the project requirement will ensure higher cement substitution but will be optimum if the volume of cement substitution is sufficient to justify the cost of testing.

Optimization accounts for several factors ranging from the cost of solution, transportation, and testing requirements to resource sustainability. Since optimum construction material varies for each project, the responsibility of optimization falls on the engineer-in-charge. There is a need for suitable strategies that the engineer-in-charge may use for the optimization of sustainable construction materials. The strategies should also account for various barriers to ensure robust industrial translation.

1.5. Scope of this study

Literature shows that the resource shortage is a recently recognized and critical threat towards sustainability in the construction industry. Among these, clinker (limestone) and aggregates face a major threat of resource shortage [2]. As a result of material shortage, the prices of cement and aggregates have drastically increased from 2010 to 2021, while the prices of chemical admixtures, water and mineral additives have remained almost constant [51, 52]. Recognizing the threat of resource shortage, it is important to introduce alternatives for cement and aggregates in the industry. However, the industrial translation of sustainable construction materials is limited by barriers.

The present work focuses on the data from the Indian construction industry to demonstrate improvement in resource sustainability. In the Indian construction industry, alternative provisions exist for overcoming the legal barriers to sustainable construction materials. These alternative materials increase the initial cost of technology implementation. Optimizing the construction material through suitable strategies can help in maximizing the sustainability gains and justify the initial costs. The present work focuses on developing strategies for the optimization of sustainable construction materials for maximizing the use of alternative resources.

1.5.1. Objectives

The study aims to identify and implement methods for the optimization of construction materials for resource sustainability in the construction industry. Considering the threat of resource shortage, the study focuses on cement substitution and alternative aggregates. Emphasis has been given to accounting for legal barriers to ensure industrial translation of the developed solutions. The overall scope of this study has been divided into four research objectives:

1. To review the factors influencing the field translation of supplementary cementitious materials and alternative aggregates in the Indian construction industry.
2. Formulation of a systematic framework for optimizing the selection and field application of supplementary cementitious materials.
3. Development of sustainable aggregates through process optimization of upcycling construction and demolition waste.
4. To demonstrate the potential of Monte Carlo simulation in designing safety guidelines for robust field application of sustainable construction materials.

1.5.2. Industrial relevance

The present study focuses on resource sustainability in the construction industry, which consumes over a third of world resources [1]. The need for resource sustainability has also been highlighted in the United Nations SDG 12, i.e., responsible consumption and production.

The present study, formulates a systematic framework for the selection, testing, and field application of SCMs as blended cement. The systematic framework will facilitate high volume substitution of existing SCMs and simplify the use of emerging and locally available SCMs. Through higher utilization of SCMs, clinker requirement can be reduced, thus extending the limestone availability. The study also demonstrates the application of thermo-mechanical treatment for mixed-recycled aggregates (MRA) for manufacturing aggregates. The manufactured aggregates can improve the circular use of resources and reduce natural resource extraction. Finally, the use of Monte Carlo simulation has been demonstrated to account for deviation in the properties of alternative construction materials. Through a case study of fire safety of limestone calcined clay cement (LC^3) (a blended cement), Monte Carlo simulation has been demonstrated for developing strategies for safe and robust application.

The present study is expected to improve the field utilization of alternative resources and improve resource sustainability in the construction industry. For the stakeholders, the study is expected to reduce the cost of construction materials and promote the use of alternative resources. At a global level, the study is expected to directly support SDG 12.2, “by 2030, achieve the sustainable management and efficient use of natural resources”, SDG 12.6, “encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle”, and SDG 12.7, “promote public procurement practices that are sustainable, in accordance with national policies and priorities”.

1.6. Organization of thesis

The various research works carried out during the study have been organized chapter-wise as follows:

• Chapter 1 (this chapter) presents a discussion on the various concepts of sustainability, the threat of resource sustainability in the construction industry, barriers to industrial translation of sustainable construction materials, and the need for optimization to ensure resource sustainability. The chapter also presents the scope of this study, including specific objectives.

• Chapter 2 reviews the factors influencing the field translation of supplementary cementitious materials and alternative aggregates in the Indian construction industry. Strategies for the optimization of sustainable construction materials have been formulated based on the discussion of legal provisions and alternative resource availability.

• Chapter 3 presents a systematic account of the formulation of a systematic framework for optimizing the selection and field application of supplementary cementitious materials.

• Chapter 4 details the procedure for manufacturing sustainable aggregates through high-value upcycling of construction and demolition waste.

• Chapter 5 demonstrates the potential of Monte Carlo simulation in designing safety guidelines for robust field application of construction materials prepared with alternative resources.

• Chapter 6 presents the conclusion and the scope for future research.

Chapter 2

Factors affecting the industrial translation of alternative construction materials in India

India is the second-largest cement manufacturer, with an annual production of 329 Mt in the year 2020 [53]. The high cement consumption indicates a large volume consumption of construction materials in India. Among construction materials, cement and aggregates have low regeneration capacity and should be substituted through alternative construction materials. The chapter provides a review of alternative construction materials to cement and aggregates and factors influencing their industrial translation in the Indian construction industry.

The present chapter has been reproduced from the journal publication (s) – **Gupta, S.**, and Chaudhary, S. (2020). "State of the art review on Supplementary Cementitious Materials in India – I: An overview of legal perspective, governing organizations, and development patterns." Journal of Cleaner Production, 261, 121203. DOI: 10.1016/j.jclepro.2020.121203 (I.F. 11.1), and **Gupta, S.**, and Chaudhary, S. (2022). "State of the art review on supplementary cementitious materials in India – II: Characteristics of SCMs, effect on concrete and environmental impact". Journal of Cleaner Production, 357, 131945. DOI: 10.1016/j.jclepro.2022.131945 (I.F. 11.1).; and technical report(s) – **Gupta, S.**, Chaudhary, S., and Gupta T. (Under publication), "Variability in the Properties of Recycled Aggregate in different countries and its effect on the Properties of the concrete" and "Codal Provisions, Standards, and Guidelines in India for the use of Recycled Aggregate in Concrete", in: Structural behaviour and innovation of recycled aggregate concrete - State-of-the-Art Report of the RILEM Technical Committee 273-RAC, RILEM.

2.1. Alternative construction materials

2.1.1. SCM as a clinker substitute

The negative environmental impact of cement manufacturing is well-recognised in the research community. Over the years, several investigations have been carried out to identify a sustainable alternative to cement. However, the focus of these studies was primarily towards reducing carbon emissions. Literature shows limited investigations on alternatives to limestone, which is facing the biggest threat to resource sustainability. Table 2.1 shows a summary of the available literature that improves the sustainability of limestone as a resource in cement manufacturing.

Table 2.1 Literature on limestone sustainability in cement

Approach	Solution	Challenge	Remark
Alternative limestone	Limestone-rich wastes like eggshells and sea shells have been used as a substitute for limestone for cement manufacturing. [54, 55]	The global estimated value of shell waste generation stands around 20 Mtpa, which is less than 1% of global limestone needs. [56]	Low availability
Clinker substitution	Wastes are used as pozzolans in cement as a substitute for clinker. [38, 57]	The level of clinker substitution depends on the type of SCM. SCMs with high substitution potential, like Ground granulated blast furnace slag (GGBS), have limited availability. [38]	Only delays limestone exhaustion
Non-limestone-based binder	Geopolymer is defined as a waste-based alternative to cement. [58]	Commercially viable geopolymers are based on GGBS, which has limited generation and is used in slag cement. [38, 58]	Development of viable non-slag-based geopolymer needed
Cement modification	Special cement, like belite cement, can lower the limestone requirement. [59]	The limestone requirement is partially reduced. It also reduces the formation of portlandite, limiting the use of SCMs. [59]	An alternative strategy for clinker substitution to delay limestone exhaustion.

It can be observed from Table 2.1 that the available literature lacks a single best solution for the resource sustainability of limestone in cement manufacturing. The strategies of alternative limestone and non-limestone-based binders can potentially become a sustainable solution. However, in their present form, they have limited applicability in cement manufacturing. Therefore, it is recommended that the construction industry push towards increasing SCM utilization to lower the dependency on limestone. This will extend the availability of limestone and provide time for developing resource-sustainable solutions. For this reason, further discussion is presented on SCM as an immediate solution towards limestone resource sustainability.

2.1.2. Alternate aggregates

The threat of resource sustainability has been well recognised for fine aggregates, particularly in the case of river sand [60]. For coarse aggregates, resource shortage is mainly gaining attention for local availability [61]. In simple terms, heavy construction activities in urban areas have led to a shortage of coarse aggregates at short distances, but this shortage is negated by availability at large distances [61]. The core driver for alternative resources in the case of coarse aggregates is the need for waste disposal and the need for reducing transportation distances [62]. Although the reasons may differ, literature shows ample studies on alternatives to aggregates that can improve resource sustainability.

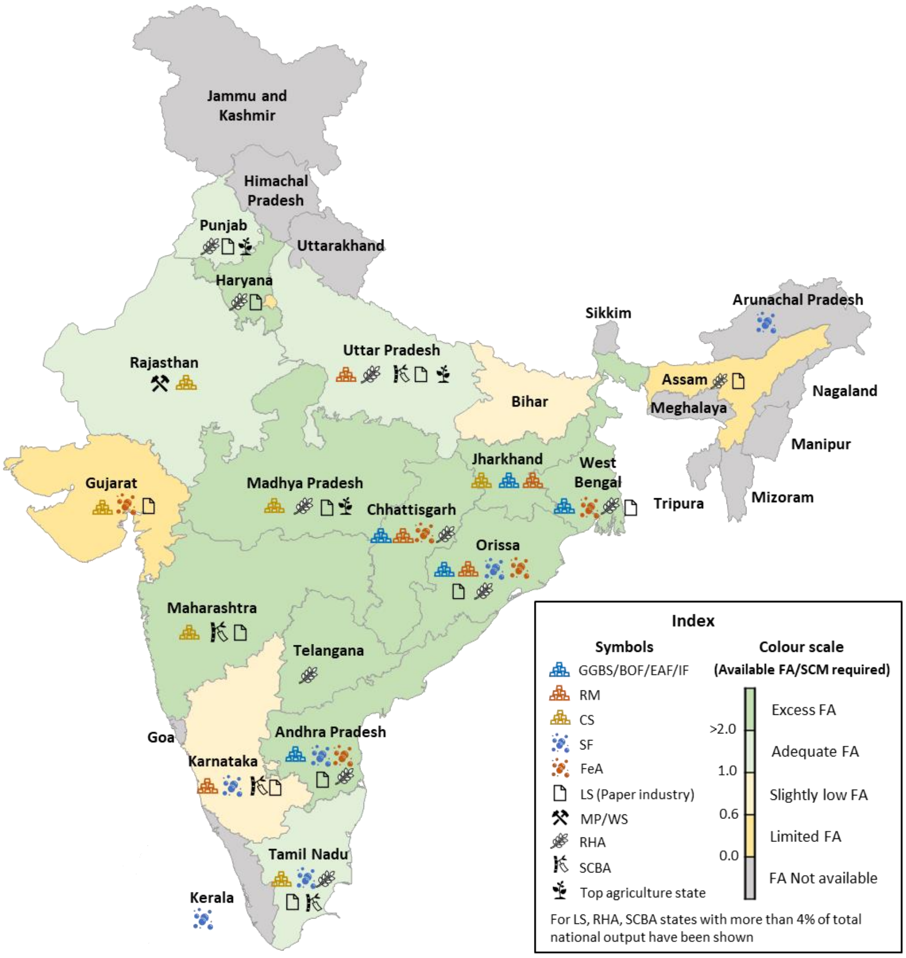
Literature shows that among the several identified alternatives for coarse aggregates, very few can be recycled directly in construction [62, 63]. The direct utilization is limited due to the loss in properties of concrete resulting from the addition of waste-based aggregates [62]. The loss in properties is compensated by the processing or treatment of aggregates [62]. Treatment helps in improving the characteristics of aggregates and makes them suitable for utilization in concrete [62]. Literature also shows several studies on the manufacturing of aggregates, like cold bonded aggregates [63]. Overall, available literature shows that the development of aggregates (through recycling, treatment or manufacturing) with desirable characteristics is required for their utilization in construction [62, 63]. Therefore, to increase resource sustainability, thrust should be given towards the development of alternative aggregates in the construction industry.

2.2. Availability of alternate construction materials

2.2.1. SCMs in India

A wide range of minerals, waste or otherwise, have been identified for their potential use as SCMs. Table 2.2 provides a summary of different SCMs in India classified as per the source of origin and their availability. It can be observed from Table 2.2 that more than 380 Mtpa of SCMs are generated through different processes in India, and this excludes naturally occurring SCMs, manufactured SCMs, and potential SCMs yet to be explored in India. The generation of SCMs in India is significantly higher than the industry needs of 105 Mtpa, at a clinker factor of 0.68 in 2022. The clinker factor of 0.68 is based on the vision of the Cement Sustainability Initiative [64]. The high availability of SCMs is also evident because 18% of generated fly ash (FA) remains unused in the country [65].

The choice of alternate SCMs can also help lower the economic and environmental costs of construction activities through local waste utilization. Athira et al. [66] observed that the reduced transportation costs associated with local waste could improve the economic feasibility of sugarcane bagasse ash (SCBA) over FA in several regions in India. Joseph et al. [67] made a similar observation on the impact of transportation costs towards the feasibility of limestone calcined clay cement over Portland pozzolan cement. The impact of transportation also extends to the environmental costs of SCMs [68]. Therefore, to maximize the sustainability benefits of SCM utilization, stakeholders should consider the local availability of SCMs in their region. Fig. 2.1 shows the regional availability of SCMs in India. SCMs like ceramic waste powder (CWP), calcined clay (CC), glass powder (GP), and sewage sludge ash (SSA) are not region-specific SCMs and, hence, not shown in the figure.



Region	SCM [a, c]	FA [b, c]	Region	SCM [a, c]	FA [b, c]
Andhra Pradesh	6.87	16.29	Manipur	0.26	-
Arunachal Pradesh	0.13	-	Meghalaya	0.28	-
Assam	2.70	0.70	Mizoram	0.10	-
Bihar	9.62	8.93	Nagaland	0.16	-
Chhattisgarh	2.41	34.82	Orissa	3.53	24.91
Goa	0.11	-	Punjab	2.28	3.95
Gujarat	5.27	2.99	Rajasthan	5.95	8.99
Haryana	2.16	4.43	Sikkim	0.05	-
Himachal Pradesh	0.56	-	Tamil Nadu	6.27	8.82
Jammu and Kashmir	1.12	-	Telangana	2.86	7.13
Jharkhand	3.00	7.68	Tripura	0.31	-
Karnataka	5.21	4.52	Uttar Pradesh	17.33	24.12
Kerala	2.60	-	Uttarakhand	0.88	-
Madhya Pradesh	6.36	25.02	West Bengal	7.55	17.82
Maharashtra	9.35	25.02	**All India**	**105.00**	**226.13**

[a] SCM requirement estimated as per population distribution
[b] FA generated data in the year 2020.
[c] All values in Mtpa

[65, 69–72]

Fig. 2.1 SCM availability and adequacy of FA across India

Table 2.2 Potential SCMs identified in India

	SCM	Abbreviation	Process	Availability	Reference
By-product of industrial origin	Fly ash (Coal ash; Fuel ash)	FA	Coal combustion residue from thermal power plants	226 Mtpa	[65]
	Ground granulated blast furnace slag	GGBS	Waste produced during the preparation of pig iron in blast furnace.	27 Mtpa	[73, 74]
	Silica fume (Micro silica)	SF	By-product of metallic silicon and iron-silicon alloys in electric arc furnaces	NDA*	[75]
	Basic oxygen furnace slag (Linz–Donawitz slag; Steel making slag; Converter slag)	BOF	Waste produced during the steelmaking process	8 Mtpa	[74, 76]
	Electric arc furnace slag	EAF	Waste produced during the steelmaking process	2.5 Mtpa	[74]
	Induction furnace slag	IF	Waste produced during the steelmaking process	1-1.5 Mtpa	[74]
	Copper Slag	CS	Copper industry waste	1.45 Mtpa	[77, 78]
	Ferrochrome ash	FeA	Dust obtained from gas cleaning of the ferrochrome manufacturing unit	0.02-0.03 Mtpa	[79, 80]
	Red mud	RM	Waste generated from m alumina refinery plants	14 Mtpa	[81]
	Jarosite slurry	JS	Toxic waste generated during zinc production	0.40 Mtpa	[82]
	Lime sludge	LS	Waste from various industries like paper industry, water softening, etc.	4.9 Mtpa [a]	[83] [84]

Naturally Occurring	Wollastonite	WS	Naturally occurring, formed upon the interaction of silica and limestone in hot magmas	N***	[85, 86]
	Marble powder	MP	Naturally occurring and slurry waste from dimensional stone processing	5-6 Mtpa	[87, 88]
	Calcined clay	CC	Calcination of clay can include minerals like kaolin, montmorolite and illite	M**	[87]
	Metakaolin	MK	Calcining kaolin clay within the temperature range of 700–850 °C	M**	[89]
Bio Ash	Rice husk ash	RHA	Burning of rice husk	2.8-3.0 Mtpa	[90, 91]
	Micronized biomass silica (Silpozz)	MBS	Amorphous silica or organic micro-silica manufactured by burning rice husk between 600 °C − 700 °C	M**	[92]
	Sugarcane bagasse ash	SCBA	Burning of dried bagasse ash 600 °C − 700 °C	21 Mtpa	[66, 93]
	Other bio ashes				
	Spent bleach earth	SBE	Waste from crude palm oil extraction	NDA*	[94]
	De- oiled earth	DOE	Waste from sunflower oil extraction	NDA*	[94]
	Egg shell powder	ESP	Washed and dried egg shell	NDA*	[95]``
Other wastes	Ceramic waste powder	CWP	Waste generated from the ceramic industry	15-30 Mtpa	[96]
	Sewage sludge ash	SSA	Incinerated form of sewage sludge, a by-product of waste water treatment	70-75 Mtpa	[97]
	Glass powder	GP	Powder form of discarded glass	0.85 Mtpa	[98]

[a] Data available for the paper industry combined value from all industries will be higher

*NDA – No data available, **M – Manufactured as per need, ***N – Naturally occurring

Fig. 2.1 also highlights the availability of FA against the estimated SCMs requirement for different regions in India. Due to the lack of region-wise data on cement production, the SCM requirement is estimated for the annual need of 105 Mtpa distributed in proportion to the regional population [99]. FA is chosen as a reference due to its high availability, relevant standards and wide acceptance as compared to any other SCM [3].

Fig. 2.1 shows a significant disparity in the regional availability of FA as compared to the regional SCM requirement. Several regions in India do not use coal-based energy; hence, there is a lack of FA availability in Arunachal Pradesh, Goa, Himachal Pradesh, Jammu and Kashmir, Kerala, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, Tripura and Uttarakhand [65]. It should also be noted that these regions lack an adequate availability of SCMs (Fig. 2.1). The lack of SCM availability, estimated at 6.56 Mtpa, in these regions highlights the need for promoting viable SCMs from municipal wastes and natural resources, like CWP, SSA, GP, CC and MK. Among the possible SCMs, CC and MK are permitted within relevant standards and are more likely to be adopted [3]. It is recommended to prioritize CC and MK in these regions to fast-track SCM utilization to meet the desired clinker substitution and carbon reduction level. At the same time, other SCMs like CWP, SSA and GP can be introduced over time.

In Assam, Bihar, Gujarat and Karnataka, there is limited availability of FA, resulting in an estimated need for 5.66 Mtpa additional SCMs (Fig. 2.1). Fig. 2.1 shows that industrial and agricultural wastes like CS, FeA, LS, RHA, SF and SCBA are available in these regions and can be used as SCMs. It is recommended to prioritize CS, RHA and SF for cement substitution, as they are permitted within relevant standards [3]. On the other hand, alternate SCMs like CC and MK are not recommended as they require manufacturing, which will result in additional carbon emissions. Other wastes in these regions, till they are accepted in standards, can be diverted to activities with lower environmental impact like landfills, reclamation of low-lying areas, etc.

In the remaining regions of India, the availability of FA is more than the estimated need for SCMs (Fig. 2.1). Fig. 2.1 estimates an excess of 131.88 Mtpa of FA, along with the wide availability of industrial and agricultural wastes. This excess volume of waste has resulted in various environmental concerns in these regions, like in the case of FA and MP [65, 88]. It is recommended to push for high-volume waste utilization through construction materials like composite cement, FA bricks, Portland slag cement and high-volume SCM-incorporated concrete.

In addition to the SCMs listed in Table 2.2, several bio-waste-based ashes, industrial effluents and municipal wastes have been identified as potential SCMs, like wheat husk ash, mine tailings, zeolites, etc.; however, their potential is yet to be explored in India. Similarly, wastes like PVC dust have been used for cement substitution in India but have not been investigated for their pozzolanic activity and may have acted as inert fillers [100]. Further research can present several viable alternatives for the SCMs to the stakeholders.

2.2.2. Aggregates in India

A large number of wastes have been identified as aggregates in India. Table 2.3 shows the various potential aggregates and their availability in India. It can be observed from the table that over 500 to 1100 Mtpa of waste can be recycled as aggregates in construction. The variation in availability occurs from the lack of clear estimates for C&D wastes. It should be needed that the availability of alternative aggregates is significantly lower than the annual consumption of aggregates, i.e., 2600 Mtpa (~2400 to 2800). Furthermore, a significant volume of these wastes, primarily SCMs (including slags), are used for clinker substitution and have limited availability as aggregates. In terms of availability, waste from construction and allied industries presents the best scenario for serving as alternative aggregates. It should also be noted that despite high availability (150 – 750 Mtpa), C&D waste in India has very limited recycling (~ 1%) [101, 102]. And therefore, a thrust should be given towards the recycling of C&D wastes.

Table 2.3 Availability of alternate aggregates in India

Category	Aggregate	Availability	Remark	Ref
Construction industry waste	Recycled concrete aggregate (RCA)	150 - 750 Mtpa [101, 102]	● Direct utilization viable for RCA ● Other recycled aggregates can be recycled after suitable treatment ● Limited information on separate availability ● Most viable solution for coarse aggregates	[103]
	Recycled brick aggregates (RBA)			[104]
	Mixed recycled aggregates (MRA)			[37]
	Reclaimed asphalt pavement aggregates (RAP)			[105]
Waste from the allied industries	Granite cutting waste	~7 Mtpa	● Mostly available as fine aggregates	[60, 106]
	Ceramic	15-30 Mtpa	● Limited information on separate availability	
	Bone China ceramic wastes			[96, 107, 108]
	Marble waste	5-6 Mtpa	● Mostly available as fine aggregates	[87, 88, 109]
Artificial Aggregates	Cold bonded aggregates	As per SCMs (~ 300 Mtpa)	● Prepared by reaction between various SCMs	[110]
	Sintered aggregates			
	Lightweight expanded clay aggregates	M	● Mostly manufactured as fine aggregates ● Primarily used in lightweight constructions	[63]
Crushed slags	Cupola slag	40 - 45 Mtpa	● Slags have been demonstrated as aggregates ● Primarily used for cement manufacturing	[111]
	LD Slag			[112]
	Ferrochrome slag			[113]
	IF slag			[114]
Recycled wastes	Tyre rubber	0.54 – 0.59 Mtpa	● Mostly recycled as fine aggregates ● Poor characteristics that limit recycling	[115, 116]
	Plastic (PET)	2.27 Mtpa		[117, 118]
	EPS beads	0.30 Mtpa		[63, 118]
	Glass	0.85 Mtpa		[98, 119]
	E waste	1.70 Mtpa		[120]
Mining waste	Coal waste	NDA	● Poor gradation limits the application of most mining wastes as aggregates	[121]
Bio aggregates	Coconut shell	3.18 Mtpa	● Improper shape limits application	[63, 122]
	Palm oil shell	NDA		[63]

2.3. Legal factors influencing the use of alternate resources

2.3.1. Technical standards on clinker substitution

Over the years, several technical standards and guidelines have been developed on the use of SCMs for clinker substitution [3]. Among various guidelines, Indian standard codes (IS codes) released by the Bureau of Indian Standards have the greatest impact on clinker utilization [3]. Other legal documents require agreement between the stakeholders for quality assurance [3]. This presents a social barrier in the utilization of SCMs outside the guidelines stipulated under the IS codes. Therefore, it is important to first understand the guidelines on SCM utilization as per relevant IS standards.

The IS codes on SCMs can be classified into three sets based on their types, i.e., standards governing SCMs as products, standards governing cement manufacturing using SCMs and standards governing the use of SCMs in the preparation of construction materials and products.

Few SCMs have their independent Indian Standards. A list of these standards and their scope on specifications have been presented in Table 2.4. Other than these, IS 1727: 1967 [123] can be used for the assessment of different materials as pozzolans.

Although limited SCMs have standards governing their use as independent products, usage of many other SCMs is permitted for the manufacturing of cement. Table 2.5 lists all permitted usage of SCMs for manufacturing of cement, its relevant standards and maximum permissible limits. Interestingly, allowable granulated slag content for manufacturing Portland slag cement was reduced from 70% to 65% through amendment no. 4 to IS 455 in May 2000, which is increases the clinker factor for Portland slag cement [124].

Other than the standards discussed so far, SCMs can be directly utilized for the preparation of construction materials and products, for their pozzolanic activity, filler effect, or for their role as an admixture.

Table 2.4 List of SCMs defined as products in IS codes

Type of SCM	Relevant Standard	Subcategories	Scope of specification on use of SCMs as products
Calcined Clay Pozzolana	IS 1344: 1981	Two grades based on physical specifications. Only grade I can be used for cement manufacturing.	Chemical specifications have been specified for raw materials. However, post calcination, only physical characteristics should comply.
Pulverized Fuel Ash	IS 3812: Part 1: 2003; IS 3812: Part 2: 2013	Based on reactive lime content, in %, pulverized fuel ash can be classified as calcareous, ≥10%, and siliceous, <10%.	Chemical specifications for classifying pulverized fuel ash as calcareous and siliceous. General physical specifications.
Granulated Slag	IS 12089: 1987; IS 16714: 2018; IS 16715: 2018	Identified by the source of slag, no separate categorization in standards. However, iron blast furnace slag or GGBS has its independent standards and is classified as GGBS and ultrafine GGBS.	Granulated slag should conform to chemical specifications and glass content (more than 85 per cent glass content). However, unlike other slags, GGBS should also conform to physical specifications.
Silica Fume	IS 15388: 2003	-	Standard covers chemical and physical specifications for silica fume.
Metakaolin	IS 16354: 2015	-	The standard covers chemical and physical specifications for metakaolin.

Additionally, there are technical guidelines and directives that encourage higher utilization of SCMs in construction activities. Furthermore, these construction materials with higher SCM utilization can be used in the construction industry through standard formulation as per the Bureau of Indian Standards (BIS) and Performance Appraisal Certificate (PAC) as per the Building Materials and Technology Promotion Council (BMTPC) [3].

Technical standards and other guidelines collectively suggest that direct utilization of SCMs is possible after ensuring all performance parameters. Therefore, stakeholders can improve resource sustainability by exploring higher utilization of SCMs outside the scope of technical standards.

Table 2.5 Use of SCMs for manufacturing of cement as per IS codes

Type of Cement	Relevant Standard	Type of SCM used	Nature of use	Maximum permissible usage
Ordinary Portland Cement; Microfine Ordinary Portland Cement	IS 269:2015; IS 8112: 2013; IS 12269: 2013; IS 16993: 2018	Fly ash, granulated slag, silica fume, limestone, rice husk ash, metakaolin, copper slag, steel slag, lead-zinc slag, and spent fluidized catalytic cracking equilibrium catalyst.	Performance improver	5%
Portland Slag Cement	IS 455: 1989	Granulated slag	Raw material	65%
Portland Pozzolana Cement	IS 1489: Part 1: 1991	Fly ash	Pozzolan	35%
	IS 1489: Part 2: 1991	Calcined clay pozzolana	Pozzolan	25%
Masonry Cement	IS 3466: 1988	Pozzolanic materials like fly ash and calcined clay pozzolana	Filler as well as pozzolan	No limit specified.
	IS 3466: 1988	Non-pozzolanic materials like limestone, granulated slag, conglomerates, dolomitic limestone, dolomite, and waste materials like carbonated sludge, mine tailings, etc	Inert filler	No limit specified.
Super-sulphated Cement	IS 6909: 1990	Granulated blast furnace slag	Raw material	70%
Composite cement	IS 16415: 2015	Fly ash and granulated slag	Raw material	65% (combined)

2.3.2. Technical standards on aggregate substitution

IS 383: 2016 is the primary technical standard for properties of aggregates in construction [4]. As per IS 383: 2016, a wide range of materials can be utilized as aggregates [4]. The alternate aggregates have to meet certain physical, chemical and mechanical characteristics as specified in IS 383: 2016 [4]. The standard specifically permits the utilization of slag aggregates, RCA and MRA (listed as RA) [4].

Although a maximum utilization has been specified for these aggregates, IS 383: 2016 does not restrict the higher utilization of these aggregates [4]. Technical standard on concrete, IS 456: 2000, also permits higher use of alternate aggregates in plain concrete after satisfying the specifications of IS 383: 2016 [50]. Higher utilization can also be possible through an agreement between stakeholders, which will likely be based on the specifications of IS 383: 2016. Therefore, it is safe to conclude that alternate aggregates satisfying the specifications of IS 383: 2016 can be easily utilized in construction activities. For other resources to be used as aggregates, stakeholders will need thorough investigations.

2.4. Strategy for optimization of sustainable construction materials

The data from the Indian construction industry shows that factors governing resource sustainability for cement and aggregate differ significantly in terms of technical studies, resource availability and governing technical standards. Due to significant differences in governing factors, a single strategy is not viable for the optimization of sustainable construction materials. Therefore, from the perspective of resource sustainability, separate strategies have been proposed for the optimization of cement and aggregates in sustainable construction materials.

2.4.1. Maximization of SCM utilization

Resource sustainability in cement manufacturing requires a viable substitute for natural limestone. The identified alternatives of natural limestone have very low generation and can hardly meet the needs of cement manufacturing. Similarly, commercially viable non-limestone-based binders have limited availability. Other potential solutions with substantial availability, like fly ash-based geopolymer, have low technological readiness levels. At this point in time construction industry can reduce limestone dependency through increased SCM utilization. The present legal framework permits the increased utilization of SCMs, but only after necessary experimental investigations. Optimization of sustainable construction material implies maximizing the use of SCMs while meeting necessary performance standards. The stakeholders can engage in local optimization (at the project level) to maximize the SCM utilization.

The practice of local optimization may vary depending on the regional availability of SCMs. In regions with high SCM availability, stakeholders need to select an SCM that can meet all performance requirements at high replacement levels. Similarly, in regions with low SCM availability, stakeholders need to identify alternative resources as potential SCMs. Random trials can increase the cost of SCM selection with sub-optimum results. The high cost of SCM selection can discourage local optimization in small and medium-sized construction projects. Therefore, to maximize SCM utilization, stakeholders need a guideline or strategy that can optimize the process of SCM selection. Optimization of the selection strategy will lower the cost of local optimization and increase stakeholder confidence. The present work focuses on developing a selection strategy which can help in maximizing SCM utilization.

2.4.2. Development of alternate aggregates

Aggregates are one of the highest consumed resources in construction, after water. The high volume needs for aggregates are primarily met through quarrying activities, which is a non-renewable source. Available literature shows several alternatives to natural aggregates. However, the availability of these resources is significantly lower than the consumption rate of the Indian construction industry. Low availability may not satisfy the requirement for aggregates, but their utilization should be maximized at every opportunity to ensure resource sustainability. Technical standards favour the utilization of alternate aggregates in construction. Therefore, thrust should be given towards identifying alternate aggregates with low levels of utilization and focus towards their industrial translations.

Special attention should be given towards field translation of C&D wastes. Aggregates recycled from C&D waste present the best possible scenario for improving resource sustainability. Recycled aggregates have high availability, are favoured by technical standards and have the potential of local recycling (reduced transportation). Despite the merits, only about 1% of C&D waste is recycled as aggregates. Therefore, the present study focuses on improving the utilization of C&D wastes to ensure better resource sustainability for aggregates.

Chapter 3
Optimizing the selection strategy for supplementary cementitious material

Cement presents a case where the reserves of limestone are rapidly decreasing, and viable[7] alternatives are not available. There is a need for identifying limestone substitutes or transitioning to non-limestone-based binders. However, observed literature shows that the construction industry is far from identifying viable limestone substitutes. Among possible solutions for resource sustainability, SCM substitution is favoured by both the technology readiness level and the existing legal framework. Increasing SCM utilization in concrete will reduce cement requirements and reduce the rate of limestone consumption. Increasing SCM utilization will extend the life of existing limestone reserves and provide time for developing alternative solutions.

SCMs in India are abundantly available but patchily scattered across the country. The sustainability of SCM utilization is primarily based on the regional availability of resources. Selecting a suitable SCM requires a series of physical, mechanical and durability tests on concrete. The series of tests are time-consuming and costly, which limits the selection of a suitable SCM for small and medium size projects. The present chapter overcomes this challenge by proposing a characterization-based approach for optimizing the selection of SCMs. The present chapter has been reproduced from the research publication – **Gupta, S.**, and Chaudhary, S. (2022). “State of the art review on supplementary cementitious materials in India – II: Characteristics of SCMs, effect on concrete and environmental impact”. Journal of Cleaner Production, 357, 131945. DOI: 10.1016/j.jclepro.2022.131945 (I.F. 11.1).

[7] Viable here represents the following – 1. Substantial availability

3.1. Background

3.1.1. Need for SCM selection

SCMs are reactive powders typically upcycled from industrial, agricultural and municipal wastes. India's diverse economy and geography result in many wastes that can be potentially used as SCMs. Relevant standards on SCMs suggest that any material can be utilized in concrete once it meets the desired performance requirements. In addition to this, many technical studies and reviews have been published to identify SCMs and promote their utilization in concrete. Despite the abundance of literature, availability of SCMs and need for sustainability, actual utilization is limited to a few SCMs only.

Table 3.1 presents an overview of previously published review articles on SCMs. Observed literature shows that existing reviews primarily highlight the effect of specific SCMs on the properties of concrete (Table 3.1). Available literature primarily helps in the incorporation of a specific SCM in concrete but fails to help in the suitable selection of SCMs for the stakeholders. Typically, the stakeholder needs to answer four critical questions for SCM utilization – (i) what are the available SCMs; (ii) which SCM will be favourable for the desired concrete properties; (iii) how much SCM can be effectively used; and (iv) which of the possible SCM improves sustainability. Available literature primarily addresses question (iii) for selected SCMs by discussing the effect of cement substitution on the properties of concrete (Table 3.1). Questions (i) and (ii) are rarely addressed and not well discussed in the observed literature. A stakeholder will need to review a large volume of literature when answering (i) and (ii), which can present a knowledge (social) barrier to SCM utilization. On the other hand, question (iv) is site-specific and cannot be answered directly in the literature. There is a possibility that the developed design may not improve sustainability, and the incurred time and cost may discourage field trials for new and alternative SCMs. The shortcoming of available literature highlights the need for a systematic approach to SCM selection to improve sustainability in the construction industry.

Table 3.1 Summary of recently published review articles on SCMs

	SCMs covered	Focus of article	Ref
1.	FA	• Use of FA as SCM. • Provides recommendations for optimum utilization.	[125]
2.	MK	• Use of MK and nano-silica as SCM. • Provides a summary of the effect of MK in concrete, without recommendations.	[126]
3.	RHA	• Use of RHA as SCM. • Provides a summary of the effect of RHA in concrete, without recommendations. • Highlights the environmental impact of RHA.	[127]
4.	MP, FA	• Use of MP as SCM and fine aggregates. • Provides recommendations for optimum utilization.	[128]
5.	SCBA, FA, GGBS	• Use of SCBA as SCM. • Provides recommendations for optimum utilization.	[129]
6.	RHA, SCBA, SF, FA, GGBS	• Use of agricultural (RHA, SCBA, etc.) and industrial waste (SF, FA, GGBS) as SCMs. • Provides a summary of literature showing their potential as SCMs.	[130]
7.	FA, GGBS, GP, CWP	• Use of FA, GGBS, GP and CWP as SCMs. • Provides a summary of literature showing their potential as SCMs.	[131]
8.	FA, GGBS, SF, MK	• Use of FA, GGBS, SF and MK as SCMs. • Provides recommendations for optimum utilization.	[132]
9.	MK, FA, SF, GGBS, SCBA, RHA,	• Use of industrial (MK, FA, etc.) and agricultural (RHA, SCBA, etc.) wastes as SCMs. • Provides a summary of the literature on the application of SCMs in lightweight concrete.	[133]
10.	FA, GGBS, SF, MK	• Use of FA, GGBS, SF and MK as SCMs. • Provides recommendations for the selection of SCMs against sulphate attack.	[134]

3.1.2. A case for characterization-based approach

The conventional strategy for SCM selection and utilization treats each SCM from different sources as an independent case [3]. In other words, RHA will be treated differently from SF. And, MBS, i.e., the processed form of RHA, will be treated similarly to RHA and different from SF. This system of classification is also followed in relevant Indian standards [3]. However, literature shows that MBS has similar characteristics and effects on the properties of concrete, as shown by SF, and not RHA [92]. The observed literature sparks the idea that SCMs with similar characteristics should have a similar classification rather than a similar source of origin.

A characterization-based classification of SCMs presents many advantages, especially for new and alternative resources. Over the years number of materials identified for their potential has increased significantly. Treating each material independently will increase the volume of literature and relevant standards. Alternatively, characterization-based classification can create a few classes of literature, which can justify the application of new and emerging resources. A similar classification is partly followed in relevant standards for aggregates, where manufactured aggregates are treated independently of their source [4]. The characterization-based classification can potentially reduce the volume of literature required and lower the knowledge (social) barrier for SCM utilization.

3.1.3. SCM selection through characterization-based approach

Observed literature indicates the potential of characterization-based classification. However, no specific study has been carried out on the same. To optimize the selection of SCMs for sustainable construction materials, the chapter describes an extensive meta-analysis of over 20 different SCMs investigated in India in terms of their characteristics and their effect on the properties of concrete. A metaheuristic selection process has been developed for SCM utilization based on a characterization-based approach. The selection process is further supported by a novel search optimization algorithm inspired by the multi-arm bandit problem. The discussion further presents a framework for applying the novel selection strategy for implementation in the Indian construction industry.

The characterization-based approach, selection process and search optimization algorithm discussed in the section are expected to resolve the explore vs. exploit question faced by the stakeholders. In other words, the discussion will address how much a stakeholder should focus on the optimization of construction materials (explore) before their gainful utilization in the construction industry (exploit). The selection strategy aims to prevent pessimistic scenarios, like identifying sub-optimum SCMs or extensive expenses on trials, during SCM selection and utilization. The selection strategy is expected to reduce required knowledge (social), trial costs (economic) and risks (social) barriers towards increasing SCM utilization. The proposed strategy can increase SCM utilization, reduce limestone requirements and improve resource sustainability of construction materials in the construction industry.

3.1.4. Scope of work

The study focused on establishing a correlation between the SCM characteristics and its overall impact on the properties of concrete. To establish this correlation, an extensive literature review was conducted for over 20 different SCMs. In order to limit the scope of work the literature search was limited to research investigations carried out in India.

The adopted review methodology primarily consists of document search and exclusion criteria. Document search was performed through Scopus, which examines the search string with the title, abstract and keywords from available databases like Elsevier, Springer, ASCE, among others. The keywords used in the search include “cement”, “concrete”, “ash”, “slag”, “silica fume”, “metakaolin”, “limestone”, “marble”, “calcined clay”, “sludge”, “pozzolan”, “glass powder”, “ceramic”, “powder”, “slurry” and “supplementary cementitious material”. A second search string of author affiliation as “India” was also applied as a filter for preliminary data gathering.

The document search includes peer-reviewed journal publications, book chapters and conference proceedings. Afterwards, the literature was screened in reverse chronological order to ensure higher weightage to the latest available information. The following criteria were used to screen the literature:

1. Include studies containing original experimental investigation. This excludes review papers and analytical papers with cited datasets and prevents data duplication.
2. Include data with cement substitution for construction applications. This excludes studies on non-cement-based applications, like, landfill, bitumen, geopolymer, fertilizer, etc., and limits the scope of use as SCMs only.
3. Exclude data where a comparison with control concrete is not possible. This excludes literature where multiple parameters like w/c ratio, cement content and SCM replacement are changing simultaneously and not one parameter at a time.
4. Include unique information. In the condition similar results are observed, e.g. same SCM has been used to replace 10% cement by weight in two separate studies in 2021 and 2018, the second reviewed articles are excluded to prevent over citation.
5. In the case of fly ash, an additional keyword “high volume” was added to exclude literature with the low volume of FA incorporation (<30%), which is widely accepted in the cement industry.

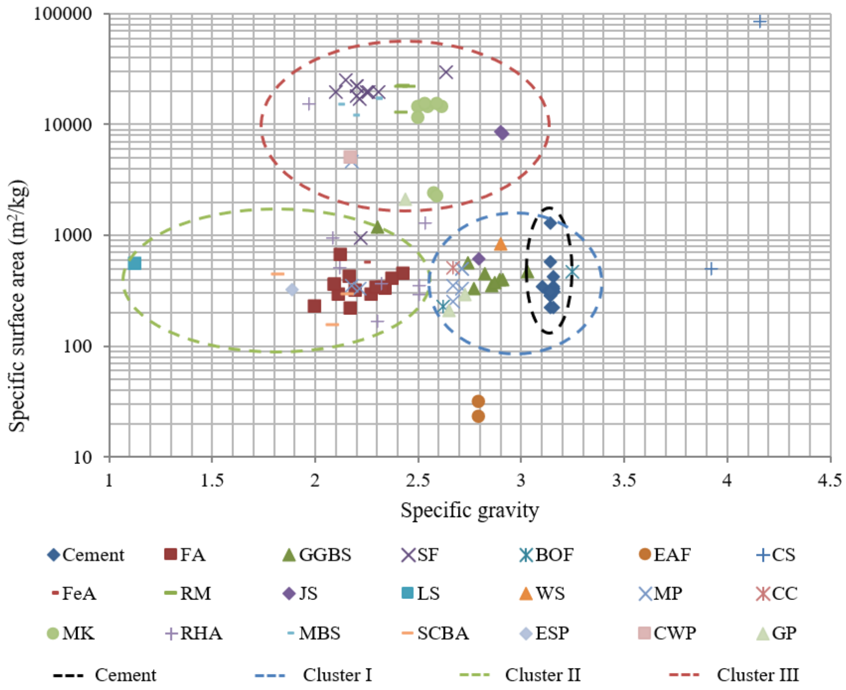
The above-specified literature was used for reviewing the characteristics of different SCMs and their effect on the properties of concrete. Additional literature has also been included in this study to support the discussions like environmental costs, resource availability and the effect of different characteristics on the properties of concrete. The search filter of author affiliation was removed for additional literature to ensure a comprehensive discussion in this study.

3.2. Characterisation-based classification of SCMs

The section presents an overview of the physical, chemical, mineralogical and microstructural characteristics of over 20 different SCMs in India, along with potential classification as per relevant standards and available literature.

3.2.1. Physical characterisation

Physical characteristics of SCMs in terms of specific gravity and specific surface area have been summarized in Fig. 3.1. It can be observed from Fig. 3.1 that based on physical characteristics, various SCMs can be grouped in 3 clusters. GGBS, BOF, WS, MP, CC and GP (cluster I in Fig. 3.1) exhibit similar particle size and specific gravity to cement. FA, FeA, LS, RHA, SCBA and ESP (cluster II in Fig. 3.1) exhibit similar particle sizes with lower specific gravity to cement. While SF, RM, MK, JS, CWP, and MBS (cluster III in Fig. 3.1) exhibit very high surface area or smaller particles as compared to cement. It can be observed that SCMs originating from the metal industry have a high specific gravity, i.e., CS, JS, GGBS, BOF and EAF, while SCMs originating from combustion have low specific gravity, i.e., FA, RHA, SCBA and ESP.



Clusters	I	II	III
Trait	Similar size, similar specific gravity	Similar size, low specific gravity	Very fine particles
SCMs	GGBS, BOF, WS, MP, CC, GP	FA, FeA, RHA, SCBA, ESP, LS	SF, RM, MK, JS, MBS, CWP, GP

[60, 73, 136–145, 80, 146–155, 81, 156–165, 86, 166–175, 92, 176–183, 93, 95, 100, 135]

Fig. 3.1 Specific surface area and specific gravity of SCM

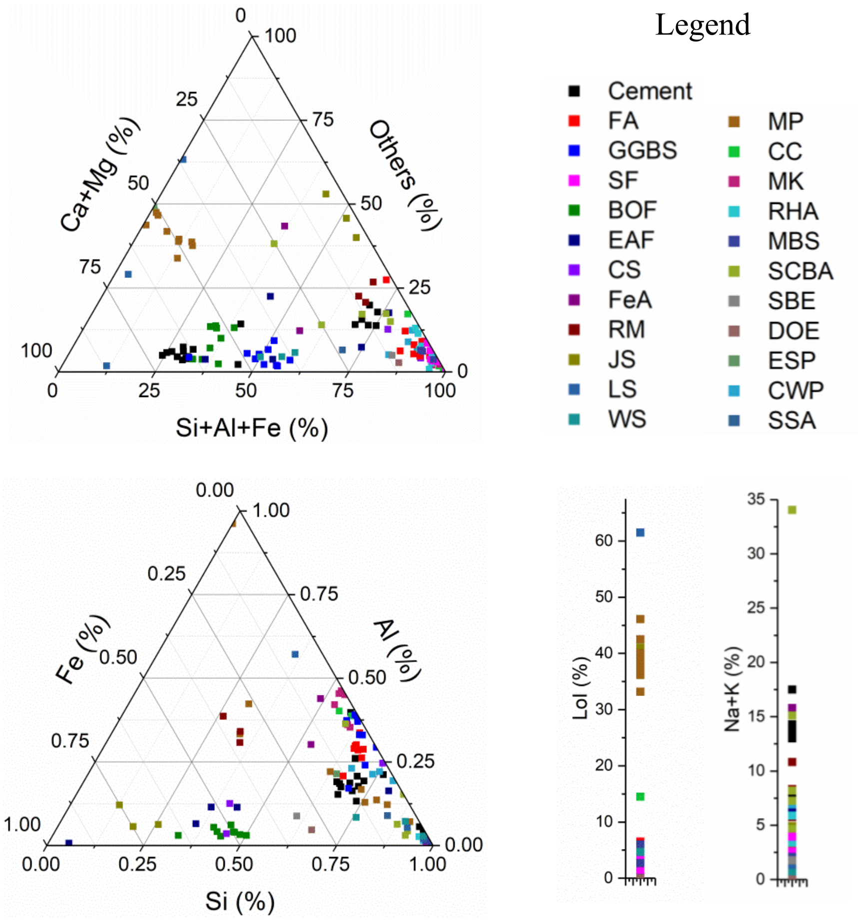
Specific gravity is primarily used as the basis of mix proportioning in concretes [184] and has not been considered as the basis of selecting SCMs. However, recent studies show that the difference in the specific gravity of mortar and aggregate affects the segregation in concrete [185]. It may be possible that by suitably proportioning the SCMs in cluster II of Fig. 3.1, the specific gravity of mortar may be reduced to control the segregation of lightweight aggregates.

Particle sizes of SCMs play a crucial role in the fresh and hardened properties of concrete. An increase in finer particles improves the degree of hydration while reducing the workability and particle packing of cement pastes [186, 187]. While at similar workability, finer particles improve the strength characteristics of cement pastes [188]. Particle size distribution through the combined effect of particle packing and strength gain can influence the hardened properties of concrete. Sevim and Demir [189] demonstrated the effect of particle size distribution on the compressive and flexural strength of cement mortar at a constant w/c ratio and constant fly ash content. It was observed that well-graded particle size yields better strength characteristics, and either an increase or decrease in the fine fraction of the SCM reduced the strength of mortars [189]. Therefore, to maximize the benefits of SCMs, the particle size distribution of the blended cement can be optimized. The SCMs identified in cluster III of Fig. 3.1 can be used to improve strength, while the SCMs identified in clusters I and II of Fig. 3.1 can be used to improve workability and particle packing.

3.2.2. Chemical characterisation

Fig. 3.2 represents the chemical composition of different SCMs observed in the literature. The chemical composition of different SCMs has been compared against the specifications listed in relevant Indian standards [190–192].

It can be observed that various SCMs can be classified into five categories based on their chemical composition. Four of the five categories are based on the relevant Indian standards, while the classification of calcite is based on observed data. It can be observed from Fig. 3.2 that SF, RHA, MBS, CC, CWP, GP, FA, MK and SCBA, corresponding to groups I and II, exhibit high alumina and silica content, which imply good pozzolanic activity. SSA, WS, SBE and DOE (group III as per Fig. 3.2) contain calcium in addition to silica and alumina and satisfy the conditions of class C fly ash. The SCMs listed in group III hold the potential of self-cementing due to the presence of CaO in them. Similarly, BOF, GGBS, JS and EAF (group IV as per Fig. 3.2) contain calcium aluminates and satisfy the requirements of slag.



Group	Category	Identifying composition	Ref.	SCM
I	Silicate	Si ≥ 85	[192]	RHA, SF, MBS,
II	Alumina silicate	(Si+Al+Fe) ≥ 70, Si ≥ 35	[190]	CC, CWP, GP, FA, MK, SCBA, RM, SBE*, DOE*
III	Calcareous alumina silicate	(Si+Al+Fe) ≥ 50, Ca ≥ 10, Si ≥ 25	[190]	SSA
IV	Slag	$CaO+MgO+Al_2O_3 \geq SiO_2$, $CaO+MgO+1/3.Al_2O_3 \geq SiO_2+2/3.Al_2O_3$	[191]	BOF, GGBS, JS, EAF, CS
V	Calcites	MgO+CaO+LoI ≥ 50, CaO ≥ 30	Observed	MP, LS, WS, ESP

*SBE and DOE can be classified as both alumina silicate and calcareous alumina silicate; however, due to low CaO content and limited reported results, SBE and DOE have been categorized as alumina silicate

[59–63,66,67,69,71–73,75,78–83,110–118,130,132,134–136,138,140–142,146–149, 151,153–155,158,168–195]

Fig. 3.2 Chemical composition and its variation for different SCMs

Pozzolanic reaction (Eq. 3.1), resulting from the presence of reactive silica (available in SCMs) and portlandite (contributed from the hydration of cement), is a well-recognized phenomenon [221]. The role of silica in pozzolanic reaction suggests that silicates (group I as per Fig. 3.2) will result in more pozzolanic activity and strength in concrete. However, recent studies show that aluminium also takes part in the reaction (Eq. 3.2) to form calcium alumina silicate hydrate, C-A-S-H [222–224]. The use of the high volume of alumina-silicates (group II as per Fig. 3.2) lowers the Ca/Si and increases the Al/Si ratios, favouring the formation of C-A-S-H over C-S-H [221, 225]. Literature shows that C-A-S-H shows denser packing and better mechanical characteristics than C-S-H [221, 226]. The superior behaviour of C-A-S-H coupled with lower Ca/Si requirement suggests that higher clinker substitution can be achieved using SCMs classified as alumina-silicates as compared to silicates.

$$\underset{\text{(Portlandite)}}{\mathrm{CH}} + \underset{\text{(Silica)}}{\mathrm{S}} \rightarrow \underset{\text{(Calcium silicate hydrate)}}{\mathrm{C-S-H}} \qquad \text{Eq. 3.1}$$

$$\underset{\text{(Portlandite)}}{\mathrm{CH}} + \underset{\text{(Alumina)}}{\mathrm{A}} + \underset{\text{(Silica)}}{\mathrm{S}} \rightarrow \underset{\text{(Calcium alumina silicate hydrate)}}{\mathrm{C-A-S-H}} \qquad \text{Eq. 3.2}$$

A recent study by Berenguer et al. [227] suggests that the hydration of SCMs with both Si and Al results in diverse mineral phases and lowers the overall pozzolanic reactivity compared to silicates. Comparison between silicates and alumino-silicates suggests that silicates offer higher pozzolanic reactivity while alumina-silicates offer higher clinker substitution. Therefore, it is recommended to use silicates in high Ca systems like lime mortar and high-strength concrete, and alumino-silicates can be prioritized for increasing clinker substitution in general applications. Clinker substitution can also be increased by the use of slags and calcites (group IV and V as per Fig. 3.2) as the source of calcium or lime in cement. Several investigations have been carried out for the development of clinker and composite cement through the use of LS [228, 229], JS [206, 230], RM [231], CS [230], BOF [76], WS [211] and MP [232]. On account of higher clinker substitution and higher resource sustainability, it is recommended that the use of alumino-silicates, slags and calcite should be prioritized.

It should be further observed from Fig. 3.2 that high alkali content (Na+K>5%) can be observed in CWP, GP, RM and SCBA. The high alkali content in concrete can cause an alkali-silica reaction and reduce the workability and strength of concrete [233, 234]. It is advised to limit the use of CWP, GP, RM and SCBA in concrete to prevent the negative impact of alkali content. It can also be observed from Fig. 3.2 that isolated samples of FeA and EAF have high alkali content. Further characterization studies will be needed on FeA and EAF to justify their safe utilization.

3.2.3. Mineral characterisation

Literature shows that mineral composition can be used to predict the cement hydration mechanism [221]. A better understanding of cement hydration can help in the optimum utilization of SCMs without extensive experimental testing [225]. Furthermore, techniques like powder XRD present a fast approach to mineral characterisation [235]. Table 3.2 provides a list of mineral phases identified in different SCMs.

XRD can also be used to identify the crystalline minerals and remaining amorphous content (minerals or compounds) in the SCM [236]. The amorphous or glass content can be used for estimating the pozzolanic reactivity of SCMs [236]. And the crystalline minerals can be used to identifying the pozzolanic activity and contribution as nucleation sites. Since, XRD can only estimate amorphous content, not the individual minerals, the prediction of pozzolanic activity using amorphous content has slightly lower accuracy than using crystalline minerals. Fast characterisation coupled with predictive modelling can play a crucial role in the optimum utilization of SCMs of vastly different mineral compositions. The list (Table 3.2) can be used for both characterization and optimization of blended SCMs.

Table 3.2 Mineral composition of different SCMs

SCM	Mineral identified	Ref.
FA	Quartz, Mullite, Hematite	[219]
GGBS	Gehlenite, Anorthite	[193]
SF	Quartz, Cristobalite	[170, 237]
BOF	Srebrodolskite, Whitlockite, Larnite, Lime, Dicalcium Ferrite, Calcium Aluminate, Wustite, Dicalcium Silicate, Tricalcium Silicate, Lime, Magnesium Oxide, Dicalcium Silicate, Tricalcium Silicate, RO Phase, Tetra-Calcium Aluminoferrite, Olivine, Kirschsteinite, Merwinite, Lime	[74, 76]
EAF	Quartz, Magnesium Chloride, Titanomagnetite, Titanium Carbide, Manganese Magnesium, Paranitisite, Monticellite, Merwinite, Magnetite, Gehlenite, Dicalcium Silicate	[161, 209]
CS	Fayalite, Magnetite, Clinoferrosilite	[77, 160, 238]
FeA	Coesite, Chromite, Spinal, Jadeite, Argaonite	[193, 196]
RM	Hematite, Sodalite, Quartz, Rutile, Boehmite, Calcite, Gibbsite, Hydrogarnets, Perovskite	[139, 140, 239]
JS	Ammonium Iron Sulphate Hydroxide, Hydrous Ammonium Iron Sulphate, Iron Sulphate Hydrate, Jarosite, Gypsum, Franklinite, Natrojarosite	[206, 240, 241]
LS	Quartz, Margerite, Tridymite, Whitlockite, Albite, Hematite, Cristobalite, Quartz, Kaolinite, Calcite	[203, 205]
WS	Wollastonite, Quartz, Calcite, Anhydrite, Goethite, Gypsum, Rutile, Microcline And Dolomite	[211]
MP	Calcite, Quartz, Dolomite, Magnesium Carbonate, Silica, Sodium Acetate	[87, 155, 170, 216]
CC	Kaolinite, Quartz, Hematite, Anatase	[87]
MK	Quartz, Muscovite, Mulite, Sillimanite	[238, 239]
RHA	Quartz, Cristobalite, Hexathiane, Amorphous Silica	[77, 218, 237]
MBS	Quartz, Silicon Oxide	[242]
SCBA	Quartz, Cristobalite	[66]

CWP	Anorthite, Aluminosilicate, Phosphorus Oxide, Quartz, Tricalcium Phosphate	[243]
SSA	Quartz, Margerite, Tridymite, Whitlockite, Albite, Hematite, Cristobalite	[203]
GP	Amorphous SiO_2	[145]

3.2.4. Morphological characteristics

Microstructural investigation shows that individual particles of different SCMs have different morphologies. Fig. 3.3 shows the four morphologies observed for different SCMs using scanning electron microscopy (SEM). Literature shows that smooth and spherical particles exhibit better workability [244]. Conversely, rough and porous particles increase water absorption and reduce the workability of concrete. The unique morphology of different SCMs has been described in Table 3.3.

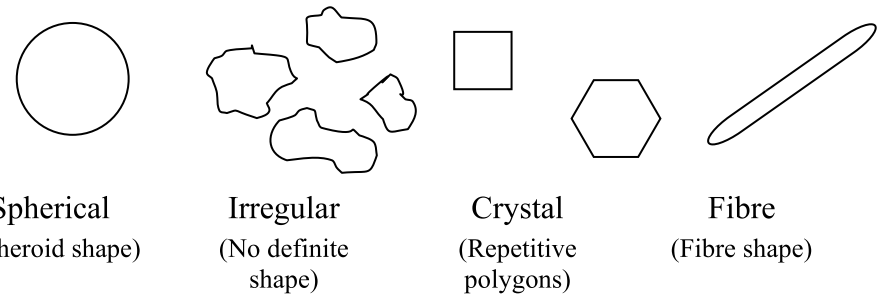


Fig. 3.3 Morphology of SCM particles

Table 3.3 Morphology of SCMs

SCM/ Cement*	Particle shape	Surface texture	Reference
Cement*	Irregular	Smooth	[168, 237]
FA	Spherical	Smooth	[60, 219]
GGBS	Irregular	Smooth	[193]
SF	Spherical	Smooth	[237]
BOF	Irregular	Rough	[163]
CS	Irregular	Smooth	[77]
FeA	Spherical	Smooth	[193]
RM	Irregular crystal	Rough	[139, 140]
JS	Irregular crystal	Smooth	[146, 195]

LS	Irregular	Porous	[203]
WS	Fibrous	Smooth	[86]
MP	Irregular crystal	Smooth	[142, 155]
MK	Layered plate-like crystal	Rough	[142]
RHA	Irregular	Porous	[168, 237]
MBS	Irregular	Rough	[158]
SCBA	Irregular fibre	Porous	[181]
SSA	Irregular	Porous	[203]
GP	Irregular crystal	Smooth	[197, 199]

*For reference

3.2.5. Effect of SCM characteristics on cement hydration

Cement hydration can be simplified as a two-stage process. The first step involves the dissolution of ionic phases [245]. Dissolution is governed by several factors, like surface morphology, mineral composition, temperature, type of solvent, etc. [221, 246]. In terms of mineral composition, amorphous minerals have a higher dissolution rate and will participate faster in cement hydration [221]. The solubility of minerals like quartz, feldspars and amorphous silica increases in the presence of Ca and sulphate ions and decreases in the presence of Al ions [247]. Observed literature suggests that the addition of gypsum (Ca and sulphate ions) can accelerate the dissolution of less soluble (slow-dissolving) minerals like quartz.

In terms of morphology, dissolutions initiate at areas of excess surface energy [246]. The effect of surface morphology suggests that dissolution will be higher in irregularly shaped particles like RM, JS, MP, and GP (Table 3.3). In terms of physical characteristics, finer-sized particles have higher surface availability for dissolution [246]. The effect of particle size suggests that fine particle-sized SCMs like SF, RM, MK, CWP, MBS and JS will dissolve faster (Fig. 3.1). In terms of overall characteristics, SCMs like RM show rapid dissolution due to fine particle size and irregular surface area. The rapid dissolution of RM can also be observed by the early heat release in the first 12 h of hydration [248]. Conversely, minerals like FA show slow dissolution due to coarser size and spherical surface area. Dissolution behaviour suggests that irregular fine-sized SCMs like JS can be used for quick-setting applications, and regular coarse-sized SCMs like FA can be diverted to low-heat cementing applications.

The second phase of cement hydration involves the chemical reaction and precipitation of hydration products [245]. The concentration of ionic phases at a given time governs the resulting hydration product, which can be estimated using different thermodynamic models [221, 249]. The resulting hydrated phases, C-S-H and C-A-S-H, deposit around undissolved particles, called nucleation. Li et al. (2022) observed higher nucleation over fine-sized particles than coarse-sized particles. The effect of particle size on the nucleation site suggests that SCMs with fine-sized particles will tend to pull nucleation away from cement particles. The reduced nucleation on cement particles also allows for better dissolution at the initial phase, resulting in a higher degree of hydration [250]. The chemical composition of SCM also affects the hydration site [251]. Literature shows that calcium-rich SCMs, like MP, have different surface charges than silicates and a higher affinity towards C-S-H nucleation [251]. The second phase of cement hydration can be influenced by nucleation and dissolved ion concentration. It is recommended to use Ca-rich SCMs (MP) or fine-sized SCMs (SF, RM, MK, CWP, MBS and JS) for change in the nucleation site to ensure a higher degree of hydration.

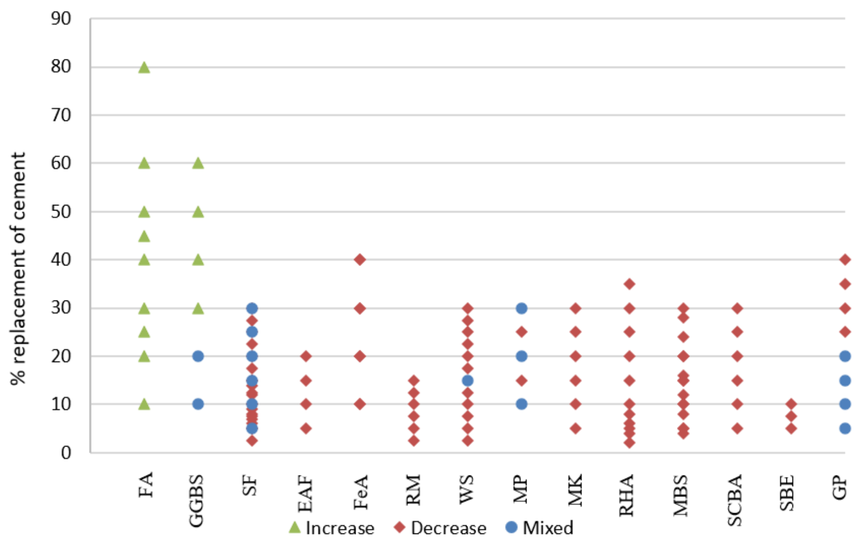
In later stages of cement hydration, SCM contributes in the form of pozzolanic reactions. Pozzolanic reactions convert excess Ca^{2+} ions into additional C-S-H and C-A-S-H hydration products and lower the conversion of Ca^{2+} into portlandite. The slow dissolution of mineral phases in SCMs is the limiting factor for pozzolanic reactivity and, hence, the longer duration required for hydration. In the scenario where early age hydration is needed, the dissolution rate of SCM can be improved by thermal treatment (change in mineral phase), mechanical treatment (change in particle size) and multi-blending (addition of chemicals that accelerate dissolution).

3.3. Correlation between characterization-based class and the effect of SCMs on the properties of concrete

Characterization presents an understanding of the possible effect of a given SCM on the properties of cementitious mixes. The subsequent section describes the effect of various SCMs on the workability, mechanical and durability characteristics of mortar and concrete.

3.3.1. Workability

Workability is used to indicate the ease of transportation, placing and compaction of fresh concrete. SCMs are often used as mineral admixtures for modifying the workability of fresh concrete. A summary of the effect of different SCMs on the workability of fresh concrete at various replacement levels has been graphically presented in Fig. 3.4.



Note: FeA results include a constant quantity of lime

[60,73,167,171,172,174,178,180,196,197,209,219,75,252–261,80,262–267,82,92,93,100,145,149]

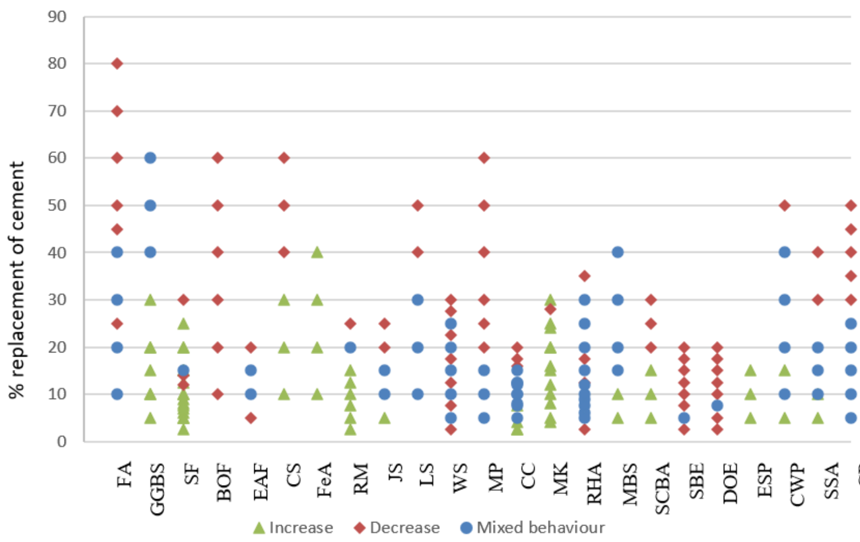
Fig. 3.4 Effect of different SCMs on the workability of concrete

It can be observed from Fig. 3.4 that FA and GGBS have the most positive impact on the workability of concrete, which may be the combined result of smooth morphology (Table 3.3) and similar particle shape (Fig. 3.1). Considering other SCMs of particle size similar to cement (Cluster I and II of Fig. 3.1), it can be seen that MP and GP under select circumstances can show an increase in workability (Fig. 3.4). The smooth and irregular crystal-like morphology of MP and GP may be responsible for the mixed behaviour on workability. WS, RHA and SCBA show a decrease in workability (Fig. 3.4). It can be speculated that the fibre-like porous morphology of WS, RHA and SCBA may have reduced the workability (Table 3.3). Similarly, considering the SCMs with particle sizes smaller than cement (Cluster III of Fig. 3.1), it can be observed that RM, MK and MBS show a reduction in workability (Fig. 3.4). SF shows a mixed effect on workability, which may be a result of favourable morphology but finer size. EAF also shows a reduction in workability (Fig. 3.4), which may be the result of coarser size and improper gradation (Fig. 3.1). The effect of workability on concrete shows that smooth and spherical SCMs with particle sizes similar to cement should be used for improving the workability of concrete. Considering the overall behaviour of different SCMs on workability, FA followed by GGBS, SF, MP, and GP should be preferred as workability modifying admixture.

3.3.2. Compressive strength

Fig. 3.5 represents the effect of different SCMs on compressive strength at various levels of cement replacement. It can be observed that very fine particles (Cluster III of Fig. 3.1), i.e., SF, RM, MK, JS, CWP and MBS, have a positive impact on compressive strength (Fig. 3.5). The increase in compressive strength from the use of fine particles can be a result of a higher surface area for nucleation [187]. It should also be noted that JS and CWP, under specific conditions, can exhibit a negative impact on compressive strength (Fig. 3.5), which may be attributed to the lack of amorphous mineral phase in both JS [241] and CWP [243]. It can also be observed that calcareous alumina silicate, slags and calcites (group III, IV and V of Fig. 3.2), i.e., SSA, GGBS, JS, EAF, CS, WS, MP, ESP and LS, have a positive impact on compressive strength (Fig. 3.5). This suggests that Ca rich SCMs have a greater impact on compressive strength. It should be noted that BOF reduced compressive strength despite having high Ca content (Fig. 3.5). The negative effect of BOF may be the result of high lime content, which can be addressed by thermal treatment of BOF [76]. The overall observations suggest that high Ca and fine-sized SCMs should be favoured for application as strength-modifying admixtures.

In addition to the discussed SCMs, FA, CC, MK, RHA, and SCBA also showed an increase in compressive strength (Fig. 3.5). The observed positive impact may be the result of thermally activated mineral phases in FA, CC, MK, RHA and SCBA (Table 3.2). It should be kept in mind that while thermal activation can improve the compressive strength, the process can make the resulting SCMs uneconomical [268]. Further investigation should be carried out to justify the calcination cost of SCMs prior to their economic use as strength-modifying admixtures.



Note: FeA results include 7% lime in addition to FeA

[59,62,66–68,71,75,78,79,81,83,112,114,116,117,119,131,136,139–141,146–150, 153,169–173,176,177,180,184,185,187,188,191,195,218,228–230,232–234,237–242,244 –256,256–265]

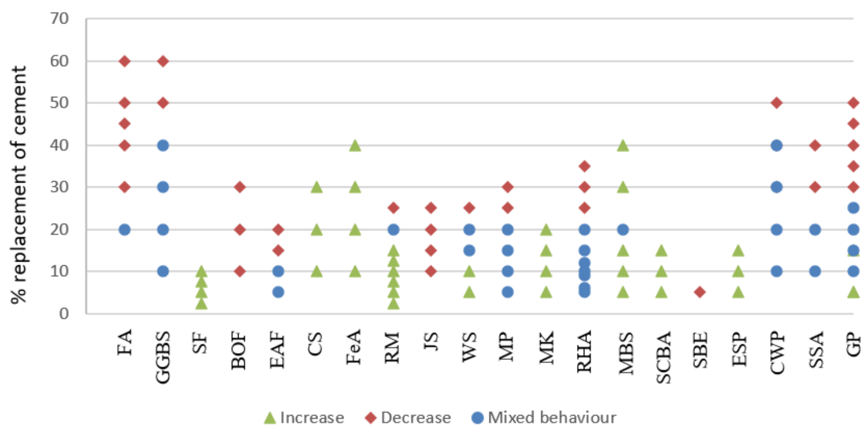
Fig. 3.5 Effect of SCMs on compressive strength

3.3.3. Flexural and split tensile strength

Fig. 3.6 and Fig. 3.7 represent the effect of different SCMs on flexural strength and split tensile strength at various levels of cement replacement. It can be observed that the effect of different SCMs on flexural strength and split tensile strength is similar to compressive strength. Similar behaviour may be the result of high pozzolanic reactions resulting from one of the three characteristics of SCMs, i.e., fine-sized particles, high Ca content and thermally activated mineral phases.

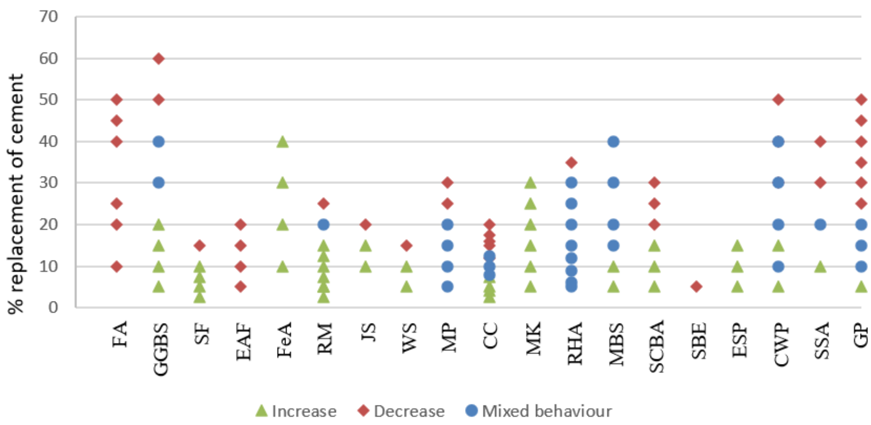
3.3.4. Durability – resistance to external chemical agents

External chemical agents, like sulphate, chloride and carbon dioxide, can damage the concrete and lower its durability. In general, SCMs have a similar effect on the resistance of concrete towards external chemical agents. The effect of SCM addition can be understood by the mineral phase changes due to the pozzolanic reaction, as shown in Fig. 3.8. The use of SCM results in the reduction of portlandite and excess pore water and an increase in C-S-H/C-A-S-H and unreacted SCM (Fig. 3.8). Excess water results in the formation of pore water, which directly contributes to the water and gas permeability of concrete [291]. Permeability governs the ingress of aggressive chemical agents. These aggressive chemicals then interact with other hydration products, like portlandite, to lower the durability of concrete. The addition of SCMs typically results in the reduction of permeability and reactive hydration products. The specific effect of SCM on permeability, carbonation, and chloride ion penetration has been discussed independently.



[66–68,78,110,112,117,119,131,141,145,146,148,149,153,158,169,172,176,177,184, 185,187,193,218,232,233,239,240,242,244–246,249,251,258,261,262,264,267–271]

Fig. 3.6 Effect of SCMs on flexural strength



[80,81,174,175,179,196,197,201,202,209,212,218,92,220,241,252,256–258,263,264, 266,268,135,269,270,274,278,280,285–288,290,136,292,296,143,145,157,167,171]

Fig. 3.7 Effect of SCMs on split tensile strength

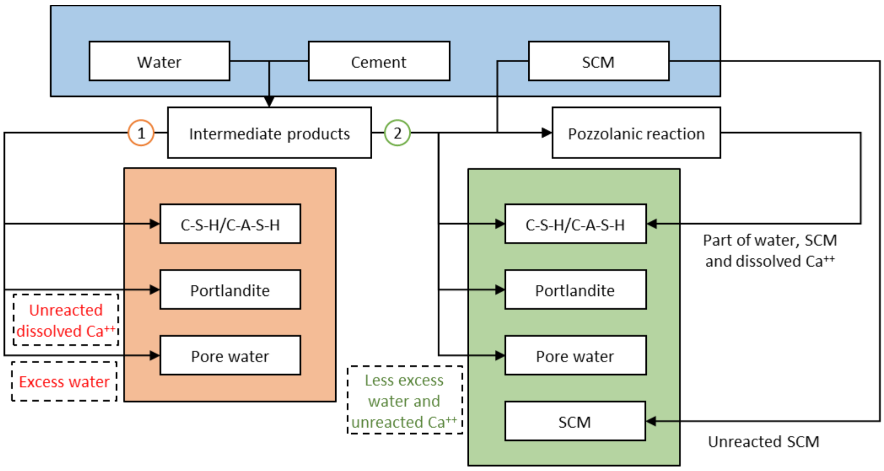


Fig. 3.8 Mineral phase changes due to clinker substitution from a durability perspective

3.3.4.1. Permeability

Literature shows that the addition of SCMs results in the reduction of permeability through sorptivity and DIN permeability tests. Permeability reduces for all SCMs, i.e., FA (35%), SF (20%), RM (20%), WS (25%), MP (30%), MK (15%), RHA (20%) and SCBA (30%) [140, 165, 298–301]. At the high-volume-addition of SCMs, an increase in permeability can be observed, i.e., FA (60%-70%) [302]. Increased permeability at high volume SCM addition can be a result of excess SCM not participating in the hydration mechanism (Fig. 3.8). In general application, the addition of SCM lowers the permeability, which is desirable for the durability of concrete.

3.3.4.2. Carbonation

Carbonation refers to the ingress of atmospheric carbon dioxide and the conversion of portlandite into calcite in concrete. Carbonation increases the strength of concrete but reduces the pH and causes corrosion in reinforcements [303, 304]. SCM typically lowers the permeability of concrete, which lowers the ingress of carbon dioxide in concrete, as observed for SF (5%-20%) and RHA (5%-20%) [165]. At the same time, SCM lowers the availability of portlandite, which lowers the pH of the concrete [305]. The lower availability of portlandite dominates the carbonation mechanism, and despite lower carbon dioxide uptake, SCM-added concrete shows higher carbonation depth and presents a greater risk of corrosion [305]. The increase in carbonation depth has been observed for SCMs like FA (15%-35%), GGBS (40%-60%), BOF (10%-60%), RHA (5%-20%) and MP (15%-30%) [140, 162, 210, 299, 306]. In contrast to this, SF (up to 20%), WS (up to 10%), MP (up to 15%), MK (up to 15%) and CWP (up to 20%) incorporation showed a slight decrease in carbonation depth [299, 301, 307–310]. The positive effect of SF on carbonation depth reduction may be a result of reduced permeability or a higher degree of hydration products formed by nucleation on fine-sized particles or Ca-rich particles [250, 307]. At higher replacement levels, WS, MP, MK and CWP showed an increase in carbonation depth, which may be a result of increased permeability. In general application, high-volume utilization of SCM presents a risk of carbonation-based corrosion in concrete. It is recommended to prioritize Ca-rich particles or very fine particle-sized SCM for mitigating carbonation-based corrosion.

3.3.5. Chloride ion penetration

Concrete when exposed to chloride ions, either from external sources like sea water and de-icing salts or from internal sources like mixing water, presents a risk of corrosion. In case of external sources, the availability of chloride ions for corrosion is mainly governed by the permeability of concrete, which governs the ingress of chloride ions, and C-S-H, which binds free chloride [311, 312]. The chloride binding ability of C-S-H is reduced by the presence of portlandite, making their reaction with SCMs desirable for corrosion inhibition [312]. The addition of SCM lowers both permeability and portlandite mineral phase, which is desirable for reducing chloride ion penetration (Fig. 3.8). Reduction in chloride ion penetration has been observed for RHA (5%-20%), SCBA (10%-30%), SF (5%-20%), MP (10%-20%), FA (15%-35%) and RM (5%-20%) [140, 165, 298, 299]. Contrary to the general trend, MP and WS at higher replacement show more chloride penetration despite lower permeability [276, 299, 313]. MP and WS have high calcite content, which may have improved nucleation without the consumption of portlandite; however, further investigation in this direction will provide a better understanding. In general application, SCMs other than calcite (MP and WS) can be used freely for chloride-based corrosion prevention.

3.3.6. Durability – resistance to physical changes and mechanical actions

Concrete, during its lifetime, undergoes several physical and mechanical changes, like wetting and drying, freeze and thaw, etc. The specific effect of different SCMs on different physical and mechanical changes has been discussed individually.

3.3.6.1. Wetting and drying cycles

The alternating seasonal change results in the cycles of wetting and drying periods on concrete. During drying, the loss of moisture causes shrinkage, C-S-H collapse and pore coarsening, which results in microcracking [314, 315]. Water is transported back inside the concrete in the wetting phase, allowing for the next drying phase [314]. The repetition of wetting and drying cycles, increases microcracks and pores in concrete [314, 315]. The microcracks and pores developed during wetting and drying cycles, also lowers the durability of concrete [314, 315]. The addition of SCM lowers pore water and increases C-S-H in concrete, which can reduce the effect of wetting and drying cycles (Fig.

3.8). Available literature shows that addition of SCM (FA and GGBS) increases the resistance to wetting and drying cycles [316, 317].

3.3.6.2. Freeze and thaw

In the cold season, pore water in concrete freezes and expands, causing internal pressure on the microstructure of concrete [318]. The internal pressure results in microcracks, which get further occupied by water during thawing [318]. Literature shows that damage from freeze and thaw is greater for pores in a specific size range [318, 319]. The addition of SCM alters the pore size distribution and can both increase or decrease the freeze and thaw resistance of concrete [318]. Observed literature on freeze and thaw shows that, addition of GGBFS (30%) shows better resistance to freeze and thaw than control concrete [320].

3.4. Application for characterization-based classification

3.4.1. Assessment of new and alternative SCMs

Meta-analysis shows that SCMs with similar characteristics have a similar effect on the properties of concrete. Analysis reveals that for the observed SCMs, three characteristics are important for classification, i.e., specific surface area, chemical composition and morphology. Although mineral phases are also important, the literature lacks sufficient data to create repetitive patterns. The three characterization-based classifications can be used for qualitatively assessing SCMs for their potential impact on the properties of concrete. This reduces the extensive investigations required for the assessment and optimization of new and alternative SCMs. Furthermore, the new and alternative SCMs can be evaluated within the existing technical standards without requiring the development of a new legal framework. For example, a new MBS, due to similarity in characteristics with SF, can be evaluated as per relevant technical standards.

3.4.2. Multi blended cement

In the condition a single SCM is not able to achieve the desired characteristics, two or more different SCMs can be incorporated to prepare multi-blend cement with desired characteristics. In multi-blended cement, the two (or more) SCMs can compensate for the shortcomings of the other SCMs. Singh et al. [137] demonstrated the advantages of multi-blending for improved particle packing and resulting compressive strength. A maximum relative density of 0.580, 0.694 and 0.720, and a resulting compressive strength of 85.00 MPa, 94.13 MPa and 100.45 MPa, was achieved in ternary blend, quaternary blend and quinary blend, respectively [137]. It can be seen that a quinary blend (4 SCMs + cement) yields better particle packing and strength; thus, it can be said that multi-blended cement can have better particle size distribution. Similarly to physical attributes, chemical/mineral composition can be optimized to improve pozzolanic reaction and resulting strength characteristics. Literature also highlights that multi-blended cement has higher compressive strength and economy than binary-blended cement at the same level of clinker substitution [268, 321] or allows for more significant clinker substitution [283]. Multi-blended cements also show higher cementing efficiency [322] and split tensile strength [323]. In terms of flexural strength multi-blended cements show slightly lower strength than binary-blended cement [324], however they still outperform OPC up to 50% clinker substitution [323]. In terms of workability, normal consistency, and setting time, the properties of multi-blended cements are observed to be between the properties of binary-blended cement [322]. The observation indicates that multi-blending does not offer any specific advantage in terms of workability, normal consistency, and setting time, and the resulting properties are the result of individual SCMs.

Overall, multi-blended cement can be considered a more sustainable approach towards the low clinker factor in the Indian construction industry. However, the exponential increase in experimental investigations associated with the additional variables may act as a barrier to the field application of multi-blended cement. This challenge can be overcome by characterization-based classification, where the proportioning of multi-blended SCMs can be adjusted to meet the desired characteristics.

3.4.3. Selection for a suitable SCM

The selection of a suitable SCM requires extensive investigations on the properties of concrete prepared using various SCMs. The resulting concrete should perform satisfactorily under several dimensions, like technical viability and environmental impact. It is possible that a given design mix may fail at a later stage of testing. This increases the cost of SCM selection and may deter stakeholders from exploring new and alternative SCMs. In order to facilitate the selection process, a characterization-based heuristic model has been demonstrated in Fig. 3.9. The heuristic model presents a sequential guide for the selection of SCMs based on their characteristic properties (Fig. 3.9). The proposed heuristic model can identify SCMs which can potentially present a sustainable solution, without the need for experimental trials. Potential SCMs among all alternatives can then be used to design and evaluate concrete.

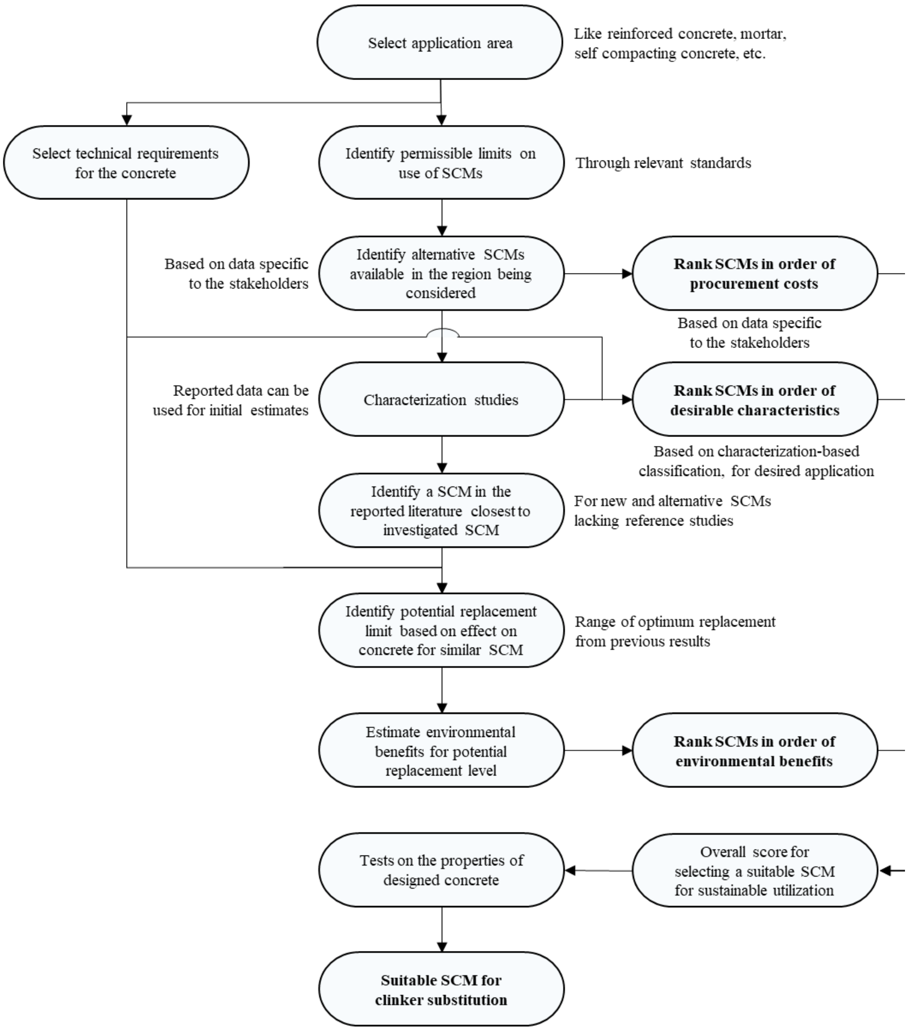


Fig. 3.9 Heuristic model for selection of SCMs

The process begins with the selection of the application area to define the desired technical properties of the concrete and identify the relevant standards for the same. Next, all available potential SCMs are identified, and their procurement costs are estimated. In the subsequent step, characterization studies are carried out over available SCMs. Characteristics will be used to rank how effective any given SCM will perform compared to other alternatives. Characteristics are then used for identifying the potential range of cement replacement based on known experimental studies. The potential cement replacement is used for the calculation and ranking of economic and environmental benefits for different SCMs. The three ranking systems can be combined by assigning points to rank and suitable weights to each ranking system. As the definition of sustainable development is subjective, the assignment of points and weights can vary for different stakeholders. For simplicity, points are suggested as the inverse of rank (point= $1/$rank), and equal weights are suggested for the selection of SCMs. The overall ranking obtained by multi-dimensional analysis will help in the selection of a suitable SCM.

The application of the heuristic model can be explained through an example of SCM selection. Consider requiring SCM selection for the development of high-strength concrete in sea water applications. The said region has four SCMs available, i.e., FA, GP, MP and MBS. For high-strength applications, SCMs should have a very fine particle size (cluster III) and high Ca content (Group IV or V). For preventing chloride ingress, the SCM should have C-S-H through pozzolanic activity. In terms of strength, MBS, MP and GP present a better choice, while in terms of chloride ingress FA, MBS and GP. MBS and GP satisfy both requirements, but MBS has finer particles and greater pozzolanic activity than GP. Overall, based on characterization-based classification, the SCMs can be ranked as MBS $>$ GP $>$ FA $>$ MP. Since MBS lacks sufficient literature, its closest resembling SCM, i.e., SF, can be used for selecting a range for optimum mix design. Now, assuming the literature suggests 15% of MBS and 20% of GP, the design mix can be evaluated for economic and environmental costs. The SCM with the highest potential towards sustainability can then be used for trials. The following procedure limits pessimistic solutions like MP or FA, which the stakeholders can avoid without going for trials.

3.5. Search optimization algorithm

3.5.1. Extending characterization-based classification

Characterization-based classification and proposed heuristic model for SCM selection identify and rank different SCMs in the order in which they are likely to present a sustainable solution. The selection strategy, while beneficial for resource sustainability, is still heuristic in nature. The reason behind adopting a heuristic approach is the limited availability of relevant datasets based on characterization-based classification. However, with the right dataset, characterization-based classification can be extended to answer the ‘explore vs. exploit’ problem of the stakeholders.

Explore vs. exploit presents a macro-economic scenario where the stakeholder has to decide on how much they wish to spend on research. In terms of SCM utilization, explore represents the phase of SCM selection and mix design modification. The stakeholder invests during the exploration phase of the project to improve the sustainability of construction materials. Exploit represents the next phase, where the construction material is utilized in the industry. In the exploitation phase, the benefits from SCM utilization are accounted as returns. It is possible that the stakeholder limits exploring and fails to identify a solution with good returns. Conversely, it is also possible that the stakeholder over-explores and fails to recover the invested amount. The stakeholders are constantly faced with the question of explore vs. exploit, i.e., how much should invest to ensure better returns.

Characterization-based classification can be quantified to present an algorithm-based solution for explore vs. exploit problems. The proposed algorithm has been termed the search optimization algorithm. A search optimization algorithm is designed as a mathematical model that identifies the optimum variables for exploration to ensure maximum return during exploitation. The search optimization algorithm introduces characterization-based classification to improve the selection of SCM at much lower costs. The proposed model will basically account for project-related information and material properties to quantify the gains as probabilistic functions. The quantitative advantages demonstrated through the model are expected to lower awareness (social) barriers and encourage stakeholders to optimize the selection of SCM for better resource sustainability.

3.5.2. Development of algorithm

3.5.2.1. Cost of exploration

The search optimization algorithm is based on the fact that known costs should be less than the probable savings. In order to ensure this, the algorithm first calculates the known costs associated with SCM selection. The costs should account for different possible tests, whether essential or optional, as per relevant standards. The total testing charges (C_{total}) can be expressed as,

$$C_{total} = \sum_{i} \sum_{j} (C_{test_j}) \qquad \text{Eq. 3.3}$$

Here, C_{test_j} represents the cost of j^{th} type of test, and i represents the iteration of SCM selection. For example, FA and GGBS replacements are being tested for compressive strength, slump and water absorption at four different replacement levels. Then, $i \in [1, 2, 3, 4, 5, 6, 7, 8]$ represents the replacement series and $j \in [1, 2, 3]$ represents the three types of tests.

As the tests are being conducted at different time intervals, the costs should be adjusted for time. To identify the adjusted cost at the start of the project, discounted cash flow is applied on all possible project expenses. Discounted cash flow uses the concept of compound interest to suggest the prevent value of potential expense, i.e., C_{test_j}. The corrected costs can be expressed as discounted present values,

$$C_{total} = \sum_{i} \sum_{j} \left(C_{test_j} \times \frac{1}{(1+r)^{t_{i,j}}} \right) \qquad \text{Eq. 3.4}$$

Here, r is the expected rate of returns, and $t^{i,j}$ is the time of conducting the respective tests. It should be noted that the unit for time in $t_{i,j}$ and r should be same, i.e., days, years, etc.

3.5.2.2. Returns during exploitation

The costs account for one part of the algorithm, and the other part is represented by probable savings. If ϕ_i represents the fraction of cement replaced by SCM, then cost savings ($C_{savings}$) will be,

$$C_{savings} = \text{original cost of binder} - \text{new cost of binder} \quad \text{Eq. 3.5}$$

$$C_{savings} = V \times (1 \times C_{cem}) - V \times (C_{cem} \times (1 - \phi_i) + C_i \times \phi_i) \quad \text{Eq. 3.6}$$

$$C_{savings} = V \times (C_{cem} - C_i) \times \phi_i \quad \text{Eq. 3.7}$$

Here, V is the volume of cement expected to be used in construction and C_{cem} and C_i are the landed costs of cement and SCM, respectively. In recurring activities, like paver block manufacturing, V can be adopted as the expected cement consumption in a specified period of time. In recurring activities, the search optimization will also be recurring for specified periods of time. It should be kept in mind that the results of the algorithm will not remain the same but will be updated for each period of time.

The savings function currently shows the returns for developing a blended SCM from scratch. However, in several projects, the stakeholders are already working with a SCM and trying to explore a better alternative. In this scenario, the savings should be adjusted for the present level of SCM utilization (C_0, ϕ_0) given as,

$$C_{savings} = V \times \left((C_{cem} - C_i) \times \phi_i - (C_{cem} - C_0) \times \phi_0\right) \quad \text{Eq. 3.8}$$

$$C_{savings} = V \times \left(C_{cem}(\phi_i - \phi_0) + (C_0 \times \phi_0 - C_i \times \phi_i)\right) \quad \text{Eq. 3.9}$$

increased substitution reduced procurement

costs

The cost savings during exploitation are also spread over a period of time. For comparing the net gains, the savings should be adjusted for time and expressed as discounted present values. Since the material procurement can also be conducted in multiple phases, the discounted present values for savings will be,

$$C_{savings} = k_T \times V \times \left(C_{cem}(\phi_i - \phi_0) + (C_0 \times \phi_0 - C_i \times \phi_i)\right) \quad \text{Eq. 3.10}$$

$$k_T = \sum_{V_f} \left(\frac{V_f}{(1+r)^{t_{V_f}}} \right) \quad \text{Eq. 3.11}$$

Here, k_T is a correction factor based on the fraction of volume (V_f) procured at various time intervals (t_{V_f}). If the procurement is made in n_T times with equal volume ($V_f = 1/n_T$) and equal time interval ($t_{V_f} = T/n_T$). The correction factor for the exploitation duration of T, will be given as per Eq. 3.12. Another special case exists; when continuous consumption of material is there, then the correction factor will be given as per Eq. 3.13.

$$k_T = \frac{1}{n_T} \times \left(\frac{(1+r)^T - 1}{(1+r)^T - (1+r)^{\left(T - \frac{T}{n}\right)}} \right) \quad \text{Eq. 3.12}$$

$$k_T = \int \frac{1}{(1+r)^{xT}} dx = \frac{1}{T \times \log(1+r)} \left(1 - \frac{1}{(1+r)^T} \right) \quad \text{Eq. 3.13}$$

3.5.2.3. Probability of successful exploration

The savings during exploitation are based on the fact that the SCM selection for a given level of replacement has successfully completed the necessary trials during exploration. The function for success can be substituted by suitable mathematical equations in the form of reliability distribution functions. Consider a probability distribution function defining the probability of optimum replacement level at a different level of replacements (Fig. 3.10). Probability distribution functions can be developed experimentally and have been discussed in subsequent sections. It can be observed from Fig. 3.10 that if an optimum level of replacement is defined by the value ϕ_p, then any replacement level below this value, i.e., $\phi \leq \phi_p$, will give a successful result. Conversely, if a value of ϕ is selected for trial, then all probable scenarios where the optimum level of replacement is higher than the selected value will give successful results. This can be mathematically expressed as a reliability function.

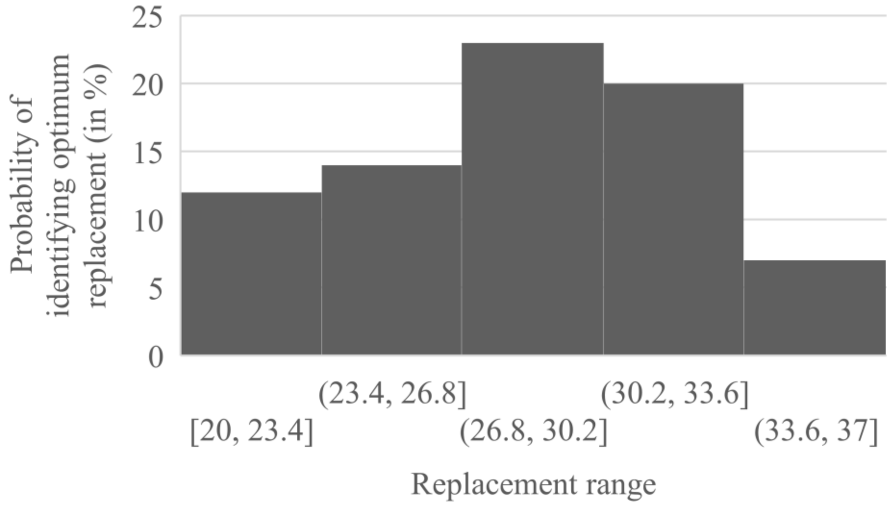


Fig. 3.10 Probability distribution function for optimum replacement of a given SCM

Consider the probability of an optimum level selection as $p\ (\phi_p)$. Then, the probability of success for trial replacement (ϕ) is the sum of all probable scenarios having an optimum level of replacement greater than ϕ_p. The probability of successful exploration ($r(\phi)$) can be given by Eq. 3.15. The graphical representation for $r(\phi)$ is also shown in Fig. 3.11.

$$r(\phi) = \sum p(\phi_p)\ \in \phi_p \geq \phi \qquad \text{Eq. 3.14}$$

$$r(\phi) = \int_{\phi}^{1} p(\phi_p)\,.\,d\phi_p \qquad \text{Eq. 3.15}$$

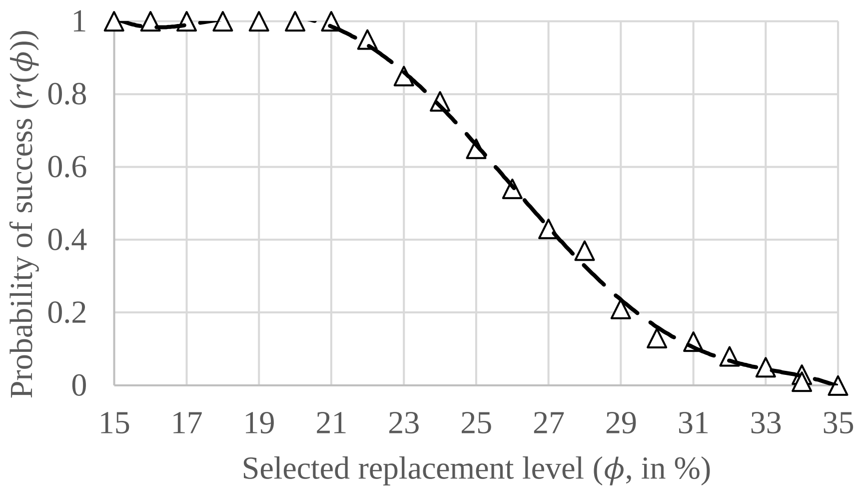


Fig. 3.11 Reliability function for successful exploration

On including the reliability functions, the probable savings during exploitation after a successful exploration can be given as per Eq. 3.16.

$$C_{probable\ savings} = r(\phi) \times C_{savings} = r(\phi) \times k_T \times V \times \left(C_{cem}(\phi_i - \phi_0) + (C_0 \times \phi_0 - C_i \times \phi_i)\right) \quad \text{Eq. 3.16}$$

3.5.2.4. Probability adjustments for subsequent trials

The results of every iteration modify the overall prediction from the algorithm. These modifications can be included by modifying the reliability functions. These modifications are based on the dependency of reliability functions and exhibit two possible scenarios – independent and dependent trials.

Independent trials represent the scenario where the reliability of one test does not correlate with the reliability of subsequent tests. For example, reliability observed for 15% of FA has no correlation with reliability for 15% of SF. In the case of independent trials, the reliability functions can be modified by Eq. 3.17 if trials are to be simultaneously satisfied or by Eq. 3.18 if trials are to be optionally satisfied. Reliability functions require simultaneous satisfaction when testing multiple properties of concrete. Eq. 3.17 shows the scenario where each property must be satisfied, like strength and workability. On the other hand, reliability functions require optional satisfaction when testing multiple SCMs. Eq. 3.18 shows the scenario where multiple SCMs are tested, and at least one should not fail the selection process.

$$r_n(\phi) = \prod_{i=1}^{n} (r(\phi)_i) \quad \text{Eq. 3.17}$$

$$r_n(\phi) = 1 - \prod_{i=1}^{n} (1 - r(\phi)_i) \quad \text{Eq. 3.18}$$

Dependent trials present the scenario where results from previous trials can be used for adjusting the reliability function of successive trials. For example, an increase in compressive strength typically indicates an increase in UPV values. In the case of dependent trials, the reliability functions can be modified by adjusting optimum ranges as per available datasets.

3.5.2.5. Expressing returns on investment

The search optimization algorithm is designed to identify parameters that ensure higher probable savings for known investment in explorations. The various terms are combined to account for success across n number of trials.

$$\text{Return} = C_{probable\ savings} - C_{total} \qquad \text{Eq. 3.19}$$

$$\begin{aligned}\text{Return} = r_n(\phi) \times k_T \times V \\ \times \left(C_{cem}(\phi_i - \phi_0)\right. \\ \left.+ (C_0 \times \phi_0 - C_i \times \phi_i)\right) \\ - \sum_{i=1}^{n} \sum_{j=1}^{m} \left(C_{test_j} \times \frac{1}{(1+r)^{t_{i,j}}}\right)\end{aligned} \qquad \text{Eq. 3.20}$$

The search optimization algorithm demonstrates the effective returns for successful n^{th} iteration of testing, along with the probability of their occurrence. By solving this equation, one can easily identify the correlation between a number of trials (n) and probable returns. The stakeholders can use Eq. 3.20 to select the optimum number of trials based on their desired requirements.

3.5.3. Application of search optimization

3.5.3.1. Fast search for assured minimum returns

In assured minimum returns value for ϕ_i is selected such that saving is similar for each SCM, i.e., $\left(C_{cem}(\phi_i - \phi_0) + (C_0 \times \phi_0 - C_i \times \phi_i)\right) = \alpha$ is the same for every i. The proposed adjustment predicts the probability of a saving value of α. The reliability or success of selection can be reiterated as avoiding rejection across n trials, in terms of Eq. 3.17. The probable savings can be rewritten as Eq. 3.18.

$$r_n(\phi)_\alpha = 1 - \prod_{i=1}^{n} (1 - r(\phi)_{\alpha,i}) \qquad \text{Eq. 3.21}$$

$$C_{probable\ savings} = r_n(\phi)_\alpha \times k_T \times V \times \alpha \qquad \text{Eq. 3.22}$$

3.5.3.2. Fast search for assured minimum success

In assured minimum success, the final selection probability is used for predicting the value of ϕ for each trial. Say after n trials, the required assured minimum success of value β. Then, the probability of rejection should be distributed across n trials, i.e., $(1-\beta)^{1/n}$. In other words, the probability of success for each trial should be $r(\phi)_i = 1-(1-\beta)^{1/n}$. Value for cement substitution, ϕ, for each trial is selected to satisfy the probability of success. The value of ϕ for different can then be used to identify the effective minimum savings. Since it is ideal to first test the SCM with the highest possible savings, then the effective saving can be calculated as per Eq. 3.19.

$$\alpha_{\beta,n} = \frac{1}{n} \times \sum_{i=1}^{n} \left((C_{cem} - C_i) \times \phi_i \times \left(1-(1-\beta)^{\frac{1}{n}}\right) \times (1-\beta)^{\frac{i-1}{n}} \right) - (C_{cem} - C_0) \times \phi_0 \qquad \text{Eq. 3.23}$$

The two scenarios of assured minimum return and assured minimum success are designed as fast selection strategies.

3.6. Summary

3.6.1. Key conclusions

The study presents a comprehensive review of over 20 different SCMs in India to help the stakeholders in selecting a suitable SCM and improve the sustainability of the construction industry. To address the questions faced by stakeholders, the reviewed literature has been analysed in terms of the availability of SCMs, the characteristics of SCMs, the effect of SCM incorporation on the properties of the concrete and the environmental impact of SCM utilization. Based on the discussion presented in the manuscript, the following conclusions can be made;

1. India generates more than 380 Mtpa of SCMs annually, more than three times the estimated need of 105 Mtpa. There is an uneven distribution of availability and need for SCM across

different regions in India. In regions with FA shortage, there is a combined need for 12.22 Mtpa of alternative SCMs. In contrast, regions with excess FA have a surplus of 131.88 Mtpa and require high-volume waste applications for effective waste management.

2. In terms of physical characteristics, SCMs can be classified into 3 clusters compared to cement, i.e., particles with similar size and specific gravity, particles with similar size and low specific gravity, and very fine particles. SCMs with very fine particles have better dissolution and nucleation, which improves the hydration of cement. In SCMs with similar sizes, low surface area reduces the water requirement and improves the workability of concrete. It is recommended to use fine-sized SCMs as strength-modifying admixtures and similar-sized SCMs as workability-modifying admixtures.
3. In terms of chemical characteristics, SCMs can be classified into five groups, i.e. silicate, alumina silicate, calcareous alumina silicate, slags and calcites. Ca-rich SCMs (i.e., calcareous alumina silicate, slags and calcites) should be prioritized for clinker manufacturing or composite cement to account for limestone sustainability. Silicates and alumina silicates should be prioritized as pozzolans.
4. In terms of mineral characteristics, amorphous minerals have a higher dissolution rate and react faster with cement. SCMs with higher amorphous content provide better pozzolanic reactivity and should be prioritized for use.
5. In terms of morphological characteristics, SCMs can be identified as spherical, irregular, crystal and fibre-shaped. Smooth and spherical particles improve workability and should be used as workability modifying admixture.
6. The workability of concrete increases for FA and GGBS because of smooth morphology and similar particle size. SF, MP and GP showed mixed behaviour due to workability. It is recommended to use FA, GGBS, SF, MP and GP for flow requirements.

7. Compressive, flexural and split tensile strength increased for SCMs with very fine particles (SF, RM, MK, JS, CWP, MBS) and high Ca content (SSA, GGBS, JS, CS, WS, MP, ESP, LS). It is recommended to use very fine particles and SCMs with high Ca content for strength requirements.
8. Durability in terms of chloride-based corrosion and wetting and drying cycles improves with the addition of SCMs due to a reduction in permeability. The addition of SCM is inferred as safe to use in these scenarios. In carbonation-based corrosion, the addition of SCMs with very fine particles and high Ca content improved the durability of concrete. It is recommended to use SCMs with very fine particles and high Ca content in reinforced cement concrete (RCC) structures with a risk of carbonation-based corrosion.
9. Multi-blended cement provides better particle packing, compressive strength and higher clinker substitution over binary blended cement. Further investigation towards the optimization of multi-blended cement is required for further increasing SCM utilization.
10. Probabilistic modelling for SCM selection can provide a quantitative indicator for the gains from exploring alternate SCMs against the investment in exploration.

3.6.2. Future needs for SCM utilization

The study shows that search optimization algorithms can improve SCM selection and utilization in the construction industry. Future investigations will be required in developing relevant data sets and field investigations for the proposed algorithm.

3.6.3. Study limitations

As the chapter presents a meta-heuristic analysis for SCM selection, the following limitations should be kept in mind while applying the results of this study.

1. The proposed classification-based approach for SCM selection can have low reliability due to limitation in data set. Therefore, it should be kept in mind that the proposed study is used for shortlisting most probable SCMs which will yield a sustainable concrete, and should not be used as a substitute for actual experimental investigations.
2. The characterization-based classification is developed from literature on SCMs available in India. It is possible that additional classifications may be required to account for other studies on SCMs.
3. The study defines a sustainable selection of SCM with construction-based application and excludes secondary environmental impacts. For example, removing RHA from agriculture may increase the need for fertilizers. It should be kept in mind that the usage of sustainability in the context of this chapter is focused on cement reduction.

Chapter 4
Developing a new strategy for upcycling low-value wastes as aggregates

Coarse aggregates present a case where resource consumption greatly exceeds the available alternatives. The simplistic strategy for resource sustainability requires the manufacturing of alternative aggregates, which is also favoured in the existing legal provisions. Aggregates can be manufactured by recycling C&D wastes or repurposing wastes from other industries. In the condition where alternative resources are to be developed, it is recommended to identify low-value resources and develop cost-effective strategies for their upcycling. MRA is considered a low-value resource among different forms of recycled C&D waste. Upcycling low-value resources, like MRA, provides significant cost benefits and improves the overall sustainability of alternative construction materials.

The chapter describes the process of upcycling MRA as sustainable construction materials to improve the circular use of aggregates. The present chapter has been reproduced from the research publication – **Gupta, S.**, Agrawal, H., and Chaudhary, S. (2023). "Thermo-mechanical treatment as an upcycling strategy for mixed recycled aggregate", Construction and Building Materials, 398, 132471. DOI: 10.1016/j.conbuildmat.2023.132471 (I.F. 7.4); and from the conference – **Gupta, S.**, and Chaudhary, S. (2023), Recirculation strategy for end-of-life concrete structures as low carbon construction materials, International Symposium on Life Cycle Maintenance of Concrete Infrastructure (LCMCI2023), September 25-26, Hong Kong, China.

4.1. Background

4.1.1. Circular use of C&D waste

Construction activity results in a significant consumption of natural resources and waste generation, which is detrimental to the environment

[325]. A sustainable solution for the construction industry can be the upcycling of waste as a natural resource in the form of a circular economy [325]. A prominent example of a circular economy in the construction industry is the utilization of construction and demolition (C&D) wastes in the form of recycled aggregates (RA). The global estimate for the generation of C&D wastes is 4.5 billion tonnes/ year, which can be a sustainable alternative to 14.06% of globally consumed natural aggregates (NA) [32]. Upcycling of recycled aggregates (RA) can substantially lower the consumption of NA but is yet to achieve its full potential. Many countries, like India, utilize less than 1% of their C&D waste, far lower than the global utilization [326, 327].

A typical C&D waste consists of concrete and unbound stones along with bricks, glass, asphalt, ceramics and several other solid wastes in varying proportions [103]. Crushing of C&D waste produces primarily two types of RA in India: recycled concrete aggregates (RCA) and mix recycled aggregates (MRA) (Fig. 4.1). RCA consists of more than 90% of concrete and unbound stones and are preferred in C&D waste for recycling [103]. On the other hand, MRA consists of other solid wastes and is heterogeneous in nature [103]. Literature shows that MRA has poor aggregate characteristics as compared to NA and is less desirable for construction applications, as per the technical standards of different countries [103, 328, 329].

In India, masonry construction has been a major part of the construction industry. The high volume of masonry waste typically results in the formation of MRA [330]. Typically, solid waste in India consists of about 30% concrete and unbound stones [330]. Although several countries follow the practice of waste segregation, the same may not be effective in India. Furthermore, segregation only favours partial recycling, and a substantial volume of materials will still require recycling. IS 383: 2016 suggests that all constituents of C&D wastes can be used in construction by manufacturing them as aggregates [4]. The process of manufacturing aggregates by improving the properties of MRA (or any other waste) is typically known as treatment.

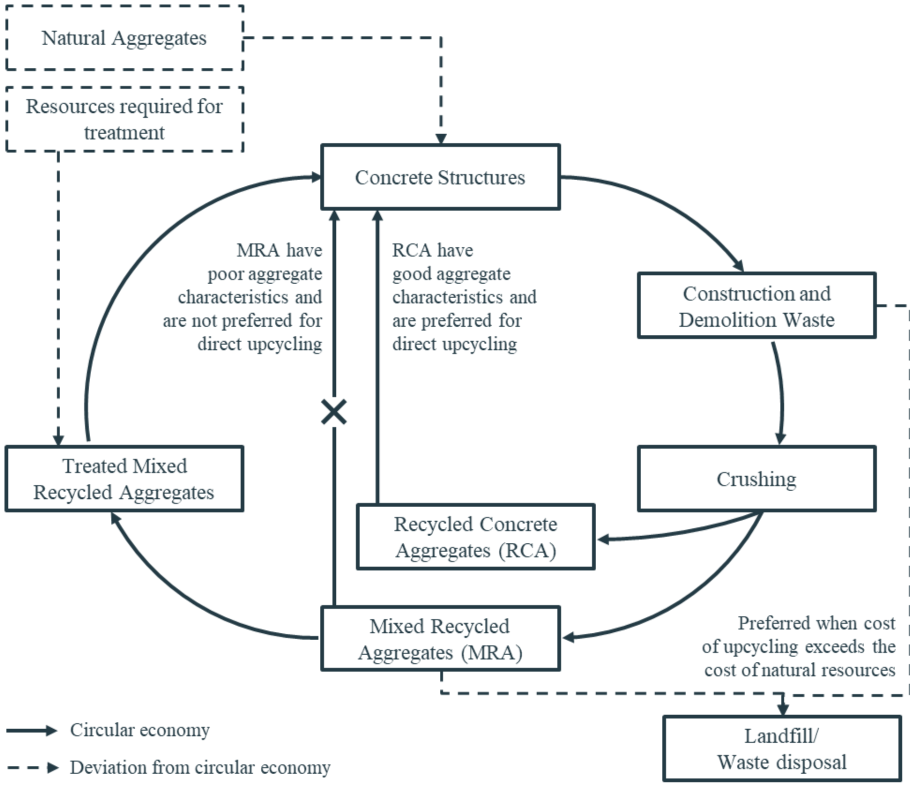


Fig. 4.1 Circular use of C&D waste as construction materials

4.1.2. Methods for upcycling MRA

Over the years, several different treatment techniques have been developed to improve the aggregate characteristics and concrete-based application of MRA [5, 331, 332]. The treatment techniques can be classified based on the strengthening of adhered mortar[8] (like polymer soaking, calcite precipitation, carbonation, pozzolan coating and cement slurry impregnation) or based on the removal of adhered mortar (like mechanical grinding, thermal treatment and chemical/acid treatment) [5, 331, 332]. In most methods of strengthening adhered mortar, the treatment process requires additional resources [5]. Among adhered mortal removal, chemical or acid treatment presents a similar challenge to resource sustainability [5]. Introducing new materials during the upcycling of MRA lowers the resource sustainability of the circular economy. Although thermal and mechanical treatment require energy as

[8] Adhered mortar refers to the cement paste or mortar coating present over the brick, stone and tile particles from previous construction applications.

a resource, the global shift towards clean energy will only improve their viability. Furthermore, in the case of RCA, the removal of adhered mortar shows better characteristics than strengthening [332]. Therefore, from both the performance and resource sustainability point of view, thermal treatment and mechanical treatment appear to be better upcycling strategies for MRA.

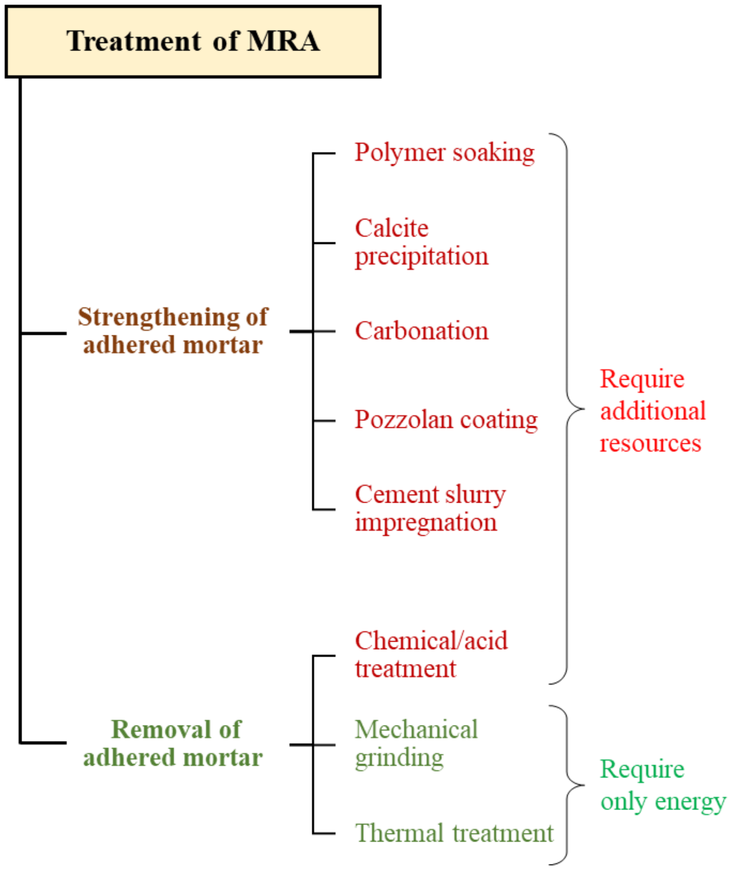


Fig. 4.2 Treatment strategies for MRA

4.1.3. Concept of thermo-mechanical treatment

In terms of MRA, combining treatment techniques is typically more effective than individual treatment techniques [333]. A combination of thermal and mechanical treatments, or thermo-mechanical treatment, is expected to be more effective for treating MRA. In thermo-mechanical treatment, C&D waste is exposed to high temperatures (above 250 °C) followed by mechanical shock (abrasion or grinding) to produce treated aggregates [334, 335]. Exposure to elevated temperature weakens the adhered mortar, which can be easily removed by mechanical shock [335, 336]. Thermal treatment is also expected to burn organic impurities and improve the properties of MRA. Despite potential viability, the investigation on thermo-mechanical treatment has been limited to recycled concrete aggregate (RCA) [335, 336]. Experimental investigations are needed to assess the viability of thermo-mechanical treatment for upcycling MRA.

The present study explores the potential of thermo-mechanical treatment as an upcycling strategy for MRA. By varying the exposure temperature (300 °C – 800 °C), six different protocols have been adopted for the thermo-mechanical treatment of MRA. The treated MRA has been compared with untreated MRA and mechanically treated MRA in terms of adhered mortar removal and various aggregate characteristics, as per IS 383: 2016 [4]. The optimum treatment protocol is further investigated for its effect on the properties of concrete and compared with both NA and untreated MRA. The study also explores the sustainability (technical, economic and environmental) of thermo-mechanical treatment of MRA, with a case study of MRA from Indore in India.

Thermo-mechanical treatment focuses on converting a low-value resource (i.e., MRA) to a high-value resource (i.e., aggregates). The upcycling strategy will be considered viable if the value addition is more than the cost of thermo-mechanical treatment. The study asses the economic and environmental costs of treated MRA as compared to NA. The assessment is then used to identify the challenges of thermo-mechanical treatment and suggest recommendations for improving the sustainability of the proposed upcycling strategy.

4.2. Experimental Program

4.2.1. Materials used

MRA was procured from a local C&D waste recycling plant in Indore, India (22.68 N, 75.92 E). MRA, by weight, consisted primarily of recycled concrete and unbound aggregates (70.1%), as shown in Fig. 4.3. Procured NA was mined and crushed locally from the village Pedmi of Indore, India (22.62 N, 76.11 E). Natural river sand was used as fine aggregate. Table 4.1 shows the classification, specific gravity, water absorption and fineness modulus of the coarse and fine aggregates as per IS 383: 2016 [4]. Commercially available ordinary Portland cement of 43-grade was used as the binder. Cement had a specific gravity of 3.15, standard consistency 31%, initial setting time of 90 min and final setting time of 300 min.

Table 4.1 Properties of fine and coarse aggregates

	MRA	NA	Fine aggregate
Classification	Recycled aggregate	Crushed stone	Natural sand
Gradation	20 mm Nominal Size	20 mm/10 mm Nominal Size	Zone II
Specific gravity	2.42	2.91	2.68
Water absorption (%)	6.10	4.00	0.81
Fineness modulus	7.6	6.4	2.6

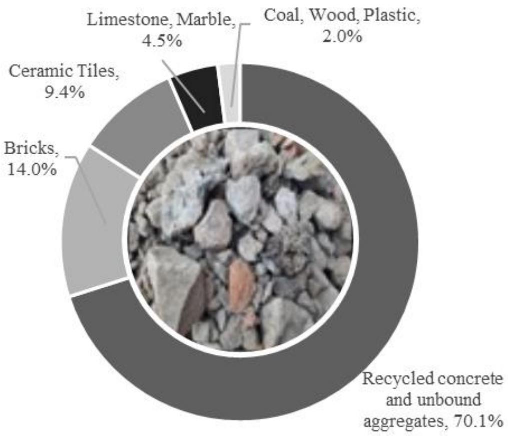


Fig. 4.3 Composition of MRA considered for the study

4.2.2. Thermomechanical treatment of MRA

A total of nine different types of aggregate were investigated in this study. Six types of aggregate were obtained by thermo-mechanical treatment of MRA at different exposure temperatures of 300 °C to 800 °C. The thermo-mechanically treated MRA are designated by the exposure temperature of their treatment, i.e., MRA-300, MRA-400, MRA-500, MRA-600, MRA-700 and MRA-800. Additionally, three types of aggregate were used as the control for evaluating the effectiveness of thermo-mechanical treatment, i.e., NA, MRA without any treatment (MRA-UT) and MRA after mechanical treatment only (MRA-MT).

A two-step process was adopted for the thermo-mechanical treatment of MRA, as shown in Fig. 4.4. In the first step, MRA is given a thermal shock by rapid heating and cooling. In this step, the electric muffle furnace was preheated to the specified temperatures of 300 °C, 400 °C, 500 °C, 600 °C, 700 °C and 800 °C. MRA was introduced in the furnace at the selected elevated temperature, allowing it to go under rapid heating. After some time, the MRA was removed and allowed to cool at room temperature. It was observed that the time required for the MRA to achieve the specified elevated temperature depended on exposure duration, the quantity of MRA and the type of crucible used. Therefore, MRA was heated for 4 h to ensure that all constituents of MRA attained the specified elevated temperature. In the second step, an abrasive action provides a mechanical shock to MRA. Thermally treated MRA was transferred to a Los Angeles testing machine and rotated without additional charges for 100 cycles at a rate of 33 revolutions per minute. After mechanical treatment, MRA was sieved on a 4.75 mm sieve to segregate thermo-mechanically treated coarse MRA.

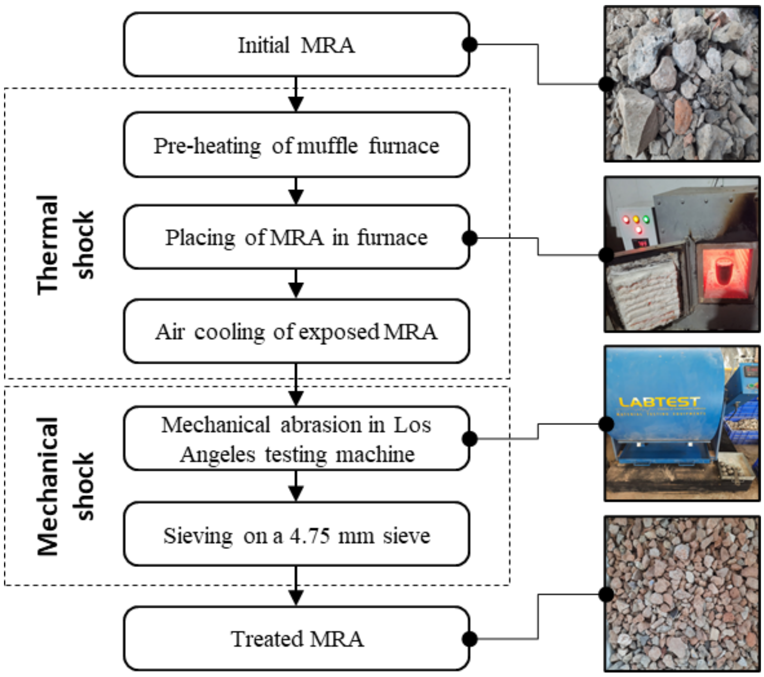


Fig. 4.4 Thermo-mechanical treatment of MRA

A sample splitter was used to divide the procured MRA into eight equal parts to ensure homogeneity between the samples. Two parts were used as control (MRA-UT and MRA-MT), and six parts were used for thermo-mechanical treatment (MRA-300, MRA-400, MRA-500, MRA-600, MRA-700 and MRA-800). Furthermore, each set of treated aggregates was divided into smaller groups using the sample splitter to ensure the homogeneity of constituents across different tests.

4.2.3. Aggregate property evaluation

The effectiveness of thermo-mechanical treatment was evaluated in terms of residual adhered mortar content, which was determined using the acid treatment technique (Appendix A). The properties of all MRA(s) were assessed in terms of specific gravity (IS 2386 – Part 3), water absorption (IS 2386 – Part 3), aggregate crushing value (IS 2386 – Part 4), aggregate impact value (IS 2386 – Part 4) and aggregate abrasion value (IS 2386 – Part 4). The properties of all MRA(s) were also compared with the required specifications for coarse aggregate listed in IS 383: 2016 [4].

4.2.4. Concrete design mix

In this study, a constant volume of coarse aggregate is been adopted for all concrete specimens. NA concrete is designed for a cement content of 400 kg and a w/c ratio of 0.4, as per IS 10262: 2019. In concrete designed with MRA, the NA was replaced entirely (100% substitution) by the same volume of different aggregates. Table 4.2 shows the design mix for the nine different types of concrete. It should be noted that the design mix is shown for coarse aggregates in saturated surface dry conditions. At the time of casting, oven-dried aggregates were used, and moisture correction was applied based on the water absorption of aggregates (specified in Section 3.2.2). Furthermore, as the removal of adhered mortar causes a reduction in particle size, particle gradation for the MRA(s) was adjusted to uniformly graded 20 mm aggregates. Uniform gradation was achieved by reducing coarse fraction in coarse aggregates. All concrete specimens were vibration cast and cured in water tanks.

Table 4.2 Design mix for concrete

Designation	Cement (kg)	Water (kg)	Fine aggregate (kg)	Coarse aggregate		
				Type of aggregate	By weight (kg)	By volume fraction
NA	400.00	160.00	765.00	NA	1075.00	37.07%
MRA-UT				MRA-UT	898.09	
MRA-MT				MRA-MT	905.10	
MRA-300				MRA-300	927.11	
MRA-400				MRA-400	935.25	
MRA-500				MRA-500	949.31	
MRA-600				MRA-600	968.58	
MRA-700				MRA-700	987.92	
MRA-800				MRA-800	971.01	

4.2.5. Concrete testing

Concrete specimen prepared using the nine different types of aggregate were tested for their effect on the 7-day and 28-day compressive strengths. A total of four sets of concrete prepared using MRA-600, MRA-700, MRA-UT (control) and NA (reference) as aggregates, were further investigated in terms of flexural strength, split tensile strength, and slump value (workability).

4.3. Results and Discussion

4.3.1. Effect of thermo-mechanical treatment

Fig. 4.5 shows the six types of thermo-mechanically treated MRA at different stages of treatment. It can be observed from Fig. 4.5 that all MRA(s) appear visually similar after thermal treatment. The visual similarity shows that adhered mortar remains preset on the MRA(s) after thermal treatment alone. After mechanical treatment the treated MRA(s) became visibly different from each other. MRA(s) exposed to higher elevated temperature shows greater presence of fine particles, which indicates separation of adhered mortar from coarse particles. The visual observation shows that exposure to elevated temperature only weakens the adhered mortar, and mechanical treatment is required to remove the same. Visual inspection also revealed that MRA(s) exposed to temperatures above 600 °C, i.e., MRA-600, MRA-700 and MRA-800 loses the volatile organic substances like wood, bitumen and plastics.

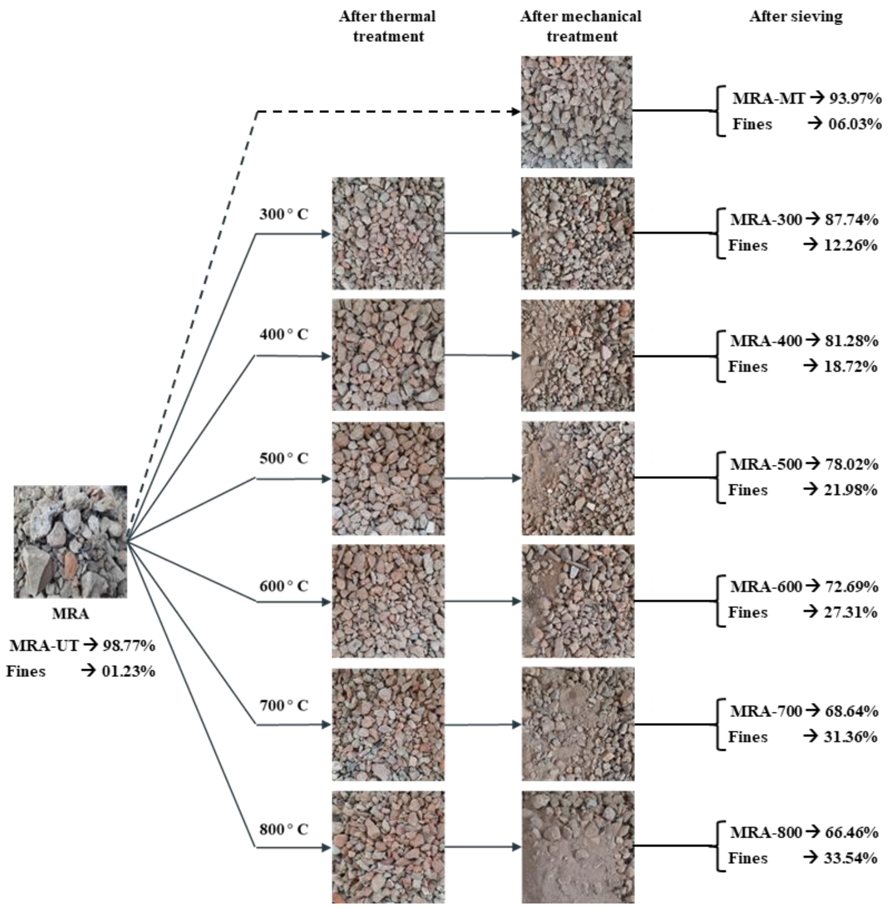


Fig. 4.5 Thermo-mechanically treated MRA(s)

4.3.1.1. Residual adhered mortar content

Fig. 4.6 shows the adhered mortar content of the different thermo-mechanically treated MRA(s). It can be observed from Fig. 4.6 that the treated MRA(s) have a lower adhered mortar content than MRA-UT and MRA-MT. MRA(s) treated at higher exposure temperatures show a lower percentage of adhered mortar content (Fig. 4.6). The observed trend of increasing loss in adhered mortar content with exposure temperature also correlates with the literature on thermo-mechanical treatment of RCA [335].

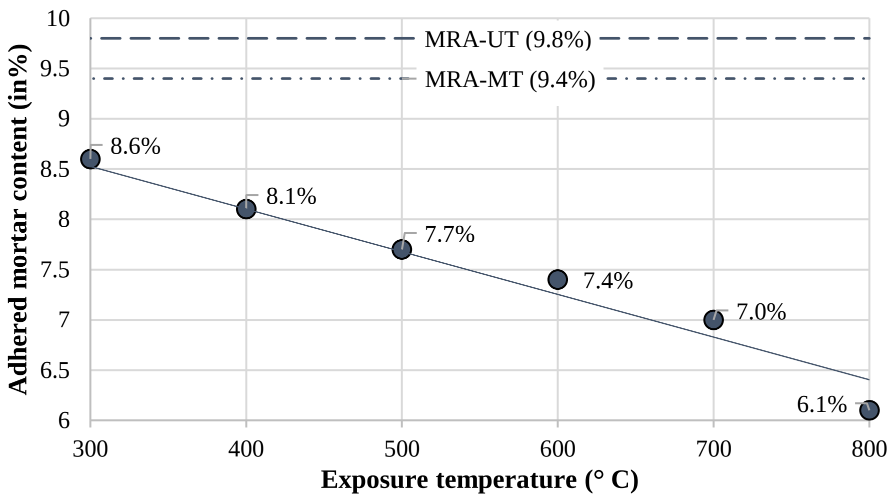


Fig. 4.6 Residual adhered mortar content in treated MRA

4.3.2. Property of treated MRA

4.3.2.1. Specific gravity

The specific gravity of the treated MRA(s) along with MRA-UT and MRA-MT is shown in Fig. 4.7. It can be observed that the specific gravity of all treated MRA(s) is higher than MRA-UT but less than NA (Fig. 4.7). The specific gravity of the treated MRA(s) increased up to the exposure temperature of 700 °C and attained a maximum value of 2.67 (Fig. 4.7).

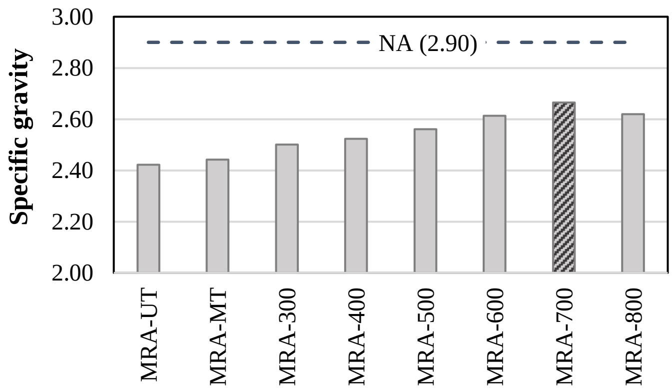


Fig. 4.7 Specific gravity of thermo-mechanically treated MRA

The increase in specific gravity might have resulted from the removal of adhered mortar (Fig. 4.6), which has a lower porosity than the stone components of MRA, and the loss of volatile components like coal, wood, bitumen and plastic. It should be noted that the specific gravity of treated MRA reduces above 700 °C. The decrease in specific gravity can be attributed to the weakening of aggregates from microcracking at high temperatures [335, 337]. Thermo-mechanical treatment of RCA also showed a similar observation of the reduction in specific gravity at higher temperatures [335]. The maximum specific gravity attained its value at 700 °C for MRA, while literature shows the maximum value at 350 °C for RCA [335]. The shift in the temperature range for maximum specific gravity for MRA may be due to the loss of low-density volatile substances at high temperatures.

The technical standard, IS 383: 2016 [4], suggests that dense aggregate should be preferred for construction without specifying any numerical limits. Since specific gravity indicates the denseness of material, MRA-700 can be considered superior to other treated MRA(s).

4.3.2.2. Water absorption

The water absorption of the treated MRA(s) along with MRA-UT and MRA-MT is shown in Fig. 4.8. It can be observed that for most exposure temperatures, thermo-mechanical treatment shows no definite trend for water absorption.

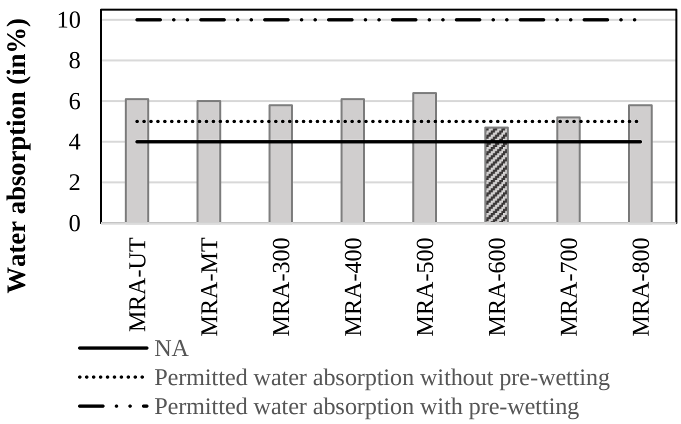


Fig. 4.8 Water absorption of treated MRA

It should be noted that the treated MRA(s) show water absorption values less than 10.00%, which is the permissible limit for recycled aggregates as per IS 383: 2016 [4]. The technical standard, IS 383: 2016 [4], suggests that recycled aggregate with water absorption above 5.00% should be used with pre-wetting. Only MRA-600 (4.70%), among the treated MRA(s), shows water absorption below 5.00 %. Therefore, MRA-600 can be used as conventional aggregates, i.e., without pre-wetting.

4.3.2.3. Aggregate crushing value, impact value and abrasion value

The aggregate crushing, impact and abrasion values of the treated MRA(s), along with MRA-UT and MRA-MT, are shown in Fig. 4.9–Fig. 4.11. It can be observed that the crushing (Fig. 4.9), impact (Fig. 4.10), and abrasion values (Fig. 4.11) of all treated MRA(s) are lower than MRA-UT. Aggregate characteristics improved up to the exposure temperature of 700 °C and attained the lowest crushing value of 18.91%, impact value of 12.47% and abrasion value of 23.55% (Fig. 4.9–Fig. 4.11).

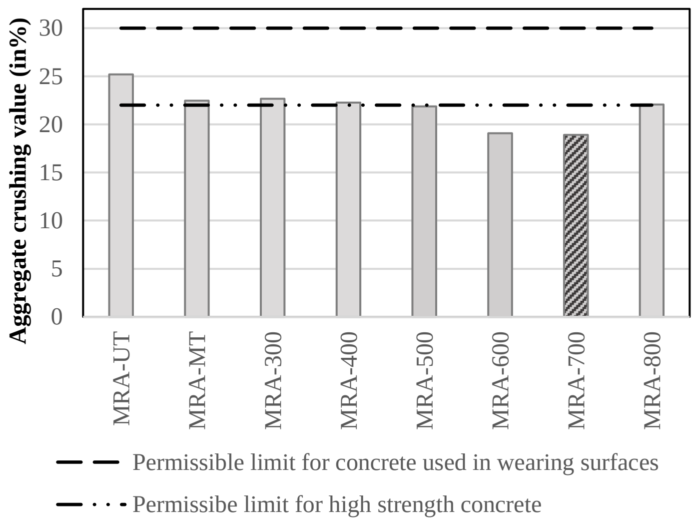


Fig. 4.9 Aggregate crushing value of treated MRA

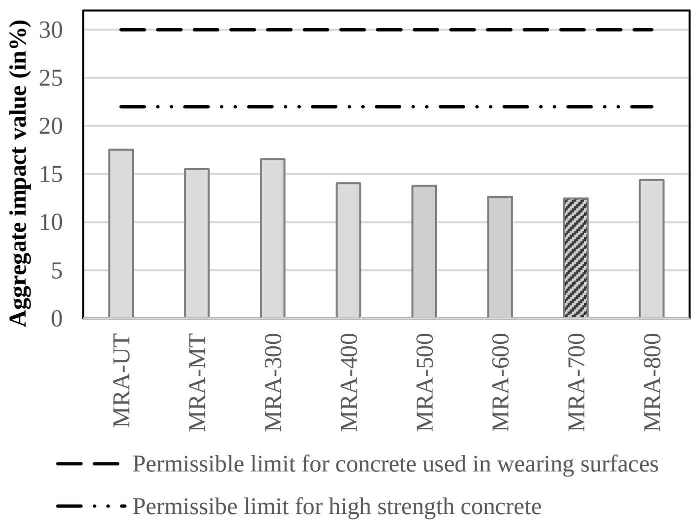


Fig. 4.10 Aggregate impact value of treated MRA

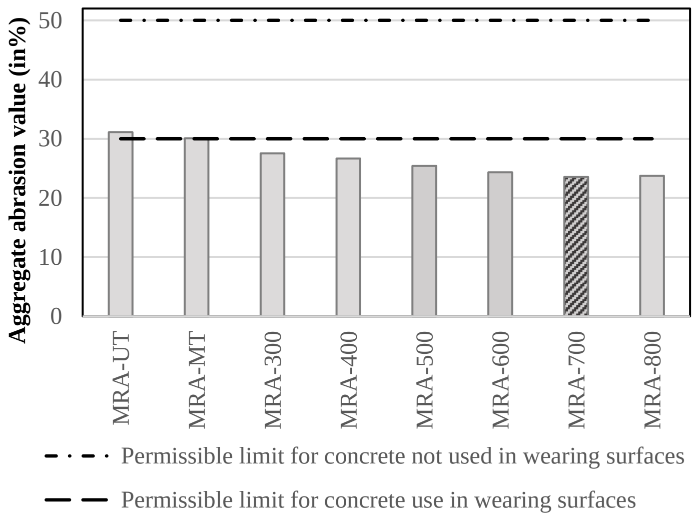


Fig. 4.11 Aggregate abrasion value of treated MRA

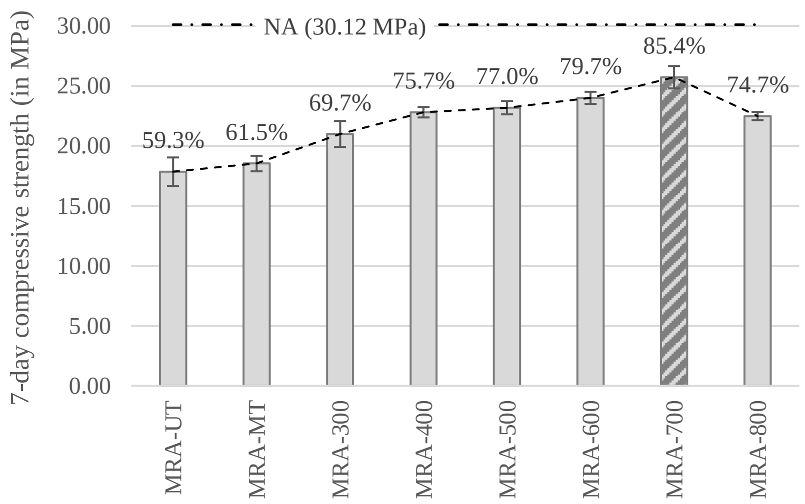
The observed improvement of aggregate characteristics can result from the loss of adhered mortar and volatile components. Above 700 °C, MRA-800 shows an increase in aggregate crushing, impact and abrasion values. The weakening of aggregate above 700 °C is similar to the loss of specific gravity (Fig. 4.7) and may be attributed to micro-cracking at high temperatures [337].

According to IS 383: 2016 [4], in terms of aggregate crushing and impact value, all MRA(s) can be used for normal-strength concrete, while MRA-500, MRA-600 and MRA-700 can also be used for high-strength concrete. Furthermore, in terms of aggregate abrasion value, MRA-UT and MRA-MT can only be used in concretes without wearing surfaces; while, the different treated MRA(s) can also be used in concrete with wearing surfaces. Results show that thermo-mechanical treatment improves the application potential of MRA while satisfying the specifications of the relevant technical standard.

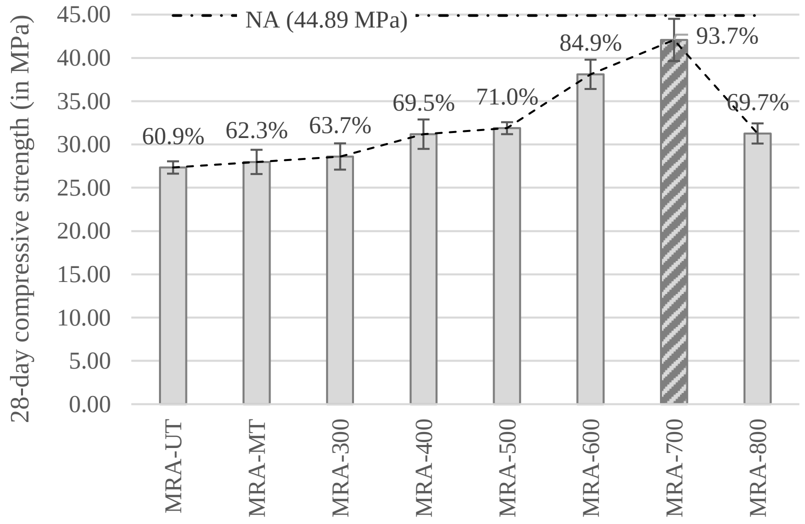
4.3.3. Effect of treated MRA on the properties of concrete

4.3.3.1. Compressive strength

The 7-day and 28-day compressive strength of concrete prepared using the treated MRA(s) along with MRA-UT and MRA-MT is shown in Fig. 4.12 (a-b). Results show that the thermo-mechanical treatment significantly improves the compressive strength of MRA(s). The compressive strength of concrete shows a continuous improvement up to the aggregate exposure (treatment) temperature of 700 °C (Fig. 4.12 (a-b)). The maximum strength improvement at 700 °C was 44.1% at 7 days and 53.9% at 28 days, as compared to MRA-UT.



(a) 7-day compressive strength



(b) 28-day compressive strength

Fig. 4.12 Compressive strength of concrete prepared using thermo-mechanically treated MRA

It can be observed that, MRA-800 shows a decrease in compressive strength at 7 days and 28 days. The observed trend of compressive strength (Fig. 4.12 (a-b)) is similar to aggregate characteristics, i.e., specific gravity (Fig. 4.7), crushing value (Fig. 4.9), impact value (Fig. 4.10) and abrasion value (Fig. 4.11). A similar trend shows that improvement in compressive strength is a direct result of aggregate strengthening, which occurs up to 700 °C of thermal treatment. It should also be noted that, compared to concrete prepared using NA, MRA-700 shows 85.4% and 93.7% strength at 7 days and 28 days, respectively (Fig. 4.12 (a-b)). It is safe to conclude that the compressive strength of concrete prepared using thermo-mechanically treated MRA (MRA-700) shows a value significantly closer to concrete prepared using NA.

4.3.3.2. Workability, flexural strength and split tensile strength

Based on aggregate characteristics and compressive strength of concrete, it can be concluded that an exposure temperature of 700 °C (MRA-700) shows the best treatment results, followed by an exposure temperature of 600 °C (MRA-600). Further investigation on concrete properties was therefore limited to MRA-600 and MRA-700, along with MRA-UT and NA as control specimens. The effect of thermo-mechanical treatment on the various properties of concrete is shown in Table 4.3.

Table 4.3 Effect of thermo-mechanical treatment on the properties of concrete

Type of aggregate	Slump (mm)	Compressive strength (MPa)		Flexural strength (MPa)	Split tensile strength (MPa)
		7-day	28-day		
MRA-UT	15	17.86	27.34	5.27	2.33
MRA-600	65	24.01	38.10	5.79	2.41
MRA-700	125	25.73	42.07	6.21	2.61
NA	75	30.12	44.89	6.21	2.67

It can be observed from Table 4.3 that MRA-700 and MRA-600 show higher workability (slump) and mechanical strength (compressive, flexural and split tensile) as compared to MRA-UT. It should also be noted that MRA-700 shows better concrete properties than MRA-600 (Table 4.3). The properties exhibited by MRA-700 are comparable with NA (Table 4.3); therefore, the exposure temperature of 700 °C is considered optimum for treating MRA.

In terms of workability, MRA-700 shows a slump value significantly higher than NA (Table 4.3). This increase in the slump may result from an increased roundness of MRA-700, which results from abrasion-based mechanical treatment. The improved workability suggests that MRA-700 can be potentially used for self-compacting concrete. Alternatively, a lower w/c ratio may be adopted in the case of MRA-700. A lower w/c will help increase the mechanical strength of MRA-700 concrete while reducing the slump to a similar value as NA concrete.

In terms of mechanical strength, concrete prepared using MRA-700 shows a comparable flexural (99.94%) and split tensile strength (97.87%) to that of NA (Table 4.3). A similar mechanical strength suggests that MRA-700 can be used as a substitute for NA without special considerations.

4.3.4. Sustainability assessment of thermo-mechanical treatment

Experimental results show that thermo-mechanically treated MRA prepared at the exposure temperature of 700 °C (MRA-700) can be upcycled as an alternative construction material. The technical study only supports the circular use of materials. Further assessment of economic and environmental costs is required to support the field application of treated MRA as a sustainable construction material.

4.3.4.1. Assessment of MRA-700 and NA

Table 4.4 compares the economic cost and equivalent carbon emission of MRA-700 with NA. The assessment has been carried out with the case study of the Indian construction industry. The economic costs for the raw materials and transportation have been adopted as per the government-specified schedule of rates [51]. The transportation distances have been adopted as the approximate distance between the city region and the source (C&D recycling plant, NA quarry). The equivalent carbon emission for MRA was not available in the study region in India, so the same has been adopted from a recent study of South Africa [338]. All remaining parameters have been adopted as per the treatment protocol described in Section 4.2.2.

Table 4.4 Sustainability assessment of thermo-mechanically treated MRA

	Analysis	Economic cost (INR/kg)		Eq. carbon emissions ($\times 10^{-3}$ eq. kg CO_2/kg)	
		MRA-700	NA	MRA-700	NA
Procurement	The procurement cost of MRA is 398 INR/m^3 or roughly 0.25 INR/kg [51]. About 1.46 kg of MRA is required to produce 1 kg of MRA-700. The procurement cost of NA is 1400 INR/m^3 or roughly 0.87 INR/kg [51]. The equivalent carbon cost of crushed and sieved MRA is 2.832 eq. kg CO_2/ton [338]. The equivalent carbon cost for NA is 4.19 eq. kg CO_2/ton [339].	0.36	0.87	4.13	4.19
Thermal shock	Energy consumption for 10 kg of MRA was 1.02 kWh, with 3.34 kWh of heat loss in the furnace. Treatment energy is 0.102 kWh/kg of MRA. In a single operation, the furnace can safely treat about 150 kg of MRA. Therefore, energy in heat loss can be reduced to 0.022 kWh/kg of MRA. The energy required can be optimized to 0.124 kWh/kg of MRA. At 68.64% aggregate recovery, the energy required is 0.181 kWh/kg of MRA-700. Electricity charges for the study area are approximately 6.00 INR/kWh [340]. Electricity production accounts for 0.004 (hydro) – 0.957 (coal) eq. kg CO_2/kWh [341].	1.08	-	0.72 – 172.88	-

Table 4.4 Sustainability assessment of thermo-mechanically treated MRA (contd.)

Mechanical shock	Power consumption for abrasion of 60 kg of MRA is 0.0375 kWh. The energy required for mechanical sieving is 0.02 kWh for 10 kg of treated MRA. The energy required is calculated as 0.0026 kWh/kg or 0.0038 kWh/kg of MRA-700.	0.02	-	0.02 – 3.66	-
Operational costs	Operational costs (labour, maintenance, etc.) are assumed at 0.20 INR/kg.	0.20	-	-	-
Transportation	The plant for MRA is located within 5 km of the city and will cost less than 217.16 INR/m^3 or roughly 0.14 INR/kg [51]. The plant for NA is located 30 km outside the city and will cost about 522.56 INR/m^3 or roughly 0.33 INR/kg [51]. Transportation accounts for 0.0924 eq. kg CO_2/ton-km [339].	0.14	0.33	0.46	2.77
By products	0.457 kg of manufactured sand is also obtained per kg of MRA-700. The value of manufactured sand is 741 INR/m^3, or roughly 0.46 INR/kg [51].	- 0.21 (recovery)	-	-1.29 (recovery)	-
Total		1.59	1.20	4.04 – 179.84	6.96

In terms of economic costs, Table 4.4 shows that the presented method for thermo-mechanical treatment can produce MRA-700 at a landed cost of 1.59 INR/kg. The landed cost of MRA-700 is 32.50% (0.39 INR/kg) higher than the landed cost of NA (1.20 INR/kg). Table 4.4 shows that the low production cost of MRA-UT, low transportation cost and fine MRA as a by-product favours the economy of MRA-700 over NA. However, the high costs incurred during thermal shock (1.08 INR/kg or 67.92% of total cost) makes MRA-700 economically less desirable.

Table 4.4 also shows that the net carbon emission of MRA-700 can vary between 4.04 eq. kg CO_2/kg for hydro-power-based electricity and 179.84 eq. kg CO_2/kg for coal (thermal) based electricity. The primary factor governing the environmental impact is the high energy cost incurred during thermal shock and the source of electricity. In the best-case scenario, if hydro-power-based electricity is used, then the carbon emission for MRA-700 will be lower than NA by 2.92 eq. kg CO_2/kg of aggregate or 41.95%. It should be further noted that the net carbon emission will depend on the source of fuel used for thermal treatment. It should be noted that if the source of energy is based on non-renewable sources like coal and natural gas, direct heating should be adopted for thermal treatment. Thermal treatment using a coal-based furnace can prevent energy conversion and transmission losses, which can lower the energy consumption to less than 10% of current energy use.

4.3.4.2. Improving the process of thermo-mechanical treatments

The viability of the present thermo-mechanical treatment needs further improvement due to the high energy requirements during thermal shock. The following should be considered, which can render the process of thermo-mechanical treatment more sustainable in future applications:

1. *Reduction in exposure duration:* During heating, MRA attained the maximum temperature in less than 1 h, while the heating protocol was adopted for 4 h. Exposure duration may therefore be optimized to lower the energy demands by over 50%. Optimization of exposure duration may reduce the cost of treated MRA-700 to 1.04 INR/kg, about 13.33% less than NA.

2. *Use of a renewable energy source:* Renewable energy sources like solar, hydro and wind can have significantly lower carbon emissions, as low as 0.004 eq. kg CO_2/kWh [341], and lower cost, as low as 0.045 USD/kWh or 3.17 INR/kWh [342]. Using a renewable energy source to produce MRA-700 can lower carbon emissions and economic costs by up to 2.92 eq. kg CO_2/kg (41.95%) and 0.13 INR/kg (10.74%), respectively, compared to NA.

4.4. Summary

4.4.1. Key conclusions

The present study investigates the viability of thermo-mechanical treatment for the upcycling of MRA as a sustainable construction material. The efficacy of different thermo-mechanical treatments was evaluated in terms of residual adhered mortar content, aggregate properties and concrete properties. MRA-700, showing viability as an alternate construction material, was further assessed for economic feasibility and environmental impact (equivalent carbon emissions). On the basis of the results of the study, the following conclusions can be drawn:

1. Thermo-mechanical treatment is an effective strategy for adhered mortar removal. The removal of the adhered mortar increases with the exposure temperature during thermal shock. The lowest adhered mortar content observed is 6.1% for MRA-800, compared to 9.8% for MRA-UT.
2. In terms of aggregate characteristics, thermo-mechanical treatment shows an increase in specific gravity and a decrease in crushing, impact and abrasion value up to the exposure temperature of 700 °C. The improvement in aggregate characteristics results from loss in the adhered mortar and volatile components.

3. Aggregate weakens on thermal treatment above 700 °C (MRA-800), and there is a decrease in specific gravity and an increase in crushing, impact and abrasion value.
4. MRA-700 shows the best aggregate characteristics among all treated aggregates, with a specific gravity of 2.66, crushing value of 18.91%, impact value of 12.47% and abrasion value of 23.55%. As per the relevant technical standard, IS 383: 2016, MRA-700 satisfies the specifications for all concrete-based applications, including high-strength concrete and concrete with wearing surfaces.
5. Improvement of aggregate characteristics also reflects on the compressive strength of concrete, which improves with thermo-mechanical treatment. The maximum compressive strength is observed for MRA-700, which shows an increase of 44.09% and 53.89% over MRA-UT, at 7 days and 28 days, respectively.
6. The properties of concrete prepared using MRA-700, as compared to NA, show a significant increase in slump value (166.66%) and comparable mechanical strength at 28 days, i.e., compressive (93.72%), flexural (99.94%) and split tensile (97.87%). Results show that MRA-700 is a technically viable alternative to substitute NA.
7. In terms of sustainability, the economic cost and environmental impact (carbon emission) of the currently adopted method for the preparation and application of MRA-700 is higher than NA. Using a renewable energy source for thermo-mechanical treatment can lower the economic cost (up to 10.74%) and environmental impact (up to 41.95%) of MRA-700, compared to NA in the Indian construction industry.

4.4.2. Learning outcomes

Resource sustainability for concrete aggregate requires alternative construction materials. Circular use of C&D waste can partially meet the needs for alternative construction materials. In the Indian construction industry, the circular use of C&D waste is limited by its heterogeneous composition and resulting MRA. Thermo-mechanical treatment, with an exposure temperature of 700 °C, can improve the characteristics of MRA. The thermo-mechanically treated MRA satisfies the relevant codal provisions (social dimension) for upcycling them as alternative construction material. Upcycling strategies, like thermo-mechanical treatment, require additional process costs. Selecting a low-value resource, like MRA, lowers the costs associated with materials and provides a significant margin for optimizing the process-related costs. In the proposed upcycling strategy, thermal treatment is contributing to the majority of costs associated with treated MRA. Solar energy-based thermo-mechanical treatment can optimize the process costs and upcycle MRA as a sustainable construction material.

4.4.3. Future scope of work

The study demonstrates the viability of solar energy-operated electric furnaces for upcycling MRA as an alternative to NA. The process still undergoes significant energy loss from conversion between solar, electric and thermal energies. The energy losses can be reduced by utilizing solar furnaces for thermal treatment. A furnace prepared with a Scheffler reflector can directly convert solar energy to thermal energy above 800 °C [343]. Future investigations can be carried out on solar furnaces for further optimizing treated MRA as a sustainable construction material.

4.4.4. Study limitations

Thermo-mechanical treatment described in the chapter is an energy intensive process. The embodied energy of treated MRA is significantly higher than the embodied energy of NA or untreated MRA. The present study works on the fact that we are underutilizing solar energy and assumes that solar energy can be safely diverted for the proposed treatment process. The present study is focused on addressing resource shortage using a cost-effective low carbon solution. It should be kept in mind that the proposed solution will not remain viable if the industry is focussing on energy efficiency over other sustainability indicators.

Chapter 5
Development of safety guidelines for sustainable construction material through simulation of field scenarios

The use of alternative construction materials can inadvertently weaken one or more properties of concrete. In the condition the new material shows lower strength or durability characteristics, the stakeholders require revised safety guidelines for the robust field application of the given material. Typically, the guidelines are built through extensive field testing, which slows the field translation of sustainable construction materials. This challenge can be overcome through simulating field scenarios and digitally developing the safety guidelines. Simulations can identify safety guidelines without extensive field trials and fast-track the industrial translation of sustainable construction materials. One such tool for the simulation of field scenarios is the Monte Carlo simulation.

The chapter explores the application of Monte Carlo simulation through a case study focused on developing fire safety guidelines for field translation of LC^3, an emerging blended cement. The present chapter has been reproduced from the previous research publication – **Gupta, S.**, Singh, D., Gupta, T., and Chaudhary, S. (2022). "Effect of limestone calcined clay cement (LC3) on the fire safety of concrete structures". Computers and Concrete, 27(4), 263-278. DOI: 10.12989/cac.2022.29.4.263 (I.F. 4.1).

5.1. Background

5.1.1. LC^3 – a sustainable alternative to cement

LC^3 is a ternary blend of limestone, calcined clay, and clinker. LC^3 has been recognized as a low-clinker, sustainable alternative to fly ash-based cement [3, 344]. The typical composition of LC^3 can vary for different mineral compositions of raw materials [345]. The most commonly reported variation of LC^3, LC^3-50, consists of 50% clinker, 30%

limestone, 15% calcined clay and 5% gypsum. The use of limestone and calcined clay significantly lowers the clinker content and resulting carbon emissions of LC^3-50 (hereafter referred to as LC^3).

The low clinker content in LC^3 results in lower compressive strength of concrete compared to ordinary Portland cement (OPC) concrete prepared with the same design mix [219]. However, for the same grade of concrete prepared with a different design mix, LC^3 offers significantly higher CO_2 savings than OPC and fly ash cement for the same grade of concrete [68, 346]. Manufacturing of LC^3 also provides higher environmental and economic benefits compared to OPC and fly ash cement [6]. The environmental benefits associated with LC^3 make it a low-carbon alternative to conventionally used cement, like OPC and Portland pozzolana cement (PPC). The economic and environmental advantages of LC^3 cement have also been recognized through several pilot studies in Cuba and India, with Cuba adopting a new standard covering the use of LC^3 [346]. In the present scenario of declining fly ash availability and growing environmental concerns, LC^3 can likely substitute OPC and PPC in commercial applications.

5.1.2. Fire performance of LC^3

A recent review on the performance of LC^3 concrete highlights that LC^3 concrete has not been well investigated for resistance to high temperature or fire [6]. Only one investigation has been reported on LC^3 cement pastes after exposure to elevated temperatures of 300°C, 550°C and 900°C [6, 347]. The study reported a slight increase in the residual compressive strength (rCS) of LC^3 paste at 300°C due to internal autoclaving and a significant reduction in rCS of LC^3 paste at 550°C and 900°C due to thermal degradation of different minerals [347]. In reference to mineral composition, the fire performance of LC^3 reduces with a combined increase in limestone and calcined clay content [347]. The weak fire performance of LC^3 compared to OPC can also be confirmed through the higher mass loss observed in thermogravimetric analysis (TGA), indicating higher thermal degradation [347, 348].

The existing literature hints toward a weaker fire performance of LC^3 concrete, which can increase the magnitude of fire risk in LC^3 concrete structures. The International Association of Fire Safety Science (IAFSS) also highlighted the concern over the impact of new materials on the magnitude of fire risk in structures [349]. There is a need to understand the magnitude of fire risk and design safety guidelines for the field application of LC^3 concrete.

5.1.3. Monte Carlo simulation

Literature shows that the temperature and duration of fire are governed by several factors, including the fuel load and building conditions [350]. In realistic fire scenarios, the fire scenarios can have probabilistic variations. Experimental investigations on the fire performance of LC^3 concrete can only indicate the fire risk over investigated elevated temperature scenarios and fail to assess the change in magnitude of fire risk over realistic fire scenarios. Monte Carlo simulation overcomes these shortcomings and uses probabilities of realistic scenarios and the expected behaviour of concrete to determine the probability of failure through extensive simulations [351].

Monte Carlo simulation is a mathematical model that accounts for uncertainties from a realistic scenario to predict the probable outcomes [351]. It simulates a large number of scenarios to account for all possible events and predicts their probability of occurrence [351]. Since the parameters governing the simulation can be altered, Monte Carlo simulation can predict the probable effect of external influences on the system. This feature can be utilized to understand the effect of safety guidelines on the magnitude of risk associated with alternative construction materials. Monte Carlo simulation can also be combined with other computational tools like finite element modelling and artificial neural networks to improve the prediction for the magnitude of risk [352, 353].

The study utilizes Monte Carlo simulation to evaluate the magnitude of fire risk in LC^3 concrete structures. The parameters adopted for the Monte Carlo simulation use experimental results for fire performance and actual data from the Indian construction industry to determine the probability of structural failure. The required experimental results for the fire performance of LC^3, OPC and PPC concrete have been described in Appendix . Monte Carlo simulation has also been used for recommending strategies for the robust industrial application of LC^3 concrete. The results presented in this study provide safety guidelines for the safe structural application of LC^3 concrete in the Indian construction industry.

The methodology of Monte Carlo simulation can also be used with other properties of construction materials and suitable regional parameters. Further simulations can help in determining the magnitude of risk and recommendations for robust applications of alternative construction materials in various regions. Overall, the study will demonstrate the potential of the Monte Carlo simulation for the development of safety guidelines for alternative construction materials.

5.2. Method

5.2.1. Development of Monte Carlo simulation

Monte Carlo simulation adopted in this study uses experimental results, parameters from the Indian construction industry and a mathematical model describing fire behaviour. Fig. 5.1 describes the methodology adopted for the simulation, Table 5.1 lists the parameters adopted in the simulation, and Table 5.2 enumerates the experimental results for residual compressive strength. The detailed account of an experimental procedure, results, and relevant discussion associated with Table 5.2 has been described in Appendix . The MATLAB code for the simulation described in this section has been documented in Appendix .

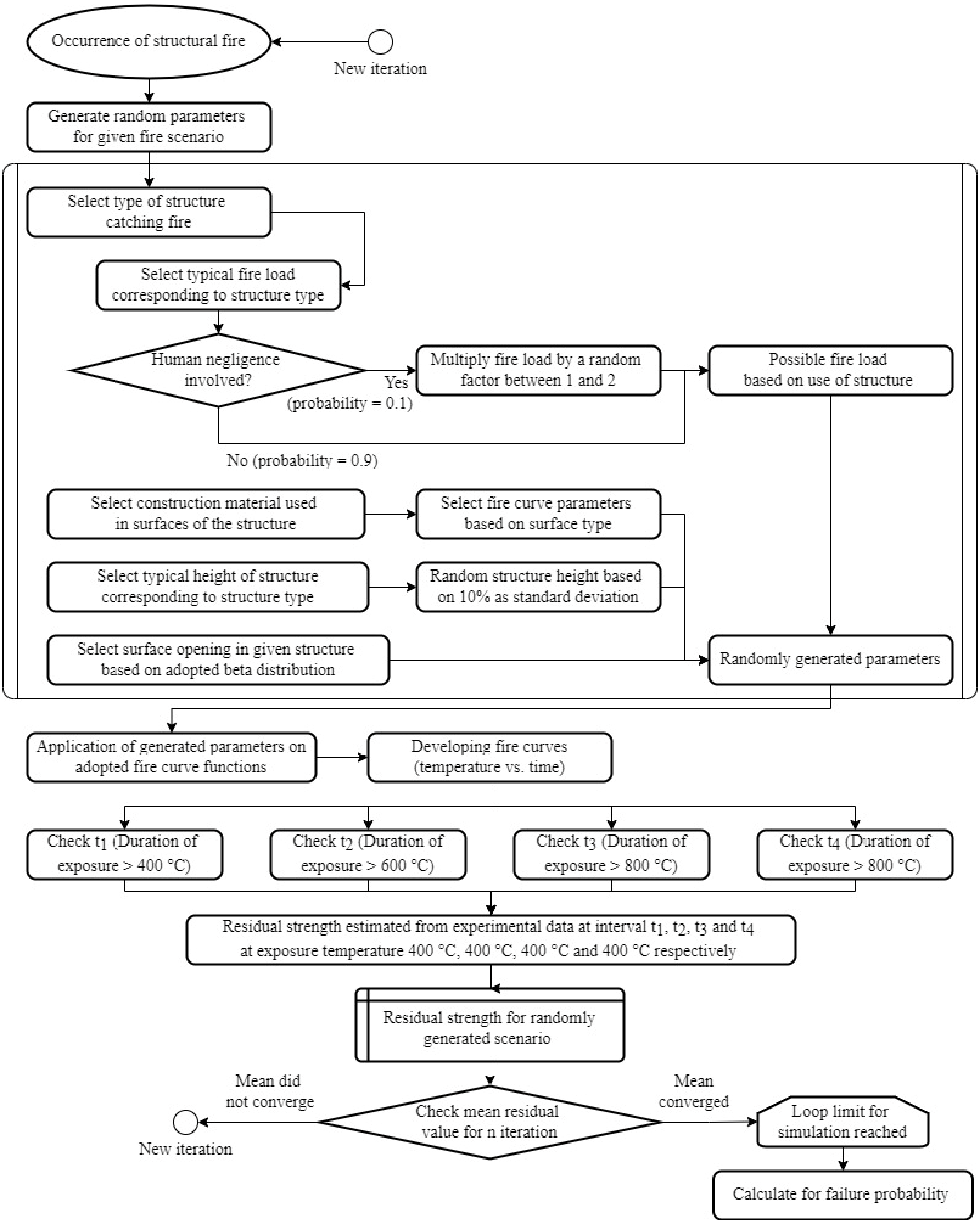


Fig. 5.1 Outline for Monte Carlo simulation

Table 5.1 Parameters adopted for Monte Carlo simulation

S. No.	Parameter	Adopted parameters for simulation						Ref.
A. Typical values reported in the literature for different types of structures								
Type of structure		Educational	Business	Residential	Govt. structure	Hazardous	Industrial	
A.1.	Probability of structure type in a fire event	0.16%	5.35%	89.98%	0.49%	1.75%	2.27%	[354]
A.2.	Typical fire load (MJ/m^2)	25	25-50	25	25-50	25-500	25-150	[355]
A.3.	Typical height	3.6 m	2.75 m	2.75 m	2.75 m	3.6 m	3.6 m	[356]
B. Typical values adopted commonly for different types of structures								
Construction material		Brick			Stone/concrete			
B.1.	Probability of use as surface	74.50%[a]			13.20%[a]			[357]
B.2.	Fire curve coefficients	$a = 1800; b = 250;\ c = 692; d = 17; m = 0.13; n = 0.67$			$a = 1800; b = 250;\ c = 623; d = 11; m = 0.14; n = 0.38$			[240]
Wall/roof openings		Small opening		Medium opening		Large opening		
B.3.	Surface opening	0.01 – 0.05[b]		0.05 – 0.20		0.20 – 0.50[b]		[356]

Table 5.1 Parameters adopted for Monte Carlo simulation (contd.)

	Parameter	Applied on	Modification function	Reasoning
		C. Probability modifications adopted for the simulation		
C.1.	Accidental load	Randomly selected 10% of scenarios	Typical fire load multiplied by a factor between 1 and 2	To account for human negligence and safety violations
C.2.	Height	All structures	Randomly select a height with typical height as mean and 0.1 times height as standard deviation	To account for variations in the height of structures
C.3.	Probability of surface opening	All structures	Beta distribution function ($a = 0.8494$ and $b = 2.4651$)	The adopted function ensures a 50% selection probability for a medium opening and 25% for a small and large opening.

[a] To limit the scenarios to structures with cement use only, construction materials like wood, bamboo, grass, etc. have been excluded; [b] Upper and lower limits of 0.01 and 0.50 have been considered in this study

Fig. 5.1 shows that the adopted simulation accounts for different types of structures, possible fire loads, building height and available surface openings across randomly generated scenarios. The overall simulation can be described as a five-step approach. The simulation first randomly selects parameters to represent possible fire scenarios. The parameters are then used to develop fire curves (exposure temperature vs. time) using the mathematical model described by Santarpia et al. [350], refer to Eq. 5.1 - Eq. 5.4.

$$T_g(t) = T_{max} \times \left(\frac{t}{t_{max}}\right) \times e^{\left(1-\frac{t}{t_{max}}\right)} \qquad \text{Eq. 5.1}$$

$$t_{max} = \frac{q}{(a \times O)} \qquad \text{Eq. 5.2}$$

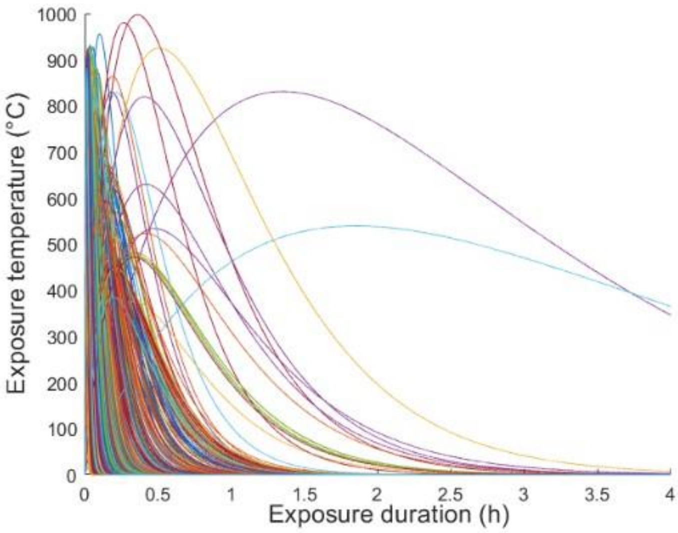
$$T_{max} = b + c \times (1 - e^{-d \times O}) \times q^{(m - n \times O)} \qquad \text{Eq. 5.3}$$

$$O = \frac{A_V}{A_t} \times h_{eq}^{0.5} \qquad \text{Eq. 5.4}$$

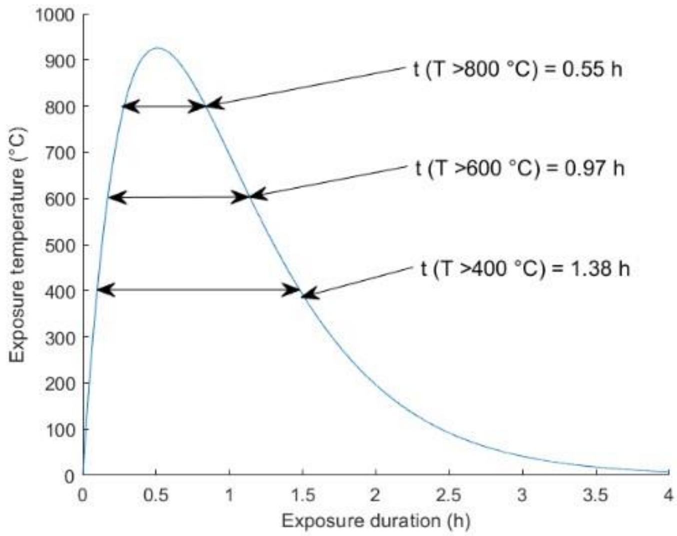
Where, $T_g(t)$ denotes the fire curve, i.e., the temperature as a function of time; T_{max} denotes the maximum temperature of fire; t_{max} denotes the time required to attain T_{max}; q denotes the fire load selected as per parameters A.1, A.2 and C.1 from Table 5.1; a, b, c, d, m and n are fire curve coefficients based on construction material used selected as per parameter B.1 and B.2 from Table 5.1; O denotes the opening factor; h_{eq} denotes the height of structure selected as per parameters A.3 and C.2 from Table 5.1; and, A_v/A_t denotes surface opening selected as per parameters B.3 and C.3 from Table 5.1.

The first 1000 fire curves are shown shown in Fig. 5.2 (a). In the third step, a fire curve is used to measure the different exposure durations for exposure temperatures greater than 400°C, 600°C, 800°C and 1000°C, as shown in Fig. 5.2 (b). In the fourth step, experimental results are interpolated to assess the possible rCS for different exposure durations at different exposure temperatures. The minimum residual strength of concrete among exposure temperatures of 400°C, 600°C, 800°C and

1000°C has been considered as the residual strength of concrete in a given fire scenario. After determining the rCS for 10^6 fire scenarios, the probability of structural failure is determined in the final step.



(a) First 1000 fire curves



(b) Single fire curve

Fig. 5.2 Typical fire curves generated during the Monte Carlo simulation

5.2.2. Experimental results used in simulation

The key experimental results used in the simulation are described in this Section; for further details, refer to Appendix . Table 5.2 shows the residual compressive strength of LC^3, OPC and PPC concrete after exposure to different temperatures (400 °C, 600 °C, 800 °C, 1000 °C) for various durations (0.5 h, 1.0 h, 2.0 h, 4.0 h). The residual compressive strength of concrete, described in Table 5.2, has been used as the basis for Monte Carlo simulation. Furthermore, statistical analysis of the results showed that exposure temperature has a more significant impact on strength loss than exposure duration (Section B.3.7). On the basis of the same, residual strength has been interpolated as a function of time at given exposure temperatures.

Table 5.2 Residual compressive strength (in %) of LC^3 OPC and PPC

Exposure temperature	Cement type	Exposure duration			
		0.5 h	1.0 h	2.0 h	4.0 h
400 °C	LC^3	69.79%	78.97%	74.04%	63.64%
	OPC	89.19%	94.19%	87.27%	83.69%
	PPC	78.74%	81.76%	72.97%	68.72%
600 °C	LC^3	75.80%	70.71%	42.69%	33.93%
	OPC	96.43%	70.42%	55.59%	44.28%
	PPC	79.98%	58.69%	43.03%	34.92%
800 °C	LC^3	57.42%	28.84%	18.92%	11.10%
	OPC	55.95%	42.39%	29.28%	23.72%
	PPC	56.04%	32.24%	17.84%	15.02%
1000 °C	LC^3	25.01%	11.36%	07.82%	05.86%
	OPC	43.64%	26.92%	07.01%	02.94%
	PPC	35.78%	11.05%	10.13%	06.71%

5.2.3. Assumptions associated with simulation

The adopted simulation uses the typical values from the Indian construction industry. In addition to the regional data set, the simulation considers the following key assumptions, which should be taken into account when interpreting the final results of this study;

1. Loss in residual properties for different exposure scenarios is independent of cement content or grade of concrete, similar to observations by Nas and Kurbetci [358].
2. The behaviour of fire in a closed space, as described by Santarpia et al. [350], satisfactorily describes the temperature-time curve

of an actual fire, and the gas temperature of the fire is the same as the exposure temperature for concrete.

3. Parameters observed in the literature for residential buildings (89.98% scenarios), i.e., B.1, B.2 and B.3 from Table 5.1, are applicable for other building types (10.02% scenarios).
4. Probability modification functions, i.e., C.1, C.2 and C.3 from Table 5.1, adopted for the simulation adequately represent real-life scenarios.
5. The concrete structure is assumed to fail for rCS below 80%.

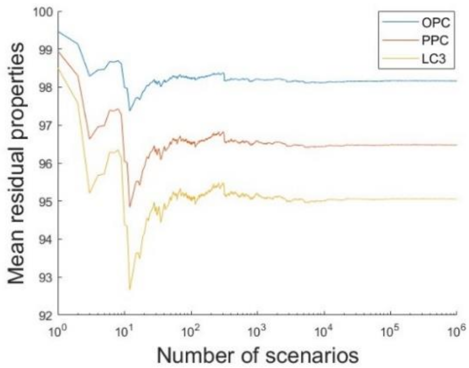
It should be noted that the above-stated assumptions are used to compensate for the limited data availability in the literature, which may be improved in the future.

5.3. Results and discussion

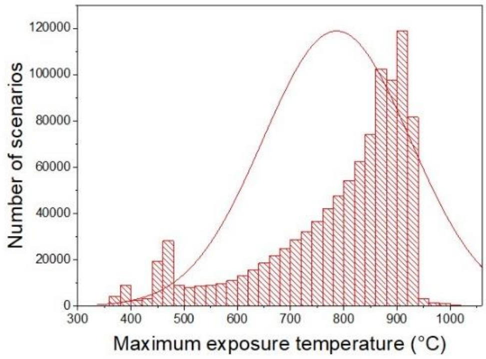
Monte-Carlo simulation has been used to evaluate the fire risk associated with the change in cement type in the Indian construction industry. The fire risk is evaluated in terms of the probability of structural failure for an LC^3 concrete structure in the event of a fire.

5.3.1. Description of fire scenarios

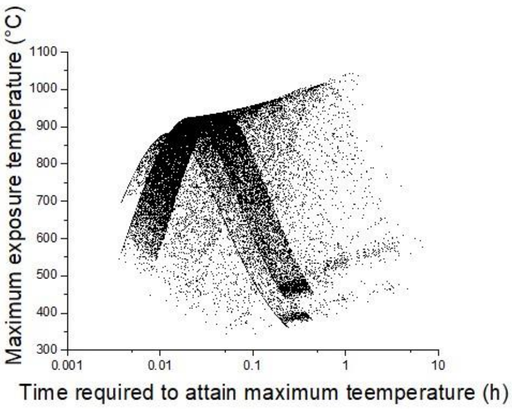
Mean results of the simulation have been observed against the number of trials and are represented in Fig. 5.3 (a). It can be observed from Fig. 5.3 (a) that mean residual strengths showed significant variation up to 10^4 scenarios (≥ 0.01 %), which significantly reduced as the number of scenarios increased to 10^6 (≤ 0.0001 %). The convergence of results in Fig. 5.3 (a) shows that the adopted 10^6 scenarios are adequate for describing the probabilistic behaviour of fire through Monte Carlo simulation.



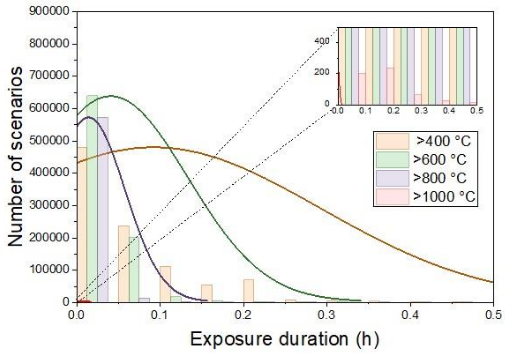
(a) Convergence of simulation



(b) Distribution of maximum exposure temperature



(c) Time required to attain maximum temperature



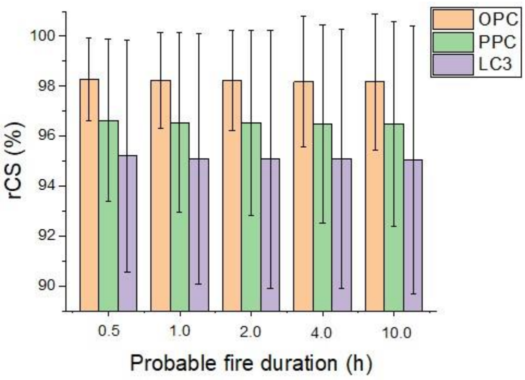
(d) Distribution of exposure duration

Fig. 5.3 Fire scenarios from the Monte Carlo simulation

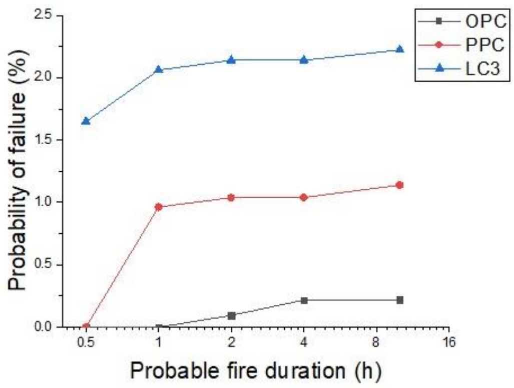
Fig. 5.3 (b)-(d) shows the typical exposure temperature and exposure duration for the fire scenario simulation. Fig. 5.3 (b) shows that most of the fire scenarios have maximum exposure temperatures between 800°C and 1000°C. Fire scenarios have a very low probability of attaining maximum exposure temperatures greater than 1000°C and below 400°C (Fig. 5.3 (b)). A comparison of maximum exposure temperature and time required to attain maximum exposure temperature (Fig. 5.3 (c)) shows that in a typical fire scenario, maximum fire temperature is attained in less than 0.5 h (99.49% scenarios). The short duration for maximum fire temperature shows that concrete undergoes rapid heating for most fires. Fig. 5.3 (d) shows the number of fire scenarios with expected exposure duration for different temperature ranges. Fig. 5.3 (d) shows that limited cases tend to have an exposure temperature of more than 1000°C, with the most probable exposure duration as 0.2 h. Exposure temperature between 600°C and 1000°C occurs for a short duration, as evidenced by the high probability for exposure duration < 0.1 h and low probability beyond that (Fig. 5.3 (d)). Exposure temperature between 400°C and 600°C shows a more uniform distribution of scenarios with exposure duration > 0.1 h (Fig. 5.3 (d)). An overview of 10^6 fire scenario (Fig. 5.3 (b)-(d)) shows that, for adopted parameters from the Indian construction industry, concrete is most likely to suffer damage from either of the two fire scenarios, i.e., prolonged exposure to a temperature below 600°C or short exposure to a temperature above 600°C.

5.3.2. Magnitude of fire risk

The effect of 10^6 fire scenarios on the residual properties of concrete for different cement types have been shown in Fig. 5.4 (a)-(b). Fig. 5.4 (a) shows the mean rCS for OPC, PPC and LC^3 concrete at 0.5 h, 1 h, 2 h, 4 h and 10 h intervals in a fire. It can be observed from Fig. 5.4 (a) that mean rCS in a fire scenario drastically changes in the first 0.5 h and has a marginal change in subsequent fire duration. The marginal change in rCS beyond 0.5 h can be attributed to the low probability of long fire durations (Fig. 5.3 (d)). Although a limited number of scenarios exhibit long-duration fires, the loss of rCS in these scenarios significantly contributes to the probability of failure (Fig. 5.4 (b)). While affecting a limited number of cases, fire duration increases the probability of failure in structures (Fig. 5.4 (b)). The probability of failure of LC^3 concrete is 2.22% compared to 0.22% in OPC and 1.14% in PPC for adopted parameters. This shows that the fire risk of LC^3 concrete is almost double that of PPC and ten times that of OPC. Higher failure probability prompts the need for risk mitigation strategies to ensure the robust application of LC^3 concrete.



(a) rCS



(b) Probability of failure (rCS≤ 80%)

Fig. 5.4 Effect of change in cement type on the fire safety of structures

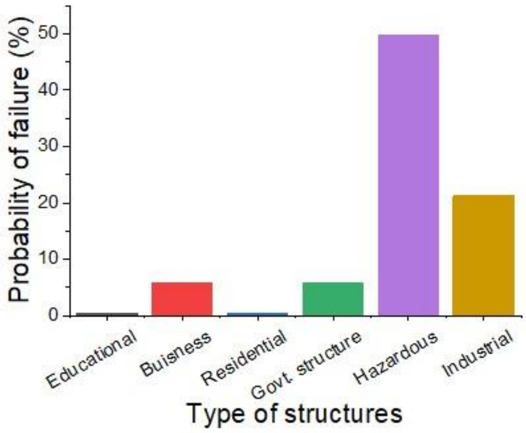
5.3.3. Recommendations for robust industrial application of LC^3

The robustness of concrete can be defined as its ability to preserve its desired properties against variations in specified parameters [359]. In a fire scenario, the robustness of concrete implies that rCS across different parameters satisfies the strength required for structural safety. The simulation highlights that the change in cement type to LC^3 significantly increases the magnitude of fire risk in concrete structures. Eurocode EN

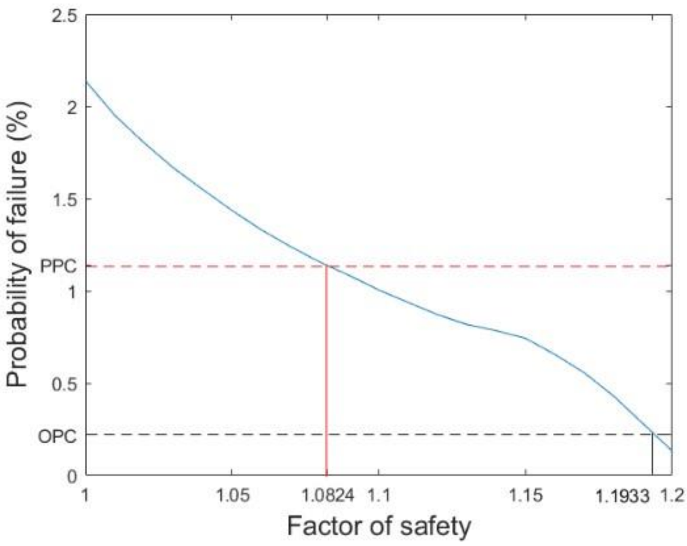
1991-1-7 [360] lists several recommendations for risk mitigation in concrete structures. Simulation parameters have been adjusted to account for the recommendations in Eurocode EN 1991-1-7 [360]. The following recommendations are made for fire risk mitigation and robust industrial application of LC^3 concrete based on Eurocode and modification in simulation;

1. *By-passing the hazard through controlled application of LC^3*: Use of LC^3 can be restricted to structures with low fire risk. Fig. 5.5 (a) shows the probability of failure in a fire scenario for different structures. It can be observed that the probability of failure in educational and residential structures is significantly lower (0.43% and 0.42%) than in other structure types (>5%). For the adopted parameters for the Indian construction industry (Table 5.1), the application of LC^3 can be restricted to educational and residential structures.
2. *Overcoming hazards by increasing the reserve strength of LC^3 concrete*: The compressive strength of LC^3 concrete can be raised by a suitable factor of safety to increase its robustness. Fig. 5.5 (b) shows the probability of failure in LC^3 concrete for different factors of safety. It can be observed from Fig. 5.5 (b) that by introducing a suitable factor of safety (>1.08), the probability of failure in LC^3 concrete can be reduced to a risk factor similar to PPC concrete.

In addition to the two recommendations, Eurocode EN 1991-1-7 [360] also suggests a reduction of hazards through modification in the composition of LC^3 [360]. In this study, the LC^3-50 variation of LC^3 has been used. TGA of other variations of LC^3, i.e., with lower clinker replacement levels, show a lower thermal degradation and can be used for robust application of LC^3 [347]. Literature shows that clinker substitution can be used as a parameter in the computational models to determine the desired characteristics of concrete [361, 362]. Simulation can be extended to include the effect of clinker substitution on the fire performance of LC^3 to identify a suitable variation of LC^3 with a low probability of failure. Other recommendations for fire risk mitigation in Eurocode are not discussed as they are not relevant to construction materials, like the use of sprinklers. For the LC^3-50 variation adopted in this study, risk mitigation strategies like controlled application and reserve strength can result in a robust application of LC^3 towards the fire safety of concrete structures.



(a) Probability of failure in different structures



(b) Factor of safety

Fig. 5.5 Effect of recommended practice on reduction in the probability of failure

5.4. Summary

5.4.1. Key conclusions

The study uses Monte Carlo simulation to determine the magnitude of fire risk and safety guidelines for LC^3 concrete structures, using actual parameters from the Indian construction industry. Based on the comprehensive investigation, the following conclusions can be drawn:

1. Monte Carlo simulation shows that for the Indian construction industry majority of fires have a high probability of damaging the concrete structures in either high-temperature, short-duration fire scenarios ($\geq$ 600°C, $\leq$ 0.1 h) or low-temperature long-duration fire scenarios ($\leq$ 600°C, $\geq$ 0.1 h). LC^3 concrete shows low rCS for exposure below 600°C and increases the risk of failure compared to OPC and PPC concrete.
2. Simulation estimates probable rCS of concrete across 10^6 fire scenarios as 95.29%, 90.73% and 86.82% for OPC, PPC and LC^3 concrete. The weaker fire performance of LC^3 concrete results in 2.22% of concrete structures failing to satisfy the adopted benchmark of 80% rCS compared to 0.22% in OPC and 1.14% in PPC.
3. In the adopted variation of LC^3 (LC^3-50), the robust application of LC^3 concrete in the Indian construction industry can be ensured by either restricting its application or introducing a factor of safety. It is recommended to restrict the application of LC^3 to educational and residential structures, having a failure probability of 0.43% and 0.42%. It is also recommended to adopt a factor of safety above 1.08 to ensure that the probability of failure does not exceed that of OPC and PPC concretes.

The results presented in this study are based on the experimental investigations of LC^3-50 and adopted simulation parameters from the Indian construction industry. Results of this study show that the fire risk of LC^3 concrete structures can be mitigated by controlled application and use of reserve strength.

5.4.2. Learning outcome

Monte Carlo simulation can simulate lab-scale results in realistic field scenarios to demonstrate the viability of alternative construction materials during industrial application. The simulation can be redefined by adjusting simulated parameters to understand their impact on the magnitude of failure. Parameters reducing the magnitude of failure can be used for developing risk mitigation strategies, which will allow for the robust industrial application of alternative construction materials. The identified risk mitigation strategies can then be analysed for cost-effectiveness to ensure that the applied alternative construction material remains sustainable. Monte Carlo simulation can reduce the cost and time required for developing safety guidelines and overall sustainability analysis associated with the industrial use of alternative construction materials. Risk mitigation will ensure the reliability of stakeholders and promote the utilization of alternative construction materials in the construction industry.

5.4.3. Future scope of work

The Monte Carlo simulation presented in this study adopts several assumptions to compensate for the lack of information available in the literature. The simulation can be further by including parameters like depth of concrete and distance from the source of the fire. Incorporating additional computational models will better simulate the damage in different elements of a concrete structure and identify the probability and nature of failure. Future studies can be carried out to incorporate additional computational models, like caloric functions, to improve the prediction and design of safety guidelines using Monte Carlo simulation.

5.4.4. Study limitations

As the chapter presents a simulation-based analysis for the development of safety guidelines, the following limitations should be kept in mind while applying the results of this study.

1. The adopted simulation is based on structural parameters from the Indian construction industry. Regional variation in

parameters can change the safety guidelines identified from the simulation.

2. The simulation uses experimental results of previous researchers to develop the present simulation. It is assumed that the previous investigations can be used in conjecture with each other, as described in Section 5.2.3. The simulation will need to be revised if future studies show that previous investigations do not hold true for the given construction materials.
3. The simulation is based on failure of concrete, and do not represent the complete structural failure. For complete structural failure, more complex simulations will need to be created with details on type of reinforcement, clear cover and structural layouts.

Chapter 6
Conclusion

The thesis aims to improve the resource sustainability of construction materials for the Indian construction industry. The present work focuses on resource sustainability for producing concrete, the most consumed artificial material on earth. The consumption, regeneration and available stocks have been reviewed for various constituent materials used in concrete production. The review shows that in terms of resource sustainability, cement and aggregates are the most stressed constituents of concrete. The present system of cement manufacturing depends heavily on cement-grade limestone. The commercially viable cement-grade limestone reserves in India can be exhausted in the next 34 years, creating a shortage of resources for the construction industry. Similarly, the coarse aggregate depends on quarrying, which has started showing localized shortages.

The thesis attempts to address the challenges of resource sustainability for cement and aggregates and develop solutions for the Indian construction industry. An extensive review has been carried out to identify the alternate resources, their technological readiness, availability and governing legal framework in the context of India.

In the case of cement, resource sustainability is based on the availability of cement-grade limestone. Literature shows that alternate sources of limestone and non-limestone-based cement have limited availability. Therefore, to ensure resource sustainability, the focus should be towards reducing limestone consumption by maximizing SCM utilization. The strategy for maximizing SCM utilization is favoured by the large availability of pozzolanic wastes and the flexibility of standards. The major challenge in this direction is the selection of the best available SCMs and optimum replacement levels without conducting extensive trials. The work present in the thesis focuses on developing a strategy to optimize the identification process for SCMs.

In the present study an extensive review has been carried out on over 20 different SCMs, their characteristics and their effect on the properties of concrete. A meta-heuristic analysis has been carried out to understand the correlation between the SCM characteristics (physical, chemical, mineralogical, and morphological) and the properties of concrete (workability, mechanical strength and durability). The analysis shows that the effect of SCMs on the various properties of concrete is primarily based on three characteristics, i.e., surface area, chemical composition, and morphology. The results are then used to present a characterization-based heuristic model for optimizing the selection of SCMs. The heuristic model uses a characterization-based approach to cluster alternate SCMs, with limited investigation, with known SCMs. The clustering can then be used to rank various available alternatives and identify the SCM with the highest likelihood of success. The characterization-based approach is further used for developing a novel search optimization algorithm, which can quantify the probability of returns against the cost of testing. Overall, the heuristic model will help in eliminating SCMs with less likelihood of increasing substitution. This will improve the probability of identifying a suitable SCM and improve stakeholder confidence in exploring resource sustainability.

In the case of coarse aggregates, the volume of available alternatives falls short of meeting the consumption needs. Furthermore, several of the alternate aggregates lower the technical performance of concrete, which lowers the availability of viable aggregates. Literature shows that these aggregates can be treated to improve characteristics for industrial applications. C&D waste is one such resource, which can be treated to produce alternate aggregates. The high availability of C&D waste and low utilization ratio present a favourable resource for intervention. This approach is favoured by technical standards. The major challenge in this direction is the overall resource sustainability and cost-effectiveness of the treated aggregates. The work present in the thesis focuses on identifying and treating a low-value, highly available and underutilized alternative for natural aggregates and developing a sustainable aggregate.

MRA shows the weakest aggregate characteristics among different forms of recycled C&D waste. MRA is treated using a thermo-mechanical treatment, which presents one of the most resource-efficient solutions in the long run. Different iterations of treated aggregates were prepared by subjecting MRA to various degrees of thermal shocks (300 °C to 800 °C) followed by a mechanical shock. The treated aggregates were evaluated in terms of residual adhered mortar content, aggregate characteristics and concrete properties. The experimental results show that MRA-700, aggregate treated at 700 °C, shows the best aggregate characteristics. MRA-700 satisfied the codal provisions of relevant technical standards (IS 383: 2016) and can be considered acceptable for industrial applications. Concrete prepared using MRA-700 shows comparable mechanical strengths (93.72% - 99.94%) and high slump value (166.66%). Due to high flowability, MRA-700 can have a high-value application in the production of self-compacting concretes. The treatment process was also evaluated for overall sustainability, and recommendations were designed for sustainable industrial application of the treated aggregates. The analysis shows that using renewable energy for thermo-mechanical treatment of MRA can produce alternate aggregates with economic costs and carbon emissions lower than NA (by up to 10.74% and 41.95%, respectively). Overall, the study shows that the proposed upcycling strategy of thermo-mechanical treatment can be used to produce sustainable aggregates and optimize the resource sustainability of concrete in terms of coarse aggregates.

It should also be noted that the use of alternate resources can lower the performance of concrete across one or more properties. The stakeholders need to understand these shortcomings and develop safety guidelines to ensure robust industrial application. Development of safety guidelines becomes challenging for probable-event-based risks like fire. Lenient safety guidelines can increase risk, while strict safety guidelines can hinder the use of alternate resources. In case of probable-event-based risks, tools like Monte Carlo simulation can be used to optimize safety guidelines. The present study demonstrates the application of Monte Carlo simulation to evaluate the magnitude of fire risk in LC^3 concrete structures. The simulation of experimental results shows that LC^3 concrete requires 1.08 as the factor of safety for compression-based applications. Monte Carlo simulation can simulate similar lab-scale results in realistic field scenarios for developing risk mitigation strategies. The identified risk mitigation strategies can then be analysed for cost-effectiveness to ensure that the applied alternative construction material remains sustainable. Monte Carlo simulation can optimize the safety guidelines between project cost and overall safety. This will ensure robust industrial application of alternate resources.

Overall, the thesis demonstrates a three-part solution for optimizing the resource sustainability of construction materials. The first-part of the solution focuses on optimizing the selection of SCMs to maximize their utilization. The second part of the solution focuses on upcycling MRA as a sustainable aggregate. The third part of the solution focuses on developing safety guidelines for alternate resources showing weaker properties in concrete. Collectively, the three solutions can improve resource sustainability for concrete in the Indian construction industry. The demonstrated solutions can also be replicated for other regions by adapting the present work for regional parameters. This will help in optimizing the resource sustainability of various construction materials.

Appendix A
Determination of adhered mortar content using acid treatment technique

The acid treatment technique is based on the decomposition of cement mortar in the presence of acids like HCl [363]. Acids react with the portlandite and decalcify the C-S-H phases of the cement mortar [363, 364]. As a result, mortar decomposes and loses its mechanical strength [363], which can be used to remove the adhered mortar. Literature shows that the adhered mortar can be entirely removed from RCA when exposed to 0.1 M acidic solution for 24 h [365]. Akbarnezhad et al. [365] have previously used this acid treatment technique to determine the adhered mortar content of RCA. The present methodology is a modification from Akbarnezhad et al. [365].

Steps adopted for determination of adhered mortar:

1. MRA sample, either treated or untreated, is oven-dried at 100 °C for 24 h, then cooled to room temperature.
2. 500 g (m_1) of the sample is placed in a flask with 0.1 M HCl solution. The flask is stirred periodically to remove trapped bubbles.
3. After 48 h, the sample is thoroughly washed to remove the acid and oven-dried at 100 °C for 24 h.
4. Finally, the sample is sieved using a 4.75 mm sieve to remove fine particles from the coarse aggregate. Weight of the coarse aggregate (m_2) is used for determining the adhered mortar content on MRA, using Eq. A.1.

$$Adhered\ mortar\ content\ (in\%) = \frac{m_1 - m_2}{m_1} \times 100 \qquad \text{Eq. A.1}$$

It should be noted that the presence of other acid-soluble components in MRA, like chalk and limestone, may show a higher value of adhered mortar content. Therefore, the adhered mortar content determined using this method should only be considered a representative value for MRA.

Appendix B
Experimental investigation on fire performance of different types of cement

Concrete prepared with LC^3, a low-carbon ternary blended cement, is expected to experience higher fire damage than concrete prepared with OPC [347, 348]. Earlier literature has only indicated the weaker fire performance of LC^3 through limited experimental investigation only [347, 348]. This presented a risk to the fire safety of LC^3 concrete structures. Chapter 5 focuses on developing fire safety guidelines for LC^3 concrete structures through Monte Carlo simulation. The simulation required additional experimental investigation, which was carried out during the scope of this study. Appendix B describes the experimental investigation of the fire performance of LC^3, OPC and PPC concrete. Appendix B has been reproduced from the previous research publication – **Gupta, S.**, Singh, D., Gupta, T., and Chaudhary, S. (2022). "Effect of limestone calcined clay cement (LC3) on the fire safety of concrete structures". Computers and Concrete, 27(4), 263-278. DOI: 10.12989/cac.2022.29.4.263 (I.F. 7.27).

B.1. Background on fire performance of concrete

In concrete structures, fire can result in elevated temperatures over 1000°C, which lowers the strength of concrete and increases the risk of structural failure [366]. The residual mechanical properties of concrete after exposure to elevated temperatures define the fire performance of concrete. Literature on OPC concrete shows that the fire performance of concrete is affected by both exposure temperature [367, 368] and exposure duration [369]. Like OPC and PPC concrete, the fire performance of LC^3 concrete is also expected to be affected by exposure temperature and duration in a given fire scenario. In terms of fire performance, exposure temperature of 400°C and above plays a more dominating role, as below 400°C, different cement types (OPC, PPC and LC^3) have shown an increase in rCS due to internal autoclaving [347, 368]. Therefore, there is a need to evaluate the fire performance of LC^3 by investigating the residual properties of LC^3 concrete for exposure temperatures above 400°C for different exposure durations.

The present experimental investigation compares the fire performance of LC^3 concrete with concrete prepared using OPC and PPC, two widely used commercial cement. Residual properties of concrete, in terms of mass loss, residual ultrasonic pulse velocity (rUPV), and rCS, have been measured after being exposed to 16 elevated temperature scenarios with elevated temperatures of 400°C, 600°C, 800°C, and 1000°C for different exposure durations of 0.5 h, 1 h, 2 h, and 4 h. XRD and TGA have been performed to understand the mineral composition and thermal degradation of cement pastes of OPC, PPC, and LC^3. Results are also analysed using three-factor ANOVA to understand the statistical significance of study parameters, i.e., change in cement type, exposure temperature and exposure duration.

B.2. Materials and methodology

B.2.1 Materials

Three different binders, OPC, PPC and LC^3, were used to prepare concrete. LC^3-50, the most commonly reported variation of LC^3, is used in this study. LC^3 was prepared by mixing limestone calcined clay (LC^2), a blended form of supplementary cementitious material, with OPC 43 grade equal proportions by weight. In contrast, OPC 43 grade cement, conforming to IS 269: 2015, and fly ash-based PPC cement, conforming to IS 1489: 2015, are commercially available cement. LC^2 used in the study was supplied by Technological Action and Rural Advancement (TARA) Delhi, India, and consists of calcined clay and limestone in 2:1 by weight. Coarse aggregates of nominal size 10 mm and 20 mm, conforming to IS 383: 2016, were used. Natural river sand, satisfying zone II of IS 383: 2016, was used as fine aggregate. Table B.1 presents the specific gravity of all material and water absorption of aggregates used in the study.

Table B.1 Properties of materials used in the study

Material	Specific gravity	Water absorption
20 mm coarse aggregate	2.90	1.60%
10 mm coarse aggregate	2.90	1.51%
Natural sand	2.64	0.83%
OPC	3.15	-
PPC	2.75	-
LC^3	2.88	-

B.2.2 Sample preparation

Table B.2 provides the mix proportion of different concretes. The adopted mix has been designed for constant cement content and w/c ratio to ensure that change in cement type remains the primary variable affecting the residual properties of concrete. In the adopted mix proportions, aggregate content was adjusted to account for the change in the specific gravity of cement as per the guidelines of IS 10262: 2019 [184]. After mixing, concrete was cast in 100 mm cube moulds using a vibrating table and water-cured for 28 days. Cement pastes were also prepared using OPC, PPC, and LC^3 with the adopted w/c ratio of 0.35 and cast in 50 mm cubes for TGA analysis.

Table B.2 Mix proportion for OPC, PPC, and LC^3

Materials (in kg/m^3)	OPC	PPC	LC^3
Binder	400	400	400
Water	140	140	140
Natural sand	677.31	660.24	665.17
10 mm coarse aggregate	690.87	673.46	678.49
20 mm coarse aggregate	690.87	673.46	678.49

After curing, specimens were air-dried for 24 h and then exposed to elevated temperatures in a muffle furnace of 42 kWh power with a maximum 1200°C temperature (Fig. B.1 (a)). The muffle furnace was preheated to the testing temperatures of 400°C, 600°C, 800°C, and

1000°C before loading of the specimen. At every testing temperature, a set of 3 samples was exposed for different time durations of 0.5 h, 1 h, 2 h, and 4 h each. After exposure to elevated temperature, samples were unloaded and air-cooled until the specimen's temperature reached an ambient temperature (Fig. B.1 (b)). In parallel, hydrated cement pastes were ground to fine powder, passing a 90-micron sieve, and used for TGA.

(a) Muffle furnace

(b) Air cooling of specimen

Fig. B.1 Experimental setup for exposure to elevated temperature

A three-part terminology is used for further referencing of the specimens. The first part uses a letter to denote the binder used in concrete: L for LC^3, O for OPC, and P for PPC. The second and third parts use a numeric value to denote exposure temperature and duration. A sample termed L-600-0.5 will imply a concrete specimen prepared using LC^3 exposed to 600°C for a period of 0.5 h. The third term is not used for specimens tested at an ambient temperature of 25°C.

Experimental methodology Fig. B.2 presents a comprehensive overview of the test protocol adopted in the study. XRD was performed on powder samples in the 2-theta scan range of 10° - 70°. Test for TGA was performed at a temperature increment of 10°C/min, at a constant gas flow of 20 ml/min. The temperature range for TGA was limited to 900°C, due to the operational limits of the instrument. Mass (in %) was recorded at an interval of 0.005 min to obtain the results for comparing the thermal degradation of cement pastes.

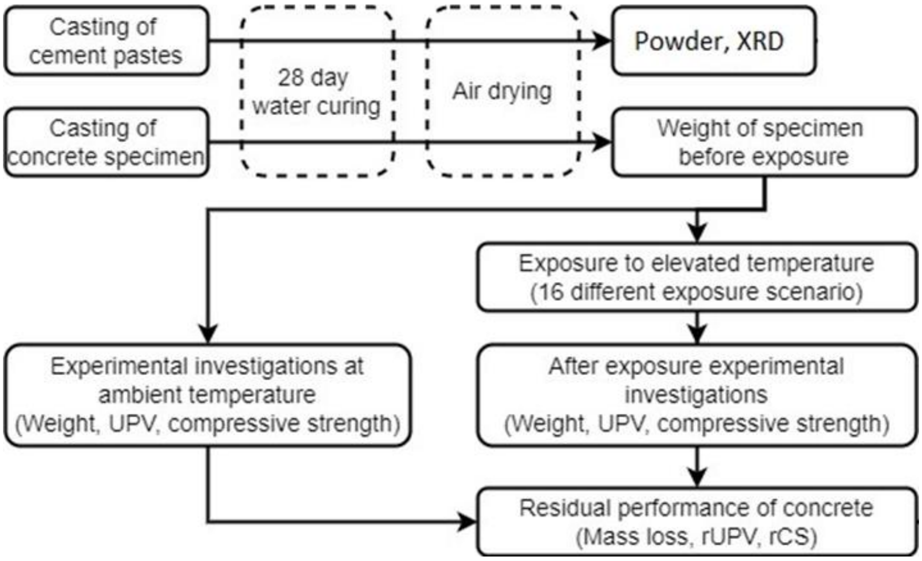


Fig. B.2 Test protocol adopted in the study

After being exposed to elevated temperatures, concrete was air-dried till it reached the ambient temperature. The weight of the specimen was recorded using a digital weighing balance. UPV values were determined after exposure to elevated temperature by cross-probing the specimen as per IS 13311 [370]. Compressive strength was determined using a 3000 kN compression testing machine. Results are expressed in mass loss, residual UPV and residual compressive strength, determined using Eq. B.1 – Eq. B.3.

$$\text{Mass loss (\%)} = \frac{(W_{be} - W_{ae})}{W_{be}} \times 100 \qquad \text{Eq. B.1}$$

$$\text{Residual UPV value (\%)} = \frac{\text{UPV value}_{ae}}{\text{UPV value}_{be}} \times 100 \qquad \text{Eq. B.2}$$

$$\text{Residual CS (\%)} = \frac{f_{ae}}{f_{be}} \times 100 \qquad \text{Eq. B.3}$$

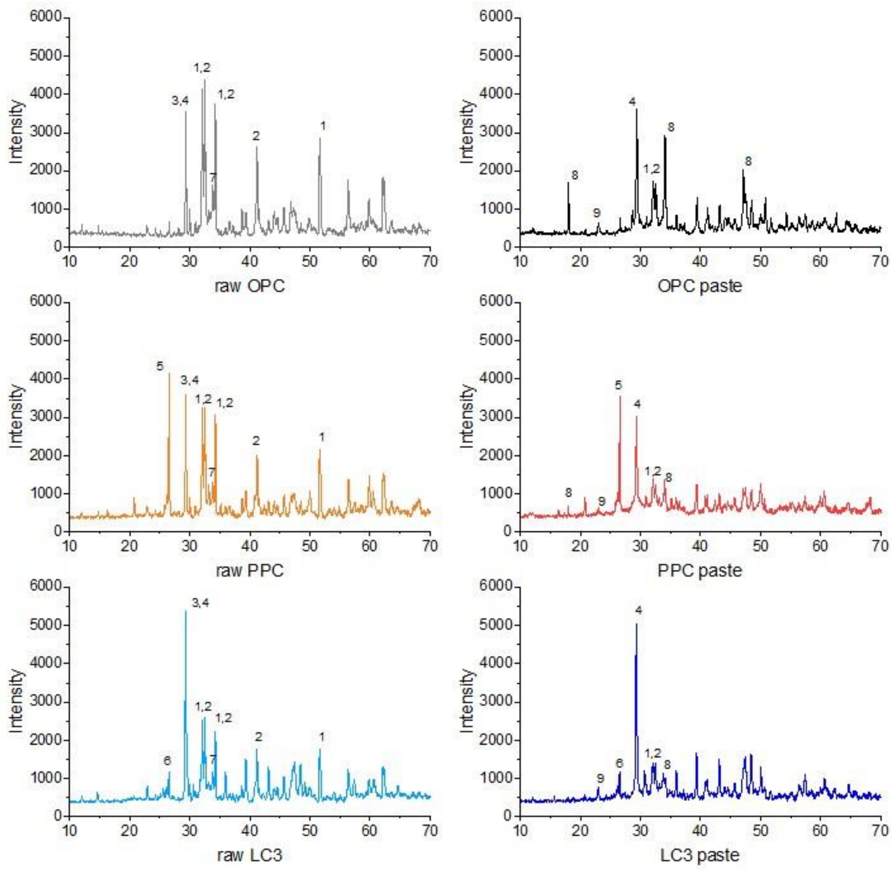
Where, W denotes the weight of the specimen; subscripts be, and ae represent before and after exposure to elevated temperature; and f_{ae} denotes the compressive strength of concrete after exposure to elevated temperature and f_{be} denotes the compressive strength of concrete before exposure to elevated temperature, represented by 28-day compressive strength of specimen at ambient temperature.

Simultaneously, the three-factor ANOVA has been used to determine the significance of studied parameters (i.e., cement type, exposure temperature, and exposure duration) on the mechanical properties after exposure to elevated temperature, with the least significant difference as 5%.

B.3. Results and discussion

B.3.1 XRD

Fig. B.3 shows the XRD pattern of raw cement and cement paste after 28 days of hydration for OPC, PPC and LC^3. It can be observed from Fig. B.3 that all three cement types show C_3S, C_2S, C_4AF, gypsum and calcite mineral phases. Raw LC^3 has more calcite (carbonate) and sillimanite (aluminosilicate) minerals, as compared to raw OPC and PPC (Fig. B.3).



Minerals: 1 = C_3S, 2 = C_2S, 3 = Gypsum, 4 = Calcite, 5 = Silica, 6 = Sillimanite, 7 = C_4AF, 8 = Portlandite, 9 = Ettringite

Fig. B.3 XRD patterns for cement powder and hydrated cement pastes

The higher carbonate and aluminosilicate minerals in LC^3 result from limestone and calcined clay [371]. The change in the XRD pattern of OPC, PPC and LC^3 paste (Fig. B.3) shows hydration of cement pastes as evident from the decrease in C_3S, C_2S, C_4AF and gypsum, and an increase in ettringite and portlandite mineral phases. Calcite mostly remains unreacted in the mineral phase for all types of cement, resulting in a high calcite concentration of LC^3, consistent with the literature [372]. Fig. B.3 also shows that LC^3 paste has a low portlandite concentration compared to hydrated OPC and PPC, which may result from a reaction between portlandite and aluminates in calcined clay [373]. Different mineral composition of LC^3 is expected to affect the overall thermal degradation behaviour of LC^3 concrete, which has also been verified through TGA.

B.3.2 TGA of cement pastes

Fig. B.4 shows the DTG curve, i.e., the first differential of TGA, for OPC, PPC and LC^3 pastes. DTG curve of cement pastes (Fig. B.4) shows thermal degradation, identified by peaks, at two regions below 200°C and two regions above 400°C, represented in Fig. B.4. Thermal degradation above 400°C (Fig. B.4 DTG curve for OPC, PPC, and LC3 pastes

) shows that LC^3 pastes have a higher calcite concentration and a lower portlandite concentration than OPC and PPC pastes. The observed portlandite and calcite concentration through TGA (Fig. B.4 DTG curve for OPC, PPC, and LC3 pastes

) agrees with the XRD patterns (Fig. B.3). Thermal degradation below 200°C (Fig. B.4Fig. B.4 DTG curve for OPC, PPC, and LC3 pastes

) shows higher physically adsorbed water and lower Afm (mono-sulfo-aluminate) concentration in LC^3 paste than in OPC and PPC pastes. The observed trend between LC^3 and OPC pastes (Fig. B.4 DTG curve for OPC, PPC, and LC3 pastes

) is in line with previous investigations [347, 348]. As residual properties of concrete are significantly affected by fires above 400°C, change in thermal degradation pattern of LC^3 in the temperature zone 400°C – 500°C, due to low portlandite, and 600°C – 800°C, due to high calcite, is expected to affect the fire performance of LC^3 concrete.

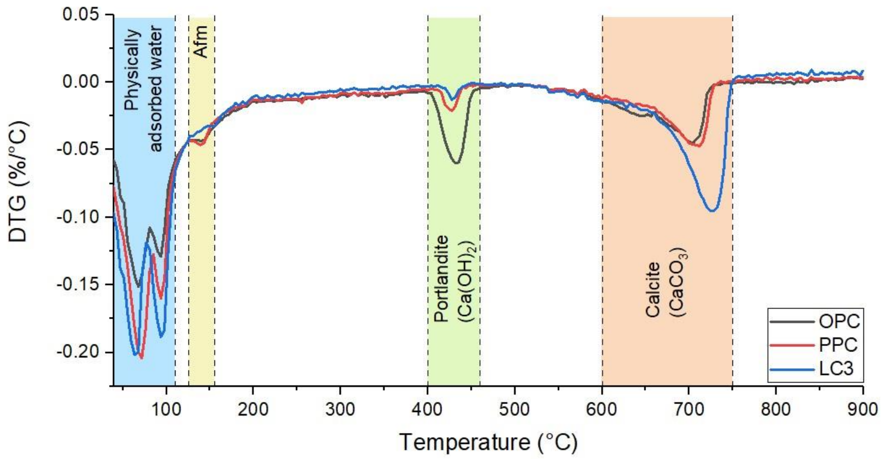


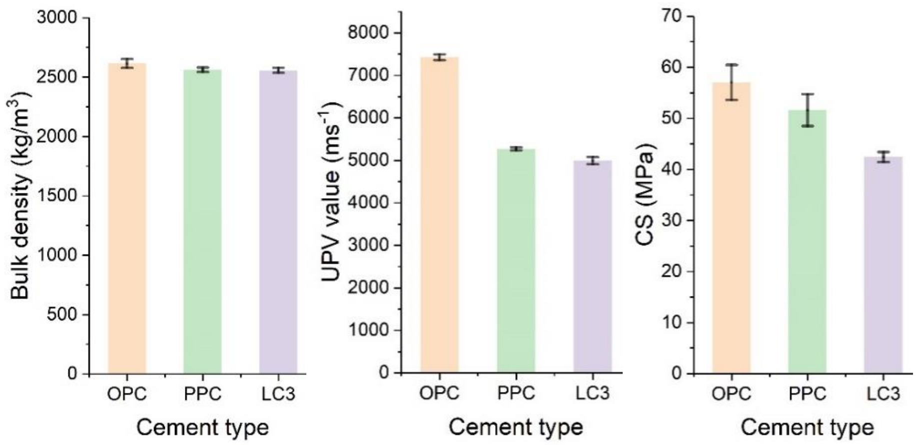
Fig. B.4 DTG curve for OPC, PPC, and LC3 pastes

Table B.3 TGA of cement pastes

Observations from DTG curve				
Peak range	Comparison between DTG peaks	Reference range	Cause of peak	Reference
< 110°C	$\mathbf{LC^3}$ > PPC > OPC	< 120 °C	Adsorbed water	[374]
125 °C-155°C	PPC > OPC > $\mathbf{LC^3}$	130 °C-155°C	Afm	[87, 375]
400 °C-460°C	OPC > PPC > $\mathbf{LC^3}$	400 °C-500°C	Portlandite	[376, 377]
600 °C-750°C	$\mathbf{LC^3}$ > PPC > OPC	600 °C-800°C	Carbonates	[376, 377]

B.3.3 Properties of concrete at ambient temperature

Fig. B.5 (a)-(c) shows the experimental results of the concrete specimen at ambient temperature. It may be observed from Fig. B.5 (a)-(c) that all concrete has a similar bulk density, but the UPV value and compressive strength of LC^3 concrete are lower than OPC concrete and PPC concrete. The lower strength in LC^3 concrete as compared to OPC concrete for a similar design mix is consistent with the literature [219].



(a) Bulk density (b) UPV value (c) Compressive strength

Fig. B.5 Performance of concrete at ambient temperature

B.3.4 Mass loss

Fig. B.6 (a)-(d) shows the mass loss (%) in OPC, PPC, and LC^3 concrete after exposure to different elevated temperatures for different exposure durations. Fig. B.6 (a)-(d) shows that mass loss in all concrete specimens increased with exposure temperature and duration. The average mass loss of LC^3 concrete (8.53%) is higher than OPC (6.70%) and PPC (7.29%) concrete and indicates higher thermal degradation of LC^3. Slightly higher mass loss in PPC than in OPC is consistent with the literature and can be attributed to higher physically adsorbed water (Fig. B.4) [378]. After exposure to 400°C (Fig. B.6 (a)), the mass loss for LC^3 concrete is higher than for OPC and PPC concrete, which can be attributed to the higher concentration of physically adsorbed water (Fig. B.4). After exposure to 400°C and 600°C, a similar mass loss can be observed for all concrete specimens (Fig. B.6 (a)-(b)). In comparison, DTG (Fig. B.4) shows a significant mass loss in the temperature range of 400°C and 600°C due to portlandite. The lack of mass loss of concrete in the temperature range of 400°C and 600°C can be understood by dehydration and rehydration of portlandite. Above 400°C, portlandite decomposes to release water and forms lime, and at the time of cooling, lime regains moisture to form portlandite [113]. Rehydration of lime can recover the mass loss of concrete in the temperature range of 400°C and 600°C. The mass loss of LC^3 concrete significantly increases after exposure to 800°C (Fig. B.6 (c)) and can be attributed to calcite decomposition between 600°C and 800°C (Fig. B.4). Mass loss of concrete suggests that concrete paste experiences a significant thermal degradation, due to portlandite and calcite, above exposure temperature of 400°C and is expected to lower the fire performance of concrete. In reference to exposure duration, Fig. B.6 (b)-(d) shows a limited impact of time on the mass loss of concrete. The limited effect of exposure duration on mass loss implies that thermal degradation is a rapid phenomenon, and fire (exposure) duration is a less significant parameter.

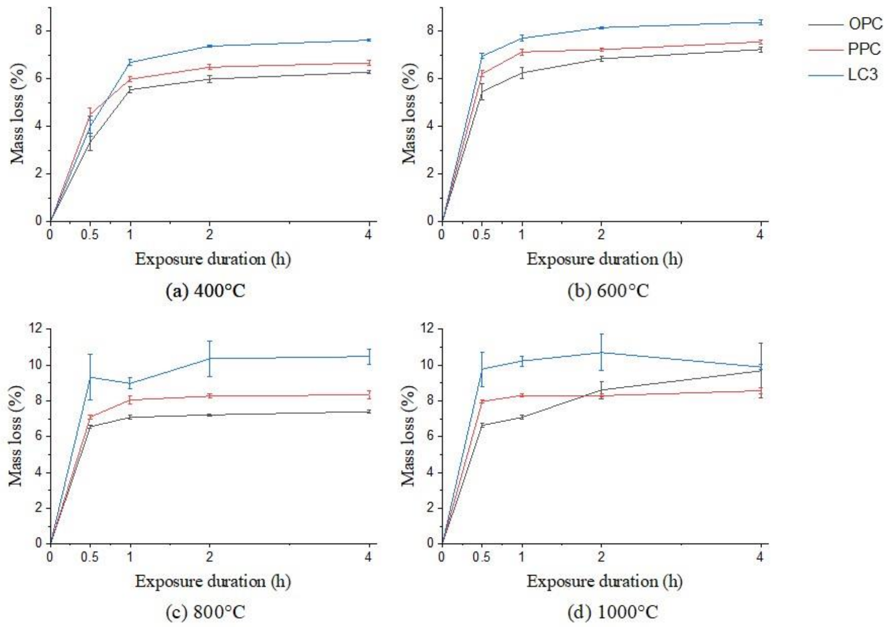


Fig. B.6 Mass loss in OPC, PPC, and LC3 concrete after exposure to elevated temperature at: (a) 400°C, (b) 600°C, (c) 800°C, and (d) 1000°C

B.3.5 rUPV

rUPV of OPC, PPC, and LC^3 concrete after the different exposure scenarios is presented in Fig. B.7 (a)-(d). A decrease in rUPV can be observed for an increase in both exposure temperature and duration. LC^3 concrete shows a higher loss in UPV after exposure to 400°C (Fig. B.7 (a)) as compared to OPC and PPC concrete, which can be the result of higher loss in physically adsorbed water (Fig. B.4) [358]. After exposure to 600°C, OPC, PPC and LC^3 concrete show similar rUPV (Fig. B.7 (b)). Higher loss in rUPV of OPC and PPC concrete than LC^3 concrete can be attributed to the higher concentration of portlandite (Fig. B.4) and resulting thermal degradation in the temperature range of 400°C and 600°C [358]. After exposure to 800°C and 1000°C, all three types of concrete show low rUPV values, ≤ 20% (Fig. B.7 (c)-(d)). Nas and Kurbetci [358] observed an increase in the porosity of concrete after exposure to elevated temperatures due to thermal degradation of cement pastes and micro-cracking from the expansion of aggregates, which results in loss of rUPV. DTG of cement pastes (Fig. B.4) shows that calcite is primarily responsible for thermal degradation in the range of 600°C and 800°C. A similar rUPV in all three concretes after exposure to 800°C (Fig. B.7 (c)-(d)) suggests that calcite decomposition has a limited impact on the loss of rUPV, as compared to other factors like microcracking from the expansion of aggregate [379].

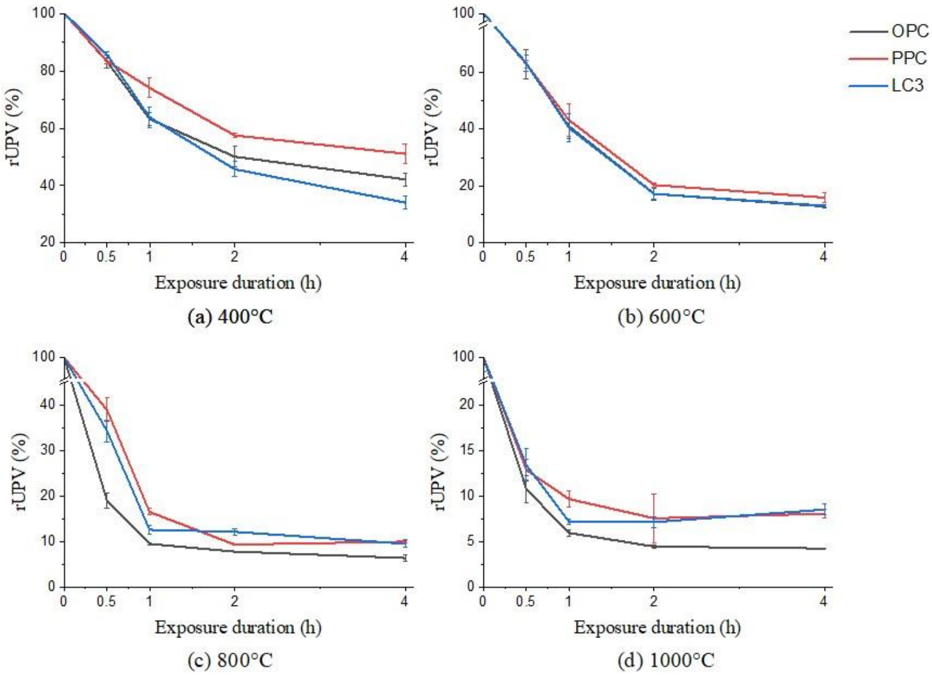


Fig. B.7 Residual UPV value of OPC, PPC, and LC3 concrete after exposure to elevated temperature at (a) 400°C, (b) 600°C, (c) 800°C, and (d) 1000°C

rUPV of concrete shows that above 600°C thermal degradation of pastes has a low impact on residual properties of concrete, and high calcite concentration in LC^3 may not be detrimental to the fire performance of concrete. The average rUPV of LC^3 concrete (29.29%) is lower than

PPC concrete (32.63%) but higher than OPC (27.58%) concrete. The slightly higher rUPV of LC^3 concrete indicates that the degree of fire damage is lower than OPC; however, the same does not reflect in either mass loss or rCS.

B.3.6 rCS

rCS of OPC, PPC, and LC^3 concrete for different exposure scenarios is presented in Fig. B.8 (a)-(d). Fig. B.8 (a) shows that all concrete specimens exposed to 400°C gained strength at an exposure duration of 1 h compared to an exposure duration of 0.5 h. At low exposure temperatures, the concrete experiences both increased strength due to secondary hydration [367] and decreased strength due to loss of adsorbed water, resulting in a mixed effect on rCS [368]. Mohamedbhai [380] observed a similar mixed behaviour of rCS at 400°C, with the heating and cooling rate of concrete affecting the exposure duration up to which an increase in rCS can be observed. Strength gain for the adopted rapid heating and cooling method is limited to 1 h exposure duration and is not affected bv y the use of LC^3 (Fig. B.8 (a)). For all other exposure scenarios, rCS reduces with an increase in both exposure temperature and duration. After exposure to 400°C (Fig. B.8 (a)), LC^3 concrete shows lower rCS as compared to OPC and PPC concrete, which can be the result of higher loss in adsorbed water (Fig. B.4) [358]. Physically adsorbed water of PPC lies between OPC and LC^3 (Fig. B.4) and shows rCS between the two types of concrete (Fig. B.8 (a)). After exposure to 600°C (Fig. B.8 (b)), the rCS of LC^3 concrete is similar to PPC concrete and slightly lower than OPC concrete. Lesser loss of rCS for LC^3 concrete in the range of 400°C and 600°C (Fig. B.8 (a)-(b)) is the result of low portlandite content in LC^3 (Fig. B.4) [358]. After exposure to 800°C and 1000°C (Fig. B.8 (c)-(d)), concrete shows a similar loss in rCS and does not appear to be affected by the change in cement type. The low impact of change in cement type is similar to rUPV and indicates that the thermal degradation of calcite has a limited effect on the rCS of concrete exposed to 600°C and above, and other factors like micro-cracking due to aggregate expansion play a more dominating role [358]. Fig. B.8 (a)-(d) also shows that exposure duration significantly affects the rCS of concrete for all exposure temperatures. The average rCS of LC^3 concrete (42.24%) is lower than OPC (53.31%) and PPC (43.98%) concrete and indicates weaker fire performance of LC^3. The weaker fire performance of LC^3 is expected to affect the fire safety of concrete structures.

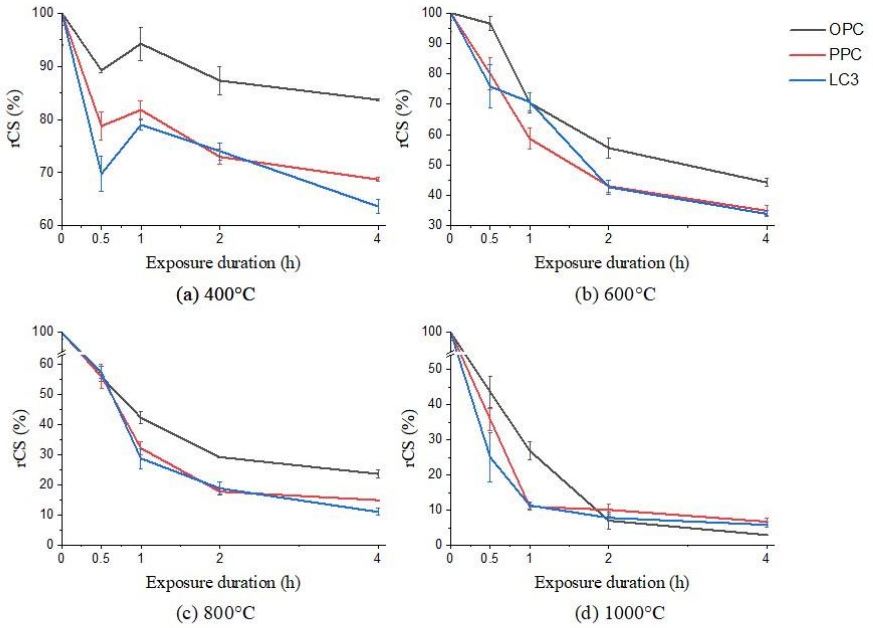


Fig. B.8 Residual compressive strength of OPC, PPC, and LC3 concrete after exposure to elevated temperature at (a) 400°C, (b) 600°C, (c) 800°C, and (d) 1000°C

B.3.7 Three-factor ANOVA

Three-factor ANOVA has been used to determine the significance of the studied parameters (i.e., cement type, exposure temperature, and exposure duration) on the rCS of concrete after exposure to elevated temperature, with the least significant difference as 5%. Table B.4 shows the results of three-factor ANOVA for rCS, both in terms of study parameters and their interactions.

Table B.4 Three-factor ANOVA for rCS

Study parameter	Sum of Squares	Degrees of freedom	Mean Square	F-value	p-value	Significance
Cement type (A)	634.12	2	317.06	42.34	2.28×10^{-31}	Yes
Exposure temp. (B)	59898.17	3	19966.06	2666.56	7.67×10^{-92}	Yes
Exposure duration (C)	19126.17	3	6375.39	851.46	5.62×10^{-63}	Yes
Interaction A × B	457.63	6	76.27	10.19	6.76×10^{-07}	Yes
Interaction A × C	132.28	6	22.05	2.94	0.001837	Yes
Interaction B × C	6979.58	9	775.51	103.57	4.85×10^{-35}	Yes
Interaction A × B × C	569.54	18	31.64	4.23	4.72×10^{-10}	Yes
Error	718.81	96	7.49			
Total	88516.30	143	619.00			

It can be observed from Table B.4 that individual parameters, i.e., cement type, exposure temperature and exposure duration, have a low p-value (<0.05), showing a significant impact on the rCS of concrete. The ascending order of p-value indicates the decreasing order of significance for the study parameters. Table B.4 shows that, for rCS, change in cement type ranks fourth after exposure temperature, exposure duration and their interaction. The lower significance of cement type on rCS implies that the use of LC^3 is a less critical parameter for residual mechanical properties of concrete than exposure temperature and durations. The lower significance of cement type implies that the use of LC^3 cement has a lower contribution towards the weaker fire performance of LC^3 compared to exposure temperature or exposure duration. Table B.4 also shows the result for the interaction of parameters, which is used to study the compound effect of different parameters on the rCS of concrete. Table B.4 shows a low p-value for the two-way interaction of cement type and exposure temperature. The low p-value indicates significant interaction, i.e., the use of LC^3 cement will modify the trend of residual properties of concrete for different exposure temperatures, as evident from the change in the loss of rCS below 600°C (Fig. B.8 (a)) due to change in physically adsorbed water and portlandite. The two-way interaction of cement type and exposure duration shows a relatively higher p-value (Table B.4) than the rest of the parameters. The high p-value indicates a low interaction, i.e., the use of LC^3 cement will have a limited effect on the trend of residual properties of concrete for different exposure durations, as evident from similar loss in rCS with exposure duration (Fig. B.8 (a)-(d)).

B.4. Conclusion

The experimental study shows the effect of change in cement, from conventionally used OPC and PPC to LC^3, on the fire safety of concrete structures. Fire performance of OPC, PPC and LC^3 concrete have been investigated after exposure to 16 elevated temperature scenarios in terms of mass loss, rUPV and rCS. Effect of adopted study parameters, i.e., change in cement type (OPC, PPC and LC^3), exposure temperatures

(400°C, 600°C, 800°C, and 1000°C) and exposure durations (0.5 h, 1 h, 2 h, and 4 h) on rCS has been statistically analysed using three-factor ANOVA. Based on the comprehensive investigation, the following conclusions can be drawn:

1. XRD shows a higher concentration of calcite and a lower concentration of portlandite minerals in LC^3 paste compared to OPC and PPC pastes. The difference in mineral composition affects the thermal degradation of cement pastes as observed from TGA in the temperature ranges of 400°C – 460°C (portlandite) and 600°C – 750°C (calcite). TGA also shows a higher concentration of physically adsorbed water (below 120°C) in LC^3 paste than OPC and PPC pastes.
2. Mass loss for LC^3 concrete (8.53%) is higher than OPC (6.70%) and PPC (7.29%) concrete due to the higher availability of physically adsorbed water and calcite minerals. Thermal degradation of portlandite, observed from TGA, shows no effect on mass loss of concrete between 400°C and 600°C.
3. rUPV and rCS of LC^3 concrete are lower than OPC and PPC concrete after exposure to 400°C due to higher concentrations of physically adsorbed water.
4. In the temperature range of 400°C and 600°C, thermal degradation of portlandite results in loss of rUPV and rCS. Lower portlandite in LC^3 concrete results in lesser loss of rUPV and rCS than OPC and PPC concrete between 400°C and 600°, resulting in similar residual properties after exposure to 600°C. After exposure to 600°C, rUPV of LC^3 concrete is similar to OPC and PPC concrete, and rCS of LC^3 concrete is similar to rUPV of PPC concrete and slightly lower than OPC concrete.
5. Thermal degradation of calcite, observed above 600°C, shows a limited impact on rUPV and rCS of concrete. A higher concentration of calcite mineral in LC^3 paste does not result in negative fire performance of LC^3 concrete above 600°C.
6. ANOVA shows that exposure temperature has the highest effect on rCS of concrete, followed by exposure duration and change

in cement type. Two-way interaction of cement type with exposure temperature also shows that the use of LC^3 affects the loss pattern of rCS for different temperature ranges due to the change in mineral composition.

The results presented in this study are based on the experimental investigations of LC^3-50. Results of this study show that change in mineral composition affects the thermal degradation pattern of LC^3 concrete and results in weaker fire performance. Safety guidelines will be required to reduce the fire risk of LC^3 concrete structures for robust industrial applications.

Appendix C

Code for Monte Carlo simulation

Following section presents the MATLAB code for Monte Carlo simulation described under Chapter 5. The flow chart describing the architecture of the code is shown in Fig. 5.1.

C.1. MATLAB code for Monte Carlo simulation

```
% Select no. of iterations for the Monte Carlo simulation
no_of_iterations=1000000;

% Residual strength for different concrete for each fire scenario
OPC=zeros (1, no_of_iterations);
PPC=zeros (1, no_of_iterations);
LC3=zeros (1, no_of_iterations);

% Dataset for fire simulations

% Building data represents building type (1="School", 2="Commercial", 3="Residential", 4="Government", 5="Factory with combustible materials", 6="Factory, other"), cumulative probability of fire occurrence, average structure height, minimum fire load, maximum fire load
Building_dataset =  [1   0.001566   3.60   25   25;
                     2   0.055079   2.75   25   50;
                     3   0.954891   2.75   25   25;
                     4   0.959823   2.75   25   50;
                     5   0.977308   3.60   25   500;
                     6   1.000000   3.60   25   150];

% Material data represents construction material type (1="Brick", 2="Concrete"), cumulative probability of occurrence, fire curve parameters c, d, m, n
```

```
Material_dataset =     [1   0.849   692   17   0.13   0.67;
                        2   1.000   623   11   0.14   0.38];

% Residual compressive strength based on experimental studies,
columns represent temp 400 °C, 600 °C, 800 °C, 1000 °C, rows represent
time 0.5 h, 1.0 h, 2.0 h, 4.0 h
OPC_rCS =   [89.188,     96.427,     55.952,     43.644;
             94.192,     70.418,     42.394,     26.923;
             87.268,     55.591,     29.282,     7.008;
             83.689,     44.284,     23.721,     2.936];
PPC_rCS =   [78.740,     79.976,     56.036,     35.779;
             81.760,     58.692,     32.244,     11.050;
             72.974,     43.034,     17.839,     10.128;
             68.725,     34.920,     15.02,      6.714];
LC3_rCS =   [69.786,     75.796,     57.424,     25.009;
             78.970,     70.714,     28.840,     11.362;
             74.037,     42.686,     18.924,     7.816;
             63.645,     33.929,     11.104,     5.856];

% Adopted scenarios
negligence_probability = 0.1;

% Simulations for fire scenarios

for i = 1:no_of_iterations
        % random building type from cumulative probability
        building_type = sum(Building_dataset(:,2)<rand())+1;
        Avg_height = Building_dataset(building_type,3);
        Min_fire_load = Building_dataset(building_type,4);
        Max_fire_load = Building_dataset(building_type,5);

        % random construction material from cumulative probability
        material_type = sum(Material_dataset(:,2)<rand())+1;
        c = Material_dataset(material_type,3);
```

```
d = Material_dataset(material_type,4);
m = Material_dataset(material_type,5);
n = Material_dataset(material_type,5);

% Possible fire load in wood eq.
if rand()<negligence_probability
        % safety guidelines ignored
        Extra_fire_load = rand()*Max_fire_load;
else
        % safety guidelines followed
        Extra_fire_load = 0;
end
Fire_load_wood = Min_fire_load + (Max_fire_load –
Min_fire_load)*rand() + Extra_fire_load ;

% Possible fire load in Mcal/m2
Fire_load = Fire_load_wood/4.1868;

% Possible surface opening
Surf_op = (0.01+0.49*betaincinv(rand(),0.8494,2.4651));

% Possible height
height = round(norminv(rand(), Avg_height, Avg_height/10),2);
% Calculation of fire curve
O = Surf_op*height^0.5;
Time_max = Fire_load/O/1800;
Temp_max = 250 + c*(1-exp(O*-1*d))*Fire_load^(m-n*O);
% time in hours, with max period of 10 hours
time = (0:10*60*60)/60/60;
Temp = Temp_max/Time_max*time.*e.^(1-time/Time_max);
% plot represents temperature vs. time of the fire curve
plot(time,Temp);

% Check for how long fire exceeds a particular temperature
```

```
t_400 = sum(Temp>=400)/60/60;
t_600 = sum(Temp>=600)/60/60;
t_800 = sum(Temp>=800)/60/60;
t_1000 = sum(Temp>=1000)/60/60;

% Residual compressive strength for different types of concrete

% loss under 400 °C,
if t_400>0
        if t_400>=0.5
                if t_400<4
                        u= floor(3+log2(t_400));
                        l = floor(2+log2(t_400));
                        O_400    =    (OPC_rCS(u,1)*(t_400-l)+
                        OPC_rCS(l,1))*(u-t_400);
                        P_400    =    (PPC_rCS(u,1)*(t_400-l)+
                        PPC_rCS(l,1))*(u-t_400);
                        L_400    =    (LC3_rCS(u,1)*(t_400-l)+
                        LC3_rCS(l,1))*(u-t_400);
                else
                        O_400 = OPC_rCS(4,1);
                        P_400 = PPC_rCS(4,1);
                        L_400 = LC3_rCS(4,1);
                end
        else
                O_400 = OPC_rCS(1,1);
                P_400 = PPC_rCS(1,1);
                L_400 = LC3_rCS(1,1);
        end
        O_400 = 100.00;
        P_400 = 100.00;
        L_400 = 100.00;
end
```

```
% loss under 600 °C,
if t_600>0
    if t_600>=0.5
        if t_600<4
            u= floor(3+log2(t_600));
            l = floor(2+log2(t_600));
            O_600 = (OPC_rCS(u,2)*(t_600-l)+
            OPC_rCS(l,2))* (u-t_600);
            P_600 = (PPC_rCS(u,2)*(t_600-l)+
            PPC_rCS(l,2))* (u-t_600);
            L_600 = (LC3_rCS(u,2)*(t_600-l)+
            LC3_rCS(l,2))* (u-t_600);
        else
            O_600 = OPC_rCS(4,2);
            P_600 = PPC_rCS(4,2);
            L_600 = LC3_rCS(4,2);
        end
    else
        O_600 = OPC_rCS(1,2);
        P_600 = PPC_rCS(1,2);
        L_600 = LC3_rCS(1,2);
    end
    O_600 = 100.00;
    P_600 = 100.00;
    L_600 = 100.00;
end

% loss under 800 °C,
if t_800>0
    if t_800>=0.5
        if t_800<4
            u= floor(3+log2(t_800));
            l = floor(2+log2(t_800));
```

```
                O_800 = (OPC_rCS(u,3)*(t_800-l) + OPC_rCS (l,3))* (u-t_800);
                P_800 = (PPC_rCS(u,3)*(t_800-l) + PPC_rCS (l,3))* (u-t_800);
                L_800 = (LC3_rCS(u,3)*(t_800-l) + LC3_rCS (l,3))* (u-t_800);
            else
                O_800 = OPC_rCS(4,3);
                P_800 = PPC_rCS(4,3);
                L_800 = LC3_rCS(4,3);
            end
        else
            O_800 = OPC_rCS(1,3);
            P_800 = PPC_rCS(1,3);
            L_800 = LC3_rCS(1,3);
        end
        O_800 = 100.00;
        P_800 = 100.00;
        L_800 = 100.00;
end

% loss under 1000 °C,
if t_1000>0
        if t_1000>=0.5
            if t_1000<4
                u= floor(3+log2(t_1000));
                l = floor(2+log2(t_1000));
                O_1000 = (OPC_rCS(u,4)*(t_1000-l) + OPC_rCS(l,4))* (u-t_1000);
                P_1000 = (PPC_rCS(u,4)*(t_1000-l) + PPC_rCS(l,4))* (u-t_1000);
                L_1000 = (LC3_rCS(u,4)*(t_1000-l) + LC3_rCS(l,4))* (u-t_1000);
            else
```

```
                    O_1000 = OPC_rCS(4,4);
                    P_1000 = PPC_rCS(4,4);
                    L_1000 = LC3_rCS(4,4);
                end
            else
                O_1000 = OPC_rCS(1,4);
                P_1000 = PPC_rCS(1,4);
                L_1000 = LC3_rCS(1,4);
            end
            O_1000 = 100.00;
            P_1000 = 100.00;
            L_1000 = 100.00;
        end

        OPC(1,i) = min(O_400, O_600, O_800, O_1000);
        PPC(1,i) = min(P_400, P_600, P_800, P_1000);
        LC3(1,i) = min(L_400, L_600, L_800, L_1000);

end

% Strength below which material may fail
failure_strength=80;

% Probability of failure
prob_OPC = sum(OPC<failure_strength)/no_of_iterations;
prob_PPC = sum(PPC<failure_strength)/no_of_iterations;
prob_LC3 = sum(LC3<failure_strength)/no_of_iterations;

% Post simulation analysis and application of fire safety guidelines have
been carried out with modification in the primary MATLAB codes
```

References

1. EEA (2015) Global total material use by resource type — European Environment Agency. In: Eur. Environ. Agency. https://www.eea.europa.eu/data-and-maps/figures/global-total-material-use-by. Accessed 19 Jan 2023

2. Lin TD, Chou S (1996) Overview of the National Plan to Elevate Concrete Technology in Taiwan. Spec Publ 159:79–94. https://doi.org/10.14359/1594

3. Gupta S, Chaudhary S (2020) State of the art review on Supplementary Cementitious Materials in India – I: An overview of legal perspective, governing organizations, and development patterns. J Clean Prod 261:121203. https://doi.org/10.1016/j.jclepro.2020.121203

4. IS 383 (2016) Coarse and Fine Aggregate for Concrete - Specification. Bureau of Indian Standards, New Delhi

5. Feng C, Cui B, Huang Y, et al (2022) Enhancement technologies of recycled aggregate – Enhancement mechanism, influencing factors, improvement effects, technical difficulties, life cycle assessment. Constr Build Mater 317:126168. https://doi.org/10.1016/j.conbuildmat.2021.126168

6. Sharma M, Bishnoi S, Martirena F, Scrivener K (2021) Limestone calcined clay cement and concrete: A state-of-the-art review. Cem Concr Res 149:106564. https://doi.org/10.1016/J.CEMCONRES.2021.106564

7. IEA (2019) 2019 Global Status Report for Buildings and Constructi on Towards a zero-emissions, effi cient and resilient buildings and constructi on sector. Int Energy Agency

8. Commission on Environment W Report of the World Commission on Environment and Development: Our Common

Future Towards Sustainable Development 2. Part II. Common Challenges Population and Human Resources 4

9. Org SU TRANSFORMING OUR WORLD: THE 2030 AGENDA FOR SUSTAINABLE DEVELOPMENT UNITED NATIONS UNITED NATIONS TRANSFORMING OUR WORLD: THE 2030 AGENDA FOR SUSTAINABLE DEVELOPMENT

10. Najjar R (2022) Four dimensional spatial sustainability (4DSS): a revolutionary approach toward utopian sustainability. Discov Sustain 3:1–13. https://doi.org/10.1007/S43621-022-00090-X/FIGURES/8

11. Pohoryles RJ (2018) The four dimensions of sustainability. Innov Eur J Soc Sci Res 31:205–206. https://doi.org/10.1080/13511610.2018.1490541

12. Husgafvel R, Pajunen N, Virtanen K, et al (2015) Social sustainability performance indicators – experiences from process industry. Int J Sustain Eng 8:14–25. https://doi.org/10.1080/19397038.2014.898711

13. Friedlingstein P, O'sullivan M, Jones MW, et al (2022) Global Carbon Project (GCP). Earth Syst Sci Data 14:4811–4900. https://doi.org/10.5194/ESSD-14-4811-2022

14. IEA (2020) Global Energy Review 2019. OECD

15. Chen C, Förster MW, Foley SF, Liu Y (2021) Massive carbon storage in convergent margins initiated by subduction of limestone. Nat Commun 2021 121 12:1–9. https://doi.org/10.1038/s41467-021-24750-0

16. Indian bureau of mines (2020) Indian Minerals Yearbook 2020 MINISTRY OF MINES INDIAN BUREAU OF MINES. Indian Miner Yearb 2020 2018:1–5

17. The problem with our dwindling sand reserves.

https://www.unep.org/news-and-stories/story/problem-our-dwindling-sand-reserves. Accessed 12 Jun 2023

18. Unasylva - Vol. 1, No. 1 - Timber Shortage or Timber Abundance in the U.S.A. https://www.fao.org/3/x5339e/x5339e07.htm. Accessed 12 Jun 2023

19. MOEF (1999) THE GAZETTE OF INDIA EXTRAORDINARY PART II-Section 3-Sub-section (ii) MINISTRY OF ENVIRONMENT AND FORESTS NOTIFICATION

20. (2021) Concrete needs to lose its colossal carbon footprint. Nature 597:593–594. https://doi.org/10.1038/d41586-021-02612-5

21. Mehta A, Ashish DK (2020) Silica fume and waste glass in cement concrete production: A review. J Build Eng 29:100888. https://doi.org/10.1016/j.jobe.2019.100888

22. The Global Water Cycle. https://www2.whoi.edu/site/globalwatercycle/. Accessed 13 Jun 2023

23. Vergara YLM, John VM (2019) Global Concrete Water Footprint. In: 2019 7th International Engineering, Sciences and Technology Conference (IESTEC). IEEE, pp 193–196

24. Bardhan S, Choudhuri IR (2016) Studies on Virtual Water Content of Urban Buildings in India. Indian J Sci Technol 9:. https://doi.org/10.17485/ijst/2016/v9i6/87671

25. Wegian FM (2010) Effect of seawater for mixing and curing on structural concrete. IES J Part A Civ Struct Eng 3:235–243. https://doi.org/10.1080/19373260.2010.521048

26. Agwe TM, Tibenderana P, Twesigye-Omwe MN, et al (2022) Concrete Production and Curing with Recycled Wastewater: A Review on the Current State of Knowledge and Practice. Adv Civ Eng 2022:1–10. https://doi.org/10.1155/2022/7193994

27. Farfan J, Fasihi M, Breyer C (2019) Trends in the global cement industry and opportunities for long-term sustainable CCU potential for Power-to-X. J Clean Prod 217:821–835. https://doi.org/10.1016/J.JCLEPRO.2019.01.226

28. Cement – Analysis - IEA. https://www.iea.org/reports/cement. Accessed 13 Jun 2023

29. Palcis RJP (2023) Sustainable Alternatives to Cement in the Face of Limestone Shortage: A Comprehensive Review of Fly Ash, Ground Granulated Blast Furnace Slag, Geopolymer, and Natural Pozzolans for the Construction Industry. In: ResearchGate. https://www.researchgate.net/publication/368541659_Sustainable_Alternatives_to_Cement_in_the_Face_of_Limestone_Shortage_A_Comprehensive_Review_of_Fly_Ash_Ground_Granulated_Blast_Furnace_Slag_Geopolymer_and_Natural_Pozzolans_for_the_Construction_Indust. Accessed 13 Jun 2023

30. Igliński B, Buczkowski R (2017) Development of cement industry in Poland – History, current state, ecological aspects. A review. J Clean Prod 141:702–720. https://doi.org/10.1016/J.JCLEPRO.2016.09.139

31. Limestone shortage in Jammu and Kashmir leaves cement workers idle - Cement industry news from Global Cement. https://www.globalcement.com/news/item/13957-limestone-shortage-in-jammu-and-kashmir-leaves-cement-workers-idle. Accessed 13 Jun 2023

32. Marvila M, de Matos P, Rodríguez E, et al (2022) Recycled Aggregate: A Viable Solution for Sustainable Concrete Production. Materials (Basel) 15:5276. https://doi.org/10.3390/ma15155276

33. MoEF&CC (2020) Enforcement & monitoring guidelines for sand mining

34. kalsi alok (2020) Government of India Compendium on

Sedimentation of Reservoirs in India. 1–460

35. Achour R, Zentar R, Abriak NE, et al (2019) Durability study of concrete incorporating dredged sediments. Case Stud Constr Mater 11:e00244. https://doi.org/10.1016/J.CSCM.2019.E00244

36. Kirthika SK, Singh SK, Chourasia A (2020) Alternative fine aggregates in production of sustainable concrete- A review. J Clean Prod 268:122089. https://doi.org/10.1016/J.JCLEPRO.2020.122089

37. Gupta S, Agrawal H, Chaudhary S (2022) Thermo-Mechanical Treatment as an Upcycling Strategy for Mixed Recycled Aggregate. SSRN Electron J. https://doi.org/10.2139/SSRN.4269956

38. Gupta S, Chaudhary S (2022) State of the art review on supplementary cementitious materials in India – II: Characteristics of SCMs, effect on concrete and environmental impact. J Clean Prod 357:131945. https://doi.org/10.1016/j.jclepro.2022.131945

39. Thakare AA, Singh A, Gupta V, et al (2021) Sustainable development of self-compacting cementitious mixes using waste originated fibers: A review. Resour Conserv Recycl 168:105250. https://doi.org/10.1016/J.RESCONREC.2020.105250

40. Misra V (1984) Use of stone dust from crushers in cement-sand mortars. Indian Concr J

41. Sarma PP, Barman K, Baruah PK (2023) Industrial barriers for the application of active and intelligent packaging. In: Green Sustainable Process for Chemical and Environmental Engineering and Science. Elsevier, pp 71–96

42. Scrivener K, Martirena F, Bishnoi S, Maity S (2018) Calcined clay limestone cements (LC3). Cem Concr Res 114:49–56. https://doi.org/10.1016/J.CEMCONRES.2017.08.017

43. Yin K, Ahamed A, Lisak G (2018) Environmental perspectives of recycling various combustion ashes in cement production – A review. Waste Manag. 78:401–416

44. John VM, Damineli BL, Quattrone M, Pileggi RG (2018) Fillers in cementitious materials — Experience, recent advances and future potential. Cem Concr Res 114:65–78. https://doi.org/10.1016/j.cemconres.2017.09.013

45. John VM, Quattrone M, Abrão PCRA, Cardoso FA (2019) Rethinking cement standards: Opportunities for a better future. Cem Concr Res 124:105832. https://doi.org/10.1016/J.CEMCONRES.2019.105832

46. Martirena F, Monzó J (2018) Vegetable ashes as Supplementary Cementitious Materials. Cem Concr Res 114:57–64. https://doi.org/10.1016/J.CEMCONRES.2017.08.015

47. Hemalatha T, Ramaswamy A (2017) A review on fly ash characteristics – Towards promoting high volume utilization in developing sustainable concrete. J Clean Prod 147:546–559. https://doi.org/10.1016/J.JCLEPRO.2017.01.114

48. Juenger MCG, Snellings R, Bernal SA (2019) Supplementary cementitious materials: New sources, characterization, and performance insights. Cem Concr Res 122:257–273. https://doi.org/10.1016/J.CEMCONRES.2019.05.008

49. IS 9103: 1999 (2018) ConcreteAdmixtures - Specification

50. IS 456:2000 (2006) Plain and reinforced concrete-Code of Practice (Fourth Revision). Indian Stand 114

51. CPWD (2021) Delhi Schedule of Rates (Vol. 1). Director General, Central Public Works Department, New Delhi

52. CPWD (2010) Delhi Schedule of Rates

53. IBEF (2021) Indian Cement Industry Analysis (January 2021)

54. Her S, Park J, Li P, Bae S (2022) Feasibility study on utilization of pulverized eggshell waste as an alternative to limestone in raw materials for Portland cement clinker production. Constr Build Mater 324:126589. https://doi.org/10.1016/J.CONBUILDMAT.2022.126589

55. Her S, Park T, Zalnezhad E, Bae S (2021) Synthesis and characterization of cement clinker using recycled pulverized oyster and scallop shell as limestone substitutes. J Clean Prod 278:123987. https://doi.org/10.1016/J.JCLEPRO.2020.123987

56. Topić Popović N, Lorencin V, Strunjak-Perović I, Čož-Rakovac R (2023) Shell Waste Management and Utilization: Mitigating Organic Pollution and Enhancing Sustainability. Appl Sci 13:623. https://doi.org/10.3390/app13010623

57. Gupta S, Chaudhary S (2021) Large Scale Waste Utilisation in Sustainable Composite Materials for Structural Applications. pp 169–177

58. Ma C, Long G, Shi Y, Xie Y (2018) Preparation of cleaner one-part geopolymer by investigating different types of commercial sodium metasilicate in China. J Clean Prod 201:636–647. https://doi.org/10.1016/J.JCLEPRO.2018.08.060

59. Kacimi L, Simon-Masseron A, Salem S, et al (2009) Synthesis of belite cement clinker of high hydraulic reactivity. Cem Concr Res 39:559–565. https://doi.org/10.1016/J.CEMCONRES.2009.02.004

60. Jain A, Gupta R, Chaudhary S (2020) Sustainable development of self-compacting concrete by using granite waste and fly ash. Constr Build Mater 262:120516. https://doi.org/10.1016/j.conbuildmat.2020.120516

61. McCarthy J Washington’s rising aggregate supply crisis. https://www.pitandquarry.com/washingtons-rising-aggregate-supply-crisis/. Accessed 1 Sep 2023

62. Gupta S, Agrawal H, Chaudhary S (2023) Thermo-mechanical treatment as an upcycling strategy for mixed recycled aggregate. Constr Build Mater 398:132471. https://doi.org/10.1016/j.conbuildmat.2023.132471

63. Chinnu SN, Minnu SN, Bahurudeen A, Senthilkumar R (2021) Recycling of industrial and agricultural wastes as alternative coarse aggregates: A step towards cleaner production of concrete. Constr Build Mater 287:123056. https://doi.org/10.1016/J.CONBUILDMAT.2021.123056

64. International Energy Agency (2018) Technology Roadmap - Low-Carbon Transition in the Cement Industry. 66

65. CEA (2020) Report on fly ash generation at coal/lignite based thermal power stations and its utilization in the country for the year 2019-2020. New Delhi

66. Athira G, Bahurudeen A, Vishnu VS (2020) Availability and Accessibility of Sugarcane Bagasse Ash for its Utilization in Indian Cement Plants: A GIS-Based Network Analysis. Sugar Tech 22:1038–1056. https://doi.org/10.1007/s12355-020-00842-x

67. Joseph S, Bishnoi S, Maity S (2016) An economic analysis of the production of limestone calcined clay cement in India. Indian Concr J 90:22–27

68. Gettu R, Patel A, Rathi V, et al (2019) Influence of supplementary cementitious materials on the sustainability parameters of cements and concretes in the Indian context. Mater Struct Constr 52:1–11. https://doi.org/10.1617/s11527-019-1321-5

69. IBM (2018) Indian Minerals Yearbook 2018 (Part- II : Metals and Alloys)

70. IBM (2018) Indian Minerals Yearbook 2018 MINISTRY OF MINES (Part-III: Minerals Reviews)

71. Census of India (2012) Census 2011. In: Minist. Home Aff. Gov. India. https://censusindia.gov.in/

72. Prasad KL (2017) Pocket Book of Agricultural Statistics. New Delhi

73. Sethy K, Rojalin Nanda S (2020) Impact of Ultrafine Ground Granulated Blast Furnace Slag on the Properties of High Strength Durable Concrete. IOP Conf Ser Mater Sci Eng 970:012016. https://doi.org/10.1088/1757-899x/970/1/012016

74. Aayog N, EU External Action (2017) Strategy Paper On Resource Efficiency in Steel Sector Through Recycling of Scrap & Slag

75. Saha S, Pal J (2021) A Study on Properties of Concrete Using Silica Fume and Brick Aggregate. In: Lecture Notes in Civil Engineering. Springer, pp 527–537

76. Reddy AS, Pradhan RK, Chandra S (2006) Utilization of Basic Oxygen Furnace (BOF) slag in the production of a hydraulic cement binder. Int J Miner Process 79:98–105. https://doi.org/10.1016/j.minpro.2006.01.001

77. Sharma K, Kumar A (2021) Influence of rice husk ash, lime and cement on compaction and strength properties of copper slag. Transp Geotech 27:100464. https://doi.org/10.1016/j.trgeo.2020.100464

78. Ministry of Mines (2020) Monthly summary summary on non-ferrous minerals & metals

79. Indian bureau of mines (2019) Indian Minerals Yearbook 2018 57 th Edition CHROMITE (ADVANCE RELEASE) GOVERNMENT OF INDIA MINISTRY OF MINES INDIAN BUREAU OF MINES

80. Acharya PK, Patro SK (2016) Utilization of ferrochrome wastes such as ferrochrome ash and ferrochrome slag in concrete

manufacturing. Waste Manag Res 34:764–774. https://doi.org/10.1177/0734242X16654751

81. Venkatesh C, Ruben N, Chand MSR (2020) Red mud as an additive in concrete: comprehensive characterization. J Korean Ceram Soc 2020 573 57:281–289. https://doi.org/10.1007/S43207-020-00030-3

82. Gupta T, Sachdeva SN (2019) Investigations on Jarosite Mixed Cement Concrete Pavements. Arab J Sci Eng 44:8787–8797. https://doi.org/10.1007/s13369-019-03801-1

83. Singh SK, Singh A, Singh B, Vashistha P (2020) Application of thermo-chemically activated lime sludge in production of sustainable low clinker cementitious binders. J Clean Prod 264:121570. https://doi.org/10.1016/j.jclepro.2020.121570

84. Kanoungo SK, Sharma U, Kanoungo A (2021) Utilization of Waste Lime Sludge and Coal Fly Ash in Construction Industry. In: Lecture Notes in Civil Engineering. Springer Science and Business Media Deutschland GmbH, pp 281–292

85. Saranyadevi D, Sabareeswaran P, Paramaguru P, Surya Prakash M (2021) Study on Mechanical Properties of M30 Grade Concrete with Replacement of Cement by Wollastonite. In: Lecture Notes in Civil Engineering. Springer Science and Business Media Deutschland GmbH, pp 63–70

86. Jindal A, Ransinchung RNGD, Kumar P (2020) Behavioral study of self-compacting concrete with wollastonite microfiber as part replacement of sand for pavement quality concrete (PQC). Int J Transp Sci Technol 9:170–181. https://doi.org/10.1016/j.ijtst.2019.06.002

87. Krishnan S, Bishnoi S (2018) Understanding the hydration of dolomite in cementitious systems with reactive aluminosilicates such as calcined clay. Cem Concr Res 108:116–128. https://doi.org/10.1016/j.cemconres.2018.03.010

88. Kori RS, Jagan P, Meena SK (2016) Draft Guidelines for Management and Handling of Marble Slurry generated from Marble Processing Plants in Rajasthan Central Pollution Control Board

89. Parande AK, Ramesh Babu B, Aswin Karthik M, et al (2008) Study on strength and corrosion performance for steel embedded in metakaolin blended concrete/mortar. Constr Build Mater 22:127–134. https://doi.org/10.1016/j.conbuildmat.2006.10.003

90. Shukla N, Sahoo D, Remya N (2019) Biochar from microwave pyrolysis of rice husk for tertiary wastewater treatment and soil nourishment. J Clean Prod 235:1073–1079. https://doi.org/10.1016/j.jclepro.2019.07.042

91. Thiedeitz M, Schmidt W, Härder M, Kränkel T (2020) Performance of rice husk ash as supplementary cementitious material after production in the field and in the lab. Materials (Basel) 13:1–17. https://doi.org/10.3390/ma13194319

92. Sutradhar R, Suda VBR (2020) Experimental investigation on optimization of micronized biomass silica for the strength characteristics of recycled aggregate concrete. In: Materials Today: Proceedings. Elsevier Ltd, pp 1331–1336

93. Jagadesh P, Ramachandra Murthy A, Murugesan R (2020) Effect of processed sugar cane bagasse ash on mechanical and fracture properties of blended mortar. Constr Build Mater 262:120846. https://doi.org/10.1016/j.conbuildmat.2020.120846

94. Shameem Banu S, Karthikeyan J, Jayabalan P (2020) Effect of agro-waste on strength and durability properties of concrete. Constr Build Mater 258:120322. https://doi.org/10.1016/j.conbuildmat.2020.120322

95. Chandrasekhar Reddy K (2021) Investigation of mechanical and durable studies on concrete using waste materials as hybrid reinforcements: novel approach to minimize material cost. Innov

Infrastruct Solut 6:1–17. https://doi.org/10.1007/s41062-021-00566-1

96. Raval AD, Patel DIN, Pitroda PJ (2013) Re-use of ceramic industry waste for the elaboration of eco-efficient concrete. Int J Adv Eng Res Stud 2:103–105

97. Chakraborty S, Jo BW, Jo JH, Baloch Z (2017) Effectiveness of sewage sludge ash combined with waste pozzolanic minerals in developing sustainable construction material: An alternative approach for waste management. J Clean Prod 153:253–263. https://doi.org/10.1016/j.jclepro.2017.03.059

98. Nandy B, Sharma G, Garg S, et al (2015) Recovery of consumer waste in India - A mass flow analysis for paper, plastic and glass and the contribution of households and the informal sector. Resour Conserv Recycl 101:167–181. https://doi.org/10.1016/j.resconrec.2015.05.012

99. Parkash S (2021) ANNEXURE REFERRED TO IN REPLY TO PART (a) OF THE LOK SABHA UNSTARRED QUESTION NO. 4617 FOR ANSWER ON 24.03.2021. New Delhi

100. Manjunatha M, Vijaya Bhaskar Raju K, Sivapullaiah P V. (2021) Effect of PVC Dust on the Performance of Cement Concrete—A Sustainable Approach. In: Lecture Notes in Civil Engineering. Springer, pp 607–617

101. K. SS, T.P. T, Siva SK (2022) Implementing construction waste management in India: An extended theory of planned behaviour approach. Environ Technol Innov 27:102401. https://doi.org/10.1016/j.eti.2022.102401

102. Sekhar AR, Varsha D, Nagrath K, et al (2015) Resource Efficiency in the Indian Construction Sector Market Evaluation of the Use of Secondary Raw Materials from Construction and Demolition Waste. Resour Effic Constr Sect 1:

103. Pacheco J, de Brito J (2021) Recycled Aggregates Produced from Construction and Demolition Waste for Structural Concrete: Constituents, Properties and Production. Materials (Basel) 14:5748. https://doi.org/10.3390/ma14195748

104. Sarkar PP, Debnath B (2023) Feasibility Study of Brick Aggregate as a Partial Replacement of Natural Stones in Dry Lean Concrete Mix. J Mater Civ Eng 35:04023263. https://doi.org/10.1061/JMCEE7.MTENG-15264/ASSET/1D5B6682-B794-4067-B546-E024C18E4648/ASSETS/IMAGES/LARGE/FIGURE15.JPG

105. Rout MD, Biswas S, Shubham K, Sinha AK (2023) A systematic review on performance of reclaimed asphalt pavement (RAP) as sustainable material in rigid pavement construction: Current status to future perspective. J Build Eng 76:107253. https://doi.org/10.1016/J.JOBE.2023.107253

106. Lohar J, Shrivastava N, Sharma A (2023) Feasibility of granite processing waste as a fill material in geotechnical applications. Mater Today Proc. https://doi.org/10.1016/J.MATPR.2023.04.655

107. Ahmad S, Khan RA, Shamim S, Chandra U (2023) Effect of waste ceramic sanitary ware as partial replacement of aggregates and cement in concrete. Innov Infrastruct Solut 8:1–13. https://doi.org/10.1007/S41062-023-01166-X/METRICS

108. Siddique S, Chaudhary S, Shrivastava S, Gupta T (2019) Sustainable utilisation of ceramic waste in concrete: Exposure to adverse conditions. J Clean Prod 210:246–255. https://doi.org/10.1016/J.JCLEPRO.2018.10.231

109. Rana A, Kalla P, Verma HK, Mohnot JK (2016) Recycling of dimensional stone waste in concrete: A review. J. Clean. Prod. 135:312–331

110. Bharamappa Bekkeri G, Shetty KK, Nayak G (1234) Synthesis

of artificial aggregates and their impact on performance of concrete: a review. J Mater Cycles Waste Manag 25:1988–2011. https://doi.org/10.1007/s10163-023-01713-9

111. Raja R, Kumar S (2023) Cupola slag as a green concrete-making material and its performance characteristics - A review. Renew Sustain Energy Rev 185:113573. https://doi.org/10.1016/J.RSER.2023.113573

112. Singh P, Singh H, Danie Roy AB (2023) Sustainably produced concrete using weathered Linz-Donawitz slag as a fine aggregate Substitute: A comprehensive study with Artificial intelligence approach. Structures 54:964–980. https://doi.org/10.1016/J.ISTRUC.2023.05.088

113. Malik M, Bhattacharyya SK, Barai S V. (2021) Thermal and mechanical properties of concrete and its constituents at elevated temperatures: A review. Constr Build Mater 270:121398. https://doi.org/10.1016/J.CONBUILDMAT.2020.121398

114. Birgonda S, Karthikeyan J (2023) Comparative analysis of quaternary blended self-compacting concrete (QBSCC) mixes incorporating induction furnace slag (IFS) and crushed stone aggregate: A performance study. J Build Eng 76:107386. https://doi.org/10.1016/J.JOBE.2023.107386

115. Sidhu AS, Siddique R (2023) Durability assessment of sustainable metakaolin based high strength concrete incorporating crumb tire rubber. J Build Eng 72:106660. https://doi.org/10.1016/J.JOBE.2023.106660

116. MoHUA (2021) Circular Economy in Municipal solid and liquid waste. Minist Hous Urban Aff GOI 112

117. Saxena R, Siddique S, Gupta T, et al (2018) Impact resistance and energy absorption capacity of concrete containing plastic waste. Constr Build Mater 176:415–421. https://doi.org/10.1016/J.CONBUILDMAT.2018.05.019

118. Circular Economy for Plastics in India: A Roadmap

119. Mohajerani A, Vajna J, Cheung THH, et al (2017) Practical recycling applications of crushed waste glass in construction materials: A review. Constr Build Mater 156:443–467. https://doi.org/10.1016/j.conbuildmat.2017.09.005

120. Luhar S, Luhar I (2019) Potential application of E-wastes in construction industry: A review. Constr Build Mater 203:222–240. https://doi.org/10.1016/j.conbuildmat.2019.01.080

121. Shariati M, Kamyab H, Habibi M, et al (2023) Sulfuric acid resistance of concrete containing coal waste as a partial substitute for fine and coarse aggregates. Fuel 348:128311. https://doi.org/10.1016/J.FUEL.2023.128311

122. Gunasekaran K, Annadurai R, Kumar PS (2012) Long term study on compressive and bond strength of coconut shell aggregate concrete. Constr Build Mater 28:208–215. https://doi.org/10.1016/J.CONBUILDMAT.2011.08.072

123. IS : 1727 - 1967 (1967) Indian Standard METHODS OF TEST FOR POZZOLANIC MATERIALS (First Revision) IS : 1727 - 1967 Sixth Repr int OCTOBER 1996 UDC 666.95.014/.017 : 691.545 0. Bur Indian Stand New Delhi

124. IS-455-1989, (Reaffirmed-1995 (1998) Indian Standard Portland Slag Cement — Specification. Bur Indian Stand New Delhi

125. Hemalatha T, Ramaswamy A (2017) A review on fly ash characteristics – Towards promoting high volume utilization in developing sustainable concrete. J Clean Prod 147:546–559. https://doi.org/10.1016/j.jclepro.2017.01.114

126. Raheem AA, Abdulwahab R, Kareem MA (2021) Incorporation of metakaolin and nanosilica in blended cement mortar and concrete- A review. J Clean Prod 290:125852. https://doi.org/10.1016/j.jclepro.2021.125852

127. Tayeh BA, Alyousef R, Alabduljabbar H, Alaskar A (2021) Recycling of rice husk waste for a sustainable concrete: A critical review. J Clean Prod 312:127734. https://doi.org/10.1016/j.jclepro.2021.127734

128. Wang D, Shi C, Farzadnia N, et al (2018) A review on effects of limestone powder on the properties of concrete. Constr Build Mater 192:153–166. https://doi.org/10.1016/J.CONBUILDMAT.2018.10.119

129. Minnu SN, Bahurudeen A, Athira G (2021) Comparison of sugarcane bagasse ash with fly ash and slag: An approach towards industrial acceptance of sugar industry waste in cleaner production of cement. J Clean Prod 285:124836. https://doi.org/10.1016/j.jclepro.2020.124836

130. Aprianti S E (2017) A huge number of artificial waste material can be supplementary cementitious material (SCM) for concrete production – a review part II. J Clean Prod 142:4178–4194. https://doi.org/10.1016/j.jclepro.2015.12.115

131. Nwankwo CO, Bamigboye GO, Davies IEE, Michaels TA (2020) High volume Portland cement replacement: A review. Constr Build Mater 260:120445. https://doi.org/10.1016/J.CONBUILDMAT.2020.120445

132. Al-Hamrani A, Kucukvar M, Alnahhal W, et al (2021) Green Concrete for a Circular Economy: A Review on Sustainability, Durability, and Structural Properties. Mater 2021, Vol 14, Page 351 14:351. https://doi.org/10.3390/MA14020351

133. Chinnu SN, Minnu SN, Bahurudeen A, Senthilkumar R (2021) Reuse of industrial and agricultural by-products as pozzolan and aggregates in lightweight concrete. Constr Build Mater 302:124172. https://doi.org/10.1016/j.conbuildmat.2021.124172

134. Elahi MMA, Shearer CR, Naser Rashid Reza A, et al (2021) Improving the sulfate attack resistance of concrete by using

supplementary cementitious materials (SCMs): A review. Constr Build Mater 281:122628. https://doi.org/10.1016/J.CONBUILDMAT.2021.122628

135. Shanmuga Priya T, Mehra A, Jain S, Kakria K (2021) Effect of graphene oxide on high-strength concrete induced with rice husk ash: mechanical and durability performance. Innov Infrastruct Solut 6:. https://doi.org/10.1007/s41062-020-00378-9

136. Sai Bharadwaj D, Ramesh A (2021) An experimental study on strength development in concrete by incorporating rice husk ash as replacement to cement with recycled aggregate for low volume roads. In: Lecture Notes in Civil Engineering. Springer Science and Business Media Deutschland GmbH, pp 679–691

137. Singh B, Pathania A, Gupta M, et al (2021) Influence of the Packing Density of Fine Particles in Ternary, Quaternary and Quinary Blends on High Performance Concrete. In: RILEM Bookseries. Springer Science and Business Media B.V., pp 465–482

138. Gopalakrishnan R, Nithiyanantham S (2020) Microstructural, mechanical, and electrical properties of copper slag admixtured cement mortar. J Build Eng 31:101375. https://doi.org/10.1016/j.jobe.2020.101375

139. Bellum RR, Venkatesh C, Madduru SRC (2021) Influence of red mud on performance enhancement of fly ash-based geopolymer concrete. Innov Infrastruct Solut 2021 64 6:1–9. https://doi.org/10.1007/S41062-021-00578-X

140. Venkatesh C, Nerella R, Chand MSR (2020) Role of red mud as a cementing material in concrete: a comprehensive study on durability behavior. Innov Infrastruct Solut 2020 61 6:1–14. https://doi.org/10.1007/S41062-020-00371-2

141. Murmu M, Singh SP (2014) Influence of mineral admixtures on strength and hydration products of lime-activated slag cement.

Adv Cem Res 26:334–343. https://doi.org/10.1680/adcr.13.00042

142. Singh R, Goel S (2020) Experimental investigation on mechanical properties of binary and ternary blended pervious concrete. Front Struct Civ Eng 14:229–240. https://doi.org/10.1007/S11709-019-0597-4

143. Venkatesh C, Nerella R, Chand MSR (2020) Experimental investigation of strength, durability, and microstructure of red-mud concrete. J Korean Ceram Soc 2019 572 57:167–174. https://doi.org/10.1007/S43207-019-00014-Y

144. Srikanth J, Chidambaram N, Karthikeyan B, Dhinakaran G (2015) Resistance to Deterioration and Water Absorption by Ternary Blended Concrete with Ceramic Powder and SiO 2. Int J ChemTech Res CODEN 8:696–703

145. Balasubramanian B, Gopala Krishna GVT, Saraswathy V, Srinivasan K (2021) Experimental investigation on concrete partially replaced with waste glass powder and waste E-plastic. Constr Build Mater 278:122400. https://doi.org/10.1016/J.CONBUILDMAT.2021.122400

146. Debbarma S, Ransinchung G, Singh S (2020) Zinc Waste as a Substitute for Portland Cement in Roller-Compacted Concrete Pavement Mixes Containing RAP Aggregates. J Mater Civ Eng 32:04020207. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003278

147. Singh P, Ghosh CN, Behera SK, et al (2019) Optimisation of binder alternative for cemented paste fill in underground metal mines. Arab J Geosci 2019 1215 12:1–8. https://doi.org/10.1007/S12517-019-4623-6

148. Murali G, Fediuk R (2020) A Taguchi approach for study on impact response of ultra-high-performance polypropylene fibrous cementitious composite. J Build Eng 30:101301.

https://doi.org/10.1016/J.JOBE.2020.101301

149. Choudhary R, Gupta R, Nagar R, Jain A (2021) Mechanical and abrasion resistance performance of silica fume, marble slurry powder, and fly ash amalgamated high strength self-consolidating concrete. Constr Build Mater 269:121282. https://doi.org/10.1016/J.CONBUILDMAT.2020.121282

150. Murugesan T, Vidjeapriya R, Bahurudeen A (2021) Sustainable use of sugarcane bagasse ash and marble slurry dust in crusher sand based concrete. Struct Concr 22:. https://doi.org/10.1002/suco.202000215

151. Chand G, Happy SK, Ram S (2021) Assessment of the properties of sustainable concrete produced from quaternary blend of portland cement, glass powder, metakaolin and silica fume. Clean Eng Technol 4:100179. https://doi.org/10.1016/J.CLET.2021.100179

152. Roy R, Mitra A, Ganesh AT, Sairam V (2018) Effect of Graphene Oxide Nanosheets dispersion in cement mortar composites incorporating Metakaolin and Silica Fume. Constr Build Mater 186:514–524. https://doi.org/10.1016/J.CONBUILDMAT.2018.07.135

153. Vivek SS (2021) Performance of ternary blend SCC with ground granulated blast furnace slag and metakaolin. Mater Today Proc. https://doi.org/10.1016/J.MATPR.2021.06.422

154. Pillai RG, Gettu R, Santhanam M, et al (2019) Service life and life cycle assessment of reinforced concrete systems with limestone calcined clay cement (LC3). Cem Concr Res 118:111–119. https://doi.org/10.1016/j.cemconres.2018.11.019

155. Singh M, Srivastava A, Bhunia D (2019) Analytical and Experimental Investigations on Using Waste Marble Powder in Concrete. J Mater Civ Eng 31:04019011. https://doi.org/10.1061/(asce)mt.1943-5533.0002631

156. Ashish DK (2019) Concrete made with waste marble powder and supplementary cementitious material for sustainable development. J Clean Prod 211:716–729. https://doi.org/10.1016/j.jclepro.2018.11.245

157. Singh M, Srivastava A, Bhunia D (2019) Long term strength and durability parameters of hardened concrete on partially replacing cement by dried waste marble powder slurry. Constr Build Mater 198:553–569. https://doi.org/10.1016/j.conbuildmat.2018.12.005

158. Vediyappan S, Chinnaraj PK, Hanumantraya BB, Subramanian SK (2021) An Experimental Investigation on Geopolymer Concrete Utilising Micronized Biomass Silica and GGBS. KSCE J Civ Eng 25:2134–2142. https://doi.org/10.1007/s12205-021-1477-8

159. Matsagar V (2015) Advances in Structural Engineering. Springer India, New Delhi

160. Sharma A, Jha BC, Mahanta A, Das A (2020) A Case Study on Sustainable Iron Ore Tailing Management Using Paste Technology. Trans Indian Natl Acad Eng 5:593–601. https://doi.org/10.1007/s41403-020-00097-8

161. Muhmood L, Vitta S, Venkateswaran D (2009) Cementitious and pozzolanic behavior of electric arc furnace steel slags. Cem Concr Res 39:102–109. https://doi.org/10.1016/j.cemconres.2008.11.002

162. Palod R, Deo S V., Ramtekkar GD (2019) Utilization of waste from steel and iron industry as replacement of cement in mortars. J Mater Cycles Waste Manag 21:1361–1375. https://doi.org/10.1007/s10163-019-00889-3

163. Singh SK, Jyoti, Vashistha P (2021) Development of newer composite cement through mechano-chemical activation of steel slag. Constr Build Mater 268:121147. https://doi.org/10.1016/j.conbuildmat.2020.121147

164. Saloni, Parveen, Yan Lim Y, Pham TM (2021) Influence of Portland cement on performance of fine rice husk ash geopolymer concrete: Strength and permeability properties. Constr Build Mater 300:124321. https://doi.org/10.1016/j.conbuildmat.2021.124321

165. Sahoo S, Parhi PK, Chandra Panda B (2021) Durability properties of concrete with silica fume and rice husk ash. Clean Eng Technol 2:100067. https://doi.org/10.1016/j.clet.2021.100067

166. Lekshmi MS, Vishnudas S, Anil KR (2021) Lignocellulosic materials as reinforcement and replacement for binders in masonry mortar. Constr Build Mater 282:122607. https://doi.org/10.1016/j.conbuildmat.2021.122607

167. Sandhu RK, Siddique R (2022) Properties of sustainable self-compacting concrete made with rice husk ash. Eur J Environ Civ Eng 26:6670–6694. https://doi.org/10.1080/19648189.2021.1955747

168. Kanthe VN, Deo S V., Murmu M (2018) Effect of fly ash and rice husk ash on strength and durability of binary and ternary blend cement mortar. Asian J Civ Eng 19:963–970. https://doi.org/10.1007/s42107-018-0076-6

169. Kannan V, Ganesan K (2016) Effect of Tricalcium Aluminate on Durability Properties of Self-Compacting Concrete Incorporating Rice Husk Ash and Metakaolin. J Mater Civ Eng 28:04015063. https://doi.org/10.1061/(asce)mt.1943-5533.0001330

170. Choudhary R, Gupta R, Nagar R (2020) Impact on fresh, mechanical, and microstructural properties of high strength self-compacting concrete by marble cutting slurry waste, fly ash, and silica fume. Constr Build Mater 239:117888. https://doi.org/10.1016/j.conbuildmat.2019.117888

171. Singh M, Srivastava A, Bhunia D (2017) An investigation on effect of partial replacement of cement by waste marble slurry.

Constr Build Mater 134:471–488. https://doi.org/10.1016/j.conbuildmat.2016.12.155

172. Jena T, Panda KC (2021) Strength and Sorptivity of Concrete Using Fly Ash and Silpozz in Marine Environment. In: Lecture Notes in Civil Engineering. Springer, pp 625–639

173. Panda R, Sahoo TK (2021) Effect of Replacement of GGBS and Fly Ash with Cement in Concrete. In: Lecture Notes in Civil Engineering. Springer, pp 811–818

174. Singh RB, Debbarma S, Kumar N, Singh S (2021) Hardened state behaviour of self-compacting concrete pavement mixes containing alternative aggregates and secondary binders. Constr Build Mater 266:120624. https://doi.org/10.1016/j.conbuildmat.2020.120624

175. Reddy AN, Reddy PN, Kavyateja BV, Reddy GGK (2020) Influence of nanomaterial on high-volume fly ash concrete: a statistical approach. Innov Infrastruct Solut 5:88. https://doi.org/10.1007/s41062-020-00340-9

176. Shaw SK, Sil A (2020) Experimental study on cyclic loading characteristics of fly ash as partial replacement of cement in beam-column joint. Case Stud Constr Mater 13:e00362. https://doi.org/10.1016/j.cscm.2020.e00362

177. Farsana C, Das BB, Snehal K (2021) Influence of Fineness of Mineral Admixtures on the Degree of Atmospheric Mineral Carbonation. In: Lecture Notes in Civil Engineering. Springer Science and Business Media Deutschland GmbH, pp 117–136

178. Isanaka BR, Akbar MA, Perumal P, Priyanka RS (2021) High performance concrete mixed with combinations of mineral admixtures. In: Lecture Notes in Civil Engineering. Springer Science and Business Media Deutschland GmbH, pp 563–572

179. Venkatesh C, Sri Rama Chand M, Ruben N, Sonali Sri Durga C

(2021) Strength Characteristics of Red Mud and Silica Fume Based Concrete. In: Lecture Notes in Civil Engineering. Springer Science and Business Media Deutschland GmbH, pp 387–393

180. Mohanty T, Patra BN, Saha P (2021) Durability Properties of Self-compacting Concrete Using Silica Fume. In: Lecture Notes in Civil Engineering. Springer, pp 789–801

181. Sindhu S, Praveenkumar S, Sankarasubramanian G (2021) Evaluation of Pozzolanic Performance of Treated and Untreated Bagasse Ash. In: Lecture Notes in Civil Engineering. Springer Science and Business Media Deutschland GmbH, pp 359–367

182. Meshram SS, Raut SP (2021) Utilization of Cupola Slag as a Sustainable Construction Material. In: Lecture Notes in Civil Engineering. Springer Science and Business Media Deutschland GmbH, pp 43–49

183. Ashish DK (2018) Feasibility of waste marble powder in concrete as partial substitution of cement and sand amalgam for sustainable growth. J Build Eng 15:236–242. https://doi.org/10.1016/j.jobe.2017.11.024

184. IS 10262 (2019) Concrete mix proportioning- guidelines. Bureau of Indian Standards, Manak Bhawan, New Delhi

185. Jiang L, Lai X, Jiao H (2020) Concrete relative velocity prediction to prevent mortar segregation for safe gravity transportation. Alexandria Eng J 59:5155–5164. https://doi.org/10.1016/j.aej.2020.09.045

186. Bentz DP, Ferraris CF, Galler MA, et al (2012) Influence of particle size distributions on yield stress and viscosity of cement-fly ash pastes. Cem Concr Res 42:404–409. https://doi.org/10.1016/j.cemconres.2011.11.006

187. Singh LP, Goel A, Bhattachharyya SK, et al (2015) Effect of Morphology and Dispersibility of Silica Nanoparticles on the

Mechanical Behaviour of Cement Mortar. Int. J. Concr. Struct. Mater. 9:207–217

188. Kim D (2018) Effect of Adjusting for Particle-Size Distribution of Cement on Strength Development of Concrete. Adv Mater Sci Eng 2018:1–6. https://doi.org/10.1155/2018/1763524

189. Sevim O, Demir I (2016) Particle size optimization of fly ash. In: International Conference on Science, Technology, Engineering and Management (ICSTEM). Rome, Italy

190. BIS (2013) IS 3812-2 (2013): Specification for Pulverized Fuel Ash, Part 2: For Use as Admixture in Cement Mortar and Concrete

191. BIS (1987) IS 12089 (1987): Specification for granulated slag for the manufacture of Portland slag cement

192. BIS (2003) IS 15388 (2003): Silica fume - specification

193. Chethan KB, Yaragal SC, Das BB (2020) Ferrochrome ash – Its usage potential in alkali activated slag mortars. J Clean Prod 257:120577. https://doi.org/10.1016/j.jclepro.2020.120577

194. Gupta T, Sachdeva SN (2020) Study of mechanical, micro-structural and environmental properties of concrete containing zinc industry waste for pavements. Constr Build Mater 245:118331. https://doi.org/10.1016/J.CONBUILDMAT.2020.118331

195. Ray S, Daudi L, Yadav H, Ransinchung GD (2020) Utilization of Jarosite waste for the development of sustainable concrete by reducing the cement content. J Clean Prod 272:122546. https://doi.org/10.1016/J.JCLEPRO.2020.122546

196. Acharya PK, Patro SK (2015) Effect of lime and ferrochrome ash (FA) as partial replacement of cement on strength, ultrasonic pulse velocity and permeability of concrete. Constr Build Mater 94:448–457.

https://doi.org/10.1016/J.CONBUILDMAT.2015.07.081

197. Patel D, Shrivastava R, Tiwari RP, Yadav RK (2021) The role of glass powder in concrete with respect to its engineering performances using two closely different particle sizes. Struct Concr 22:E228–E244. https://doi.org/10.1002/SUCO.201900182

198. Jain KL, Sancheti G, Gupta LK (2020) Durability performance of waste granite and glass powder added concrete. Constr Build Mater 252:119075. https://doi.org/10.1016/J.CONBUILDMAT.2020.119075

199. Raut AN, Gomez CP (2020) Utilization of Glass Powder and Oil Palm Fibers to Develop Thermally Efficient Blocks. Arab J Sci Eng 2020 455 45:3959–3972. https://doi.org/10.1007/S13369-019-04316-5

200. S. BH, A RB, Raj CL, Sowmya (2020) Performance Of The Concrete Containing Waste Glass Powder As Partial Replacement. Int J Sci Technol Res 9:6681–6685

201. Kumar VP, Reddy KC (2017) Durability aspects of concrete by partial replacement of cement by ceramic waste. Int J Civ Eng Technol 8:22–30

202. Atkuri VK, Rama Rao G V (2021) Strength properties of ceramic waste concrete. IOP Conf Ser Mater Sci Eng 1025:012017. https://doi.org/10.1088/1757-899X/1025/1/012017

203. Goswami S, Shukla DK, Singh PK (2021) Sustainable transformation of sewage sludge ash and waste industrial additive into green cement blend. Struct Concr. https://doi.org/10.1002/suco.202100120

204. Reddy KR, Agnihotri AK, Yukselen-Aksoy Y, et al (2021) Sustainable Environment and Infrastructure. Springer International Publishing, Cham

205. Vashistha P, Singh ; S K, Kumar V (2020) Sustainable Utilization

of Paper-Industry Lime Sludge through Development of Metakaolinite-Based Cementitious Binder. https://doi.org/10.1061/(ASCE)MT.1943

206. Agarwal SK, Pahuja A, Ali MM, et al (2015) Mineralising effect of jarosite: A zinc industry by-product in the manufacturing of cement. Adv Cem Res 27:248–258. https://doi.org/10.1680/adcr.13.00102

207. Soumya Pradhan S, Chandra Panda K (2020) Studies on influence of mineral admixture on mechanical properties of CC and SCC. IOP Conf Ser Mater Sci Eng 970:. https://doi.org/10.1088/1757-899X/970/1/012007

208. Sabat L, Pradhan SS (2020) Experimental evaluation of a composite material using GFRC. Mater Today Proc 21:1330–1334. https://doi.org/10.1016/j.matpr.2020.01.170

209. Roslan NH, Ismail M, Abdul-Majid Z, et al (2016) Performance of steel slag and steel sludge in concrete. Constr Build Mater 104:16–24. https://doi.org/10.1016/j.conbuildmat.2015.12.008

210. Palod R, Deo S V., Ramtekkar GD (2020) Sustainable Approach for Linz-Donawitz Slag Waste as a Replacement of Cement in Concrete: Mechanical, Microstructural, and Durability Properties. Adv Civ Eng 2020:1–9. https://doi.org/10.1155/2020/5691261

211. Saxena SK, Kumar M, Chundawat DS, Singh NB (2019) Utilization of wollastonite in cement manufacturing. Mater Today Proc 29:733–737. https://doi.org/10.1016/j.matpr.2020.04.502

212. Das S, Patra RK, Mukharjee BB (2021) Feasibility study of utilisation of ferrochrome slag as fine aggregate and rice husk ash as cement replacement for developing sustainable concrete. Innov Infrastruct Solut 6:1–18. https://doi.org/10.1007/s41062-021-00461-9

213. Parashar AK, Gupta N, Kishore K, Nagar PA (2021) An experimental investigation on mechanical properties of calcined clay concrete embedded with bacillus subtilis. Mater Today Proc 44:129–134. https://doi.org/10.1016/j.matpr.2020.08.031

214. Gill AS, Siddique R (2018) Durability properties of self-compacting concrete incorporating metakaolin and rice husk ash. Constr Build Mater 176:323–332. https://doi.org/10.1016/j.conbuildmat.2018.05.054

215. Imam A, Kumar V, Srivastava V (2018) Empirical predictions for the mechanical properties of Quaternary Cement Concrete. J Struct Integr Maint 3:183–196. https://doi.org/10.1080/24705314.2018.1492668

216. Siddique S, Jang JG, Gupta T (2021) Developing marble slurry as supplementary cementitious material through calcination: Strength and microstructure study. Constr Build Mater 293:123474. https://doi.org/10.1016/j.conbuildmat.2021.123474

217. Saha S, Mohanty T, Saha P (2021) Mechanical Properties of Fly Ash and Ferrochrome Ash-Based Geopolymer Concrete Using Recycled Aggregate. In: Lecture Notes in Civil Engineering. Springer, pp 417–426

218. Varadharajan S, Jaiswal A, Verma S (2020) Assessment of mechanical properties and environmental benefits of using rice husk ash and marble dust in concrete. Structures 28:389–406. https://doi.org/10.1016/j.istruc.2020.09.005

219. Yu J, Wu HL, Mishra DK, et al (2021) Compressive strength and environmental impact of sustainable blended cement with high-dosage Limestone and Calcined Clay (LC2). J Clean Prod 278:123616. https://doi.org/10.1016/j.jclepro.2020.123616

220. Jeyalakshmi R, Gopalakrishnan R, Katyal D (2020) Effect of colloidal nanosilica as an admixture on chloride ion diffusion of Portland cement–fly ash mortars. J Aust Ceram Soc 56:1217–

1228. https://doi.org/10.1007/s41779-020-00463-3

221. Lothenbach B, Kulik DA, Matschei T, et al (2019) Cemdata18: A chemical thermodynamic database for hydrated Portland cements and alkali-activated materials. Cem Concr Res 115:472–506. https://doi.org/10.1016/j.cemconres.2018.04.018

222. Ding Q, Yang J, Zhang G, Hou D (2018) Effect of magnesium on the C-S-H nanostructure evolution and aluminate phases transition in cement-slag blend. J Wuhan Univ Technol Mater Sci Ed 33:108–116. https://doi.org/10.1007/s11595-018-1794-z

223. Rößler C, Steiniger F, Ludwig HM (2017) Characterization of C–S–H and C–A–S–H phases by electron microscopy imaging, diffraction, and energy dispersive X-ray spectroscopy. J Am Ceram Soc 100:1733–1742. https://doi.org/10.1111/jace.14729

224. Pacewska B, Wilińska I (2020) Usage of supplementary cementitious materials: advantages and limitations Part I. C-S-H, C-A-S-H and other products formed in different binding mixtures. J Therm Anal Calorim 142:371–393. https://doi.org/10.1007/s10973-020-09907-1

225. Krishnan S, Bishnoi S (2020) A numerical approach for designing composite cements with calcined clay and limestone. Cem Concr Res 138:106232. https://doi.org/10.1016/j.cemconres.2020.106232

226. Puertas F, Palacios M, Manzano H, et al (2014) C-A-S-H gels formed in alkali-activated slag cement pastes. Structure and effect on cement properties and durability. MATEC Web Conf 11:. https://doi.org/10.1051/matecconf/20141101002

227. Berenguer R, Lima N, Pinto L, et al (2021) Cement-based materials: Pozzolanic activities of mineral additions are compromised by the presence of reactive oxides. J Build Eng 41:102358. https://doi.org/10.1016/J.JOBE.2021.102358

228. Bhagath Singh GVP, Subramaniam KVL (2019) Production and characterization of low-energy Portland composite cement from post-industrial waste. J Clean Prod 239:118024. https://doi.org/10.1016/j.jclepro.2019.118024

229. Singh M, Garg M (1999) Cementitious binder from fly ash and other industrial wastes. Cem Concr Res 29:309–314. https://doi.org/10.1016/S0008-8846(98)00210-5

230. Ali MM, Agarwal SK, Pahuja A (2013) Potentials of copper slag utilisation in the manufacture of ordinary Portland cement. Adv Cem Res 25:208–216. https://doi.org/10.1680/adcr.12.00004

231. Singh M, Upadhayay SN, Prasad PM (1997) Preparation of special cements from red mud. Waste Manag 16:

232. Gunjal SM, Kondraivendhan B (2020) Study on Fresh and Harden Properties of Limestone Calcined Clay Cement (LC<Superscript>3</Superscript>) Production by Marble Stone Powder. RILEM Bookseries 25:535–543. https://doi.org/10.1007/978-981-15-2806-4_60

233. Li Z, Afshinnia K, Rangaraju PR (2016) Effect of alkali content of cement on properties of high performance cementitious mortar. Constr Build Mater 102:631–639. https://doi.org/10.1016/J.CONBUILDMAT.2015.10.110

234. Multon S, Cyr M, Sellier A, et al (2010) Effects of aggregate size and alkali content on ASR expansion. Cem Concr Res 40:508–516. https://doi.org/10.1016/J.CEMCONRES.2009.08.002

235. Tech JAB, Chauhan A, Chauhan P (2015) Usage of Powder XRD Technique for Material Characterization and Analysis of Portland Cement. J Anal Bioanal Tech 6:1–3. https://doi.org/10.4172/2155-9872.1000e123

236. Glosser D, Suraneni P, Isgor OB, Weiss WJ (2021) Using glass content to determine the reactivity of fly ash for thermodynamic

calculations. Cem Concr Compos 115:103849. https://doi.org/10.1016/J.CEMCONCOMP.2020.103849

237. Pandey A, Kumar B (2019) Preliminary study of cement paste admixed with rice straw ash, microsilica & rice straw ash-microsilica composite. Int J Recent Technol Eng 7:302–307

238. Singh J, Singh SP (2019) Development of Alkali-activated Cementitious Material using Copper Slag. Constr Build Mater 211:73–79. https://doi.org/10.1016/j.conbuildmat.2019.03.233

239. Rathan Raj R, Brijitta J, Ramachandran D, Perumal Pillai EB (2019) Microstructure Evolution in Ordinary Portland Cement–Metakaolin–Red Mud-Based Ternary Blended Cement. J Inst Eng Ser A 2019 1004 100:707–718. https://doi.org/10.1007/S40030-019-00398-4

240. Mehra P, Gupta RC, Thomas BS (2016) Assessment of durability characteristics of cement concrete containing jarosite. J Clean Prod 119:59–65. https://doi.org/10.1016/J.JCLEPRO.2016.01.055

241. Ali MM, Singh BK, Agarwal SK, et al (2014) Utilisation of by-product jarosite in the manufacture of ordinary Portland cement. Adv Cem Res 26:41–51. https://doi.org/10.1680/adcr.12.00063

242. Jena T, Panda KC (2018) Mechanical and durability properties of marine concrete using fly ash and silpozz. Adv Concr Constr 6:47–68. https://doi.org/10.12989/acc.2018.6.1.047

243. Siddique S, Shrivastava S, Chaudhary S (2019) Influence of ceramic waste on the fresh properties and compressive strength of concrete. Eur J Environ Civ Eng 23:212–225. https://doi.org/10.1080/19648189.2016.1275985

244. Ma J, Wang D, Zhao S, et al (2021) Influence of particle morphology of ground fly ash on the fluidity and strength of cement paste. Materials (Basel) 14:1–18.

https://doi.org/10.3390/ma14020283

245. Li Z, Gao X, Lu D, Dong J (2022) Early hydration properties and reaction kinetics of multi-composite cement pastes with supplementary cementitious materials (SCMs). Thermochim Acta 709:179157. https://doi.org/10.1016/j.tca.2022.179157

246. Juilland P, Nicoleau L, Arvidson RS, Gallucci E (2017) Advances in dissolution understanding and their implications for cement hydration. RILEM Tech Lett 2:90–98. https://doi.org/10.21809/rilemtechlett.2017.47

247. Bagheri M, Lothenbach B, Shakoorioskooie M, Scrivener K (2022) Effect of different ions on dissolution rates of silica and feldspars at high pH. Cem Concr Res 152:106644. https://doi.org/10.1016/j.cemconres.2021.106644

248. Romano RCO, Bernardo HM, Maciel MH, et al (2018) Hydration of Portland cement with red mud as mineral addition. J Therm Anal Calorim 131:2477–2490. https://doi.org/10.1007/s10973-017-6794-2

249. Ogoro E, Holmes N, Kelliher D (2020) Predicting Mortar Compressive Strength Using HYDCEM. In: Ruane K, Jaksic V, Ghosh B, et al (eds) Civil Engineering Research in Ireland. Civil Engineering Research Association of Ireland, Ireland

250. Zhao W, Ji X, Jiang Y, Pan T (2021) Effect of C-S-H nucleating agent on cement hydration. Appl Sci 11:1–14. https://doi.org/10.3390/app11146638

251. Ouyang X, Koleva DA, Ye G, van Breugel K (2017) Insights into the mechanisms of nucleation and growth of C–S–H on fillers. Mater Struct 50:213. https://doi.org/10.1617/s11527-017-1082-y

252. Verma NK (2021) Influence of partial replacement of cement by industrial wastes on properties of concrete. In: Lecture Notes in Civil Engineering. Springer Science and Business Media

Deutschland GmbH, pp 693–713

253. Bajad MN (2019) Conglasscrete with EPCO KP-200. Int J Innov Technol Explor Eng 8:180–184. https://doi.org/10.35940/ijitee.K1275.0981119

254. Vardhan K, Goyal S, Siddique R, Singh M (2015) Mechanical properties and microstructural analysis of cement mortar incorporating marble powder as partial replacement of cement. Constr Build Mater 96:615–621. https://doi.org/10.1016/j.conbuildmat.2015.08.071

255. Ransinchung GD, Kumar B, Kumar V (2009) Assessment of water absorption and chloride ion penetration of pavement quality concrete admixed with wollastonite and microsilica. Constr Build Mater 23:1168–1177. https://doi.org/10.1016/j.conbuildmat.2008.06.011

256. Lalitha Devi G, Srinivasa Pasad K, Rani MS, Bhanu L (2019) Strength and durability research on concrete with partial replacement of cement by rice husk ash and spent bleaching earth. Int J Recent Technol Eng 8:1035–1040. https://doi.org/10.35940/ijrte.B1174.0982S1119

257. Padhi RS, Patra RK, Mukharjee BB, Dey T (2018) Influence of incorporation of rice husk ash and coarse recycled concrete aggregates on properties of concrete. Constr Build Mater 173:289–297. https://doi.org/10.1016/j.conbuildmat.2018.03.270

258. Kannan V (2018) Strength and durability performance of self compacting concrete containing self-combusted rice husk ash and metakaolin. Constr Build Mater 160:169–179. https://doi.org/10.1016/j.conbuildmat.2017.11.043

259. Praveenkumar S, Sankarasubramanian G, Sindhu S (2020) Strength, permeability and microstructure characterization of pulverized bagasse ash in cement mortars. Constr Build Mater 238:117691. https://doi.org/10.1016/j.conbuildmat.2019.117691

260. Kumar VVP, Prasad DR (2019) Study on strength and durability characteristics of lime sludge based blended cement concrete. J Build Pathol Rehabil 4:2. https://doi.org/10.1007/s41024-018-0041-5

261. Ransinchung R. N. GD, Kumar B (2010) Investigations on Pastes and Mortars of Ordinary Portland Cement Admixed with Wollastonite and Microsilica. J Mater Civ Eng 22:305–313. https://doi.org/10.1061/(asce)mt.1943-5533.0000019

262. Y B R, Y RR, Hossiney N, H T D (2021) Properties of high strength concrete with reduced amount of Portland cement– a case study. Cogent Eng 8:. https://doi.org/10.1080/23311916.2021.1938369

263. Vittalaiah A, Ravinder R, Vivek Kumar C (2020) Study on effect of strength and durability parameters and performance of Self Compacting Concrete replacement with GGBS at different dosages. E3S Web Conf 184:2–6. https://doi.org/10.1051/e3sconf/202018401106

264. Mani S, Murugan A, Ponnusamy R (2020) Study on behaviour of GGBS as partial replacement of cement in concrete with addition of polycarboxylate ether. AIP Conf Proc 2240:. https://doi.org/10.1063/5.0011112

265. Chandak MA, Pawade PY (2020) Compressive strength and ultrasonic pulse velocity of concrete with metakaolin. Civ Eng Archit 8:1277–1282. https://doi.org/10.13189/cea.2020.080611

266. Mukesh TS, Shobakiruthika RK, Sowmini S, Subaash M (2021) Performance of additive blended high volume fly ash concrete-a systematic literature study. Mater Res Proc 19:181–190. https://doi.org/10.21741/9781644901618-23

267. Thiyagarajan H, Mapa M, Kushwaha R (2018) Investigation on the Rheological Behavior of Fly Ash Cement Composites at Paste and Concrete Level. J Inst Eng Ser A 99:295–301.

https://doi.org/10.1007/s40030-018-0284-9

268. Khan RA, Haq M (2020) Long-term mechanical and statistical characteristics of binary- and ternary-blended concrete containing rice husk ash, metakaolin and silica fume. Innov Infrastruct Solut 5:1–14. https://doi.org/10.1007/s41062-020-00303-0

269. Anwar A (2016) The Influence of Waste Glass Powder As A Pozzolanic Material In Concrete. Int J Civ Eng Technol 7:131–148

270. Velayutham K, T S, V V, et al (2015) Strength characteristics on concrete with ceramic waste as a partial replacement of cement. J Chem Pharm Sci 8:793–797

271. Krishna AS, Krishna EV, Kumar SY, et al (2020) Experimental investigation of fiber reinforced concrete using septage ash. IOP Conf Ser Mater Sci Eng 872:012177. https://doi.org/10.1088/1757-899X/872/1/012177

272. Pawar PM, Ronge BP, Balasubramaniam R, et al (2020) Techno-Societal 2018. Springer International Publishing, Cham

273. Priya AK, Nithya M, Rajeswari M, et al (2016) Experimental Investigation on Developing Low Cost Concrete by Partial Replacement of Waste Sludge. Int J ChemTech Res 9:240–247

274. Raghunath PN, Suguna K, Karthick J, Sarathkumar B (2019) Mechanical and durability characteristics of marble-powder-based high-strength concrete. Sci Iran 26:3159–3164. https://doi.org/10.24200/sci.2018.4953.1005

275. Agarwal A, Bhusnur S, Chaudhary K, Shanmuga Priya T (2019) Experimental Investigation on Bacterial Concrete with Micronized Biomass Silica. Mater Today Proc 22:2475–2481. https://doi.org/10.1016/j.matpr.2020.03.375

276. Kalla P, Rana A, Chad YB, et al (2015) Durability studies on

concrete containing wollastonite. J Clean Prod 87:726–734. https://doi.org/10.1016/j.jclepro.2014.10.038

277. Banu SS, Kartikeyan J, Jayabalan P (2020) Influence of using agro-waste as a partial replacement in cement on the compressive strength of concrete – A statistical approach. Constr Build Mater 250:118746. https://doi.org/10.1016/j.conbuildmat.2020.118746

278. Gobinath R, Awoyera PO, Praveen N, et al (2020) Effects of calcined clay on the engineering properties of cementitious mortars. Mater Today Proc 39:110–113. https://doi.org/10.1016/j.matpr.2020.06.322

279. Bishnoi S (2020) RILEM Bookseries Calcined Clays for Sustainable Concrete Proceedings of the 3rd International Conference on Calcined Clays for Sustainable Concrete

280. Singh M, Garg M (2006) Reactive pozzolana from Indian clays-their use in cement mortars. Cem Concr Res 36:1903–1907. https://doi.org/10.1016/j.cemconres.2004.12.002

281. Sudha P, Selvaraj R, Palanisamy T (2015) Intensification of calcined clay as a pozzolanic material in cement mortar. Int J Appl Eng Res 10:35640–35644

282. Jain N (2012) Effect of nonpozzolanic and pozzolanic mineral admixtures on the hydration behavior of ordinary Portland cement. Constr Build Mater 27:39–44. https://doi.org/10.1016/j.conbuildmat.2011.08.006

283. Kalla P, Misra A, Gupta RC, et al (2013) Mechanical and durability studies on concrete containing wollastonite-fly ash combination. Constr Build Mater 40:1142–1150. https://doi.org/10.1016/j.conbuildmat.2012.09.102

284. Sahoo S, Priyadarshini N, Kumar N, et al (2021) Simultaneous Optimization of Strength and Acid Resistance in Concrete Composed of Carbonated Fly Ash. In: Lecture Notes in Civil

Engineering. Springer, pp 687–698

285. Udgata G, Bhowmik P, Das SP (2021) Effect of Lime on Mechanical Properties of Silica Fume Modified Concrete. In: Lecture Notes in Civil Engineering. Springer, pp 649–657

286. Vaghela KB, Pitroda JR (2021) To investigate the impact of ceramic tile powder on concrete properties. Int J Eng Trends Technol 69:11–16. https://doi.org/10.14445/22315381/IJETT-V69I8P202

287. Parthasarathi N, Prakash M, Satyanarayanan KS (2017) Experimental study on partial replacement of cement with egg shell powder and silica fume. Rasayan J Chem 10:442–449. https://doi.org/10.7324/RJC.2017.1021689

288. Bhavani Chowdary T, Teja J (2020) Pragmatic studies on automated properties of High Efficiency Concrete. J Phys Conf Ser 1451:012020. https://doi.org/10.1088/1742-6596/1451/1/012020

289. Kumar M, Siddharth B, Maneeth PD (2019) Potential utilization of micro silica as a limited substitution with addition of glass and polypropylene fiber for M40 concrete. Int J Innov Technol Explor Eng 8:4961–4967. https://doi.org/10.35940/ijitee.L3742.1081219

290. Rao MK, Kumar CNS (2021) Influence of fly ash on hydration compounds of high-volume fly ash concrete. AIMS Mater Sci 8:301–320. https://doi.org/10.3934/matersci.2021020

291. Zhang Y, Xu S, Fang Z, et al (2020) Permeability of Concrete and Correlation with Microstructure Parameters Determined by 1 H NMR. Adv Mater Sci Eng 2020:1–11. https://doi.org/10.1155/2020/4969680

292. Ashok Kumar N, Velayutham T (2019) Experimental research on rice husk ash as replacement to cement in construction industry.

Int J Recent Technol Eng 8:1197–1200. https://doi.org/10.35940/ijrte.B1037.0882S819

293. Parmar S, Das SK (2021) Effect of marble slurry as a partial substitution of ordinary Portland cement in lean concrete mixes. Struct Concr 22:E514–E527. https://doi.org/10.1002/suco.202000059

294. Mahendra B, Reddy TA, Kumar PR, Harish T (2018) Partial replacement of cement and fine aggregate with metakaolin and manufactured sand. Int J Civ Eng Technol 9:9–15

295. Gaddam K (2021) Sustainability Studies on Concrete Partial Replacement of Sugarcane Granular Bagasse-ash in Cement. IOP Conf Ser Earth Environ Sci 822:. https://doi.org/10.1088/1755-1315/822/1/012037

296. Kumar B, Tike GK, Nanda PK (2007) Evaluation of Properties of High-Volume Fly-Ash Concrete for Pavements. J Mater Civ Eng 19:906–911. https://doi.org/10.1061/(ASCE)0899-1561(2007)19:10(906)

297. Ganesan K, Rajagopal K, Thangavel K (2008) Rice husk ash blended cement: Assessment of optimal level of replacement for strength and permeability properties of concrete. Constr Build Mater 22:1675–1683. https://doi.org/10.1016/j.conbuildmat.2007.06.011

298. Jittin V, Bahurudeen A (2022) Evaluation of rheological and durability characteristics of sugarcane bagasse ash and rice husk ash based binary and ternary cementitious system. Constr Build Mater 317:125965. https://doi.org/10.1016/J.CONBUILDMAT.2021.125965

299. Choudhary R, Gupta R, Alomayri T, et al (2021) Permeation, corrosion, and drying shrinkage assessment of self-compacting high strength concrete comprising waste marble slurry and fly ash, with silica fume. Structures 33:971–985.

https://doi.org/10.1016/J.ISTRUC.2021.05.008

300. Dinakar P, Sahoo PK, Sriram G (2013) Effect of Metakaolin Content on the Properties of High Strength Concrete. Int J Concr Struct Mater 7:215–223. https://doi.org/10.1007/S40069-013-0045-0/FIGURES/11

301. Kalla P, Rana A, Chad YB, et al (2015) Durability studies on concrete containing wollastonite. J Clean Prod 87:726–734. https://doi.org/10.1016/J.JCLEPRO.2014.10.038

302. Krishnaraj L, Ravichandran PT, Kannan Rajkumar PR (2016) Investigation on Effectiveness of the Top Down Nanotechnology in Mechanical Activation of High Calcium Fly Ash in Mortar. Indian J Sci Technol 9:1–8. https://doi.org/10.17485/IJST/2016/V9I23/95860

303. Ekolu SO (2016) A review on effects of curing, sheltering, and CO2 concentration upon natural carbonation of concrete. Constr Build Mater 127:306–320. https://doi.org/10.1016/J.CONBUILDMAT.2016.09.056

304. You K, Jeong H, Hyung W (2014) Effects of Accelerated Carbonation on Physical Properties of Mortar. J Asian Archit Build Eng 13:217–221. https://doi.org/10.3130/jaabe.13.217

305. Woyciechowski P, Woliński P, Adamczewski G (2019) Prediction of Carbonation Progress in Concrete Containing Calcareous Fly Ash Co-Binder. Materials (Basel) 12:. https://doi.org/10.3390/MA12172665

306. Nisar N, Bhat JA (2020) Effect of Rice Husk Ash on the Carbonation Depth of Concrete under Different Curing Ages and Humidity Levels. J Mater Civ Eng 33:04020427. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003520

307. Pandey A, Kumar B (2020) Investigation on the effects of acidic environment and accelerated carbonation on concrete admixed

with rice straw ash and microsilica. J Build Eng 29:101125. https://doi.org/10.1016/j.jobe.2019.101125

308. Gautam L, Kumar Jain J, Jain A, Kalla P (2022) Valorization of bone-china ceramic powder waste along with granite waste in self-compacting concrete. Constr Build Mater 315:125730. https://doi.org/10.1016/J.CONBUILDMAT.2021.125730

309. Ashish DK (2019) Concrete made with waste marble powder and supplementary cementitious material for sustainable development. J Clean Prod 211:716–729. https://doi.org/10.1016/J.JCLEPRO.2018.11.245

310. Lenka S, Panda KC (2017) Effect of metakaolin on the properties of conventional and self compacting concrete. Adv Concr Constr 5:31–48. https://doi.org/10.12989/acc.2017.5.1.31

311. Svenum I-H, Ringdalen IG, Bleken FL, et al (2020) Structure, hydration, and chloride ingress in C-S-H: Insight from DFT calculations. Cem Concr Res 129:105965. https://doi.org/10.1016/j.cemconres.2019.105965

312. Glass GK, Reddy B, Buenfeld NR (2000) The participation of bound chloride in passive film breakdown on steel in concrete. Corros Sci 42:2013–2021. https://doi.org/10.1016/S0010-938X(00)00040-8

313. Rana A, Kalla P, Csetenyi LJ (2015) Sustainable use of marble slurry in concrete. J Clean Prod 94:304–311. https://doi.org/10.1016/J.JCLEPRO.2015.01.053

314. Wu Z, Wong HS, Buenfeld NR (2017) Transport properties of concrete after drying-wetting regimes to elucidate the effects of moisture content, hysteresis and microcracking. Cem Concr Res 98:136–154. https://doi.org/10.1016/j.cemconres.2017.04.006

315. Scherer GW (2015) Drying, Shrinkage, and Cracking of Cementitious Materials. Transp Porous Med 110:311–331.

https://doi.org/10.1007/s11242-015-0518-5

316. Saha AK, Sarker PK (2018) Durability of Mortar Incorporating Ferronickel Slag Aggregate and Supplementary Cementitious Materials Subjected to Wet–Dry Cycles. Int J Concr Struct Mater 12:1–12. https://doi.org/10.1186/S40069-018-0264-5/FIGURES/10

317. Jee AA, Pradhan B (2019) Durability of Fly Ash Added Reinforced Concrete in Chloride and Composite Chloride–Sulfate Environment. In: Lecture Notes in Civil Engineering. Springer Singapore, pp 773–785

318. Wang R, Hu Z, Li Y, et al (2022) Review on the deterioration and approaches to enhance the durability of concrete in the freeze–thaw environment. Constr Build Mater 321:126371. https://doi.org/10.1016/J.CONBUILDMAT.2022.126371

319. Grubeša IN, Markovi´cmarkovi´c B, Vračevi´c MV, et al (2019) materials Pore Structure as a Response to the Freeze/Thaw Resistance of Mortars. https://doi.org/10.3390/ma12193196

320. Dhinakaran G, Sreekanth B (2017) Physical, Mechanical and Durability properties of Ternary blend Concrete. Sci Iran 25:0–0. https://doi.org/10.24200/sci.2017.4210

321. Pal A (2018) Developing Low-Clinker Ternary Blends for Indian Cement Industry. J Inst Eng Ser A 2018 993 99:433–447. https://doi.org/10.1007/S40030-018-0309-4

322. Zhu H, Chen W, Cheng S, et al (2022) Low carbon and high efficiency limestone-calcined clay as supplementary cementitious materials (SCMs): Multi-indicator comparison with conventional SCMs. Constr Build Mater 341:127748. https://doi.org/10.1016/j.conbuildmat.2022.127748

323. Donmez I, Katlav M, Turk K (2023) Improvement of fresh and hardened properties of a sustainable HFRSCC using various

powders as multi-blended binders. https://doi.org/10.1016/j.conbuildmat.2023.130773

324. Wang L, Ur Rehman N, Curosu I, et al (2021) On the use of limestone calcined clay cement (LC3) in high-strength strain-hardening cement-based composites (HS-SHCC). Cem Concr Res 144:106421. https://doi.org/10.1016/J.CEMCONRES.2021.106421

325. Norouzi M, Chàfer M, Cabeza LF, et al (2021) Circular economy in the building and construction sector: A scientific evolution analysis. J Build Eng 44:102704. https://doi.org/10.1016/j.jobe.2021.102704

326. Biswas A, Chaudhary K, Singh R, et al (2021) Waste-Wise Cities: Best practices in municipal solid waste management. Centre for Science and Environment and NITI Aayog, New Delhi

327. López Ruiz LA, Roca Ramón X, Gassó Domingo S (2020) The circular economy in the construction and demolition waste sector – A review and an integrative model approach. J Clean Prod 248:119238. https://doi.org/10.1016/j.jclepro.2019.119238

328. Tam VWY, Soomro M, Evangelista ACJ (2018) A review of recycled aggregate in concrete applications (2000–2017). Constr Build Mater 172:272–292. https://doi.org/10.1016/j.conbuildmat.2018.03.240

329. Hoffmann C, Schubert S, Leemann A, Motavalli M (2012) Recycled concrete and mixed rubble as aggregates: Influence of variations in composition on the concrete properties and their use as structural material. Constr Build Mater 35:701–709. https://doi.org/10.1016/j.conbuildmat.2011.10.007

330. Ram VG, Kishore KC, Kalidindi SN (2020) Environmental benefits of construction and demolition debris recycling: Evidence from an Indian case study using life cycle assessment. J Clean Prod 255:120258.

https://doi.org/10.1016/J.JCLEPRO.2020.120258

331. Velardo P, Sáez del Bosque IF, Matías A, et al (2021) Properties of concretes bearing mixed recycled aggregate with polymer-modified surfaces. J Build Eng 38:102211. https://doi.org/10.1016/j.jobe.2021.102211

332. Wang R, Yu N, Li Y (2020) Methods for improving the microstructure of recycled concrete aggregate: A review. Constr Build Mater 242:118164. https://doi.org/10.1016/j.conbuildmat.2020.118164

333. Gong Y, Chen P, Lin Y, et al (2022) Improvement of recycled aggregate properties through a combined method of mechanical grinding and microbial-induced carbonate precipitation. Constr Build Mater 342:128093. https://doi.org/10.1016/j.conbuildmat.2022.128093

334. Prajapati R, Gettu R, Singh S (2021) Thermomechanical beneficiation of recycled concrete aggregates (RCA). Constr Build Mater 310:125200. https://doi.org/10.1016/j.conbuildmat.2021.125200

335. Al-Bayati HKA, Das PK, Tighe SL, Baaj H (2016) Evaluation of various treatment methods for enhancing the physical and morphological properties of coarse recycled concrete aggregate. Constr Build Mater 112:284–298. https://doi.org/10.1016/j.conbuildmat.2016.02.176

336. Gupta S, Singh D, Gupta T, Chaudhary S (2022) Effect of limestone calcined clay cement (LC 3) on the fire safety of concrete structures. Comput Concr 29:263. https://doi.org/10.12989/CAC.2022.29.4.263

337. Ahmed HM, Hefni MA, Ahmed HAM, et al (2022) Effect of Elevated Temperature on Rhyolitic Rocks' Properties. Materials (Basel) 15:3204. https://doi.org/10.3390/ma15093204

338. Ruviaro AS, Silvestro L, Pelisser F, et al (2022) Long-term effect of recycled aggregate on microstructure, mechanical properties, and CO2 sequestration of rendering mortars. Constr Build Mater 321:126357. https://doi.org/10.1016/j.conbuildmat.2022.126357

339. Pillai RG, Gettu R, Santhanam M, et al (2019) Service life and life cycle assessment of reinforced concrete systems with limestone calcined clay cement (LC3). Cem Concr Res 118:111–119. https://doi.org/10.1016/j.cemconres.2018.11.019

340. MPERC (2022) Aggregate Revenue Requirement for FY 2022-23 to FY 2026-27and Retail Supply Tariff Order for FY 2022-23. Madhya Pradesh Electricity Regulatory Commission, Bhopal

341. Committee on Energy (2019) Forty-Third Report on Hydro-power relating to the Ministry of Power. Lok Sabha Secretariat, New Delhi

342. IRENA (2020) Renewable Power Generation Costs in 2019. International Renewable Energy Agency, Abu Dhabi

343. Kashyap AC, Kesari JP (2014) Feasibility Study of a Solar Crematorium in India. Int J Res Sci Innov 1:1–9

344. WBCSD (2018) Low Carbon Technology Roadmap for the Indian Cement Sector : Status Review 2018. 52

345. Krishnan S, Bishnoi S (2020) A numerical approach for designing composite cements with calcined clay and limestone. Cem Concr Res 138:106232. https://doi.org/10.1016/j.cemconres.2020.106232

346. Scrivener K, Martirena F, Bishnoi S, Maity S (2018) Calcined clay limestone cements (LC3). Cem Concr Res 114:49–56. https://doi.org/10.1016/j.cemconres.2017.08.017

347. Lin RS, Han Y, Wang XY (2021) Macro–meso–micro experimental studies of calcined clay limestone cement (LC3) paste subjected to elevated temperature. Cem Concr Compos

116:103871. https://doi.org/10.1016/j.cemconcomp.2020.103871

348. Zhang D, Jaworska B, Zhu H, et al (2020) Engineered Cementitious Composites (ECC) with limestone calcined clay cement (LC3). Cem Concr Compos 114:103766. https://doi.org/10.1016/j.cemconcomp.2020.103766

349. McNamee M, Meacham B, van Hees P, et al (2019) IAFSS agenda 2030 for a fire safe world. Fire Saf J 110:102889. https://doi.org/10.1016/j.firesaf.2019.102889

350. Santarpia L, Bologna S, Ciancio V, et al (2019) Fire temperature based on the time and resistance of buildings—predicting the adoption of fire safety measures. Fire 2:1–12. https://doi.org/10.3390/fire2020019

351. Ghosh P, Konečný P, Lehner P, Tikalsky PJ (2017) Probabilistic time-dependent sensitivity analysis of HPC bridge deck exposed to chlorides. Comput Concr 19:305–313. https://doi.org/10.12989/cac.2017.19.3.305

352. Cai B, Hao L, Fu F (2020) Postfire reliability analysis of axial load bearing capacity of CFRP retrofitted concrete columns. Adv Concr Constr 10:289–299. https://doi.org/10.12989/acc.2020.10.4.289

353. Benýšek M, Štefan R, Procházka J (2020) Effect of fire model parameter variability on determination of fire resistance of concrete structural members. Solid State Phenom 309 SSP:208–215. https://doi.org/10.4028/www.scientific.net/SSP.309.208

354. NCRB (2021) Accidental Deaths & Suicides in India (ADSI) | National Crime Records Bureau. https://ncrb.gov.in/en/accidental-deaths-suicides-india-adsi. Accessed 15 Dec 2021

355. IS 1641 (2013) FIRE SAFETY OF BUILDINGS (GENERAL):

GENERAL PRINCIPLES OF FIRE GRADING AND CLASSIFICATION — CODE OF PRACTICE. New Delhi

356. SP 7 (2005) National Building Code of India 2005. Manak Bhawan, New Delhi

357. Ministry of Home Affairs (2001) Houselisting and Housing Census Data - 2011

358. Nas M, Kurbetci Ş (2018) Mechanical, durability and microstructure properties of concrete containing natural zeolite. Comput Concr 22:449–459. https://doi.org/10.12989/cac.2018.22.5.449

359. Ashish DK, Verma SK (2021) Robustness of self-compacting concrete containing waste foundry sand and metakaolin: A sustainable approach. J Hazard Mater 401:123329. https://doi.org/10.1016/j.jhazmat.2020.123329

360. EN 1991-1-7 (2006) Eurocode 1 - Actions on structures - Part 1-7: General actions - Accidental actions. European Union

361. Ashish DK, Verma SK (2019) Determination of optimum mixture design method for self-compacting concrete: Validation of method with experimental results. Constr Build Mater 217:664–678. https://doi.org/10.1016/j.conbuildmat.2019.05.034

362. Ashish DK, Verma SK (2019) Cementing Efficiency of Flash and Rotary-Calcined Metakaolin in Concrete. J Mater Civ Eng 31:04019307. https://doi.org/10.1061/(asce)mt.1943-5533.0002953

363. Yang H, Che Y, Leng F (2018) Calcium leaching behavior of cementitious materials in hydrochloric acid solution. Sci Rep 8:8806. https://doi.org/10.1038/s41598-018-27255-x

364. Liu X, Feng P, Yu X, Huang J (2022) Decalcification of calcium silicate hydrate (C-S-H) under aggressive solution attack. Constr Build Mater 342:127988.

https://doi.org/10.1016/j.conbuildmat.2022.127988

365. Akbarnezhad A, Ong KCG, Zhang MH, Tam CT (2013) Acid Treatment Technique for Determining the Mortar Content of Recycled Concrete Aggregates. J Test Eval 41:20120026. https://doi.org/10.1520/JTE20120026

366. Gupta T, Siddique S, Sharma RK, Chaudhary S (2017) Effect of elevated temperature and cooling regimes on mechanical and durability properties of concrete containing waste rubber fiber. Constr Build Mater 137:35–45. https://doi.org/10.1016/j.conbuildmat.2017.01.065

367. Ma Q, Guo R, Zhao Z, et al (2015) Mechanical properties of concrete at high temperature—A review. Constr Build Mater 93:371–383. https://doi.org/10.1016/j.conbuildmat.2015.05.131

368. Babalola OE, Awoyera PO, Le DH, Bendezú Romero LM (2021) A review of residual strength properties of normal and high strength concrete exposed to elevated temperatures: Impact of materials modification on behaviour of concrete composite. Constr Build Mater 296:123448. https://doi.org/10.1016/J.CONBUILDMAT.2021.123448

369. Gupta T, Patel KA, Siddique S, et al (2019) Prediction of mechanical properties of rubberised concrete exposed to elevated temperature using ANN. Meas J Int Meas Confed 147:106870. https://doi.org/10.1016/j.measurement.2019.106870

370. IS 13311-1 (1992) Method of Non-destructive testing of concret, Part 1: Ultrasonic pulse velocity. Bureau of Indian Standards, Manak Bhawan, New Delhi

371. Ez-Zaki H, Mwiti Marangu J, Bellotto M, et al (2021) materials A Fresh View on Limestone Calcined Clay Cement (LC 3) Pastes. https://doi.org/10.3390/ma14113037

372. Antoni M, Rossen J, Martirena F, Scrivener K (2012) Cement

substitution by a combination of metakaolin and limestone. Cem Concr Res 42:1579–1589. https://doi.org/10.1016/j.cemconres.2012.09.006

373. Hay R, Li L, Celik K (2022) Shrinkage, hydration, and strength development of limestone calcined clay cement (LC3) with different sulfation levels. Cem Concr Compos 127:104403. https://doi.org/10.1016/j.cemconcomp.2021.104403

374. Saridhe SP, Selvaraj T (2021) Reporting the ancient green construction technology of limecrete slabs adopted in Udaipur, Rajasthan. J Clean Prod 279:123682. https://doi.org/10.1016/j.jclepro.2020.123682

375. Krishnan S, Kanaujia SK, Mithia S, Bishnoi S (2018) Hydration kinetics and mechanisms of carbonates from stone wastes in ternary blends with calcined clay. Constr Build Mater 164:265–274. https://doi.org/10.1016/j.conbuildmat.2017.12.240

376. Chen Y, Romero Rodriguez C, Li Z, et al (2020) Effect of different grade levels of calcined clays on fresh and hardened properties of ternary-blended cementitious materials for 3D printing. Cem Concr Compos 114:. https://doi.org/10.1016/j.cemconcomp.2020.103708

377. Rodriguez C, Tobon JI (2020) Influence of calcined clay/limestone, sulfate and clinker proportions on cement performance. Constr Build Mater 251:119050. https://doi.org/10.1016/j.conbuildmat.2020.119050

378. Sahani AK, Samantaa AK, Roy DKS (2019) Influence of mineral by-products on compressive strength and microstructure of concrete at high temperature. Adv Concr Constr 7:263–275. https://doi.org/10.12989/acc.2019.7.4.263

379. Savva A, Manita P, Sideris KK (2005) Influence of elevated temperatures on the mechanical properties of blended cement concretes prepared with limestone and siliceous aggregates. Cem

Concr Compos 27:239–248. https://doi.org/10.1016/J.CEMCONCOMP.2004.02.013

380. Mohamedbhai GTG (1986) Effect of exposure time and rates of heating and cooling on residual strength of heated concrete. Mag Concr Res 38:151–158. https://doi.org/10.1680/macr.1986.38.136.151