Report on Activities of

Centre of Excellence on

Technologies for Low-Carbon & Lean Construction (TLC2)

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1 INTRODUCTION

The Institute of Eminence (IoE) Research Initiative (RI) Project on Technologies for Low Carbon and Lean Construction (TLC2) was undertaken with a view towards addressing issues that would lead to the true adoption of the concepts of circular economy in construction and minimal impact on global climate change. The project was established with the following four major objectives:

1. to utilize suitable waste materials from construction, demolition, power, steel, and agricultural industries and thereby enhance the durability, service life, and sustainability of reinforced concrete structures,
2. to minimize the wasting of materials, money, and time during the construction processes using lean principles, digital/3D printing tools and precast concrete applications,
3. to develop policies to enable the BEST and NEXT practices in the Indian construction industry, with an eventual goal of minimizing the carbon footprint and enhancing the circular economy of the concrete construction industry, and
4. to develop and suggest organizational practices and policies that help in scaling up the implementation of such technologies and be an eye-opener for policy makers in the country and beyond.

While the investigators involved in the project were already addressing these issues in their previous work for more than a decade, the current project gave an opportunity to really amalgamate the individual pieces into a collective approach, which is an aspect that is lacking in the handling of this subject worldwide. In that sense, this RI project presents a bold and first-of-its-kind step to holistically address the problem of sustainability in concrete construction.

Although the focus in the first phase was to develop the critical infrastructure needed to tackle the above identified issues, the group has made significant advances in the areas associated with this RI project. The impact can be best judged by a comparison with internationally benchmarked research groups that are working on this subject. In the past year, the group produced 55+ journal publications (including 37 in Q1 journals), which is comparable to a benchmarked group at Imperial College London, and better than the homologous groups at UC Berkeley and UT Austin. Further, the group registered a higher international collaboration impact than the groups at UC Berkeley and UT Austin (as per SciVal analysis). Also, the group has filed four patents on concrete 3D printing and construction automation (202141042286, 202141015253, 202141012578, 202041057308) and another patent in the area of service life extension of concrete structures using cathodic protection has been granted (387704). The group has graduated seven PhD students in the last one year and one more PhD student has submitted the thesis and is expected to graduate soon.

Towards international research partnerships, the TLC2 group has been able to strengthen its existing partnerships and bring in more strategic partners from academia and industry. More than 40 top researchers in the areas of concrete materials and construction (from more than 20 universities) are aware of the group's work and some are collaborating actively in some joint research projects (e.g., SPARC, UKIERI, IGSTC, and other consulting projects). Additionally, through the means of webinars and presentations at conferences, as well as video conferences with specific researchers, the group's activities are now well known across continents. Because of such visibility/networking and impactful and relevant research output, our graduates are able to get research positions in top groups worldwide. For example, in the last one year, two of our students have been placed as postdocs in research labs abroad. Some of the key research highlights from the work done in the 1st year are:

- For first time in the world, demonstrated the use of concentrated solar energy for thermomechanical beneficiation of concrete from demolition waste for recycling in new structures.
- Implemented low-carbon technologies to ensure longevity of large-scale construction projects in the country, such as Ram Mandir in Ayodhya, Metro Rail projects in Chennai and Bangalore. Initiated involvement in the National High-Speed Rail and Regional Rapid Transit System projects
- Demonstrated the recyclability potential of demolished concrete in the Chennai Metro Rail project
- Demonstrated the application of concrete 3D printing for structures with unconventional geometry, using low carbon binders.

- First of its kind implementation of low carbon concrete materials and durable repair systems (cathodic protection) in the repair of sunshades in Rashtrapati Bhavan, New Delhi
- Developed data-driven service life design charts for reinforced concrete with different cementitious binder systems in aggressive environments – industry has already started using these tools.
- Developed a multi-criteria decision-making model for evaluation of mass housing construction technologies and demonstrated the application through pilot projects.
- Developed a system-thinking-based framework to test the government policies that can increase the development of Construction and Demolition waste recycling infrastructure in India.
- Developed a simulation model to estimate the total carbon footprint due to construction in a city like Chennai, and quantified the extent to which this footprint can be reduced through the use of low carbon and lean construction techniques.

Also, the group has actively contributed to the following national and international committees:

- RILEM technical committees: TC-ECS, TC-CCL, and TC-TRM
- Drafting of the Model Code 2020 for the International Federation for Structural Concrete (*fib*).
- Drafting of the new IS456 Code of Practice, and IS1786, IS12594, IS15916, IS11447, IS19165, IS18904, and IS13620 specifications for Bureau of Indian Standards (BIS)
- Drafting of Compendium on Practices on Maintenance of Cement Concrete Roads for Indian Roads Congress (IRC)
- Drafting of Report on Self-Healing Roads for Department of Science & Technology (DST) - Technology Information Forecasting and Assessment Council (TIFAC)
- Participated in updating the IRC SP:68-2022 code on Roller Compacted Concrete Pavements for Indian Roads Congress (IRC)

The restrictions imposed by the pandemic in the last year posed several challenges from the perspective of research, travel and infrastructure development. Despite these challenges, our RI project has been successful in disseminating our work at several national and international conferences (online/in-person) and in accomplishing all major equipment purchases to accelerate the work in Phase II. The infrastructure created in the first year will help address the following research objectives in the next three years:

(i) To map the resources and waste streams across the country using database/GIS enabled tools for optimizing the use of materials in concrete construction.
(ii) To identify low energy pathways for valorization of agricultural, industrial and construction & demolition (C&D) waste, and creation of value-added products from the various waste streams
(iii) To identify/develop less carbon dioxide intensive binders for durable concrete construction for sustainable infrastructures, as well as for special applications such as 3D printing and repair materials and systems including Textile Reinforced Concrete (TRC)
(iv) To develop data-driven tools to model the service life of concrete structures and develop design charts and software programs to facilitate Design-for-Durability of concrete structures.
(v) To create a virtual test bed for optimizing the resources and processes in concrete construction to enable the adoption of lean practices.
(vi) To liaise with various government agencies and create policy notes/statements to enable the utilization of waste materials and implementation of lean construction technologies in ongoing and upcoming concrete construction projects, especially large/mega projects in the country.

It is expected that the work towards the above research goals would help in creating a truly unique R&D centre that would be able to influence national (and perhaps international) policies on systematic methodologies for utilization of value-adding waste streams in construction, in addition to providing a platform for budding entrepreneurs, who wish to test their ideas, virtually and physically, on alternative materials.

2 HIGHLIGHTS OF THE CENTRE ACTIVITIES

2.1 Infrastructure development

1. A pilot-scale rotary kiln for the production of new cements, including calcination of clays and clinkering of alternative cements, was installed and commissioned.
2. Updated equipment and procured relevant modules of COMSOL software for assessment and modelling of durability of reinforced concrete systems.
3. A concrete 3D Printer, integrated with robotics with the capability to insert reinforcement and other objects into 3D printed concrete elements, is being commissioned.
4. A new state-of-the-art advanced aggregate laboratory is being established.
5. Test beds are being established for the following:
    - Simulation, processing and characterization of recycled aggregates.
    - Processing of agricultural and construction & demolition wastes.
    - Assessment of glass textile reinforced concrete systems.
    - A physical and AI-VR integrated test-bed environment to identify optimal materials use and minimize carbon footprint is also being developed.
6. An Infrastructure Systems laboratory has been established for research in construction automation.

2.2 Collaborations (Academic, Industrial, Governmental, NGOs, MSMEs, etc.)

One of the most important aspects of focus of the TLC2 is collaboration with leading international researchers and experts working in the areas of construction materials and management. Our group has been actively collaborating with prominent researchers across the globe via GIAN, SPARC, VAJRA, UKIERI schemes, as well as international working groups and companies.

2.3 Academic Collaborations

Collaborative projects/publications

a. Continued collaboration with two key research groups – at University of Cape Town (UCT) and University of the Witwatersrand (WITS) in South Africa. Prof Mark Alexander (UCT) and Prof Yunus Ballim (WITS) visited IITM in Feb/Mar 2022, and had extensive interactions on recycled aggregate concrete, primarily under the aegis of the SPARC project dealing with the subject. Two of our PhD students are visiting South Africa as a continuation of the collaboration. The interactions will result in the publication of a monograph shortly. There is also some joint work planned between the three universities in areas linked to TLC2, such as durability (acid attack) and low carbon binders.

b. Collaboration with Prof. Elsa Olivetti at the Massachusetts Institute of Technology (MIT), USA, has continued through a short course on life cycle assessment. One PhD student from Prof. Elsa's group visited IIT Madras for 3 weeks in Jan 2023.

c. Initiated formal collaboration with groups at Hong Kong Polytechnic University, ETH Zurich, Tongji University, China, and University of Sao Paulo, Brazil, through a project funded by the Global Cement and Concrete Association, on LCA/LCCA of construction and demolition waste.

d. Prof. Xijun Shi from Texas State University, San Marcos, USA, collaborated on research related to recycled asphalt concrete, leading to a Q1 publication.

e. Initiated research collaboration with Dr Taehwan Kim from University of New South Wales (Australia) and Dr Faiz Shaikh from Curtin University (Australia). Dr Taehwan Kim will visit IIT Madras during Sep-Oct 2022.

f. The visit of Prof Prasada Rangaraju from Clemson University is planned in July 2022, and discussions on 3D printing using low carbon binder systems will be a key point of discussion.

g. Dr Solomon Debbarma (Adjunct Lecturer) from Texas State University, San Marcos, US, collaborated on research related to recycled asphalt concrete leading to a Q1 publication.

h. Prof. Frank Dehn from KIT Germany: jointly submitted DST-IGSTC project on recycling.

i. Dr Isabel Milagre (Nacional de Engenharia Civil Brasil, Lisboa, Portugal) Jointly submitted DST Indo-Portugal project.

j. Interactions with Prof Paul Chan of TU Delft and Prof Timo Hartmann of TU Berlin are in progress.

Research visits (inbound)

a. Prof Raul L. Zerbino, National University of La Plata, Argentina – June 2022 to Aug 2023
b. Prof Mark Alexander, University of Cape Town, South Africa – 2 weeks
c. Prof Yunus Ballim, University of Witwatersrand, South Africa – 3 weeks
d. Prof Vellore S Gopalaratnam, University of Missouri, USA – 3 weeks
e. Prof Surendra Shah, University of Texas at Arlington – 2 weeks (2021, 2022)
f. Dr Prannoy Suraneni, University of Miami, USA – 1 week
g. Dr Kalyan Piratla, Clemson University, USA – brief visit
h. Prof Neeraj Buch, Michigan State University will be visiting in December 2022.
i. Prof Prasada Rangaraju, Clemson University, USA – short visit (expected on Jul 14)
j. Prof David Trejo, Oregon State University, USA – expected to visit in Sep 2022.
k. Prof Ram Rajagopal, Stanford University, USA – scheduled to visit in June/July 2022.
l. Academic collaboration has been established between several prominent researchers in the area of construction robotics, including Prof. Thomas Bock (Germany), Prof. Jochen Teizer (Denmark), and Prof. Frederic Bosche (UK). These researchers will be invited to spend 2-4 weeks at IITM in 2022-23.

Knowledge sharing initiatives

a. The group co-organized the Materials and Value Chains for Sustainable, Inclusive, and Resilient Urbanisation in Africa, Virtual Workshop, with BAM, Germany, the University of Lagos and RILEM, in January 2021.
b. Webinar on "Utilization of Off-Spec Fly Ash for low-carbon concrete" by Prof Farshad Rajabipour was organized in Sep 2021
c. Webinar on "Closed Loop Life Cycling by Construction Automation & Robotics" by Prof Thomas Bock in Oct 2021
d. Prof Surendra P Shah, Dr Andreas Leemann, Dr Edna Possan, Dr Liberato Ferrara, Dr C S Poon, Dr Prannoy Suraneni, Dr -Ing Viktor Mechtcherine, Dr John E Taylor attended and delivered lectures on low-carbon construction, Supplementary Cementitious Materials (SCMs), C&D waste utilization, 3D printing etc. during the first 2-day in-person international workshop on "Advances in Technologies for Low-Carbon & Lean Construction" held in December 2021 at IIT Madras.
e. Webinar on "Opportunities for Natural Pozzolans as Supplementary Cementitious Materials" by Prof Maria Juenger in April 2022
f. Prof John Taylor of Georgia Tech spoke at the Symposium held in December 2021 at IITM.
g. Dr Sivakumar Palaniappan at the IEA EBC Annex 72 committee. Responsible for developing guidelines to establish a simplified national LCA database along with other experts from Europe.

Research guidance & capacity building

a. Almost all the research scholars of the group have had interactions with top international experts, which has been extremely positive for capacity building. Many have joined institutions abroad as post-docs and PhD students.
b. The group has been endeavouring to recruit PhD students and post-docs from other countries, with the success limited by the pandemic and the salaries offered.

International Postdocs

Dr Luis Edgar Menchaca Ballinas from Mexico joined TLC2 group as a postdoctoral associate in August 2022.

TLC2 Graduates

- Six PhD, seven MS, three M. Tech and ten Dual Degree scholars have graduated with theses in the areas of TLC2. One PhD scholar has submitted his thesis and is expected to graduate in 2023.

TLC2 current scholars

22 PhD scholars (Seven are Prime Ministers Research fellows), 3 MS scholars and 5 M. Tech students are working on the TLC2 theme. The following areas are covered: Durability and service life of reinforced concrete structures, Life cycle assessment of concrete, Low-grade limestone for concrete construction, Recycling of concrete, concrete waste, Recycled aggregate concrete, Textile reinforced

concrete, Novel methods to utilize recycled concrete fines in 3D printing and for mineralization using CO_2, Utilization of Industrial Wastes in Manufacturing of Low CO_2 Cements, Sustainability assessment and housing, Safety of automated construction through sensor-based monitoring of construction activities, Adoption and Diffusion of Sustainable Building Technologies, Lean Construction

2.4 Industrial, Government, NGO collaborations

a. Research project on the development of binders for E-glass reinforcement, Funded by Holcim Center de Recherche, Innovation Center of Holcim Group, 2021-25. The Holcim group is the largest construction material supplier in world.
b. Initiated engagement with Saint Gobain through two projects on developing low-carbon construction materials based on clay and on low-carbon glass reinforcement.
c. TLC2 group continues to collaborate with TARA (Development Alternatives, an NGO from New Delhi) in the research and development of the low carbon cement called 'Limestone Calcined Clay Cement (LC3)'. The next stage of the work is expected to occur in Malawi, Africa, where a large research study will be jointly undertaken by TARA and IITM for the use of locally available clays for producing such binders. Apart from TARA, IIT Madras has IIT Delhi, EPFL Switzerland, and UCLV Cuba as partners in the low carbon cement project. There has also been a steady engagement with the Bureau of Indian Standards (BIS) to bring out a standard for LC3. It is expected that this standard will be out within the current year. Housing and Urban Development Department, Government of Tamil Nadu (GoTN) and Industries Department (SIPCOT) GoTN. The importance of TLC2 was also mentioned by the finance minister in last year's budget speech.
d. Westart Communications Pvt Ltd (Chennai recycling plant) - signed MoU; one funded Project
e. Schwing Stetter (recycling equipment manufacturers; conducted onsite recycling with them)
f. Advanced Concrete Technologies (jointly conducted onsite recycling at CMRL Chennai)
g. Rock Crystal (Bangalore recycling plant; agreed to supply recycled materials whenever required at free of cost).
h. K.K. Plastic Waste Management Ltd. (jointly working on plastic waste for concrete).
i. Ms Larsen & Toubro: Jointly submitted DST-IGSTC Proposal on waste recycling.
j. Ms Larsen & Toubro: Development of a sustainability assessment tool for building and infrastructure construction projects in collaboration with L&T construction (in progress).
k. Chennai Metro Railway Limited along with the TLC2 team jointly conducted the onsite recycling demonstration of C&D waste from the CMRL Phase I sites.
l. Conducted multiple workshops on good concreting/grouting practices for the National High Speed Rail Corporation Limited (NHSRCL) and Regional Rapid Transit System (RRTS) projects.
m. Rashtrapati Bhavan – Collaborated with Central Public Works Department and extended the service life of sunshades at Rashtrapati Bhavan to another 50+ years using special concrete systems with fly ash as binders and aggregates; and retaining the existing steel and cathodically protecting them – first of its kind of restoration project in a Class I heritage structure.
n. Started a project with International Zinc Association on the durability assessment of galvanized steel in low-carbon cementitious materials.
o. Starting a multi-institutional project on Ultra-High Performance Concrete (UHPC) with Kerala Highway Research Institute
p. Completed a project sponsored by the World Monuments Funds, New York - performed condition assessment and developed a conservation management plan for the 60-year-old Sardar Patel Stadium in Ahmedabad, Gujarat. A Pilot project on the recommended repair strategies to conserve the structure for another 30+ years is expected to start soon.
q. Habitat for Humanity: will be signing one MoU with them by May end and as a part of this MoU, we would be collaborating on different topics related to sustainable materials.
r. Initiated research collaboration with Team Malba Projects, an NGO based in Delhi to trace the location and quantity of Construction and Demolition Waste in the City of New Delhi. A joint research proposal through a socially relevant project scheme of IIT Madras has been proposed.
s. New research ideas related to TLC2 have been initiated with leading industries such as: (i) Tata Steel - on the use of Air-Cooled Blast Furnace Slag and LD Slag as aggregate in concrete,

(ii) Reliance Industries Ltd - on the carbon dioxide curing of concrete products using the exhaust gases from their factories, and (iii) Vedanta - on the use of red mud and other waste in geo-polymeric binder systems.

t. Initiated collaboration with CarbonCraft, a startup that intends to commercialise tiles with waste materials and a binder that sequester carbon dioxide.

2.5 Innovation/Entrepreneurship (Patents, Start-ups, etc.)

1. Innovated a novel beneficiation technique for treating recycled aggregates through concentrated solar energy from a large-scale industrial facility in Mount Abu, Rajasthan.
2. There has been a constant engagement with the 3D printing start-up Tvasta Manufacturing Solutions. Our group has been guiding them on the use of sustainable mixture designs for 3D printing. A large research program is also being started under the Affordable and Sustainable Housing Accelerator (ASHA) program from the Ministry of Housing and Urban Affairs, which will involve mentoring the (i) M/S Tvasta on extensive large-scale investigations with 3D printed concrete and (2) M/S Slabs Engineering on 3D-volumetric precast concrete systems. In addition, another start-up named M/S Modulus Housing is also being mentored by our group.
3. One patent has been sanctioned in the area of cathodic protection to extend the service life or durability of corroding reinforced concrete structures.
4. Four patents have been filed in the areas of automated construction and 3D printing.

2.6 Visible outputs (Publications, Conferences, Experimental facility creation, etc)

Publications relevant to the TLC2 initiative

The findings/output from the research projects undertaken by TLC2 team over the past year have been published in Q1 journals. A total of 37 Q1 journal publications in 2021-22, out of which more than 30 relate to the areas of the TLC2 initiative.

Conferences/Webinars/Workshops

The TLC2 Group has conducted online webinars on various themes related to these technologies. In addition, the group members were invited speakers and presented papers in various international conferences.

Matching grants

In the past one year, the members of the TLC2 group were able to generate more than **Rs. 4.7 Crores** in external funding as well as participate in a linked project worth **Rs. 9.58 Crores**.

Experimental Facilities created

Details are given in Section 2.1

Implementation on structures with national importance and heritage values

- **Ram Mandir, Ayodhya** – Implemented mixture design and methodology for implementation of concrete with low carbon binders and lean technologies such as Roller Compacted Concrete for the construction of the foundation system.
- **Rashtrapati Bhavan, New Delhi** - Special low-carbon concrete systems were designed and used for the repair of the sunshades/chhajjas in Rashtrapati Bhavan, New Delhi. The century-old steel rebars were retained and are now being protected using embedded galvanic anodes.
- **Sardar Patel Stadium, Ahmedabad** – After conducting a detailed condition assessment project with the Worlds Monuments Funds, a proposal for the Pilot scale demonstration project has been submitted for rehabilitation of the corroded/deteriorated reinforced concrete elements. This project will demonstrate how to extend the service life this heritage structure by another 30+ years (repair-free 30+ years) by using cathodic protection, textile reinforced concrete, and high-performance concrete using recycled concrete aggregates.

Involvement in policy and standards development

- Active in several RILEM Technical committees, including: (i) ECS – Assessment of electrochemical methods to study corrosion of steel in concrete, (ii) CCL – Calcined clays as sustainable materials for concrete, (iii) TRM – Testing reactivity of materials
- Drafting of the Model Code 2020 for the International Federation for Structural Concrete (fib) – Chapters on Materials and Durability design
- Bureau of Indian Standards (BIS): (i) IS456 Code of Practice – Chapters on (1) Materials and (2) Limit State of Durability; (ii) IS1786 – Steel reinforcement bars for structural concrete – Specifications; (iii) IS12594 – Galvanized steel reinforcement or concrete applications; (iv) IS15916 & IS11447 – Merging these two documents on precast concrete for CED 32; (v) IS19165 & IS18904 – New Specifications and Test methods for fibre reinforced polymer bars for applications in concrete structures; (vi) IS13620 – Revision of specifications for Fusion Bonded Epoxy Coated rebars; (vii) Proposed new committee to make a standard on Textile Reinforced Concrete; (viii) Proposed new committee to make standard on corrosion tests on steel rebars in concrete (aiming at enhancing and estimating the service life of concrete structure); (ix) Proposed new committee to make a standard on cathodic protection of concrete structures (for the extension of service life of concrete structures)
- Indian Roads Congress (IRC) - Drafting of Compendium on Practices on Maintenance of Cement Concrete Roads; Participated in updating the IRC SP:68-2022 code on Roller Compacted Concrete Pavements
- Department of Science & Technology (DST) - Technology Information Forecasting and Assessment Council (TIFAC): Drafting of Report on Self-Healing Roads
- Conducted multiple workshops on low-carbon materials for the National High Speed Rail project in Gujarat and Regional Rapid Transit Project in New Delhi

3 WHAT THE CENTRE SETS OUT TO ACHIEVE

For the last few decades, concrete and construction technologists have been working to reduce the carbon footprint of the construction industry by lowering the consumption of pristine natural materials, enhancing the durability, and minimizing the generation of waste during the entire life cycle of structures. Durable concrete structures with minimal repairs can be made by appropriate use of processed/beneficiated (physico-chemical modifications) wastes and by-products from construction, power, metal manufacturing, and agricultural industries. These materials include fly ash, bagasse ash, rice-husk ash, blast furnace slag, limestone (non-cement-grade), calcined clay (produced from impure kaolin), recycled concrete aggregates, reclaimed asphalt pavement, coir fibres (from coconut) etc. Further, there is also a lack of a systematic approach to understanding the ideal physico-chemical processing that can maximize the potential of such materials. Additionally, a holistic approach is needed to understand the utility of these materials in the service life of the concrete structure, through a well-developed sustainability framework.

Techniques to **reuse and recycle** some of the waste materials (as cementitious binders, fillers, and recycled aggregates) for producing **low-carbon concrete** are available. However, lack of information on some newly identified waste materials, variability in their chemical composition, difficulties in segregation and sorting, and high processing energy have led to difficulties in high-volume usage - leading to the continual environmental burden. A robust framework involving low energy processes for high-volume utilization of widely available wastes is essential to implement the technologies further. For example, we have developed solar energy-based technology for processing C&D waste utilization on a laboratory scale. Nevertheless, the ability of such valorized waste materials (VWMs) to resist the time-dependent mechanical and environmental loads and enhance the durability and service life of structures is not well known and our group is actively working in this area. Also, a suitable framework to assess sustainability indices by considering the cradle-to-grave approach and socio-economic environmental scenario is not available and is essential to quantify the impact of the usage of VWMs and construction processes.

Along with this, research on automated and lean construction technologies to reduce process waste during construction is ongoing. Led by initiatives that developed planning systems and digital models for process analysis, researchers are now attempting to use AI/ML and immersive AR/VR techniques along with Digital Twin models of buildings to virtually identify and minimize wastes to smoothen the construction process. However, large-scale implementation/adoption of these technologies in major infrastructure and mass housing projects (the need of the hour in many countries) has been a challenge. Clients and engineers are not well enough acquainted with these technologies to understand the benefits that they will derive and to choose or prescribe specific functionality and objectives that they would like to develop, analyze and optimize. Scholars in the field have identified other specific challenges relating to expensive, unreliable technologies that required trained manpower, as well as the introduction of workflows that conflict with existing work practices. Policies and standards to optimize wastes are available but, not widely implemented due to various reasons such as lack of organizational and institutional setups relating to technology adoption in construction. These result in high processing costs and the re-use of waste material is often more expensive than the use of pristine material, leading to a tendency to avoid the reuse of waste. This is one of the most significant gaps in this area and it is increasingly becoming acceptable that a systems-thinking based multi-prong approach that integrates materials, supply-chain, construction, and policy is necessary to tackle these gaps. Adapting these technologies to fit in with the chaotic and heterogenous construction project environment and how they can guarantee long-term sustainability in addition to waste reduction during construction is also an emerging area of research.

Techniques to **reduce waste** (in terms of time, material, and energy) are available to some extent and have been used to promote **lean construction** in many countries. However, significant difficulties exist in implementing these technologies due to the organizational work culture and construction-related challenges, and their differences in many countries. Building Information Modelling (BIM), Digital Twins and Automation in construction (e.g., Precast concrete and 3D printing) have been identified as technologies to accelerate construction, avoid rework, and reduce waste. Our group has developed tools with varying levels of sophistication to synthesize construction data and predict/recommend strategies to reduce the process waste (idle inventory, excess transportation, rework, etc.). Recent and ongoing work includes the use of AI and image recognition techniques to automate construction progress monitoring, using Virtual Reality (VR) for construction scenario planning, developing **India's first 3D printer** to reduce both material and labour wastes, and developing a process that integrates BIM and Lean techniques in construction. BIM and automation are being combined and used to increase the efficiency of the precast concreting processes.

Researchers are now focussing on tailor-made concrete materials and a new generation of work practices for various stakeholders that align with the motto of reuse, recycle, and reduce waste. In this regard, research needs to be done to develop a robust decision-support framework to sustainably support operations during the construction of large infrastructure systems – i.e., from the material selection to commissioning of facilities. Such a framework or 'test-bed' that integrates the ability to test and choose appropriate building materials, visualize and optimize construction processes, simulate and help understand the most appropriate level of automation for a site, evaluate sustainability indicators and optimize energy consumption and also help train practitioners on a more systemic and integrated view of construction, and can create a low-carbon, lean construction eco-system, where long-term sustainable solutions are adopted by the stakeholders. Also, the current and future availability of various waste materials in various parts of the world is not well known. Such information (in the form of regional maps) will help in assessing the sustainability of the approach and policy developments.

Overall, current scientific research has focused on process innovations both on the material production and construction fields, the re-use of waste materials and the use of digital technology to enable enhanced decision making around sustainability. The current state of the art is limited to the development of prototypical processes and systems, none of which have been widely adopted. Our group is working on all of these aspects – identifying materials for re-use, rearchitecting production and delivery processes, using digital tools for sustainable decision making, and understanding how these technologies can be more widely adopted. We have been trying to strengthen industry-institute collaborations to propel large-scale field implementations of technologies for low-carbon, lean construction. Through research projects with material manufacturers, builders, and government agencies associated with the construction industry (e.g., BASF, UltraTech, Lafarge, L&T, SPCL, AutoDesk, GoTN, GoI, BIS, etc.) we have been developing ways to maximize the use of waste materials in concrete and minimize the waste from construction. We have been focusing on both fundamental and applied research on cement chemistry, special concretes, and long-term performance of concrete systems - through several sponsored projects from DST and international collaborative projects with groups in other IITs, Italy, UK, South Africa, France, Germany, and Switzerland. The key contributions from these collaborations are in the areas of valorization and promotion of various waste/by-products for use in concrete, their effects on hydration and various properties of concrete, and the long-term performance and service life of concrete systems. Besides the large impact that these projects have had on construction practices in India, as well as on the standardization, they have also resulted in 165+ publications in Q1 journals in the last 6 years and the average FWCI of the group is 1.2, which is well above the IITM average of 1.

Recently, these efforts have received significant global recognition and we are among the top research groups in this area. The integration of materials technology, construction technology, and policy is a fertile research area and essential for a large-scale reduction in the carbon footprint of the construction industry, and the BTCM group's track-record with international leadership in diverse areas is set to guide and lead such initiatives.

4 PRIOR WORK FROM THE GROUP

4.1 Research needs and focus

More than a decade ago, some PIs on the group had recognized the theme of TLC2, which aligns well with the UN's Sustainable Development Goals #11 (Sustainable cities and communities), #12 (Responsible consumption and production), and #13 (Climate Action) [the Goals 6, 9, and 15 are also relevant to TLC2]. The group is well-networked internationally, with several faculty and trained at top-ranking universities in these areas. The team had worked in understanding and developing 'circular economy' concepts in construction by **reusing and recycling** materials and waste from other industries for making concrete and **reducing** the process waste during construction.

4.2 Major research projects and technical achievements

In the last decade, the following two industry-institute sponsored laboratories with additional funding from other sources have been set up at IIT Madras: (i) Construction Materials Research Laboratory supported by Lafarge de Researche, France (ii) the Integrated Construction Practices Lab supported by Autodesk and Trimble Inc. With these labs, we have conducted the following major collaborative research projects/initiatives (along with many other minor projects).

Durability & long-term performance of low-carbon concretes – Sponsored by Lafarge, France

This project was started in 2010 and was in collaboration with the UT Austin, USA, Univ. New Brunswick, Canada, Lafarge, France, and Hunan Univ., China. Through this project the group was able to elevate the status of the Construction Materials Laboratory and get greater international visibility. This project also led to a Q1 journal publication on durability of concrete with low-carbon materials, which received 19 citations in 2 years (Vu et al., 2019)*. One of PhD theses evolved from this project received the Best Thesis Award from the Indian Concrete Institute. The collaboration was so successful that the TLC2 group is now part of another similar multi-institutional, 4-year collaborative project with Holcim, France on carbonation and durability of steel in low-carbon concretes.

*Vu et al. (2019) Impact of different climates on the resistance of concrete to natural carbonation, *Construction and Building materials*, Elsevier (19 citations since 2019)

Limestone Calcined Clay (LC3) project - Sponsored by Swiss Development Agency

This project started in 2014 and the 3rd phase is currently ongoing. Through this project, we have collaborated with EPFL in Switzerland, UCLV in Cuba, TARA in New Delhi, and IITs at New Delhi and Bombay. Through this project, our group has developed cement and concrete laboratories to truly international standards, generated significant scientific database, and made an impact on the scientific development and implementation of LC3 systems in Indian context. Multiple PhDs have been generated through this project and we have developed good international standing in terms of publications. Following are our noteworthy publications (since 2018) from this project, which received good number of citations in short period.

- Dhandapani et al. (2018), Mechanical properties and durability performance of concretes with Limestone Calcined Clay Cement (LC3), *Cement and Concrete Research*, Elsevier
- Gettu et al. (2018) Sustainability-based decision support framework for choosing concrete mixture proportions, *Materials and Structures*, Springer
- Pillai et al. (2019), Service life and life cycle assessment of reinforced concrete systems with limestone calcined clay cement (LC3), *Cement and Concrete Research*, Elsevier,
- Rengaraju et al. (2019), Investigation on the polarization resistance of steel embedded in highly resistive cementitious systems–An attempt and challenges, *Electrochimica Acta*, Elsevier,
- Gettu et al. (2019) Influence of supplementary cementitious materials on the sustainability parameters of cements and concretes in the Indian context, Materials and Structures
- Nair et al. (2020) A study on fresh properties of limestone calcined clay blended cementitious systems, Construction and Building Materials,

Durability and long-term performance of low-carbon concrete systems – Sponsored through DST Indo-South African programme, DST-SERB, and other public/private agencies

Since early 2000s, the TLC2 group has started working on the durability and long-term performance of concrete systems. The collaboration initiated in the late 2000s and still ongoing with the Univ. of Cape Town and Univ. of Witwatersrand in South Africa were mutually beneficial to the groups in India and South Africa. Based on this collaboration, the PIs of TLC2 group gained energy and expertise and initiated the development of the concrete durability laboratory in IIT Madras. In 2010s, the TLC2 group continued upgrading the laboratory and research output through three major projects funded by DST-SERB and various other public/private agencies. Our lab possesses the best such facilities in India and has received The Best Laboratory Award from the NACE International – Gateway India Section in 2019. Our team has made the following key achievements.

- Significant understanding of the deterioration mechanisms and a database on the characteristics of materials available in India for making concrete and the durability and mechanical properties of concretes made in India. Such databases were highly acclaimed and were further used for use in various decision-making activities in various across India.
- Significant understanding and database on the performance of fibre reinforced concrete (FRC) and BIS standard test methods for the assessment of critical properties of FRC.
- Developed test procedures to assess durability and service life of steel-cementitious systems.
- Developed nomograms for enabling the design of concrete structures for achieving a particular target service-life in a particular exposure condition.

Development of TendonFill grout using low-carbon materials – Sponsored by IMPRINT India

The PIs of TLC2 group received funds through an IMPRINT India scheme project on developing a high-performance grout for enhancing the durability of major concrete bridges. This project was in collaboration with the Ministries of Human Resources and Housing, UltraTech Cements Ltd., and L&T Construction. The project led to the development of **"*TendonFill*"** grout, which is **India's first high performance grout made using low-carbon materials** and can enhance the durability of segmental post-tensioned concrete bridges, which are widely used in elevated metro and highway bridges and high-speed rail projects. This technology was licensed to Ultratech Cements Ltd. and is now being commercialised and soon will be implemented in major infrastructure projects in India. This project also resulted in two Q1 journal publications.

3D printing of concrete – Sponsored by various public and private agencies

Observing the global trend towards research on 3D printing of concrete, our group had initiated research in this area and built the ***first 3D printed house in India***. The group has been successful in evaluating and optimizing the carbon footprint and sustainability of 3D printable concrete systems. The major publications from this study from our group are:

- Rahul et al. (2019) 3D printable concrete: Mixture design and test methods, *Cement and Concrete Composites*,
- Rahul et al. (2019) Mechanical characterization of 3D printable concrete, *Construction and Building Materials*,
- Rahul and Santhanam (2020) Evaluating the printability of concretes containing lightweight coarse aggregates, *Cement and Concrete Composites*,
- Bhattacherjee et al. (2021) Sustainable materials for 3D concrete printing, *Cement and Concrete Composites*,

Integrated and Lean Construction Practices – Sponsored by L&T Construction, The World Bank, AutoDesk, and Trimble

For two decades, the TLC2 team members have been coordinating with L&T Construction, India's largest construction conglomerate and running arguably the world's longest running MTech User-Oriented Program (MTech UoP) on Construction Technology and Management (CTaM). By graduating about 30 MTech students every year, the groups influence in the construction industry is significant. Also, we have built one of the finest Integrated Construction Practices Laboratory, originally created by Autodesk and now supported by Trimble. Our group has been a pioneer in the area of Building Information Modeling (BIM) and digitalization in construction in India. India's first 4D BIM model was built here in 2006. Group has also developed a plan for the execution of Building Information Modeling (BIM) tools in India - with varying levels of sophistication to synthesize construction data and predict/recommend lean construction strategies to reduce the process waste. The work in this lab has also been focused on helping designers and construction managers make decisions on projects through the use of digital tools. These include helping understand how stakeholders can best be managed in the construction processes, the extent to which wearables, sensors, drones etc can create impacts on projects, and methods by which these tools can effectively be used. We also have put together one of the first integrated teaching courses in this area. We also actively advise and work with contractors and service providers to create standards, policies and platforms for disseminating knowledge in these areas. Team has also run a project with the World Bank on developing toolkits for policy makers engaged in designing and managing sectoral and cross sectoral PPP Interventions in Infrastructure. Also, the group has developed tools (and implemented in various construction projects) for automating various construction processes such as alignment checking and quantity estimation, to make the process ‘lean’er.

Research from this lab has been published in the top journals in the field such as Automation in Construction, the ASCE Journal of Construction Management and so on. Some of the recent noteworthy publications from the TLC2 group in the areas of construction management are:

- Ninan et al. (2020) ICT for external stakeholder management: sociomateriality from a power perspective, Construction management and economics
- Ninan et al (2019) External stakeholder management strategies and resources in megaprojects: an organizational power perspective, Project Management journal,
- Ninan et al (2019) Branding and governmentality for infrastructure megaprojects: The role of social media, International Journal of Project Management,

4.3 Publication records and subject-wise rankings

During 2015 to 2020, we published 125+ papers in Q1 journals and numerous papers at the leading international conferences. Table 1 provides a comparison of our scientific output in 2020 vis a vis UT Austin, UC Berkeley, and Imperial College London, all of whom have comparable number of faculty members that carry out similar research.

Table 1 Benchmarking of TLC2 group against Top Peer Research Groups (in 2020)*

Institute	QS Ranking 2020 in Civil & Structural Engg.	h-index	Citations per Publication	International Collaboration Impact	Field-Weighted Citation Impact (FWCI)	Publications in Top 10% Journal Percentiles by CiteScore Percentile (%)
UC Berkeley (USA)	4	63	29.7	30.9	2.12	51.8
Imperial College of London (UK)	5	63	34.6	34.8	2.21	55.9
Univ. of Texas at Austin (USA)	27	48	21.4	28.6	1.45	31.7
IIT Madras (TLC2 Team)	**51-100**	**49**	**17.3**	**16.7**	**1.20**	**35.7**
IIT Madras (as a whole)	51-100	--	13.4	18.8	1.0	30.0
*All the data was extracted from SciVal on Sept 9, 2020.						

The data indicates that our output is on par with UT Austin. Also, the average FWCI of the group was 1.2, which is well above the IITM average of 1. It must be noted that the TLC2 group has achieved this high standing although the current perception ranking of our institute as a research university is less when compared to the benchmarked institutes. While we are already recognized as being at the cutting edge of research in the area of low-carbon and lean construction, we have been scaling up and internationalizing our work, attain greater academic and practical impact and contribute to IIT Madras' growth in the subject-wise international rankings framework.

4.4 Alumni & Awards

During 2015 to 2020, we have graduated 24 Ph.D. students and most of them are working in research laboratories as post docs and some have already joined Indian (including IITs and NITs) and foreign research labs and academia in Africa, USA, and Europe.

- Six graduates as faculty members in IITs (3 in IIT Bombay and 1 each in IITs at Tirupati, Guwahati, Palakkad)
- Three graduates as faculty members in NITs (1 each in NIT Calicut, Trichy, Warangal)
- 10+ graduates as postdocs/faculty in the USA, UK, The Netherlands, Finland

Our efforts have received significant global recognition and we are among the top research groups in this area. We have received the Best Public Sector Laboratory Award from the NACE International – Gateway India Chapter (NIGIS). A few of the key awards our students received are as follows:

- Two Best Poster Awards in American Concrete Institute (ACI) Conventions in 2018 and 2019
- Two Best Poster Awards in RILEM Week Conferences (in India and Mexico)
- Four Best MS & PhD Thesis awards from Indian Concrete Institute (ICI)
- One Best MS & One Best PhD Thesis awards from NIGIS
- Two Best PhD Thesis Award from Indian National Academy of Engineering (INAE)
- One PhD student was nominated from India and came second for the prestigious NanoCem Award
- One PhD student was nominated from India for the prestigious NACE Outstanding Graduate Student Award from NACE, USA

4.5 International/national standing in the professional bodies

Our group is widely regarded as the best construction materials and management group in the country and at par with many of the foreign universities working actively in our areas. The PIs of this proposal are also internationally well-recognized in the area of low-carbon, lean construction, which is the focus of this proposal. Testimony to this fact is that two PIs (Ravindra Gettu and Koshy Varghese) have held top leadership roles in key international organizations in this field such as the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) and The International Association for Automation and Robotics in Construction (IAARC), while almost all the other PIs are either Fellows of or holding responsible positions in these and similar societies and on the editorial boards of Q1 journals. The PIs have been regular attendees and have published several papers at the leading international conferences in this area. In addition, we have organized top-notch international conferences such as 71st RILEM Week & Conference in 2017, the International Group for Lean Construction (IGLC) conference in 2018. Also, we have been conducting several outreach programs for academicians and practitioners and participating in several national level committees to influence the policies and standards by the Bureau of Indian Standards (BIS).

The integration of materials technology, construction technology, and policy is a fertile research area and essential for a large-scale reduction in the carbon footprint of the construction industry. Our group's track-record with international leadership in these diverse areas is set to guide and lead such initiatives.

5 KEY ELEMENTS AND OBJECTIVES OF THE PROJECT

The four key elements of the proposed TLC2 research initiative and the associated objectives are:

Element 1 - Basic Scientific Research

a. To develop low-energy techniques for physico-chemical processing and assess the suitability of waste (from agricultural, industrial and construction/demolition sources) for high-volume use in construction materials
b. To complete the sensor technology development to automate the sorting and segregation of useful materials from the randomly mixed C&D waste
c. To assess the use of processed waste in producing concrete for 3D printing and in making durable precast concrete systems
d. To study durability properties, service life extension techniques, and develop service life models for low-carbon concrete systems in various environmental conditions
e. To develop a framework to assess the sustainability indicators of construction materials and construction processes using the principles of life cycle assessment.
f. To assess the prevalence of occupational health and safety issues and suggest improvements in working conditions for all humans involved through formal and informal sectors for C&D waste management

Element 2 - Applied Research leading to technology development

a. To develop 3D printing technology for in-situ and precast construction of reinforced concrete and demonstrate robotic assembly
b. To correlate the performance of low-carbon concretes in laboratory studies to large-scale field implementation studies and develop and demonstrate durable precast concrete systems
c. To develop software and tools to estimate service life and sustainability indices to enable faster material selection and durability-based design
d. To develop low-cost, 'lighter', ready-to-use analytical tools and dashboards to minimize waste of time and materials from construction processes/practices and assess carbon footprint indices.

Element 3 – An Integrated Test-Bed for large-scale processes and visualization

a. To design and install a physical recycling test-bed for automated screening and physico-chemical processing of various waste materials
b. To integrate a ML analysis capability to predict the optimal usage of recycled material, based on a material characteristics database
c. To develop a physical and AI-VR integrated testbed environment to identify optimal use of materials, simulate and optimize construction practices, and minimize carbon footprint
d. To establish an integrated simulation and game-based learning facility on management adoption strategies, organizational training, and specialty skill training on lean process

Element 4 - Organizational & policy research for large-scale technology adoption

a. To develop national maps on current/future availability of waste materials (based on socio-economic-environmental sustainability aspects)
b. To develop strategies for modifying organizational work practices to increase the adoption of lean construction practices.
c. To develop a framework for leveraging the private sector participation across supply-chain of concrete materials during the life-cycle of construction projects
d. To develop Policy Notes for large-scale implementation of various waste utilization and reduction technologies.

6 PROGRESS MADE AND WORK PLANNED

The details of the work performed in the first phase of the project (Phase I: 2021-2023), along with the planned activities in the next phase (Phase II: 2023 – 2025) are provided in this section. The description is based on the four specific elements of the project described in the previous section.

6.1 Element 1- Basic Scientific Research

Obj. 1a: To develop low-energy techniques for physico-chemical processing and assess the suitability of waste for high-volume use in construction materials

Work done in Phase I

The current focus is on agricultural/stubble waste (e.g., crop residues, coconut coir fibres), industrial waste (e.g., biomass ash, red mud, non-cement grade limestone), and construction and demolition (recycled concrete aggregates and reclaimed asphalt pavement) waste. A summary of completed and on-going activities in Phase I are listed below:

<u>Agricultural waste</u>

Physico-chemical characterization of various agricultural feedstock & wood waste: The data is collected from at least 10 different types of agricultural residues and wood saw dust samples available in our lab. The analyses include proximate analysis, elemental CHNS/O analysis and bomb calorimetry. For some 6 samples, the biochemical characterization (cellulose, hemicellulose, lignin, extractives) has also been completed.

Optimization of process conditions (temperature, speed of rotation, and residence time) in a rotary tubular furnace for maximum bio-char production, and characterize condensable oil and gases: After commissioning of rotary kiln, the tests will begin and continue until the end of 2022.

Perform experiments by co-pyrolyzing wastes with petcoke: Preliminary experiments were performed to co-pyrolyze green pet-coke with biomass agricultural residues. The characterization activity is on-going and will be completed by the end of 2022.

Characterization of biomass ash and formulation of alternative cementitious binder: Biomass ashes from various sources were procured and characterized for determining physical and chemical properties. Reactivity assessment of biomass ashes in alkaline medium is currently on-going. After characterization various formulations (non-Portland cement-based) incorporating biomass ash will be developed and tested for strength. This activity is expected to be completed by the end of 2022.

Characterization and treatment of discarded coconut fibres for concrete roads application: Discarded coconut coir fibres from several locations were sourced and studied for their physical and chemical characteristics. These fibres were treated with different physico-chemical techniques to improve their performance in high-alkaline environment. Also, a methodology has been framed for uniform dispersion of both short and long fibres with varying concentrations in concrete mixes.

<u>Construction and demolition (C&D) waste</u>

C&D wastes such as recycled concrete aggregates (RCA) and reclaimed asphalt pavement (RAP) etc. consist of 60-90% of natural aggregates coated with a contaminant layer (adhered mortar and asphalt) and thus, extracting the aggregates from C&D waste could reduce the consumption of pristine aggregates for infrastructure application. In the first phase, RCA was brought from different parts of the country (Bangalore, Chennai, and Delhi), characterized physically and chemically, and the following novel low-energy techniques are developed to enhance the performance of concrete containing RCA:

Optimization of thermo-mechanical technique to produce high quality RCA: In this technique, the RCA chunks were heated at 500°C for 60 minutes followed by sudden cooling at room temperature and processing of the cooled aggregates in a ball mill containing steel charges. The beneficiated aggregates thus obtained could give concrete performance comparable to that of concrete containing pristine aggregates.

Use of concentrated Solar Energy for thermo-mechanical beneficiation of RCA: The working principal is similar to the optimized thermo-mechanical technique; however, concentrated solar energy was employed to heat the RCA chunks. Figure outlines the methodology followed to beneficiate the RCA using solar energy.

Figure 1: Producing high quality aggregates from C&D Waste using Concentrated Solar Energy

Optimization of Slurry Impregnation Technique for fully carbonated RCA: In this technique the slurry impregnation technique was optimized for fully carbonated RCA for paving quality concrete (PQC); RCA was fully carbonated by stockpiling in the natural environment in loose condition for around 12-14 months. The parameters optimized are slurry material type (silica fume, fly ash, and cement), their concentrations, exposure duration, and RCA sizes. The findings suggest soaking the RCA sizes in any of the considered cementitious/waste material slurry at 40% concentration for 6 hours for enhanced performance of both RCA and PQC made with treated RCA.

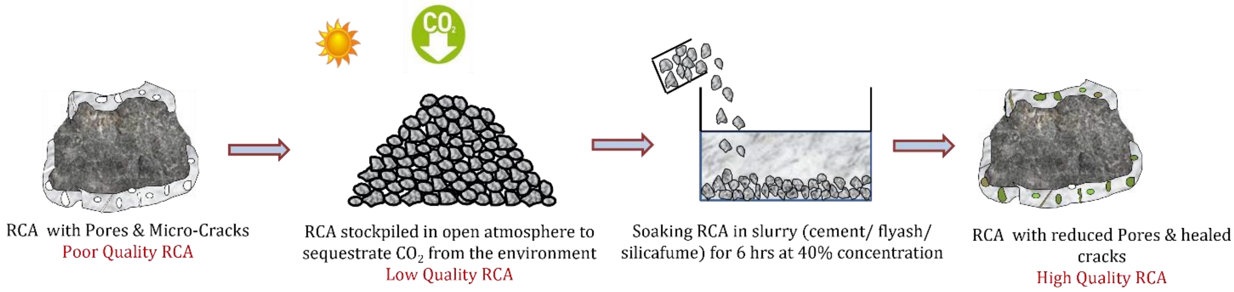

Figure 2: Methodology to enhance the quality of RCA through natural carbonation and SM technique

Planned activities in Phase II

Agricultural waste

Characterization of bio-char and evaluate its compatibility with cement and its cementitious nature: The biochar characterization will be done as and when it is generated during pyrolysis activity. Its compatibility with cement will be evaluated.

Composition-property relationship of biomass ash-based binders: The binder formulations developed in Phase I will be evaluated for their long-term durability. In addition to durability characteristics, thermal performance of biomass ash-based binders will also be examined.

Development of a framework to use discarded coconut fibres as concrete reinforcement: Based on the results of the Phase I, the next task is to study the effectiveness of untreated and treated fibres in arresting the plastic shrinkage cracks, and enhancing mechanical and durability characteristics. Also, guidelines and protocols for constructing low-volume rural roads containing coir fibres will be developed based on field studies.

Construction and demolition waste

Understanding the role of parental composition on the quality of RCA and concrete produced with RCA: Typically, 3 –4 grades of concrete are used for any building infrastructure and are commonly mixed together during the demolition process. In this activity, the effect of parental composition on the physico-chemical properties of RCA and the concrete produced with RCA of different grades will be investigated. The results of this study will help in choosing between two pathways for different applications viz. Conventional mixed demolition and preferential demolition.

Understanding the effect of crushing mechanism on the quality of RCA and concrete produced with RCA: Through extensive literature review and field visits (Delhi, Chennai, Surat and Mumbai recycling plants) during the first phase, it was observed that different crushing mechanisms viz. Compressive crushing (jaw crusher), impact crushing (vertical and horizontal shaft impact crushers; HSI and VSI) and shear crushing (cone or gyratory crushers) and different crushing sequences viz Jaw – VSI, Jaw-Jaw-VSI, HSI, Jaw-HSI and Jaw – cone are employed to recycle the RCA.

The choice of the crushing mechanism and crushing cycles have a significant impact on the economy, aggregates quality as well as on the environment. Therefore, in this phase, the effect of crushing mechanisms and crushing sequence on the quality of RCA and thus the performance of concrete containing RCA will be delineated followed by life cycle assessment. Also, the parental composition analysis will be included to develop a framework that could help in generating high-quality RCA fractions that could be used for different high-end applications such as cement regeneration, SCMs and fillers, sand and coarse aggregates. The methodology to be followed is illustrated in Figure 3

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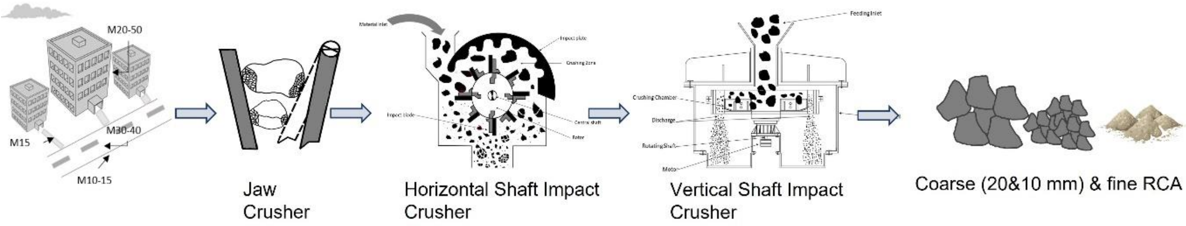


Figure 3: Methodology for fractionation of RCA

Elucidating the role of cement-asphalt-aggregates interaction on failure and durability of PQC containing RAP: The main objective of this phase is to critically understand the mechanisms governing the strength and durability properties of rigid pavements made with RAP aggregates. To achieve this broad objective, the following sub-objectives have been framed: a) Developing an understanding of the cement-asphalt-aggregate interaction mechanism, b) Investigation of the mechanisms governing the strength and durability behavior of RAP-concrete, and c) Analysing the efficacy of existing models for predicting the strength and shrinkage behaviour of RAP-concrete. The methodology to be followed for this study is illustrated in Figure 4.

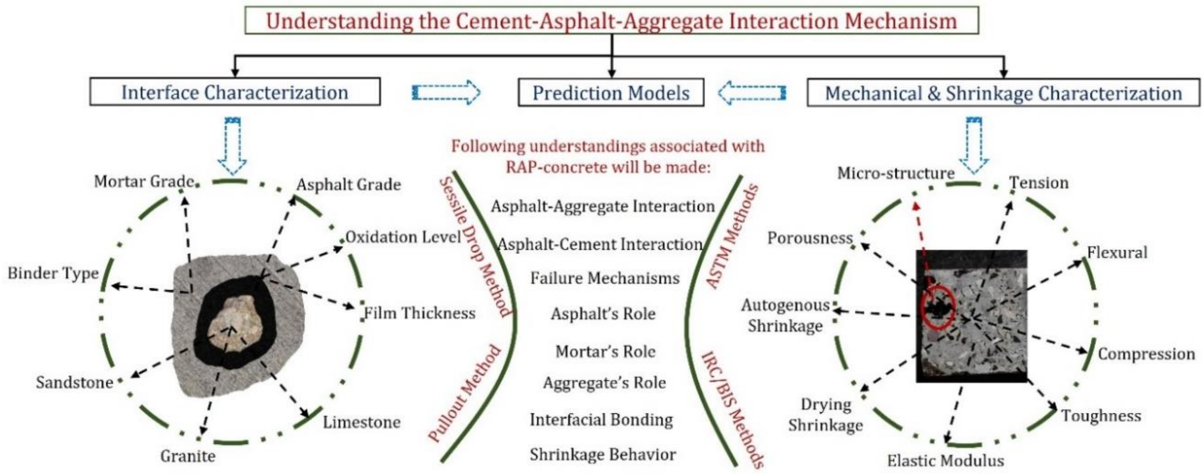


Figure 4: Methodology to be followed for understanding the cement-asphalt-aggregate interaction mechanism for RAP-PQC

Obj. 1b: To develop a suitable sensor technology to automate the sorting and segregation of useful materials from the randomly mixed C&D waste

Work done in Phase I

The methodology for identifying recyclable objects among construction and demolition waste through computer vision has been demonstrated. Both standard cameras and thermal imaging cameras have been used for testing and evaluation. The potential for various machine learning algorithms for identifying objects such as bricks, thin plastic, plastic bottles, cementitious material, etc. has been evaluated. It has been shown that reasonable accuracy in identification can be achieved using standard ML algorithms such as CNN and Yolo. Picking and placing recyclable objects has been demonstrated using a 6DOF industrial robot (see Figure 5). Challenges in practical implementation of these techniques have been identified. Better systems and algorithms are being developed.

Figure 5: DOF industrial robot being trained to pick & place recyclable objects

Planned activities in Phase II

1. Data collected from multiple locations in the city have to be integrated into a common platform for extracting useful information related to the volume of waste in the city. Images captured with standard mobile phone cameras and more sophisticated cameras with GPS will be uploaded to a web portal. The location of waste dump will be extracted from the image data. Data analytics will be carried out with highest level of automation possible.
2. Drones or vehicles with cameras and laser scanners will be used for capturing images of construction sites. Waste material that are dumped on sites will be automatically detected using image recognition algorithms. Dimensions and volumes will be computed. Conventional machine learning algorithms as well as more recent methods such as convolutional neural networks will be used and appropriate methods for the task will be identified. Selection and preparation of training data for this task require considerable domain knowledge. It will be explored how the integration of domain knowledge with advanced algorithms help in improving the performance. Issues and challenges will be brought out. Directions for future research will be formulated.
3. Algorithms developed using the work done above will be used to group together images having similar type of waste. A knowledgebase will be created for identifying the recycling processes that are appropriate for each type of waste.

Obj. 1c: To assess the use of processed waste in producing concrete for 3D printing and in making durable precast concrete systems

Work done in Phase I

- *Development of a framework for 100% utilization of RCA for roller compacted concrete* — A novel framework has been developed to enhance the performance of roller compacted concrete made with recycled concrete aggregates through synergetic improvement in packing density, lubrication of the paste, and aggregates’ moisture states.

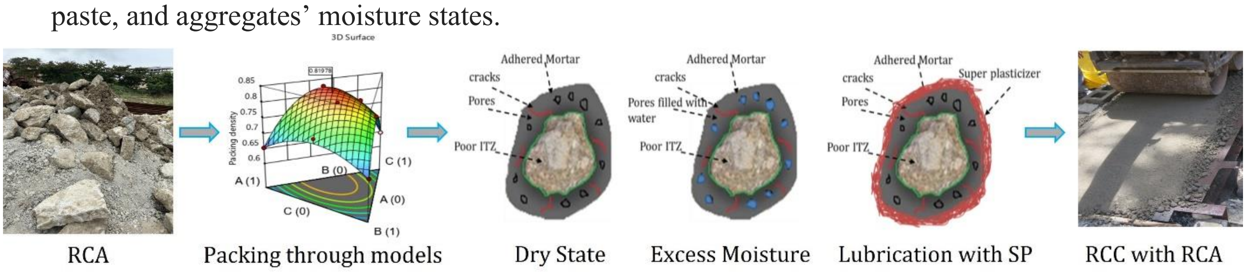


Figure 6: Developed framework to upcycle 100% RCA for roller compacted concrete

Planned activities in Phase II

- Optimal design of mixtures for 3D printed concrete involves a careful selection of materials that provide an optimally packed system, in order to maximize the extrudability and buildability of the mix. In this context, the use of the fines generated from the crushing of concrete during its recycling process could be potentially useful. The sub-150-micron fines can enhance the overall particle gradation of the 3D printable mix, and lead to a lower tendency for phase separation, and thus a lesser possibility of blockages when the material flows out of the nozzle. The impact of such additions on the thixotropic build-up of the mix also needs to be assessed using rheological methods.
- Precast products such as paver blocks and building blocks made of concrete can be successfully created using C&D waste of all sizes. Such products are only designed for the performance characteristics (such as compressive strength, water absorption etc.) and there are no restrictions on the specific ingredients. Therefore, a large volume of C&D waste can be utilized. The research challenges that need to be addressed pertain to the optimal design of the concrete mixtures to obtain the minimal use of cementitious materials for the products.
- *Sustainable concrete pavements using high volumes of construction, demolition, and industrial wastes as constituent replacements*: Following are the key objectives planned to be achieved: a) Develop a consistent processing technology to enhance the engineering parameters of the locally sourced wastes. b) Develop models to help designing consistent mixes with high level of substitution of cement constituents with wastes and predict their engineering properties by conducting in-depth laboratory investigations. c) Establish field performance of the rigid pavements made with concrete containing high volume of wastes by full scale demonstration using modern sensor technologies and numerical modelling. d) Demonstrate through life cycle and cost analysis economic and environmental benefits of utilizing high volume wastes-based mixes for rigid pavement constructions.
- *Use of Slurry Treated RCA for Ultra/High Performance Concrete Mixes:* The optimized parameters of slurry impregnation technique developed in Phase I would be use to beneficiate the RCA, followed by assessing the suitability of the same for ultra/high performance concrete mixes (UHPC) – see Figure 7.

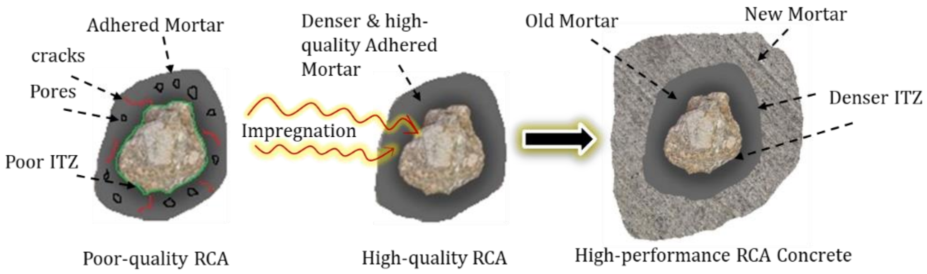


Figure 7: Densification by slurry impregnation

Obj. 1d: To study durability properties, service life extension techniques, and develop service life models for low-carbon concrete systems in various environmental conditions

Work done in Phase I

TLC2 team has developed scientific knowledge, databases, design charts and computer programs for estimating service life of steel-concrete systems with valorized waste materials (VWMs) and exposed to chlorides and carbon dioxide. Group is also developing the performance specifications and acceptance criteria for such constructions using VWMs and in marine/coastal conditions. Also, significant work has been done on assessing the carbonation resistance of concretes with VWMs. Team has also studied the durability and service life of prestressed concrete systems with low-carbon concrete materials. Based on the experimentally observed deviations from the expected corrosion parameters, it was found that the service life of many prestressed concrete systems would be much different than that are predicted by the existing models. It was also found that conventional repairs on corroding structures are failing in about 5 years. Extension of service life or enhancing durability of concrete structures by suitable repair technique helps in reducing the life cycle carbon foot-print of structures. Towards this, a new laboratory test method (i.e., GAP test method) to assess the long-term performance of galvanic anodes has been developed and patented. Also, a set of specifications based on anticipated long-term performance of embedded galvanic anodes have been developed and is now slowly being implemented in various projects. Two papers have been published. As a field demonstration, cathodic protection of about 1.2 m long sunshades of Rashtrapati Bhavan (a Class I Heritage building; see Figure 2) and a 500-unit apartment complex has been completed/ongoing. Also, IITM is going to start a Pilot Demonstration projects on cathodic protection and other low-carbon repair techniques to conserve the corroding 60-year old Sardar Patel Stadium in Gujarat and coastal highway bridges in Kerala – thereby preventing the demolition of such structures for the next at least 30 years. Also, work on cathodic protection of post-tensioned concrete bridges has been started in Phase 1. All these will be continued in Phase 2.

Planned activities in Phase II

TLC2 will continue the ongoing Round Robin tests (with Lafarge) and have started a new project in similar lines (with Holcim) on carbonation and carbonation-induced corrosion of steel in concretes with VWMs. TLC2 is planning to investigate the effect of internal moisture on the rate of carbonation and the threshold pH required to initiate corrosion in carbonated concretes containing VWMs and in various climatic conditions. These data will be combined and service life models will be developed for various concretes in various climatic conditions. Also, performance specifications and acceptance criteria for concretes in various climatic conditions will be developed. The studies on the durability properties of prestressed concrete systems in chloride environments will be continued. With all these information, a software program (named *ConcreteLife*) will be developed to estimate service life of conventional and prestressed concrete structures exposed to chlorides and carbon dioxide. Also, the team will work on developing standard documents on the assessment of corrosion initiation of conventional and prestressed steel in concrete systems and service life design of concrete structures. TLC2 will also perform laboratory studies and develop practically feasible cathodic protection techniques for concrete structures. Focus will be on developing tools to design and inspect cathodic protection systems in concrete structures. Experiments will be conducted to develop a technique to non-destructively assess the performance of embedded cathodic protection systems in concrete structures. This database will be combined with electrical and electrochemical models of reinforced concrete systems with cathodic protection systems. Such a technique, if developed, is going to be a game-changer for the clients to monitor and ensure durable cathodic protection systems – thereby delaying the corrosion and minimizing waste from the demolition of corroding concrete structures at an early date. There is a possibility of a start-up coming up from this work. Also, the team will work on developing national standards on cathodic protection of concrete structures.

Obj. 1e: To develop a framework to assess the sustainability indicators of construction materials and construction processes using the principles of life cycle assessment

Work done in Phase I

An LCA database consisting of inventory datasets for cement and concrete production processes was developed and the effect of different types of raw materials used, fuels and alternative fuels used for cement manufacturing in India was analysed. An LCA based 'ab initio' framework has been developed based on ISO 14040 and 14044 to choose concrete mixes by integrating sustainability, mechanical integrity and durability parameters. Further, the impacts associated with different SCMs like production of GGBS and calcined clay were determined. Reduction in impacts due to the application of blended cements such as PPC, PSC and LC3 has been investigated.

Planned activities in Phase II

In Phase 2, we would like to expand the scope of the LCA database based on large number of cement manufacturing plants in India. The effect of different allocation methods used to calculate the impacts of supplementary cementitious materials and its influence on blended cements and concrete systems would be investigated. Validation of the sustainability framework based on site based concrete mixes will be considered in addition to laboratory concrete mixes. Extension of the sustainability framework to other types of degradation during the service life would be considered. The proposed sustainability framework can be extended to other systems, including concrete components or products, such as blocks, prefabricated elements and recycled aggregates. The outcome can help cement, concrete manufacturers, other stakeholders and policymakers to promote carbon-friendly cement/concrete production, and further track the progress towards low emissions targets set by the government and to accomplish Sustainability Development Goals (SDGs). The uncertainty in the values of sustainability indicators will be used to provide guidance on the variability and ranges of the impacts under certain conditions.

Obj. 1f: To assess the prevalence of occupational health and safety issues and suggest improvements in working conditions for all humans involved through formal and informal sectors for C&D waste management

Work done in Phase I

Interactions with various stakeholders led to the conclusion that more specific organizational, psychological, and social factors need to be assessed to provide comprehensive solutions that can help improve the health and safety conditions of workers involved in C&D waste management in both formal and informal sectors.

Planned activities in Phase II

a) Conduct a systematic review of prevalent health and safety issues for workers in the C&D waste management sector. The preliminary assessment suggests that such a topic has not been explored systematically, even in the global literature; b) Trace the prevalence of OHS issues in the Indian context for workers in both formal and informal C&D waste management; c) Develop a comprehensive understanding of contributory factors for OHS issues in the Indian context; d) Develop recommendations for improving work practices and organizational processes based on an extensive analysis using a work-sampling approach.

6.2 Element 2 - Applied Research leading to technology development

There are four objectives in this Element.

Obj. 2a: To develop 3D printing technology for in-situ and precast construction of reinforced concrete and demonstrate robotic assembly

Work done in Phase I

In the past one year, research on 3D printing has continued in our group at a fast pace. The primary objectives in this time period have been related to the use of low carbon binders such as Limestone Calcined Clay cement, as well as the use of a higher aggregate to binder ratio in order to improve the sustainability (i.e., lower the economic and environmental footprint) of the mixes used for 3D printing (see Figure 8).
A new full-scale concrete 3D printer integrated with robotic arms has been designed. It is being commissioned and expected to be ready by the end of June 2022. The equipment has features that are not present in the prototypes that were implemented earlier in the Civil Engineering Department. These include:

a. Ability to pick and place reinforcement bars, pipes, and other objects into the printed specimen
b. Ability to monitor the quality of printed material and auto-diagnose problems. For example, the concrete mix properties such as rheology would be fine-tuned to suit the needs of the specific element being printed, to achieve the best possible constructability.
c. Integration of 3D printing into the overall construction workflow. This involves systems to automatically move printed elements from the bed, load them into the transportation system, track the status in the materials management software, etc. The whole process will be accurately modelled and performance parameters such as time, resource usage, and waste generated will be computed.
d. Integration with the design system. The path planning and control actions will be determined automatically using models of the building parts with minimum details
e. Smart control to accommodate a wide variety of materials. If the extruded material involves special components extracted from recycling, the nozzle, pump and other parts might have to be changed. The 3D printing system will be adapted to the material used with minimum intervention by the operator.

Figure 8: 3D printed elements using low carbon binder and high aggregate to cement ratio

Planned activities in Phase II

The 3D printer will be used to demonstrate the construction of small full-scale buildings. Metrics will be computed for evaluating the advantages of this technology. Quantitative evaluation of the potential for waste reduction will be performed using real data.

In addition to process improvements, the 3D printer will also demonstrate the possibility of introducing recycled material into 3D printing. Such materials include crushed aggregates and filler materials such as thin plastic. Volumes within structural elements where high strength is not required will be filled with filler materials obtained through recycling. This reduces the amount of fresh material required for construction and also avoids burning of these materials resulting in adding more CO2 in the atmosphere. Concrete 3D Printing offers these possibilities which are difficult with conventional construction. These concepts will be demonstrated when the printer is fully functional.

The work on low carbon binders and increased aggregate content (and aggregate size) in 3D printable mixes will further continue in Phase II. The use of geopolymer binders as well as calcium sulphoaluminate (CSA) Cement will be explored to evolve alternative mix designs with lower carbon footprint. Additionally, steel industry waste such as air-cooled blast furnace slag and LD slag will also be utilized in lieu of the natural aggregate to further improve the sustainability score of 3D printed concrete.

Obj. 2b: To demonstrate the performance of low-carbon concretes in large-scale field implementation studies and durable precast concrete systems

Work done in Phase I

- Demonstration of C&D waste recycling at Chennai Metro: To promote the use of RCA on a wider scale, a joint venture was made between IITM, Chennai Metro Rail Limited (CMRL), Advanced

Construction Technologies Limited (ACT), Westart Communication Pvt Ltd. (start-up in association with Greater Chennai Corporation), Schwing Setter (an international equipment company) and other stakeholders through demonstration of recycling at Chennai metro station. Two pathways were selected for this task, on-site recycling of waste pile caps through mobile crushers and off-site recycling at Stationary plant at Perungudi without changing the parent concrete waste. Currently, the RCA produced following both the pathways are being studied and it has been planned to use the same for different applications in Chennai Metro Stations.

Initial Crushing of Pile Caps | Crushing at Chennai Metro | Recycling at Perungudi Plant, Chennai | IITM Team with other stakeholders

Figure 9: Demonstration at Chennai Metro

- Construction of New Ram Mandir Foundation with Roller Compacted Concrete: Roller compacted concrete designed at IIT Madras was used for the foundation of the Shree Ram Mandir at Ayodhya.

Proposed Ram Mandir | RCC Foundation Laying | Inspection of Foundation | IITM Team with Stakeholders

Figure 10: Construction of RCC foundation at Shree Ram Mandir in Ayodhya

- Pilot Demonstration Recycling using Concentrated Solar Energy: To demonstrate the beneficiation of concrete waste using the cleanest form of energy, IITM team in association with Bramha Kumari's conducted a joint study at Mount Abu, Rajasthan. High-quality RCA fractions (coarse & fine aggregates and concrete fines) were extracted from concrete waste using the concentrated solar energy. Concrete produced with the beneficiated aggregates was having comparable performance to conventional concrete.

Figure 11: Use of solar concentrators for thermal treatment of recycled concrete

- Use of fibre reinforced concrete for IITM main gate road: The use of steel fibres could enhance the fatigue life of concrete pavements, thereby leading to a significant reduction in the thickness of the Pavement Quality Concrete. This concept was adopted and demonstrated in the IITM Campus.



Old Road | Laying of Fibre Reinforced Concrete | Constructed New Road

Figure 12: Fibre reinforced concrete for the pavement near the main gate of IITM campus

- Use of waste materials and cathodic protection at Rashtrapati Bhawan, New Delhi: The team had taken a key role in designing and repairing the 1.2 km long sunshades in this Class I Heritage Building (about 100 years old) by retaining the existing mild steel reinforcement, using low-carbon material (fly ash) and galvanic anodes for enhanced durability of the repair work (for about 30+ years). This is the first of its kind of application in India with low carbon footprint and durability in mind.

Pilot work being done on corroded chhajjas/sunshades (in 2018)

Repaired Chhajjas (top portion in the figure) with low-carbon concrete and cathodic protection

Figure 13: Repair of the 1.2 km long sunshades/chhajjas at Rashtrapati Bhawan, New Delhi

Planned activities in Phase II

Construction of World's first concrete road containing discarded coconut fibres

Cracking of concrete during the initial stages of construction (shrinkage cracking) is a serious problem in concrete pavements. Technologies will be developed to minimize such cracks using treated coconut fibre waste in concrete. A road stretch will be constructed to demonstrate this.

Demonstration of selective and preferential demolition

In general, demolition activities do not occur in a controlled manner resulting in the waste containing a random mixture of various types of materials. Such scenarios make it difficult to segregate the materials from demolition waste, which in turn lead to less usage of waste materials. The team will work on developing and demonstrating strategies for selective and preferential demolition, which is expected to minimize the efforts for segregation of demolition waste and maximize the usage of demolition waste and hence, a good approach for achieving sustainability.

Development of durable precast concrete building elements using waste materials and functionally graded concretes

The usual practice of providing uniform material design for most volume of structural and/or non-structural elements satisfying all the functional requirements lead to overdesign and adversely impacts the cost and carbon footprint of construction. We intend to design and create prototype building elements to demonstrate the structural, functional and durability performance using functionally graded concrete materials and valorized and recycled waste materials. The potential benefits of the proposed system in terms of cost and sustainability will be demonstrated by performing Life cycle cost and life-cycle energy/emission assessments. Also, the concepts of "design for durability, disassembly, and, reassembly" (D3R) will be developed to promote mass housing units. This would also be useful for building temporary housing units with good functionality indices, which could be dismantled, transferred to a new location and rebuilt – thereby minimizing carbon footprint in long term.

Obj. 2c: To develop software to estimate service life and sustainability indices to enable faster material selection and durability-based design

Work done in Phase I

Group has generated significant database on durability characteristics of various concretes with materials like fly ash, slag etc. However, there are still some missing links in this database, which are preventing the acceleration of promoting the performance-based specifications for concrete structures based on the target service life and specific exposure conditions. Also, the available software and frameworks for sustainability assessment of the construction industry are based on the database from the developed world, which may not be relevant for India and many developing countries. In the past few years, the IIT Madras group has collected significant data on the energy emissions and carbon footprint of cement and aggregate industry in India.

Planned activities in Phase II

The TLC2 team will now focus on experimentally obtaining durability parameters for concrete systems with low-grade limestone and clay materials. Also, focus will be on correlating the various durability parameters for various concretes with various waste materials. This is expected to enable a faster adoption of the developed computer programs and nomograms into the Indian codes and practices through performance specifications. To enable faster large-scale implementation of such low-carbon concrete materials, TLC2 will use the available database and develop simplified durability-based design charts and software programs (tentatively named as "*ConcreteLife*"). Software programs will consider various physico-chemical characteristics of the waste materials and concrete, other correlated properties of concrete, exposure conditions, chloride ingress, and carbonation, etc. and estimate the service life of concrete systems. This work is connected to Obj. 1(e). With respect to studies on sustainability assessment, the TLC2 will focus on generating database and frameworks for sustainability assessment in India. This work is connected to Obj. 1(f).

Obj. 2d. To develop low-cost, 'lighter', ready-to-use frameworks to promote sustainable construction

Work done in Phase I

A BIM Execution Plan template (BEP) was developed for Indian conditions. Using this tool, companies can create a robust BIM process that can improve process efficiencies. A simulation model was developed to determine the expansion of Chennai, and to estimate the number of new buildings that would be developed as well as the number of buildings that would be retrofitted. This model was then used to estimate the amount of carbon emissions that buildings in Chennai would contribute to (both in construction as well as operations). This methodology can be replicated for other Indian cities as well. In addition, development of criteria for evaluation of mass housing construction technologies in India was undertaken. A multi-criteria decision-making model for evaluation of mass housing construction technologies was undertaken and this was demonstrated on pilot projects.

Planned activities in Phase II

We plan to build upon these efforts and develop other tools and frameworks that are simple to use, are widely applicable and can aid decision making with regards to sustainability. For instance, we plan to develop a framework to determine the embodied energy in pre-cast vs conventional construction for a project. We also plan to develop a framework and a proof of concept for the use of Augmented Reality based tools such as Microsoft HoloLens, to enable sustainable decision making in the design stage of projects.

Currently, the industry suffers from a lack of process clarity on how to use existing digital technology to drive sustainable decision making. While our objective is not necessarily to develop new technology, we hope to develop implementation frameworks and templates that can be used to demystify the use of digital technology for decisions around sustainability and thereby increase the use of such technologies in practice. We also plan to conduct an investigation of sustainability indicators for alternate housing construction technologies such as precast/prefabricated building construction, compare embodied energy of concrete-framed residential buildings and steel-framed residential buildings and conduct Studies on variability in the sustainability indicators of residential buildings as a result of change in materials, construction planning and methods.

6.3 Element 3 – An Integrated Test-Bed for large-scale processes and visualization

Obj. 3a: To design and install a physical recycling test-bed for automated screening and physico-chemical processing of various waste materials

Work done in Phase I

The instruments necessary for the test-bed were purchased and are being commissioned.

Exploratory work has been carried out to test the ability to automatically detect recyclable material among construction and demolition waste. Two approaches have been tested successfully. The first one uses normal cameras to take pictures and use machine learning to detect objects such as bricks, plastic bottles, and cementitious debris. The second approach uses thermal imaging camera for the same purpose. The waste material is gently heated using halogen lamps. Then, the change in pattern of infra-red radiations emitted by the heated waste material is used to identify and segregate different types of objects.

Planned activities in Phase II

Two physical testbeds (Figures 14 and 15), one for binder production and other for aggregates production are being developed. Rotary kiln and temperature-controlled incinerator have been installed to enable pilot-scale processing of agricultural wastes, clay calcination and cement manufacturing. These test beds will provide effective utilization of the resource materials in developing alternative supplementary cementitious materials (SCMs), aggregates, and low CO_2 cements; thereby developing protocols and frameworks in terms of optimized production parameters that could be directly applied in the real scenario. These test beds also include tools for physico-chemical processing and analysis, proportioning of materials for enhanced performance, aggressive/accelerated exposure of various waste materials and systems; and subsequent characterization and material selection is envisioned.

Since the main objective of the proposed centre is not only to recycle the civil engineering related waste; but, also to extract value-added benefits out of it, various iterations of beneficiation will be carried out on the input waste until the physical, mechanical, and durability properties of extracted engineered materials will fall within the acceptable limits of Indian & International guidelines such as Bureau of Indian Standards (BIS), American Society of Testing Materials (ASTM), Indian Roads Congress (IRC), Ministry of Roads Transport and Highways (MoRTH), etc. Thereafter, various solutions and recommendations will be provided based on the waste application sector. Since there can be different methods for beneficiation of waste material and each treatment can be assumed to affect the final outcome in terms of economy, desired properties of the structure, etc., life cycle cost & environment analysis become inevitable.

The proposed centre will also evaluate the infrastructure suitability and environmental effectiveness of recycled waste. Besides, validation of the final product could be made via field trials. The following data will be collected to design & install the recycling research plant: (a) mapping of waste (b) equipment for preliminary processing of waste, (c) types of machinery for detailed processing, (d) requisite beneficiation techniques, manpower requirement, etc.

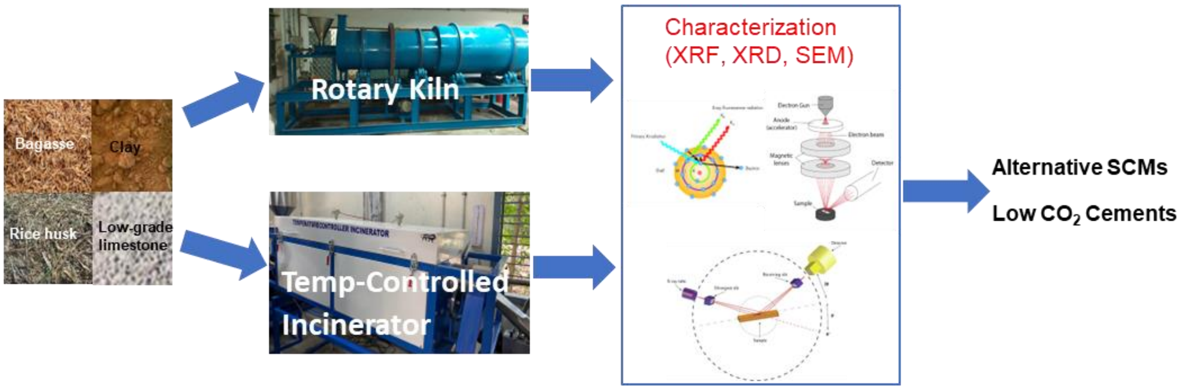


Figure 14: Schematic showing processing of agricultural wastes and other materials using rotary kiln and temperature-controlled incinerator

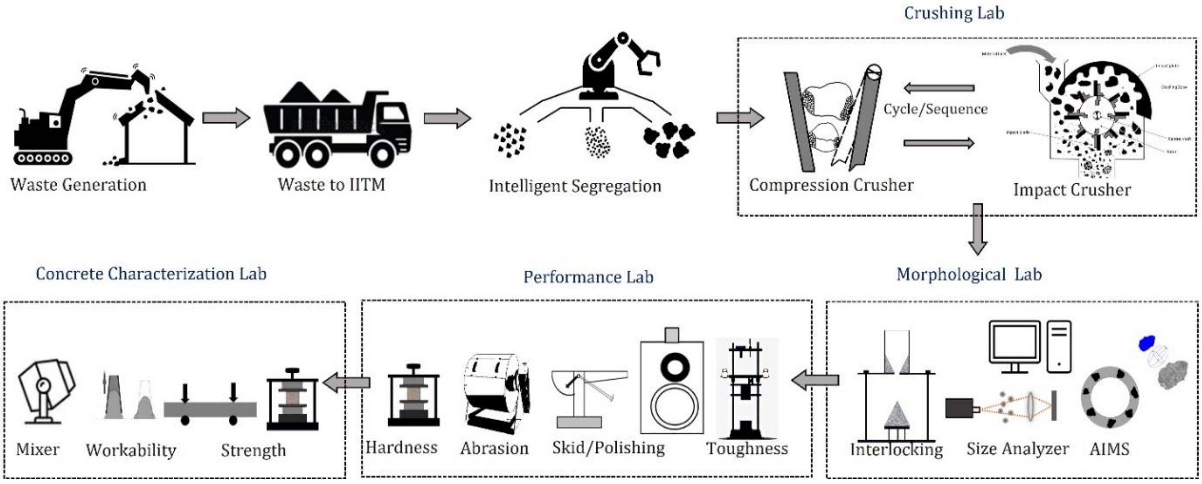


Figure 15: Schematic for a Testbed for Aggregates

Obj. 3b: To integrate a Machine Learning (ML) analysis capability to predict the optimal usage of recycled material, based on a material characteristics database

Work done in Phase I

Recognizing the value of the data obtained from the functioning of the test-bed described for Objective 3a, the data will be systematically collected in the form of a central database, one of its kind in India. Such a database will then enable the integration of ML analysis capability for data analysis for future work. The main advantage of such ML capability will be to reduce the time taken to predict the adequate mix-design for a specific material for which the field application is desired. Currently, the experiment-based study is necessary to identify the suitable proportion of materials that goes into the mix design of concrete with waste material. With the integration of the ML capability, such trials can be reduced by a significant amount, also contributing to a reduction in waste generated from experimental phases. The physical test bed developed so far has been able to generate a large quantity of relevant data that is currently being collated for further processing during Phase 2.

Work to be done in Phase II

An overview of the process to achieve ML integration is shown in Figure 16. The output of the Objective 3a will be systematically stored in a database, as shown in Figure 16. The data here will contain information not only the successful cases but also the failure cases, as part of the experimentation conducted to fulfill Objective 3a. Work to achieve integrated ML classifiers will also start. Several types of ML classifiers will be trained to achieve high accuracy in prediction for some observations with known outcomes taken from the database. Once such ML classifiers with high prediction accuracy have been obtained, a few test cases will then be generated from the trained classifier, and the result predicted by the ML classifiers will then be validated against results obtained from the experiments. Hence, through an iterative process (Figure 16) a fully integrated ML data analysis capability will be achieved through the early days of Phase 2, which can allow us to predict the optimal usage of recycled material, for a given material characteristic.

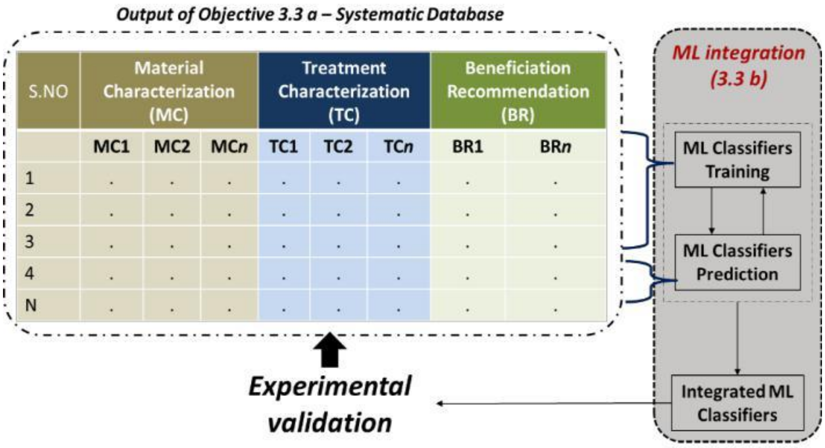


Figure 16: Process to achieve ML integration to predict optimal use of recycled material

Figure 17 then describes the efficiency that can be achieved in the functioning of the recycling test-bed through ML integration. For commonly used materials, the time to generate recommendations can be reduced significantly. For recycled materials used rather infrequently, the experimental cycle can be shortened, as ML tools can help in narrowing down the experiment requirements. Such integration with ML will then free-up the capacity of the test-bed, which can be subsequently utilized to test different types of waste materials for their usage in construction, allowing us to further enhance the scope of the database and scientific knowledge in the field.

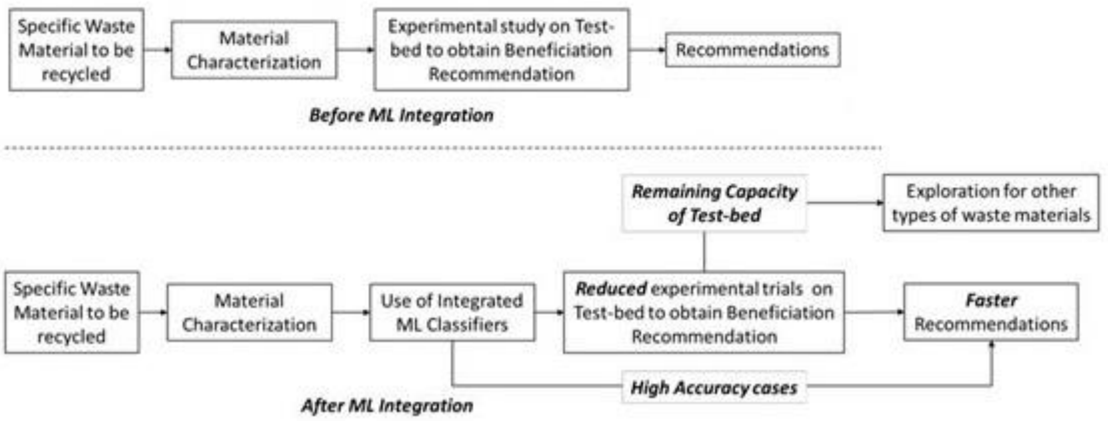


Figure 17: Efficiency in process through ML integration

TLC2 team has proven capabilities in integrating ML processes in the construction industry, and the use of ML for the application described here will enable the IITM to have a state-of-the-art, one of a kind of facility on recycled waste characterization and optimal usage for industry partners.

Obj. 3c. To develop a physical and AI-VR integrated testbed environment to identify optimal use of materials, simulate and optimize construction practices, and minimize carbon footprint

Work done in Phase I

Progress was made on developing automated sensor-based approaches to classify the raw materials. The PIs in association with The International Association for Automation and Robotics in Construction

(IAARC), and American Society of Civil Engineering (ASCE) are organizing a hackathon to develop algorithms that can differentiate between various types of raw materials in a stream of C&D waste material based on 2-D images. An inherent focus of the hackathon is also on to rely on the low-resolution images as much as possible, so that the developed algorithms can provide good classification performance but not be computationally and resource intensive. Such a technique thus developed can then be deployed in many applications where quantification of constituent elements in C&D waste stream is often needed.

Planned activities in Phase II

Phase II of the proposal will continue to extend the work done in in Phase I. A prominent extension includes developing a LIDAR scanning integrated with the GIS platform, that could be useful for the municipal corporations around India for testing and optimizing the C&D waste collection process in their respective geographic regions.

Despite the formal framework, the progress towards effective management of the C&D waste remains a crucial challenge in many Indian cities. One of the fundamental challenges in this regard is the lack of reliable information across the supply chain of CDW management, including unreliable data about the quantity and location of CDW waste generation. The current approaches for CDW estimation rates are imprecise and resource intensive due to their reliance on many manual inputs, making them unsuitable for near real-time information. Such a lack of timely and reliable information is one of the primary motivations for developing an automated data collection technology (LIDAR-based) for near real-time monitoring of CDW generation and a CDW supply chain optimization framework (GIS-based). Such automated technology and framework are expected to be valuable for various Indian municipalities to enhance the efficiency of their formal CDW recycling efforts and long-term planning of the relevant infrastructure. LIDAR is a 3-D laser scanning tool that can generate a point cloud capturing the geometrical and optical features of the surface. Such a 3-D point cloud can then be used to calculate the volumetric features of various elements. In Phase II, the PIs will implement the algorithms developed for Phase 1 and optimize their performance for fast processing large quantities of frequent 3D CDW stockpiles scan preferably taken from multiple locations in city with low-cost handheld devices. Phase II extension will also rely on lower resolution images (compared to conventional cameras) generated by LIDAR sensors to develop techniques for differentiating among different materials within a stockpile of CDW. The limitation with LIDAR images related to their lower resolution will be compensated by advanced Machine Learning (ML) algorithms. The ML algorithms can provide accurate results even in low-resolution images and potentially be managed without being computationally intensive. The patterns in geographic information combined with LIDAR-based quantity estimation can then help municipalities optimize the path for CDW waste collection from the formal and citizen-reported dump sites. The GIS location of CDW can then also be processed in conjunction with other geographic characteristics of the transport infrastructure, such as accessibility to roads and width of streets for a particular location. Such a piece of information could also help optimize the selection of vehicles that is necessary for the collection process. The information combined with the traffic information (readily available through a variety of GIS tools) can help optimize the schedule of CDW collection within a city and help get a very reliable estimate of the transportation cost involved in transferring the CDW waste from the dumping areas to the recycling plants. In the long term, such information can also be helpful for the cities to determine the optimal location for the new recycling facilities to be created in the urban space. The proposed project will develop a simplified software system using free and open-source tools as much as possible that can enable a user-friendly interaction of municipal authorities for planning such activities. Such a proposed system is then expected to be scalable across different cities in India.

Proposed work in Phase 2 related to material "What-if" Scenario analysis

Going beyond optimizing recycled and re-used material, the testbed will also help model the construction process and supply-chain logistics. By integrating simulation systems such as stroboscope with Lean processes such as Value Stream Mapping, visualization techniques such as BIM, and AR/VR toolkits such as HoloLens, the test-bed will allow for immersive visualization of construction practices and for testing out of construction/material scenarios. For instance, in the case of project such as the Chennai Metro Rail, this virtual test-bed component can help contrast the economic and environmental performance of say construction using Waste Material 1 vs Waste Material 2. Several of these components already exist. BIM Holoview for instance, allows users to immerse themselves in 3D models BIM models. However, the integration across these components is likely to be unique to this testbed, where the large quantity of the data generated through the TLC2 will be helpful.

Obj. 3d. To establish a simulation and game-based learning facility on management adoption strategies, organizational training, and specialty skill training on lean process

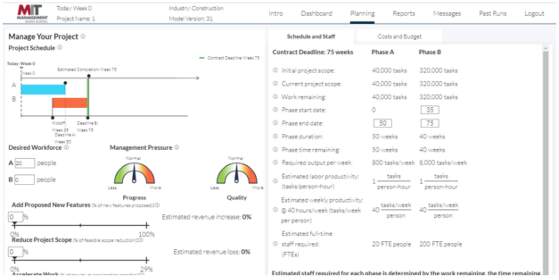
Work done in Phase I

During Phase 1, a System Dynamics-based simulation game was developed that could help deliver the lessons related to project management and lean practices to game participants. The game was redeveloped using open access materials available from MIT and has been tested with other project management students/professionals enrolled in various degree programs at IIT Madras. The initial results have been very effective, as shown in Figure 18.

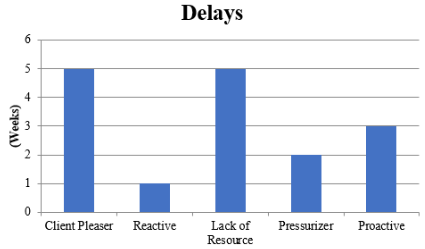
Planned activities in Phase II

The game development will be completed sequentially, starting with simple models based on SD and ABM for limited scenarios and advancing to include multiple modules and player characteristics as we move along. PIs will also engage with industries to promote the training aspects of the testing facility based on the results from Phase I and adapt the facility to further fine-tune as per the industry demands. PIs will then also utilize the results from the testing facility to be taught as a course, which will be a significant departure from conventional theory-based courses. At the same time, students will be engaged to "play" with the facilities, enabling their contribution to further developing the facility. In Phase II, more advanced games will then achieve integration among the inputs and outputs of these numerical simulation models. These tools can be visually represented using the AR/VR tools that will constitute the virtual component of our test-bed (described earlier), thus allowing the test-bed to be used as the 'game room' for testing out strategies and learning from them.

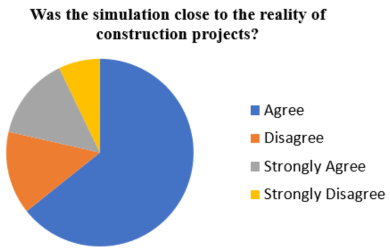
Research, training, and education processes will also follow a gradual development approach similar to the development of the game-based facility. Through continuous monitoring of and engagement with the players, i.e., practitioners from the construction industry, the PIs will synthesis the characteristics of the players' behaviours. PIs also aim to publish such findings unique to the Indian context through top-rated journals in the field. Outcomes of this part of the research will then feed to another objective of our proposal focusing on assessing tool adoption in the Indian construction industry.



Dashboard of the game



Player personality and effect on project outcomes



Players' experience with the game

	Pre-game (out of 4 marks)	Post-game (out of 4 marks)
Question 1 (Avg score)	3	3.79
Question 2(Avg score)	1.93	3.29
Question 3(Avg score)	1.93	3.29
Total Avg Score	6.64	10.36
Percentage Avg Score	55.36%	86.31%
Improvement in score	55.91%	

Statistically significant improvement in learner's outcomes

Figure 18: Results of simulation game

6.4 Element 4 - Organizational & policy research for large-scale technology adoption

Obj. 4a To develop national maps on current/future availability of waste materials (based on socio-economic-environmental sustainability aspects)

Work done in Phase I

Mapping of wastes in India: This activity aims at mapping of agricultural, industrial, and construction & demolition (C&D) wastes to assess their potential for beneficial utilization in construction materials. A GIS based approach is being adopted for mapping of wastes. Our team is collaborating with Technology for Action for Rural Advancement (TARA) as they have previously developed a framework for clay mapping across India. A database consisting of composition, quantity, and location of different wastes will be created for India with the help of local government bodies, academic institutions, and NGOs. As a first step, various industries responsible for biomass ash generation have been mapped and current work is focussed on estimating the amount of waste. Figure 19 shows the distribution of paper mills, one of the sources of biomass ash generation, in India. Along with mapping of wastes, detailed physico-chemical characterization of wastes sourced from different regions is currently being performed. The waste as potential aggregates will be mostly characterized for mechanical properties, mineralogical compositions, and morphological properties adopting different techniques. For potential binders/fillers, characteristics such as oxide composition, phase composition, morphological characteristics, and particle size distribution will be determined. The outcome of this activity will result in a map of agricultural/industrial/construction wastes including their physico-chemical characteristics, quantity, and location.

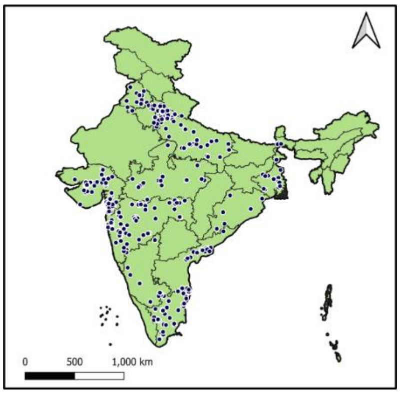


Figure 19: Mapping of paper mills in India (2020-21)

Planned activities in Phase II

The technology development will be coupled with a systems analysis module to evaluate the socio-economic and environmental impact of proposed strategies. Life cycle assessment (LCA) methods make it possible to quantify the materials depletion, energy usage, emissions, and particularly of a potential by-product synergy. For many beneficially reused materials, there is a trade-off between the environmental benefit and any burdens associated with transporting supplemental materials to where they would be processed. Therefore, this final evaluation stage will be critical for assessing the economic feasibility of where the waste materials are generated and where they will be processed.

Obj. 4b. To develop strategies for modifying organizational work practices to increase the adoption of lean construction practices

Work done in Phase I

In this phase, we focused on answering a critical question that practitioners ask – are these ideas truly beneficial? Can we quantify these benefits in terms of time and cost savings as well as in terms of a return on Investment? Through projects undertaken in the Nuclear Power Plant and offshore bridge sectors, we conducted 2 case studies that helped us quantify the impact of Building Information Modelling as well as benchmark the use of a Lean technique called Value Stream Mapping. The results are telling – a single use case of BIM was able to save close to 2% of project costs. Similarly, benchmarking value stream maps, which have been shown to make construction 'green' as well as 'Lean' will help the industry set achievable goals for improved efficiency and carbon reduction. The benefits of Lean construction to both sustainability and financial stability have now been well established and quantified.

Planned activities in Phase II

We plan to first adopt a comparative case-study approach to look at waste reduction technologies that are already being used with varying degrees of success across firms and projects, to understand key organizational structure and strategy factors that either contribute to or hinder adoption. We plan to conduct 2-4 in-depth case studies of projects across the country that can also be converted into teaching material. Roughly half of these will feature the successful adoption of waste-reducing technologies, while the other half will represent failed efforts. This effort is likely to result in a journal publication as well. As a second step, we plan to develop an existing theme of research that suggests that while top-down efforts in 'enforcing' technology adoption are necessary, bottoms-up efforts are likely to lead to greater sustainability of the use of innovations. Bottoms-up approaches are effective when the work-practices of professionals align with work-practices required to adopt a waste-reducing tool or innovation. Using constructs from a branch of organizational theory that studies routines and practices and how they may influence changes in work-practices, we plan to conduct deep-dive studies of practitioners in 2 organizations where BIM technologies have been successfully adopted to minimize wastes, to understand (a) the practices that they undertake to successfully deploy these tools and technologies, and (b) ways in which these practices changed from conventional studies in the past. One of the projects that we have identified for this purpose is the Rapid Rail Transit System (RRTS) being built in the NCR region, where BIM has been extensively deployed. We are about to embark upon a case study on this project. In addition, there are projects that outside the traditional civil engineering sphere where Lean project management techniques are used to ensure successful and sustainable project delivery. The Indian elections, for instance is one such megaproject that fits this description. We are in the process of conducting a case study on this megaproject as well with a view towards understanding the adoption of innovation. A draft of a paper along these lines has been prepared. These efforts have been supported by one full time PhD student and several MTech/Dual Degree students.

Towards the end of Phase 2, with our test-bed ready, we hope to go one step further and investigate not only practices related to adoption but also the management of stakeholders in process of developing waste-free projects. We plan to allow organizations to simulate construction sequencing scenarios on the BIM enabled test-bed in the presence of multiple stakeholders and to observe how collaboration between stakeholders takes place to iron out process-related wastes on projects. In phase 2, we plan to publish at least 2-3 papers in high impact journals from this work.

Obj. 4c. To develop a framework to leverage private sector participation across supply-chain of concrete materials during the life-cycle of construction projects

Work done in Phase I

During Phase 1 of the project, we have established a partnership with a New-Delhi based non-profit group named “Malba Projects” for tracing the C&D waste and recycled material flows through formal and informal sectors. Malba Project has already developed the Malba Map (Figure 20), an open-source map of New Delhi's formal waste infrastructure, previously unavailable in the public domain. Through the current project, teams at TLC2, IIT Madras, and Malba Project propose to collaborate, leveraging their respective strengths to understand and map New Delhi's formal and informal waste management system.

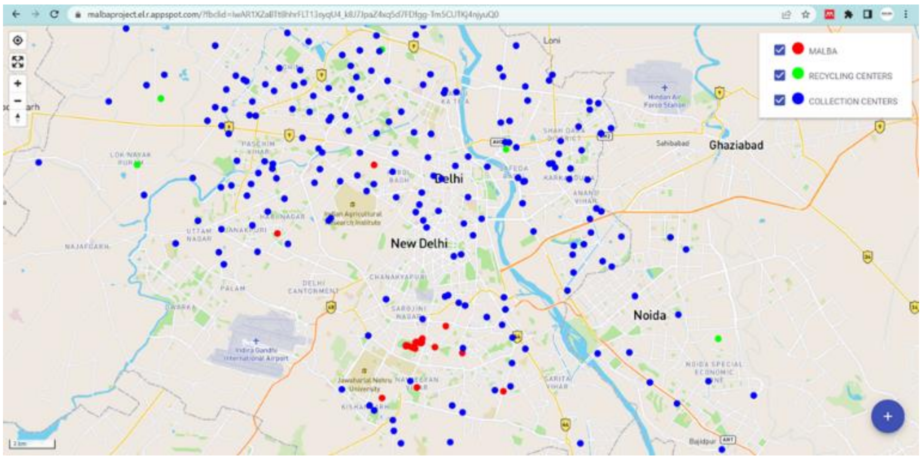


Figure 20: Malba Map, an open-source map of New Delhi's formal waste infrastructure and crowd-sourced illegal dumping hotspots (Source : https://malbaproject.el.r.appspot.com/)

We have also developed a system-thinking-based understanding of the causal links that govern the patterns of private sector participation in enhancing the recycling rate of a city’s CDW. A high-level conceptual framework tracing the perspectives of government, private recycling, and the construction industry for the CDW material and financial flow at a city level is shown in Figure 21. The framework is rooted in the academic literature.

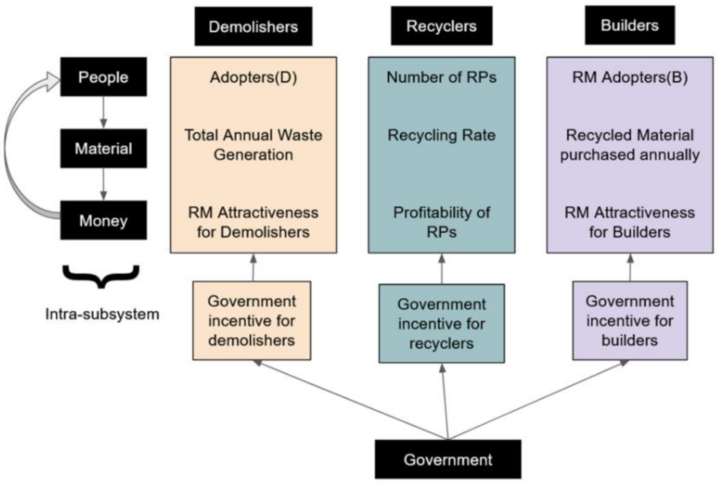


Figure 21: Systems thinking framework

Planned activities in Phase II

In Phase II of the project, we aim to conduct Spatial mapping of secondary material Flow for the city of New Delhi. We mainly aim to identify the significant secondary-material hubs in New Delhi through on-ground investigation and estimate material flow over few months through on-ground data collection (counting trucks, weigh-in slips, etc.). We also aim to conduct stakeholder analysis and understand their perspectives to develop synergistic development policies integrating the formal and informal waste management sectors.

The framework developed in Phase 1 will be validated against the real-case studies from various cities in India. A partnership with several industrial partners such as Godrej and TARA have already been established. Upon validation, such a framework will be converted to a simulation model that can facilitate what-if scenario analysis and be used as policymakers' policy making and training tools.

The data thus collected will then be analyzed considering a lens of private sector participation and the level of involvement of the government. Questions answered at this stage would be 1. Would the private sector involvement be necessary and bring efficiency to manage the supply chain effectively? 2. How could a PPP in this sector be structured? Would, for instance, Viability Gap Funding be required, and if so, how much? What kinds of flexibilities can be introduced in these contracts to combat uncertainties? And finally, 3. Even if the private sector could be involved, what roles will the government have to play to ensure the sustainability of their involvement? Answers to each of these questions will contribute to identifying the suitable management strategies that the policymakers need to adopt for the Indian context, and the same will be published through appropriate academic and policy platforms. One Master's student has already been deployed on this project.

Then in the future, the framework developed in this study, the data collected using the framework, and the research questions answered can set the foundation for a nationwide implementation of the approach. At this stage, PIs will actively participate in promoting the results, guiding the course of future studies, as well as exploring further research questions even beyond the scope of the current TLC2.

Obj 4d. To develop Policy Notes for large-scale implementation of various waste utilization/reduction technologies

Work done in Phase I

PIs to this proposal are currently chairing the Confederation of Indian Industries (CII) Southern Region Task Force on Infrastructure and Smart Cities, and can use this as a platform to speak about the TLC2s work and also to bundle our results into concept notes that CII puts out. In addition, PIs are member of groups such as the Indian Concrete Institute, the American Association of Cost Engineering, the Project Management Institute, etc, all of whom can be leveraged to sensitize practitioners to our findings. The third step in the policy development process is to then create a policy working group with a few selected practitioners and government representatives. This working group, created under the aegis of a government department will then host a series of invitation-only roundtables and workshops, to refine our recommendations into a coherent policy note which government departments can then use to enact legislation. Internationally relevant work will also be published as Policy Briefs from prominent think-tanks such as the Asian Development Bank Institute. PI Nikhil, has extensively published with ADBI as part of his previous engagements. A series of policy notes have been identified based on work done in Phase 1. An initial policy note on the need for low carbon lean construction will highlight the magnitude of the problem of wastes in construction and their environmental impact. This will be followed by policy notes specific to technologies – the advantages and economics of recycling C&D waste, pre-cast construction, low-carbon cement, and the use of Lean and BIM. The final note in the 6-part series will bring these ideas together to propose a model of development going forward. We also hope to influence policy in specific organizations.

Planned activities in Phase II

We are entering into early conversations with the Department of Industries in the Government of Tamil Nadu, who are embarking upon an ambitious scheme of building several industrial parks across the state and hope to influence their development policy whereby they commit to the use of low carbon and lean techniques.

In parallel, we plan to work with The Bureau of Indian Standards (BIS) in developing industry standards for construction processes based on our work. Specifically, the Construction Management Sectional Committee, CED 29, is already looking into these issues, are consulting our PIs on standards relating to construction practices that minimize waste, and would be the key group that we will coordinate with. Two areas in which the initial stages of policy development are already in progress are Building Information Modelling (a draft policy note has been submitted to GoTN, Niti Aayog and discussions with CED 29 on adopting relevant standards is already underway) and the use of

Construction & Demolition waste in projects. In addition, standards and policies to maximize the use of wastes in concrete as well as emission guidelines and standards for construction processes will also be developed. This activity is intended to contribute to practical impact as well as the perception of our TLC2.

7 SUMMARY

The uniqueness of the centre lies in its vision to straddle the entire gamut of basic and applied research activities involved in construction – starting from identification and characterization of waste to design, to process planning, to organization, and policy development for large-scale implementation. This systemic focus will help us make significant improvements in making construction 'low-carbon' and 'lean'. The integrated test-bed will provide a first-of-its-kind 'one-stop' learning experience to the practitioners and researchers alike. We are not aware of such an integrated approach being taken to research or such integrated facilities being available anywhere in the world. The research activities have been carefully selected in domains, where there is a significant gap in existing knowledge and where there is potential to expand the frontiers of technology. Some of the key intellectual merits are highlighted below.

- The work already completed and the work envisaged for the future address critical gaps in evaluating low energy / emission pathways for processing of agricultural, industrial and construction & demolition (C&D) waste. While there have been several past attempts in this direction worldwide, it is expected that the current project will lead to a systematic methodology with quantified impacts.
- The use of sensors and automation to sort C&D waste will provide a tool for segregating the different types of C&D waste and enable more efficient use of the same in forward applications. For instance, when masonry waste is mixed with demolished concrete, it is difficult to develop proper mixture design strategies for concrete with such aggregate. On the other hand, concrete waste segregated properly will lead to a complete utilisation.
- The work in Phase II will also lead to some insights into the creation of value-added uses for the waste. For instance, there is a plan to study the pyrolysis of the agricultural waste in order to develop its use as an alternative fuel. Additionally, the fines obtained from crushing C&D waste will be assessed for their suitability as high surface area 'seed' for accelerating hydration of cement, as well as for enhancing the particle size distribution of 3D printable cementitious composites.
- Durability is the key to sustainability in concrete construction. With this view, the tools for service life assessment integrated with LCA will help in providing a judicious approach to the selection of materials for new concrete construction, especially with high volumes of alternative materials.
- Technology is an enabler in the promotion of the use of alternative materials in construction. For instance, 3D printing provides unique possibilities of optimizing structural forms to obtain the best performance with minimal use of materials. Here, the integrated robotics planned in the project will enable greater levels of automation and intelligent control of the construction process, which will help cut the wastage in terms of the process. Further, simulation tools such as BIM will extend the capability of visualizing construction processes in order to optimize on cost and time.
- One of the key shortcomings of the approaches for utilizing alternative materials is that there are no clear inputs on the modelling of the material flow across its supply chain. This is one aspect that the current project will attempt to address. Similarly, case studies of large projects involving successful and failed adoption of waste-reducing technologies will provide insights into the current understanding of theoretical constructs on the diffusion of innovations and technology in construction.
- The proposed AR/VR gaming/simulation-based test-bed with a focus on lean management will be a first of its kind in the world. Gamification based approaches have been used for construction management such as project planning and control, and safety, but rarely for lean management.
- Finally, the integrated approach planned for the project will help in the drafting of suitable policies for large scale implementation of technologies for low carbon and lean construction. Often, specifying agencies need guidance in translating research into practice, which has hitherto been difficult because of the lack of such an integrated approach. The end goal of this project is to influence policymakers to come up with judicious strategies for application of the concepts developed in the project.

The work done in our TLC2 will impact several UN Sustainable Development Goals and therefore is likely to have direct societal impact. Our findings on utilizing and reducing waste in construction will lead to a direct reduction in green-house gas (GHG) emissions by reducing the consumption of virgin materials and optimizing waste (of time, materials and fuel) during transportation and energy-intensive construction processes. In addition to publishing in Q1 journals, we will also develop several policy briefs and play a role in formulating standards that will make the entire construction industry lean and carbon friendly. We are already in discussions with the Bureau of Indian Standards (BIS) on developing standards and code of practices for the implementation of Building Information Modeling (BIM), low-carbon cements, durability-based design procedures to reduce the carbon footprint during the entire life-cycle of concrete infrastructure. The group also plans to approach Niti Aayog for developing policies in these lines. Through an organization called CDCPIndia we have touched base with Niti Aayog. Our connections with the World Bank and Asian Development Bank Institute (ADBI) will allow us to disseminate our information internationally, thereby potentially impacting society globally, particularly in developing countries. We hope to engage with APEX bodies such as the INAE and/or CIDC, to attempt to influence policymakers. These activities will start soon and continue even beyond 5 years.

Apart from influencing society through policy we also hope to influence practitioners directly so that they can convert our discoveries into practice. This can be done in short and medium terms. We hope to catalyze a new breed of construction practitioners, who truly value sustainability alongside cost, time, and quality control. We will do this through summer schools, where we hope to train 100-150 professionals over 5 years, and through inviting practitioners to use our 'test-bed' to understand the various avenues to utilize waste in construction materials and virtually simulate their construction sites. In this way, we hope to educate and convince practitioners to boost adoption of waste minimization and management practices. We are also envisaging the launch of an online MTech program that will be widely available and accessible, and which will provide information on these topics.

We also plan to transfer technology to the field in the medium term (say, about 5 years). Our waste recycling processes as well as the frameworks that we will develop to address sustainability outcomes can be used in a number of practical settings such as Housing-For-All projects in rural areas, for instance. We plan to fund some of these efforts through CSR funding, without relying entirely on the TLC2s funds. CUBE (Center for Urbanization, Buildings and the Environment) is a center that our PIs have recently set up at IITM Research Park, primarily to help with technology transfer. CUBE has undertaken similar CSR funded projects, for developing facilities using pre-cast and other cutting-edge technologies. Using CUBE as our project manager, we plan to leverage CSR funds and research from the TLC2 to build rapid, low-carbon houses for some of India's poorest inhabitants in the medium term. Such technologies can also be transferred to numerous developing nations. Of course, this will require considerable rapport with the government, which the PIs to this proposal do enjoy, having executed several projects successfully for GoTN and other arms of government. CUBE was also set up in partnership with TN's Housing and Urban Development Department and therefore our likelihood to be able to work simultaneously with both government and CSR donors is quite high.

Finally, in addition to policy and practice, we hope to impact academia as well. We will collaborate with other IITs/NITs in the research that we do, thereby building capacity at these universities as well (the PIs have already conducted joint work with faculty from IIT Bombay and IIT Delhi). Further, the TLC2 will generate several Ph.D. students and plan to place as leaders in academia and industry. We hope that these alumni will be ambassadors of our research directions, and setup complementary programs in a host of other universities and industrial organizations across the country.