BILINGUAL PUBLISHING GROUP

Journal of Architectural Environment & Structural Engineering Research

Volume 6 • Issue 2 • April 2023 ISSN 2630-5232(Online)

BILINGUAL PUBLISHING GROUP

Editor-in-Chief

Müslüm Arıcı
Kocaeli University, Turkey

Associate Editor

Nasir Shafiq
Universiti Teknologi Petronas, Malaysia

Editorial Board Members

Yonggao Yin,China
Mehdi Shahrestani,UK
Humphrey Danso,Ghana
Alireza Joshaghani,USA
Mohamed El-Amine Slimani,Algeria
Dario De Domenico,Italy
Amos Darko,Hong Kong
Mehmet Cetin,TURKEY
ANTONIO FORMISANO,ITALY
António José Figueiredo,Portugal
Latefa Sail,Algeria
Amjad Khabaz,Syria
Mohammad Ahmed Alghoul,Saudi Arabia
Jian-yong Han,China
Huaping Wang,China
Banu Manav,Turkey
Alper Aldemir,Turkey
Yushi Liu,China
Rawaz M. S. Kurda,Portugal
Ahmed Elyamani Ali,Spain.
Mohammed Jassam Altaee,Iraq
Yuekuan Zhou,China
Rabah Djedjig,France
Mª Dolores Álvarez Elipe,Spain
Marco Di Ludovico,Italy
Alper Bideci,Iran
Uneb Gazder,Bahrain
Yeong Huei Lee,Malaysia
Seongkyun Cho ,Republic of korea
Wen-Chieh Cheng,China
Marco Breccolotti,Italy
Manish Pandey,Indian
Fadzli Mohamed Nazri,Malaysia
Vail Karakale,Turkey
Ana-Maria Dabija,Romania
Li Ying hua,China
You Dong,China
Fabrizio Scozzese,Italy

Volume 6 Issue 2 • April 2023 • ISSN 2630-5232 (Online)

Journal of Architectural Environment & Structural Engineering Research

Editor-in-Chief

Müslüm Arıcı

BILINGUAL PUBLISHING GROUP

Volume 6 | Issue 2 | April 2023 | Page1-79

Journal of Architectural Environment & Structural Engineering Research

Contents

Articles

BILINGUAL PUBLISHING GROUP

Journal of Architectural Environment & Structural Engineering Research
https://journals.bilpubgroup.com/index.php/jaeser

ARTICLE

Best Practices in Construction 4.0—Catalysts of Digital Innovations (Part II)

Bianca Weber-Lewerenz**, *Marzia Traverso

Institute of Sustainability in Civil Engineering (INaB), RWTH Aachen University, 52062, Germany

ABSTRACT

Part II on Best Practices in Construction 4.0 follows up on the previously published study Part I. This study examines corporate strategies from different angles, defines potential fields of application and works out existing empirical values and trends in the digitization process of the building sector. It highlights the unintended consequences of technological development and offers concrete practical approaches for responsible use. Using the qualitative research method, the study concludes that digital methods, such as Building Information Modelling (BIM) and Digital Twins, and Artificial Intelligence (AI) can add value, significantly reduce resources and increase sustainability. The study is part of a larger primary research on Corporate Digital Responsibility (CDR) in Construction 4.0; it identifies, analyzes and systematically evaluates the pillars of a sustainable digital transformation, especially in the Construction Industry. The holistic, interdisciplinary view of this study aims to provide orientation for small to medium-sized companies (SMEs) developing their individual digital strategy. An outline of the necessary prerequisites but also design options, as they result from the evaluation of expert interviews and literature research, supports companies in the design of Construction 4.0 that is in line with the needs of people, society and the environment and shaping more economically efficient building life cycles. It highlights that digital transformation has also reached the traditionally small-scale AEC industry (small-scale architecture, engineering and construction industry) and catalyzes the variety of innovations.

Keywords: Digitization; AI; Digital transformation; Best practices; Smart cities; Circular economy; Cradle-to-cradle; Construction 4.0

*CORRESPONDING AUTHOR:
Bianca Weber-Lewerenz, Institute of Sustainability in Civil Engineering (INaB), RWTH Aachen University, 52062, Germany; Email: bianca.christina@gmx.de

ARTICLE INFO
Received: 13 January 2023 | Revision: 20 March 2023 | Accepted: 7 April 2023 | Published Online: 20 April 2023
DOI: https://doi.org/10.30564/jaeser.v6i2.5408

CITATION
Weber-Lewerenz, B., Traverso, M., 2023. Best Practices in Construction 4.0—Catalysts of Digital Innovations (Part II). Journal of Architectural Environment & Structural Engineering Research. 6(2): 1-21. DOI: https://doi.org/10.30564/jaeser.v6i2.5408

COPYRIGHT
Copyright © 2023 by the author(s). Published by Bilingual Publishing Group. This is an open access article under the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License. (https://creativecommons.org/licenses/by-nc/4.0/).

1. Introduction

New technologies such as AI are increasingly finding their way into the integration and operation of existing buildings, fire protection systems, circular economy, cradle-to-cradle and smart cities. The intelligent network of existing buildings and infrastructure enables smart cities to operate according to the latest energy and security standards. An innovative design may significantly support the achievement of sustainability and climate goals, and lead to a higher sense of human security and safety, and an overall increase in quality of life [1]. The building sector causes almost 40% of global CO_2 emissions and is the key to central climate neutrality by 2050. Innovative building technologies in existing buildings enable intelligent ecosystems as part of the 5th industrial revolution [2]. Empirical values from user practice, gained by expert interviews over the period from 2019 to 2021, are the basis for deriving new approaches and for setting the main pillars for a sensible, sustainable use of digital technologies. Overall, German companies were able to generate sales of €60 billion in 2019 with products and services that directly use AI [3]. In 2019, 30% of companies using AI in the German economy were previously vacant in the field of AI [4]. BIM and new technologies such as AI, Artificial Intelligence of Things (AIoT), Internet of Things (IoT) are technological prerequisites for sustainable digital transformation in all areas of buildings, mobility and smart cities [5]. However, this is based on human and social transformation, recognizing both ethical digital responsibility and the use of trustworthy technologies by showing transparency and human autonomy. Thus, Feroz, A.K. et al. [6] proposed that only human-technology interaction can ensure the development of resilient ecosystems. The literature research specifies comprehensive milestones that have already been achieved in the development of the AI strategy in Europe. Nevertheless, according to one of the results of the study, data sovereignty needs to be expanded in order to strengthen trust in new technologies and the will to innovate in the Construction Industry, which is still reserved. Dealing responsibly with digitization, as this primary study analyzes and gave its name to this new scientific niche, takes particular account of the "dark" side of this change presented in Section 6.

This study shows that new innovative technologies represent important catalysts both in the life cycle of buildings and in reducing the ecological footprint. Its design and application are inclusive and independent of time and place, thus, especially for people who are disadvantaged. The emerging technologies enable the access to digital participation and strengthen participation for everyone [7]. Digital technologies and AI enable data preparation that provides a more structured, transparent basis for decision-making processes and for predictions of potential risks to increase efficiency but also safety in working routines, as experts who were surveyed share in the study. Technologies such as Digital Twins, BIM, Virtual Reality (VR), Metaverse visualize the planned end product with its technical operating equipment, the building usage data and operating data. Malfunctions, risk hazards, environmental impacts, user behavior, energy consumption and a holistic life cycle of the building can be simulated. The study considers this as one of the decisive turning points if the digital change succeeds with a focus on sustainable economic development and the Sustainable Development Goals (SDGs) by the United Nations. BIM and AI provide the essential technical basis for making decisions as part of agile environments using consolidated planning results and a common data environment. As a consolidated coordination model, in which all relevant data and data interfaces are brought together centrally, BIM adds considerable value [8]. BIM, according to one of the research findings, is rising towards the next consolidated methodology: Building Life Cycle Assessment Management. In this way, the digital transformation can be designed collaboratively and environmental protection-related challenges can be consciously tackled [9].

AI, VR, Metaverse support human work with increasingly sophisticated technology, simulate the planned project in design and use all technical interfaces. As such, it not only allows the assessment of the necessary resources, completion and operating costs, time and quality, efficiency, but also offers a consistent data structuring without data loss, and a visualized representation of scenarios [10]. The study concludes that only through the sensible, responsible use of humane AI for reducing resource waste and protecting the climate and the environment, sustainability in a holistic sense can be achieved. Fields of application of AI and digital methods are being researched at various German and international locations; some have been partially put into practice based on the assessment of first practical experiences follow-up adjustments. The study recognizes Best Practices as role models for encouraging innovations. Innovation champions inspire others and encourage them to shape their own entrepreneurial digital future motivating to further explore new innovations [11]. Accordingly, this article presents findings from interviews with innovation champions and provides scenarios for the sustainability and future of the construction branch.

2. Primary study and method (Part II)

As demonstrated in detail in Part 1 of the article, section "Materials and Method", the qualitative method with interview surveys with experts was used in this primary study (*Part I, Journal of Architectural Environment & Structural Engineering Research JAESER, Vol.6, Issue 1, 2023*). Their experience and the study's observation, especially the lack of framework conditions for a successful digital transformation in the Construction branch, contribute to innovative approaches. Literature sources consulted that deal with similar research questions in other disciplines proving to be particularly useful in scientific research in the Construction Industry. This help to transfer to the construction industry similar questions and problem areas that other departments are also dealing with. Secondary data were collected to allocate the new scientific niche and get engaged in the cross-discipline debate. As part of this development, the study disclosed, that the social, economic and political influencing factors driven by innovative technologies have so far been neglected in the construction industry, thus, a more critical debate is recommended. And especially, due to the emerging technologies' severe negative impacts on people, the society and the common good, the value chain, nature and environment, the responsible design and use of such technologies mean strong signal to set new standards. The increasing technical feasibility requires social responsibility, as the study concludes. Therefore, the study recommends conducting the relevant discourse at all political, economic and social levels [12]. The corporate responsible application of digitization and AI (CDR) is not only one of the key approaches in the digital era, but defines a first time new scientific field to be researched more deeply. The Construction Industry is still hesitant to take on ethical, social issues, to cope with the multicomplex human factors involved, but driven by such a new research field and the transfer of knowledge between research and practice—can be considered as the decisive element for success and sustainability of the overall digital transformation, beyond the digital age. One in which the focus lies on people and human transformation, as requirement and enabler for the digital one, and which is holistically embedded. The primary study identified the critical path and factors that depend on or influence each other. As experts interviewed confirm, the study enabled an increasing awareness in the Construction Industry for a balanced, sustainable human-machine interaction. The interdisciplinary debate with research findings from Technology Ethics [13-15] and Technology Assessment by Armin Grunwald [16] and Hans Jonas, Christoph Hubig's [17] Practical Philosophy and Philosophy of Technology [18,19] represent fundamental scientific literature sources, as well as Ethical Engineering Responsibility [20], BIM and Digitization in Construction [21] and Corporate Compliance [22-24]. These fields of interest have several common interfaces in the processing of the research focus of this primary study in construction.

3. Key factors in the digital change in construction

The increasing will to innovate in companies and the search for ways to design digital business models, workflows and work processes more efficiently are catalyzed by the increasingly complex data environment, occupational safety, quality of data and time efficiency. The evaluation of the surveys has shown that one of the positive impact factors consists in using innovative technologies to implement highly efficient cost-time planning, to reduce production costs and achieve thorough economic efficiency, to merge data from all end devices, accessible for all users and without data loss, on one unified data platform. Since 2020, the development and application of AI in Construction steadily increases in Europe. According to forecasts Europe will be a pioneer and have overtaken other nations by 2027. In particular, the responsible, value-based design of new smart cities contributes not only to a significant reduction of CO_2 but to strengthening sustainable green tech and environment [25]. The study identified key elements for successful digital change in Construction (**Figure 1**) and summarizes milestones in Construction 4.0—specifically using corporate innovative Champions shaping the digital transformation based on initial experience in diverse fields of application (**Table 1**). **Table 1** provides an overview of the AI applications already implemented in practice, in selected areas ranging from structural and civil engineering, technical building automation, real estate management and monument preservation, tunnel technology, timber construction, to fire protection, intelligent buildings and smart cities.

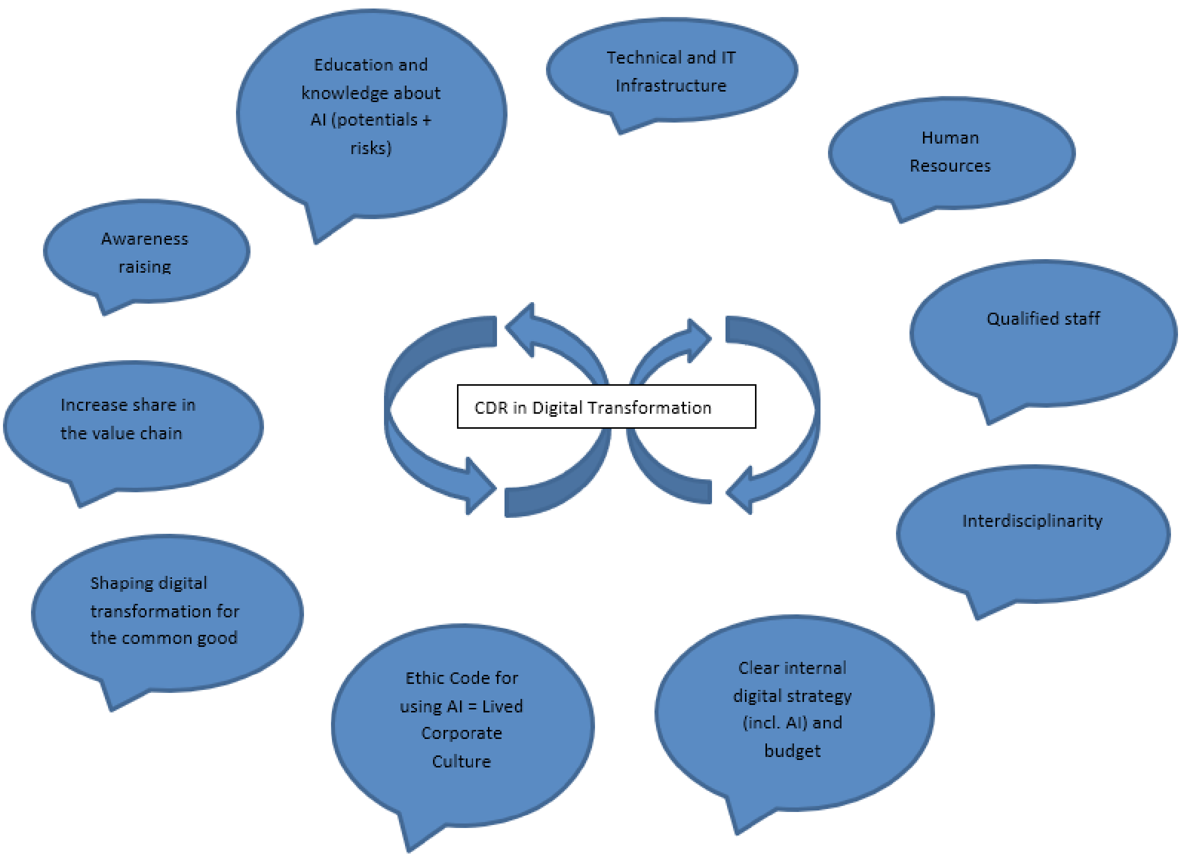


Figure 1. Mind map digital transformation strategy—Interaction of the key elements.

Source: Bianca Weber-Lewerenz.

Table 1. Milestones in Construction 4.0—Corporate use cases.

Milestones in Construction 4.0: Digital Transformation – Made in Europe. Companies developing and applying AI (Status: 2021)		
Fields of Application	**Fields of Research, Potential of Application of digital methodd / AI-based solutions**	**Companies**
Real Estate, Facility Management	Predictive Maintenance (PM):	**APLEONA**
	"Fully automated building technology control" (goal: Energy Monitoring)	
	"energyControl" (goal: Predictive Control)	
Technical Building Automation	AI-based building simulations, PM with self-learning software for Predictive Maintenance, Remote Monitoring and Remote Maintenance. Detects hazards and identifies unknown incidents weeks before failure.	**general (see Anacision GmbH Karlsruhe focussing on Mechanical Engineering)**
	AI-based Operator Optimization	**general**
	AI-based Resource Optimization (energy consumption, electricity, water)	**general**
	AI-based Recommendation for Action	**general (applies to all areas of construction)**
IT- and Software Developpers for Construction Branch	Semantic Web, AI-based Hybrid Models (autoML combined with expert knowledge), Intelligent Product Development, AI-supported Product Generation Development, Automatic Quotation and Capacity Planning, as well as Process Automation	**EDI GmbH Engineering Data Intelligence Karlsruhe**
	Product "EDI hive IoT Framework" (Construction Industry): AI-based creation and design of Offer(large, simple hub), e.g. BIM can be used to collect a lot of data for the craftsman, and they - based on their experience - derive the right conclusions.	
	·EDI business consulting workshops (goal: demystifying the terms AI, cloud, BIG DATA, platforms),	
	·AI-based Data Analysis to quantify gut feelings and generate new insights,	
	·Semantic Data Management for experimental data, which is the origin of the company,	
	·Development of Digital Business Models with intuitive apps for customers, trades and management.	
Civil engineering (Building Construction, Formwork Technology)	In terms of **Visual Object Recognition**, we are currently using newer networks to ensure that parts can be recognized based on specific characteristics. The advantages here lie in the unnecessary marking of the parts. This can be particularly challenging due to the use of materials on construction sites etc. There are already prototypes/ models that can also be tested in an application (app) (goal: visual object recognition), e.g. QR code, tagging on the material is not sufficiently durable, e.g. for comparison: GPS transmitter for locating the building material, but : high cost factor. Current: Photos with data information for part definition (e.g. anchors, formwork panel), chip with no. to recognize the part, without QR/tag: the algorithm recognizes the building material through the photo and the photo data. Neural networks with automated detection.	**PERI Digital Transformation & Corporate Development**
	Automation of engineering tasks: Trying to solve engineering tasks (data-driven) using historical data by using appropriate models. Topic very complex, reaching the limits of computing capacity (goal: data-driven solution of engineering tasks) e.g. floor plan, formwork planning via spatial mapping, definition via rules	

Table 1 continued

Milestones in Construction 4.0: Digital Transformation – Made in Europe. Companies developing and applying AI (Status: 2021)		
Fields of Application	**Fields of Research, Potential of Application of digital methodd / AI-based solutions**	**Companies**
	ESKIMO = Research project on AI application on construction sites (https://www.eskimo-projekt.de/)	**https://www.eskimo-projekt.de/**
	"VINCI Chronsite Program" (www.leonard.vinci.com): The VINCI Chronsite Program (www.leonard.vinci.com) involves the automated merging of all construction project data and information using Computer vVision and Deep Learning Technology can be gained.	**VINCI Construction**
	3D -Scans were carried out after the Notre Dame Cathedral in Paris burned down in 2019. The point cloud-based model captures the original structures and digitally preserves them for future generations. VINCI uses VINCI Construction Group's "Sixense" software and its ScanLab to carry out high-precision 3D and photogrammetric measurements that enable automated risk detection. The company's internal AI program is referred to as "Leonard VINCI". Façade recordings automatically depict the technical floor plans. The advantages and empirical values are that the intervention times and scaffolding times are drastically reduced. This results in an increasingly efficient, shorter restoration time, so that tourist masterpieces can quickly be accessed again. A classic practical example is Mont Saint Michel in Normandy, France.	**VINCI Construction**
Civil engineering (Construction and Civil Engineering)	Workflow up to 7-D as a continuous project flow	**WAYSS & FREYTAG INGENIEURBAU (Subsidiary of the Royal BAM Group)**
	Modeling: Deep Learning approach to model creation, e.g. for the basis of (partly) automatic component recognition from point clouds	
	Parametric Design (architecture) Objectives: Saving material, requirements for light transmission and aligned with the position of the sun.	
	"Generative Design": Design process in which the result is generated by a programmed algorithm.	
	Visual Image Recognition, e.g. of damage photos on motorways (crack detection)	
	Scheduling (4D) based on process building blocks that are linked to the model or derived from it (assign processes, assign sequences, sequences, use big data and algorithms for optimization.	
	AI-based Resource and Construction Process Optimization	**general**
	AI-based Supply Chain Optimization	**general**
	AI-based Lean Construction	**general**
Civil engineering (Building Construction)	Support for repetitive work and hard physical work (e.g. artificial, machine exoskeletons)	**general**
	3D printer for serial construction and prefabrication (e.g. Max Modul by Max Bögl, advantage with precast plant)	**Max Bögl**
	HOCHTIEF ViCon: Artificial Intelligence (AI), Internet of Things (IoT), Mixed Reality (MR), Augmented Reality (AR) and Virtual Reality (VR)	**HOCHTIEF**

Table 1 continued

Milestones in Construction 4.0: Digital Transformation – Made in Europe. Companies developing and applying AI (Status: 2021)		
Fields of Application	**Fields of Research, Potential of Application of digital methodd / AI-based solutions**	**Companies**
	Incorporating Artificial Intelligence (AI), sensor-driven Internet of Things (IoT) technology and blockchain.	**Nexplore: HOCHTIEF Research and Development Center in cooperation with the Massachusetts Institute of Technology (MIT), University of Madrid and University of Darmstadt**
	Real-time control of the construction progress and improved planning processes through to the simplification of maintenance and operation of a building.	
	-“Cognitive Document Risk Analyzer” und	
	-“Cognitive Document Analyzer”	
	They should help to make the processing of offers more efficient through digitization and standardization, for example in contract analysis or in the preparation of tenders.	
	IoT applications can be used with the help of AI for Predictive Maintenance: Construction-related status data then enable proactive maintenance.	
	Factory and Building Planning using VR Virtual Reality	**MÖRK GmbH & Co. KG S-Leonberg**
	Digitized processes simplify construction registration, measurement and reconstruction work, component sections and measurements; they enable more efficient municipal management (firefighting, policing, sanitation, waste management). A strong signal to the construction industry to deal with potential and already implemented areas of application of AI: Self-learning construction sites, self-propelled construction machines (risks of failure of construction machines can be displayed in real time via machine learning), digital online construction site inspection with VR glasses, simulation of renovation concept + building in existing buildings and ongoing operation, simulation of acoustic + fire protection concepts, AI sensors for detecting and detecting defects/damage in the event of material, humidity, temperature changes, AI monitoring and controlling in the construction progress with continuously generated invoicing, forecast and strategy data systems as a basis for business decisions (predictive technologies). Remote monitoring and maintenance become even more efficient with AI. 3D-7D twin with simulation, reality and prognosis models provide mapping of the construction progress, time and costs at any time.	**general**
	Building types/classes can be recognized and localized on images by object recognition using machine learning and maintenance can be planned. 3D measurements, documentation and construction site monitoring can be implemented using a drone. In public relations, high-resolution 3D models can be used for digital tours. Tailor-made measures for energy-related renovation and energy-efficient construction can be agreed. Access to a uniform data platform of the model is guaranteed for all project participants with end devices at any time, from any location, without data loss.	**general**

Table 1 continued

Milestones in Construction 4.0: Digital Transformation – Made in Europe. Companies developing and applying AI (Status: 2021)		
Fields of Application	**Fields of Research, Potential of Application of digital methodd / AI-based solutions**	**Companies**
	• 3-, 4-, 5-D twin with simulation, reality and forecast models, • Use of machine learning, deep learning, social computing, • Systems for structuring the data complexity, • Comparison between historical construction project data and new construction project data and selection for data evaluation and planning of a resource-, climate-friendly, cost- and time-efficient construction process, • smart technology and smart buildings, • Self-learning construction site. • Digitization tools that go beyond BIM, • Networking of all digital devices for complex data collection from all technical trades, • Forecast and strategy data systems as a basis for business decisions,	**general**
Building in stock, Renovation of old buildings	AI methods also enable data to be compared with stored data in order to comply with structural requirements and regulations (monument protection, fire protection, environmental protection) when taking measures. With the help of digital technologies, 3D measurements can be carried out by drone (UAV photogrammetry, UAV laser scanning). Drones for inventory and 3D documentation for the digitization of cultural assets are routine, stone-based measurements of facades (UAV photogrammetry) using high-resolution and calibrated camera systems or LiDAR scanners, true-to-scale, high-resolution facade documentation (UAV photogrammetry), the recording of listed buildings, high-resolution 3D -Scans of relics for the digitization of cultural assets and high-resolution facade views in the form of orthophotos (corrected measurement images) are used as a basis for planning and for damage mapping.	**general**
	High-resolution 3D models can be used for digital tours in the public relations work for building, ground and area monuments; high accuracy requirements can be met, and the entire documentation, cataloging and archiving, planning of rehabilitation measures and reconstruction can be supported. AI methods enable tailor-made measures for energy-related renovation, energy-efficient evaluation and acoustics on listed buildings.	
Protection of Monuments, Restoration of Monuments	Measurement and reconstruction work, component sections and measurements, fitting of reproduced components into the existing building, production of building materials, forecast modeling (investment planning, control) and simulation of construction models (3-7D, i.e. with continuous depiction of the actual construction time, costs and quality during construction compared to the Original planning).Virtual Reality and Augmented Reality are used to make churches, castles and historical buildings virtually accessible. Object recognition using machine learning makes it possible to identify building types, classes, damage or anomalies in images. Defective, often hard-to-reach areas can be localized and repair and maintenance can be planned. Digital construction site inspections are possible with VR glasses, simulation of renovation, acoustic and fire protection concepts can be implemented, AI sensors detect and detect defects and damage in the event of material, humidity and temperature changes.	**general**

Table 1 continued

Milestones in Construction 4.0: Digital Transformation – Made in Europe. Companies developing and applying AI (Status: 2021)		
Fields of Application	**Fields of Research, Potential of Application of digital methodd / AI-based solutions**	**Companies**
Civil Engineering, Tunnel Construction	AI-based data on the drilling progress, typification of the soil layers encountered, movement of the machine, device data (dissolving energy requirement, fuel consumption, temperature), change of drilling tool and wearing elements, faults and the cause of the fault, maintenance or repair requirements, representation of the construction site performance, generation of the "as-built "Data.	**BAUER AG Schrobenhausen**
Timber Construction	AI supports the crafting process of better engineered wood. Machine Learning (ML) is already being used in wood technology applications: AI supports the digital wood selection and wood processing strategy to obtain specific physical properties. ML optimizes the functionalization of wood: material selection, physical data of the raw material, production steps, process parameter setting, quality control, processing, product quality prediction in real time. This replaces endangered tropical wood and enables particularly good, precise milling. With this social and economic contribution, the share in the value chain increases. The central topic in the context of the sustainability discussion about building materials is dismantling, re-usability, recycling, ecological and energy concepts.	**general**

Source: Bianca Weber-Lewerenz.

Note: In December 2022 the author's book "Accents of Added Value in Construction 4.0" was published by SPRINGER Publishing.

4. Signposts in the digital transformation—Part II

Dealing comprehensively and across disciplinary boundaries in discourses dedicated to digital transformation, the study considers the close interface work of several departments and adapted science communication as key for creating consciousness and to increasing knowledge. Where is knowledge, fear decreases. Thus, new skills, innovative approaches are needed along the critical path, which is not limited to the "dark" side of new technologies, such as digital ones and AI.

The 3rd Symposium Building the Future investigated the corresponding signposts [26]. Heike Klussmann, University of Kassel, emphasized that "*digitization must start in teaching and that the curricula must be adapted in the short term*". For Lucio Blandini, University of Stuttgart, Marvin Bratke, Urban Beta, Peter Kaufmann, Kaufmannbau, and Claus Nesensohn, Hochschule für Technik Stuttgart, this represents a success factor for future-proof sustainable Construction: "*The early integration of diverse and interdisciplinary teams and the collaboration using a sensible use of technology ensures cost savings and much more efficient communication*". Peter Kaufmann and Claus Nesensohn look at the "*human-centered approach as an important lever so that not only digital, but also human change is successful*". Laura Lammel, from Lammel Construction and Board Member of the Central Association of the German Construction Industry, emphasizes that "*value creation can be achieved only through responsible action in business processes in the Construction Industry*". The discussion participants emphasized "*that sustainability and a successful digital transformation in Construction can only succeed through human-centered work, close interface work with integral teams—far away from 'silo thinking'. This requires a fundamental re-thinking of the Construction Industry, innovative ways and the exchange between research and user practice*". According to the results of the study, meaningful and technically sustainable progress can only succeed if the common good, environmental and climate goals and resource conservation are taken into account. These include, for example, an innovative circular economy and a cradle-to-cradle approach. As a result, new technologies are taking on an increasingly important design role and require a new culture of thinking and value-based action.

5. Best practices—Key competence "AI—Made in Germany". Challenges and innovation champions

AI not only enables self-learning construction sites, but also real-time progress and performance checks and thus more transparency, corrective interventions real-time and construction projects that can be overall designed more efficiently. The study proves that the entrepreneurial will use innovations to fully exploit the potential increase. However, only large companies so far have been able to conduct their own research and implement innovations through their own departments led by Chief Digital or Chief Information Operations, simply on the fact to possess the required financial background. The interviewed experts highlight interdisciplinary interface work is a basic requirement. In corporate environments, such processes are based on close cooperation between the departments for development, design, Information Technology (IT), project management, execution, controlling, law and Human Resources (HR). In addition, uniform data platforms are used, which record all project data and continuously update according to the project's progress. SMEs have introduced BIM sporadically but not in a standardized way. More as individual processes and not over the entire project cycle, thus, holistically digitized processes are not guaranteed. Such inconsistent working habits lead to severe data gaps, and other weak points such as inefficient project processes, reduced controllability and low data communication. To ensure higher data security and compliance with the code of values, the focus of the study lies in drafting contracts with customers and suppliers in accordance with corporate compliance standards and risk analyses. With the help of AI-based methods, companies could significantly simplify the increasingly complex subcontractor checks, contract design and performance checks in real time. Thus, one of the study results consists in strengthening such digital applications since they may result in new decision-making bases speeding up contract reviews and risk analysis. Only a few—and most of them are experts in their field—recognize digitization and AI as the most suitable technological support for human work by linking multiple areas with each other, increasing transparency, safety, economical efficiency and sustainability. Companies with a pioneering role are aware of the severe impacts AI has on people and society as a whole. Therefore they assign AI innovations embedded in a value-based engineering environment and a new corporate thinking culture a very high value. They also address the responsible role of large best practice companies to share their newly won experience with SMEs. Such exchange may significantly ease the process of defining the own digital strategy, to choose first AI methods tailored to their individual business challenges. Here, start-ups offer support using the data already available in high quantity. Despite different financial backgrounds, SMEs must not be disadvantaged in the digital transformation process, but should be consciously supported. The study considers as one critical process, that digital change requires to be shaped from the bottom up, instead of dictate from above. The study derives constructive approaches based on individual entrepreneurial digital strategies in a targeted manner and to use methods responsibly. The study considers legal regulations and ethical standards as important guidelines as to ensure data protection, the protection of fundamental rights and the prosecution of illegal actions. In the interview surveys, experts consistently confirmed that every company in Construction is confronted with facing the challenges of digital transformation. Therefore, companies in the Construction Industry should consciously promote education and awareness-raising in order to increase skills, knowledge and strengths in the industry as decisive path for the equally important human transformation. In order to do justice to all technical aspects of responsibility towards people and society, ethical considerations play a key role. Corporate pioneers do justice via using interdisciplinary cooperations (innovation, IT, HR, law). They cooperate closely with universities and technical colleges in order to transport the most actual topics in guest lectures, and then use such exchanges between academics and economic practical knowledge to adjust teaching contents and curricula. Some of the interviewees involved see the severe content overloading of the educational landscape, due to the gap between basic engineering training and the new qualification profiles required—both for digital but especially human transformation—based on the lack of adequate professional competence among teachers and insufficient digital equipment [27,28]. On the other hand, universities use their excellent strategies to set themselves apart from the competition with research clusters, innovations and interfaces to entrepreneurship. The study noticed the same tendency in large, globally active companies aiming to redesign their attractiveness as employers, but also to fulfill their social responsibility and comply with ethical standards based on self-responsible action. AI as an engine of innovation can only be sustainable, responsible, safe and of the best support for human work to the extent that people make these technologies accessible, train and explain them, use them responsibly and provide orientation in what makes sense and where the line must be drawn to distinguish between artificial and human intelligence as to maintain autonomy and create trust.

5.1 Circular economy and cradle-to-cradle

To illustrate with practical examples, the study focuses on a few selected Best Practices in Smart Cities. The Smart City Strategy has 3 main goals: resilience, the city in transition and circular economy [29]. The European Circular Cities Declaration [33] defines how the digital transformation in municipalities can be shaped sustainably and how smart networking and intelligent operation of urban infrastructure according to the European Green Deal are increasingly finding their way in the design of Smart Cities and circular economy. The idea behind this is to decouple resource consumption from economic activity by preserving the value and benefits of products, components, materials and nutrients for as long as possible in order to close material cycles and minimize harmful resource consumption and waste [31,32]. With 75% of natural resource consumption occurring in cities and 50% of the world's waste coming from cities, the potential is huge. The signatory cities recognize their full commitment to the transition to a circular economy, thereby increasing their share in the value chain. In line with the Climate Strategy 2030 and the UN Agenda 2030, some German cities are pioneers, such as the city of Aachen. The Institute for Anthropogenic Material Cycles (Center for Circular Economy (CCE)), led by Kathrin Greiff, and the Institute for Sustainability in Construction (INaB), led by the second author, both located at RWTH Aachen University Germany—have an important role model function: They both bring their expertise to shape the transformation of the city of Aachen towards a sophisticated circular economy. What does sustainable building lifecycle management mean as part of the new urban agenda? [33] There are two goals: Develop livable cities; strengthen planners and operators of urban development [34]. Further samples of international pioneer cities represent Amsterdam, Copenhagen, Vienna, Barcelona and Singapore. The Governing Smart Cities Report [35] provides policy benchmarks for the ethical and responsible development of smart and sustainable cities. This should strengthen the trust of citizens as well as planners, manufacturers, users and operators of buildings and infrastructure. Sustainability also means firmly integrating the Cradle-to-Cradle Principle [36] in building practice wherever possible. The concept is based on three principles: understanding waste as food, using renewable energy and promoting diversity. A practical example: Digital twins—of both buildings and infrastructure—automatically generate real-time information and quantities of materials, the data is stored and can be called up at any time if the building is to be dismantled and the recycled material returned for use in the new building. Cradle-to-Cradle means building along the material cycle. Setting up a digital urban mining cadaster is an option, with an evaluation scheme standardized by so-called passports of buildings and goods. Thus, stocks of durable goods in the Construction sector can be recorded, future material flows can be forecast at an early stage and the best possible recycling routes can be derived. Especially through concrete recycling, 60 million tons of recycled building rubble could be used as aggregate for concrete production; but in reality *only about 0.6 million tons are used*. A nationwide mandatory reuse as part of the *Circular Economy standardization roadmap* and the guarantee of maintaining the necessary quality represents a constructive approach [37]. Through the increased *use of existing technologies, resources could precipitously be saved immensely and emissions reduced to a fraction, as well as* CO_2 *neutrality could be further accommodated* [38]. With increasing technical feasibility, societal responsibility and the need to specify and tighten the applicable legal framework data sovereignty may be increased [39,40]. In particular, the economic ecological responsibility in Europe is increasing, based on a common language to evaluate the sustainability performance of buildings, e.g. using a common European method of "Level(s)" in the life cycle assessment [41].

5.2 Integrating existing buildings into smart cities

Smart cities not only include new construction, but the upgrading of the comparatively larger building stock to intelligent building automation systems in accordance with standards, SDGs, climate and ecological strategies [42]. Innovative building technologies in existing buildings enable efficient construction planning through visual representation of all trades involved and support independent monitoring, control, analysis and optimization of energy consumption. In order to become neutral with the CO_2 emissions from real estate in Germany by 2045, with the aim to almost halve by 2030. The study recognized that Smart Cities are expected to reduce emissions by at least two-thirds and at least 90% by 2035 [43]. However, this goal can only be achieved if the potential of digital technology solutions is already being used on a large scale today, for example by controlling air conditioning systems efficiently and on demand by a cloud-based solution (*Remark: a cloud-based solution means controlling systems from anywhere, anytime, with a smartphone app and the computer interface, through a router connected to a cloud.*). It is of the utmost importance that such application of technology does not base on efficiency but on resilience. Because resilient Smart Cities can quickly, effectively and efficiently adapt to shocks and increasing natural and other risks to which they are exposed, learn from them and adapt to changing environmental conditions and social changes. One of the benefits the study identified is that new technologies allow decision-makers to understand the implications of policy recommendations or new proposals for urban systems. On the user side, they enable improved designs and analysis of city-scale interventions. In addition, smart technologies in existing buildings enable a much more efficient, economical and secure form of testing, building operation and maintenance (building automation, communication between buildings).

In view of the diverse challenges in dealing with the climate change caused by natural disasters and a sustainable design of the built environment, the study highlights the need to plan and build cities and buildings even more "with nature" and following changing natural and temperature conditions according to climate change. When planning Smart Cities, particular attention must be paid to less surface sealing, intelligent wastewater management, warning systems, e.g. flood disaster (e.g. Ahrweiler Germany in 2021), flood protection, stability and safety of tunnels, bridges and dams. The adaptation goes far beyond the newly required building materials and standards that are adapted to the requirements of climate change (e.g. acid rain, periods of heat).

Green building standards and certification schemes not only are limited to new requirements for both new and existing buildings. However, much of the existing building stock in cities have been built with limited attention to green design, energy efficiency and low carbon emissions, but its refurbishment can help meet national energy saving targets and reduce environmental impact. In addition, retrofitting existing buildings can often be less expensive than building new facilities. The potential of an existing building to achieve certification to a specific green standard, defined in this work as its Green Potential (GP), depends significantly on critical factors determined during the original design and construction process. Field reports from user practice demonstrate that digital twins, AI, AIoT, cloud computing, intelligent building operation and communication represent powerful tools for integrating existing buildings and upgrading to Smart City standards. But what are further advantages for owners, operators and users? To this end, the study summarizes several potential fields:

- More efficiency, comfort and safety;
- Increased efficiency and need for intelligent services through intelligent networks of technical building equipment;
- The construction sector causes almost 40% of global CO_2 emissions (= key lever for achieving climate neutrality by 2050);
- Independent monitoring, control, analysis and optimization of energy demand;
- Buildings that "think" and operate fully independently and for themselves;
- Recognize and rectify faults quickly, recognize pending maintenance early and embed automatically, optimize the use of areas and rooms;
- New dialogue between buildings and people = changed management processes, simpler maintenance, longer maintenance cycles, simplified remote maintenance;
- The intelligent building communication itself becomes the best partner for facility and energy managers, supports the daily work of everyone involved, simplifies processes and helps to permanently reduce operating costs.

Technical building solutions can be:

Building automation, light and energy management systems, security technology;

Integration of technical building systems and systems with fire alarm systems, access and intruder alarm systems, building automation and video surveillance systems as well as IoT components: connection to cloud-based platforms;

Digitized frequency of use: Utilization of areas in the building known and thus solutions for area management;

Basic requirement: Digital building twin that generates the holistic digital image of the building.

Building 4.0 means gaining a new sense of security [44] and "*greater responsibility of people for technology-based innovations.... and for the sustainable preservation of the world....*" [45]. The study concludes, that such progress and involved transformation processes require a new culture of thinking and a new way of thinking about unintended impacts and risks that technological innovations put on people.

6. The "dark" side of digitization

When it comes to designing smart Cities of Tomorrow, the question raises how intelligent digital standards can be achieved. How can Smart Cities not only be smart, but sustainable and resilient? In this respect, technological progress in Construction 4.0 is catalyzing the digital transformation. Unintended consequences and severe negative effects of digitization and AI are referred to as the "dark" side of digitization [46] because they have social and ecological effects, e.g. on the raw materials sector. Economic growth is difficult to decouple from resource consumption, which already exceeds the limits of the planet. The technologies of the future require extensive resources and critical raw materials. However, the recycling potential of these raw materials is very low and the return strategy is inadequate. Four times of the current lithium production, a three times increase in heavy rare earths and a one and a half times increase in light rare piles of earth and tantalum. The European Committee of the Regions therefore takes a specific position on the action plan for critical raw materials in order to supply Europe with raw materials more safely and sustainably [47]. Due to the increased use of electronics, the global demand for copper will grow between 231% and 341% by 2050 [48]. According to the DERA study, in 2035 up to 34 percent of the global indium production may be used exclusively for the production of displays [49].

The study identified several interdependent fields: Digitization and AI require new machines (robots, automation technology), much higher data speeds (fiber optic cables, routers, high-performance microchips, sensors, data transfer infrastructure) and data storage with larger volumes such as significant higher data capacity (data clouds, IoT, AIoT) for real-time transmission and error-free network communication. Such basic infrastructure has to be rebuilt and computers and, due to the high heat produced during operation, storage rooms are required to be continuously cooled and air-conditioned. The entire infrastructure must be expanded or completely rebuilt, and dismantling and recycling must be taken into account in the planning stage, as part of a holistic life cycle design. The health effects of continuous radiation generated during the operation of these innovative technologies on humans have not yet been adequately researched nor recognized in high-speed technical development: fully functioning Smart Cities require uninterrupted, intelligent networking of buildings, e-mobility, smartphones they all require data clouds, IoT and the expansion of multiple base stations. Therefore high, uninterruptible power supply and acceptance of the additional energy consumption, the high intensity of electromagnetic radiation (networking among the devices, radio) and further CO_2 production must be applied. The end-to-end full automation of buildings requires hardware such as machines and sensors, and thus an increasing production of the necessary inventory materials and with the corresponding consumption of resources. The fifth generation of mobile data transmission (5G) requires broadband expansion using fast fiber optic networks. 5G combines the previous mobile communications standards, Wi-Fi, satellite and landline networks into a holistic communication network. Such scenarios demonstrate, that digitization leads to significantly high energy consumption, because in 2025 data centers will account for around 4%-11% of global energy consumption. At the same time, high energy saving and waste heat utilization potentials are forecast and localized [50]. The study comes to the conclusion that the digital value chain is being taken as absurdum: How can the CO_2 footprint be reduced, managed sustainably when raw materials are increasingly consumed, inhumane mining work, abuse of people and the environment and long-term damage to health are accepted, in order to develop and apply more and more innovative technologies and with incessant focus on the economical benefits [51]? The study considers potential dangers not only in the consumption of resources, but in increasingly complex risk areas of data misuse. Protection is one of the success criteria for sustainability. This also applies to data communication: Municipalities are largely administratively unable to handle approval processes digitally, since many companies lack a digital infrastructure [52]. The Digital Innovation Agenda 2022 (EU), the Strategic Perspective on Digital Change 2022 (EU), declarations of intent by the German government and the G20 - Summit 2022 on digitization, innovations and data sovereignty do not correspond to current practice in public administration, in the companies as well as in the project-related data and knowledge communication between these parties.

Although the digitization of the supply chain offers great growth opportunities and long-term cost savings, it is accompanied by additional problems that are also covered in this study: the expansion of the IT infrastructure is not keeping pace with the development of new digital business models and the end-to-end digitization of the supply chain, companies are stuck in the test phase and projects are not used operationally, digitization is not yet declared an important corporate goal, development and expansion with targeted investment is not made a top priority and is promoted with the involvement of suppliers, traditional contractual and commercial processing structures are used recorded, real-time information and traceability are missing. However, research on CDR in Construction 4.0 recognizes these above mentioned conditions as the decisive factors for successful digital change and for adding value [53,54]. Blockchain technology cannot be built, nor can intelligent business transactions, cryptocurrencies and reliable asset tracking be implemented without transparent, end-to-end digitized supply chains [55].

Based on the knowledge gained, the study points out that when designing the digital transformation, it must be considered where innovative technologies make sense, reduce resources, and support people in efficient and safe work. A clear distinction should be made between the lack of knowledge, the lack of ability to assess security risks, the misuse of data and the exploitation of people and resources. There is a severe danger of becoming part of so-called greenwashing, i.e. propagating superficial advantages and high benefits, which, however, come at the expense of violations of personal and data rights, environmental depletion and resource consumption that is harmful to people and society. The research "CDR in Construction 4.0" investigates the question of how such a countermeasure can succeed. The *Excellence Initiative for sustainable, human-led AI in the Construction* raises awareness and gets engaged the branch in the global debate - especially recognizing that the Scientific Advisory Council of the Federal Government and the German Federal Office for Radiation Protection both warn against unchecked digitization that is not aligned with sustainability criteria.

7. Discussion

AI strongly influences the scientific discussion about technological feasibility, its sustainability in the AEC industry and ecosystems for shared value creation. The study provides concrete innovative approaches for the future of cities, working and living environments for today's society and all future generations. The sustainable design of intelligent, smart urban mobility, transport and traffic systems, assistive smart cities may only succeed through interdisciplinary cooperation and the integration of human and social science considerations. They are crucial for holistically thought-out legal, social and technical decision-making processes, the study determines. The results of the evaluation of the interviews, and experiences of best practice companies in combination with a comprehensive literature research emphasize education is the engine of success. In addition to an adapted competence profile of the Civil Engineer and contents of curricula, it also requires the adaptation of the qualification of academic and training staff.

From the surveys it can be deduced that companies do not only rely on legal and official guidelines to tackle emerging digital challenges. Such policies typically cannot keep up with the pace of technological advances. Rather, it is important to play a responsible role in shaping the digital transformation, as the EU Commission is striving for with the Digital Innovation Agenda 2022 [56], the Strategic Foresight 2022 [57] and the Task Force for Digital Common Goods [58]. The Construction sector stands out of other branches as one of the most important catalysts for CO_2 reduction.

8. Conclusions

The study concludes that the pioneers in Construction are role models offering other companies orientation in navigating innovative technologies in Construction 4.0. Thus, a milestone for Germany as a location for research and education may be achieved. In order to take into account the entrepreneurial, social, legal and political aspects that are critical for successful digital transformation, which makes up a significant part of the value chain for the Construction Industry, the study recommends deepening research work in this new scientific field. Engineers, architects, designers and craftsmen are more than just designers of living and working environments. They design technical, social, societal and human changes in construction 4.0. In the sense of the trustworthy development and use of a human-friendly AI, the study identifies as a critical path, that not only designer's planning but the holistic life-cycle of projects and the built environment involve dealing with the "dark" side of the technical feasibility. Considering technological development at high speed means a turning point to set the course immediately.

This success-critical factor has not been adequately researched though represents a significant limitation. Previous studies, e.g. by the Fraunhofer Institute Austria in 2022, highlight that sensible and sustainable technology development and the increase in the maturity of AI applications require new qualifications, new knowledge, improved transfer of knowledge between research and practice and a new corporate culture of thinking and openness towards innovation. Only then, so the study analyzes, digitalization and AI may be weighed up in a differentiated manner. The study also comes to the conclusion that there are still too few use cases and innovative champions, though having a high trust-inspiring effect on other companies. New insights won from interviewed Best Practice clarify that a radical re-thinking in the AEC industry is necessary to achieve an intended sustainable technical, social and human change of Baukultur 4.0 [59] and achieve trustworthy human-machine interaction [60,61]. This is one of the motivational elements for the first author's "*Excellence Initiative for sustainable, human-led AI in Construction*" - in research cooperation with the *Institute for Sustainability in Construction INaB at RWTH Aachen University*—to bring the Construction Industry into the global ethics and AI dialogue for the first time in an interdisciplinary manner and further expand this newly discovered field of research.

Author Contributions

This research article has been conceptualized and written by Bianca Weber-Lewerenz and reviewed by Prof. Marzia Traverso (Ph.D.).

Conflict of Interest

The authors declare having no conflict of interest.

Ethical Statement

The first author of this study conducts external research, is company-independent and is not financially supported by third-party funds, companies or other institutions. This enables neutral, critical, and inclusive research and promotion of ethical debate about AI technologies.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Acknowledgments

The authors appreciate all of the interviewees, expertise shared with this research, sharing the vision of the "Excellence Initiative for Sustainable, human-led AI in Construction" and moving digital innovations forward.

Statistics and reports were of great support with data and facts to underlay the statements and recommendations made in this paper. Some public statements, which come from internet, literature and archive research, also underline the quality and statistical values of the expertise and survey values obtained.

References

[1] ElMassah, S., Mohieldin, M., 2020. Digital transformation and localizing the Sustainable Development Goals (SDGs). Journal of Ecological Economics. 169, 106490.
DOI: https://doi.org/10.1016/j.ecolecon.2019.106490

[2] Lopes de Sousa Jabbour, A.B., Jabbour, C.J.C., Godinho Filho, M., et al., 2018. Industry 4.0 and the circular economy: A proposed research agenda and original roadmap for sustainable operations. Annals of Operations Research. 270, 273-286.
DOI: https://doi.org/10.1007/s10479-018-2772-8

[3] BMWi, 2019. Einsatz von Künstlicher Intelligenz in der Deutschen Wirtschaft Stand der KI-Nutzung im Jahr 2019, Studie des Bundesministeriums für Wirtschaft und Energie (German) [Use of artificial intelligence in the German economy Status of AI use in 2019, study by the Federal Ministry for Economic Affairs and Energy]. p. 20. [Internet] [cited 2021 May 6]. Available from: https://www.bmwk.de/Redak-

tion/DE/Publikationen/Wirtschaft/einsatz-von-ki-deutsche-wirtschaft.pdf?__blob=publicationFile&v=8#:~:text=Im%20Jahr%202019%20setzten%20rund,17%2C8%20%25%20erheblich%20h%C3%B6her

[4] BMWi, 2019. Einsatz von Künstlicher Intelligenz in der Deutschen Wirtschaft Stand der KI-Nutzung im Jahr 2019, Studie des Bundesministeriums für Wirtschaft und Energie (German) [Use of artificial intelligence in the German economy Status of AI use in 2019, study by the Federal Ministry for Economic Affairs and Energy]. p. 28. [Internet] [cited 2021 May 6]. Available from: https://www.bmwk.de/Redaktion/DE/Publikationen/Wirtschaft/einsatz-von-ki-deutsche-wirtschaft.pdf?__blob=publicationFile&v=8#:~:text=Im%20Jahr%202019%20setzten%20rund,17%2C8%20%25%20erheblich%20h%C3%B6her

[5] Gomez-Trujillo, A.M., Gonzalez-Perez, M.A., 2021. Digital transformation as a strategy to reach sustainability. Smart and Sustainable Built Environment. 11(4), 1137-1162.
DOI: https://doi.org/10.1108/SASBE-01-2021-0011

[6] Feroz, A.K., Zo, H.J., Chiravuri, A., 2021. Digital transformation and environmental sustainability: A review and research agenda. Journal for Sustainability. 13(3), 1530.
DOI: https://doi.org/10.3390/su13031530

[7] Weber-Lewerenz, B., Vasiliu-Feltes, I., 2022. Empowering digital innovation by diverse leadership in ICT—A roadmap to a better value system in computer algorithms. Humanistic Management Journal. 7(1), 117-134.
DOI: https://doi.org/10.1007/s41463-022-00123-7

[8] Lo, C.K., Chen, C.H., Zhong, R.Y., 2021. A review of digital twin in product design and development. Journal of Advanced Engineering Informatics. 48, 101297.
DOI: https://doi.org/10.1016/j.aei.2021.101297

[9] Ye, Z.P., Yang, J.Q., Zhong, N., et al., 2020. Tackling environmental challenges in pollution controls using artificial intelligence: A review. Journal of Science of the Total Environment. 699, 134279.
DOI: https://doi.org/10.1016/j.scitotenv.2019.134279

[10] Ernstsen, S.N., Whyte, J., Thuesen, C., et al., 2021. How innovation champions frame the future: Three visions for digital transformation of construction. Journal of Construction Engineering and Management (ASCE). 147(1).
DOI: https://doi.org/10.1061/(ASCE)CO.1943-7862.0001928

[11] Leiringer, R., Cardellino, P., 2010. Tables of the expected: Investigating the rhetorical strategies of innovation champions. Journal of Construction Management and Economics. 26(10), 1043-1054.
DOI: https://doi.org/10.1080/01446190802389394

[12] Xue, X., Zhang, R., Yang, R., et al., 2014. Innovation in construction: A critical review and future research. International Journal of Innovation Science. 6(2), 111-126.
DOI: https://doi.org/10.1260/1757-2223.6.2.111

[13] Grunwald, A., Hillerbrand, R., 2021. Überblick über die Technikethik (German) [Overview on technical ethics handbook technical ethics]. J.B. Metzler Publishing: Stuttgart.
DOI: https://doi.org/10.1007/978-3-476-04901-8_1

[14] Grunwald, A., 2020. Verantwortung und Technik: zum Wandel des Verantwortungsbegriffs in der Technikethik (German) [Responsibility and technology: On the change in the concept of responsibility in technology ethics]. Springer Publishing: Berlin, Heidelberg.
DOI: https://doi.org/10.1007/978-3-662-60564-6_13

[15] Jonas, H., 1987. Warum die Technik ein Gegenstand für die Ethik ist: fünf Gründe. Technik und Ethik (German) [Why technology is a subject for ethics: Five reasons. Technology and ethics]. 2, 81-91.

[16] Grunwald, A., 2001. Technikfolgenabschätzung: Eine Einführung (German) [Technical assessment: An introduction]. Sigma Publishing: Rawalpindi.

[17] Holz, H.H., Hubig, C., 2013. Technik-und Wissenschaftsethik. Ein Leitfaden (German) [Technical and economical ethics: A guide]. Nachden-

ken über Technik. Nomos Verlagsgesellschaft mbH & Co. KG Publishing: Baden-Baden. pp. 449-454.

[18] Hubig, C., 2015. Einleitung (German) [Introduction]. Die Kunst des Möglichen I. Transcript Publishing: Bielefeld. pp. 15-36.
DOI: https://doi.org/10.14361/9783839404317

[19] Hubig, C., 2015. Die Kunst des Möglichen III: Grundlinien einer dialektischen Philosophie der Technik (German) [The art of the possible III: Basic lines of a dialectical philosophy of technology]. Transcript Publishing: Bielefeld.
DOI: https://doi.org/10.1515/transcript.9783839428122

[20] Hubig, C., 2004. Ethische Ingenieurverantwortung. Handlungsspielräume und Perspektiven der Kodifizierung (German) [Ethical engineering responsibility. Scope for action and perspectives of codification]. Verein Deutscher Ingenieure: Düsseldorf.

[21] Blankenbach, J., Becker, R., 2020. BIM und die Digitalisierung im Bauwesen (German) [BIM and digitization in construction]. Handbook Industry 4.0: Law, Technic, Society. Springer Publishing: Berlin, Heidelberg.
DOI: https://doi.org/10.1007/978-3-662-58474-3_40

[22] Wieland, J., 2014. Handbuch Compliance-Management: Konzeptionelle Grundlagen, praktische Erfolgsfaktoren, globale Herausforderungen (German) [Compliance management handbook: Conceptual foundations, practical success factors, global challenges]. Erich Schmidt Publishing: Berlin.

[23] Eming, K., 2011. Compliance als Problem der Wirtschafts- und Unternehmensethik (German) [Compliance as a problem of business and corporate ethics]. Interdisciplinary Aspects of Compliance. Nomos Verlagsgesellschaft mbH & Co. KG Publishing: Baden-Baden. pp. 39-64.

[24] Hauschka, C.E., 2016. Corporate compliance. C.H. Beck Publishing: Munich.

[25] Sun, M.L., Zhang, J., 2020. Research on the application of block chain big data platform in the construction of new smart city for low carbon emission and green environment. Journal for Computer Communications. 149, 332-342.
DOI: https://doi.org/10.1016/j.comcom.2019.10.031

[26] Region Stuttgart, 2022. Symposium Zukunft Bauen | 3. Symposium [Video]. [cited 2023 Mar 30]. Available from: https://www.youtube.com/watch?v=fcQDL01kDKE

[27] Schranz, C., 2022. Mit (Digital-) Kompetenz in die Zukunft. Standpunkt (German) [With (digital) competence into the future. Taking position]. Der Bauingenieur. 97(4), A3.
DOI: https://doi.org/10.37544/0005-6650-2022-04

[28] Adam, C., 2020. Mit solider Grundlagenausbildung in eine (bau-) dynamische Zukunft (German) [With solid basic training in a (construction) dynamic future]. Der Bauingenieur. 95(12), A3.
DOI: https://doi.org/10.37544/0005-6650-2020-12

[29] Bundesministerium des Innern, für Bau und Heimat BMWi, 2021. Modellprojekte Smart Cities 2021 Gemeinsam aus der Krise—Raum für Zukunft. Studie des Bundesministeriums für Wirtschaft und Energie (BMWi) (German) [Model projects Smart Cities 2021. Together out of the crisis—room for the future. Study by the Federal Ministry for Economic Affairs and Energy (BMWi)] [Internet] [cited 2022 Mar 15]. Available from: https://www.smart-city-dialog.de/wp-content/uploads/2021/10/BMI-SmartCities_Modellprojekte2021.pdf

[30] ICLEI—Local Governments for Sustainability, 2021. The European Circular Cities Declaration [Internet] [cited 2022 May 6]. Available from: https://circularcitiesdeclaration.eu/

[31] Sarc, R., Curtis, A., Kandlbauer, L., et al., 2019. Digitalisation and intelligent robotics in value chain of circular economy-oriented waste management—A review. Journal for Waste Management. 95, 476-492.
DOI: https://doi.org/10.1016/j.wasman.2019.06.035

[32] Goralski, M.A., Tan, T.K., 2020. Artificial intelligence and sustainable development. The International Journal of Management Education. 18(1), 100330.

DOI: https://doi.org/10.1016/j.ijme.2019.100330

[33] Council of the European Union, 2016. Schlussfolgerungen des Rates zu einer Städteagenda für die EU (German) [Council conclusions on an urban agenda for the EU] [Internet] [cited 2022 May 6]. Available from: https://www.consilium.europa.eu/de/press/press-releases/2016/06/24/conclusions-eu-urban-agenda/

[34] Federal Institute for Building, Urban and Spatial Research, 2021. Smart City Charta [Internet] [cited 2022 May 6]. Available from: https://www.smart-city-dialog.de/wp-content/uploads/2021/04/2021_Smart-City-Charta.pdf

[35] World Economic Forum WEF, 2021. Governing Smart Cities Report. Governing Smart Cities: Policy Benchmarks for Ethical and Responsible Smart City Development. White Paper July 2021 [Internet] [cited 2022 May 6]. Available from: https://www3.weforum.org/docs/WEF_Governing_Smart_Cities_2021.pdf

[36] Braungart, M., McDonough, W., 2014. Cradle to Cradle: Einfach intelligent produzieren (German) [Cradle to cradle: Simply produce intelligent]. Piper Verlag: München.

[37] Jehle, P., 2022. Inkonsequenz bremst Betonrecycling (German) [Inconsistency slows down concrete recycling]. Der Bauingenieur. 97(4), A16.
DOI: https://doi.org/10.37544/0005-6650-2022-04

[38] Fajga, K.W., 2022. Ehrgeizige Ziele gesetzt. Interview mit Fred Cortes (German) [Ambitious goals set. Interview with Fred Cortes]. Allgemeine Bauzeitung ABZ. 18, 3.

[39] Giannakidis, A., Weber-Lewerenz, B., Stolze, D., 2021. KI im Bauwesen in Deutschland. Forschungsstudie des Fraunhofer Instituts Stuttgart IAO (German) [AI in construction in Germany. Research study by the Fraunhofer Institute Stuttgart IAO]. Fraunhofer Piublishing: München. [cited 2022 May 6]. Available from: https://publica.fraunhofer.de/handle/publica/300849

[40] Rosha, A., Lobanova, L., 2022. Ethical responsibility of a company in the context of digital transformation of work: Conceptual model. Journal of Sustainability. 14(18).
DOI: https://doi.org/10.3390/su141811365

[41] Del Rosario, P., Backes, J.G., Traverso, M., 2022. Level(s)—Eine gemeinsame europäische Methode zur Bewertung der Nachhaltigkeitsleistung von Gebäuden (German) [Level(s)—A common European method for assessing the sustainability performance of buildings]. Der Bauingenieur. 11(3), 385-392.
DOI: https://doi.org/10.37544/0005-6650-2022-11-67

[42] Weber-Lewerenz, B., 2022. Thinking otherwise: Integrating existing buildings and monument protection in smart cities—Experience shared from user practice. Impact of Digital Twins in Smart Cities Development. IGI Global Publishing: Hershey.
DOI: https://doi.org/10.4018/978-1-6684-3833-6

[43] Razmjoo, A., Østergaard, P.A., Denaï, M., et al., 2021. Effective policies to overcome barriers in the development of smart cities. Journal of Energy Research & Social Science. 79, 102175.
DOI: https://doi.org/10.1016/j.erss.2021.102175

[44] Agnusdei, G., Elia, V., Gnoni, M.G., 2021. Is digital twin technology supporting safety management? A bibliometric and systematic review. Journal of Applied Sciences. 11(6), 2767.
DOI: https://doi.org/10.3390/app11062767

[45] Kirchschläger, P.G., 2021. Ethische Verantwortung in der digitalen Transformation (German) [Ethical responsibility in the digital transformation]. Journal of Risk, Fraud and Compliance ZRFC. 9(6), 253.

[46] Pilgrim, H., 2017. The dark side of digitalization: Will Industry 4.0 create new raw materials demands? PowerShift e.V. Publishing: Berlin.

[47] European Commission of Regions, 2021. Stellungnahme zum Aktionsplan für kritische Rohstoffe (German) [Opinion on the action plan for critical raw materials] [Internet] [cited 2022 Jul 13]. Available from: https://cor.europa.eu/de/news/Pages/critical-raw-materials-role-future-of-europe.aspx

[48] Elshkaki, A., Graedel, T.E., Ciacci, L., et al., 2016. Copper demand, supply, and associated

energy use to 2050. Journal of Global Environmental. 39, 305-315.
DOI: https://doi.org/10.1016/j.gloenvcha.2016.06.006

[49] DERA Deutsche Rohstoffagentur, 2016. Rohstoffe für Zukunftstechnologien 2016. Bundesanstalt für Geowissenschaften und Rohstoffe BGR (German) [Raw materials for future technologies 2016. Federal Institute for Geosciences and Natural Resources] [Internet] [cited 2022 May 6]. Available from: https://www.deutsche-rohstoffagentur.de/DERA/DE/Downloads/Studie_Zukunftstechnologien-2016.html

[50] Höfer, T., Bierwirth, S., Madlener, R., 2020. Energie-Mehrverbrauch in Rechenzentren bei Einführung des 5G Standards. Konferenzpapier zur Tagung "Nachhaltige Rechenzentren—Chancen und Entwicklungsmöglichkeiten am Standort Baden-Württemberg" (German) [Additional energy consumption in data centers when the 5G standard is introduced. Conference paper for the conference "Sustainable data centers—opportunities and development opportunities in Baden-Württemberg"] [Internet] [cited 2022 May 6]. Available from: https://www.nachhaltige-rechenzentren.de/wp-content/uploads/2020/03/1-Madlener_5G-Standard-und-Rechenzentren.pdf

[51] Rüttinger, L., 2016. Fallstudien zu Umwelt- und Sozialauswirkungen der Bauxitgewinnung und -weiterverarbeitung in der Boké und Kindia-Region, Guinea (German) [Case studies on environmental and social impacts of bauxite mining and processing in the Boké and Kindia region, Guinea]. Adelphi (Edt.) Publishing: Berlin.

[52] Fiedler, M., 2022. BIM und Baubehörde—ein Erfahrungsbericht. Strukturierte Daten für die digitale Zusammenarbeit im Infrastrukturbau: BIMSTRUCT (German) [BIM and building authorities—a field report. Structured data for digital collaboration in infrastructure construction: BIMSTRUCT] [Internet] [cited 2022 May 6]. Available from: https://www.bsdplus.de/fachartikel/von-einem-der-auszog-das-fuerchten-zu-lernen-bim-und-baubehoerde-ein-erfahrungsbericht.html

[53] Frieske, B. Huber, A., Stieler, S., et al., 2022. Zukunftsfähige Lieferketten und neue Wertschöpfungsstrukturen in der Automobilindustrie (German) [Sustainable supply chains and new value creation structures in the automotive industry]. Project report, Institute for automobile concepts. p. 247. Available from: https://elib.dlr.de/187017/

[54] Gharaibeh, L., Eriksson, K.M., Lantz, B., et al., 2022. Toward digital construction supply chain-based Industry 4.0 solutions: Scientometric-thematic analysis. Smart and Sustainable Built Environment. (Preprint).
DOI: https://doi.org/10.1108/SASBE-12-2021-0224

[55] Tezel, A., Papadonikolaki, E., Yitmen, I., et al., 2020. Preparing construction supply chains for blockchain technology: An investigation of its potential and future directions. Journal of Frontiers of Engineering Management. 7(4). 547-563.
DOI: https://doi.org/10.1007/s42524-020-0110-8

[56] European Commission, 2022. New European Innovation Agenda [Internet] [cited 2022 Jul 13]. Available from: https://www.eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022DC0332

[57] European Commission, 2022. Neue Strategische Vorausschau. Verzahnung von grünem und digitalem Wandel im neuen geopolitischen Kontext (German) [New strategic forecast: Dovetailing of green and digital change in the new geopolitical context] [Internet] [cited 2022 Jul 13]. Available from: https://www.ec.europa.eu/info/files/strategic-foresight-report-2022_en

[58] Building Europe's Digital Sovereignty Conference, 2022. Task Force on Digital Commons [Internet] [cited 2022 Jul 13]. Available from: https://www.presidence-francaise.consilium.europa.eu/en/news/the-building-europe-s-digital-sovereignty-conference/

[59] Weber-Lewerenz, B., 2021. Die unternehmerisch verantwortungsvolle Digitalisierung im

Bauwesen (German) [CDR in construction]. Der Bauingenieur. 96(01-02), 19-25. DOI: https://doi.org/10.37544/0005-6650-2021-01-02-45

[60] German Ethics Council, 2023. Humans and Machines—Challenges of Artificial Intelligence [Internet] [cited 2023 Apr 6]. Available from: https://www.ethikrat.org/fileadmin/Publikationen/Stellungnahmen/deutsch/stellungnahme-mensch-und-maschine.pdf

[61] Future of Life Institute, 2023. Pause Giant AI Experiments: An Open Letter [Internet] [cited 2023 Apr 6]. Available from: https://www.futureoflife.org/open-letter/pause-giant-ai-experiments/

BILINGUAL PUBLISHING GROUP

Journal of Architectural Environment & Structural Engineering Research

https://journals.bilpubgroup.com/index.php/jaeser

ARTICLE

Study on Phase Change Material in Grooved Bricks for Energy Efficiency of the Buildings

***Niharika Pawar*[1], *Yasmeen Qureshi*[1], *Rachit Agarwal*[2], *Srinivasarao Naik B*[2*]**

[1] *Institute for Excellence in Higher Education, Bhopal, Madhya Pradesh, 462016, India*

[2] *CSIR-Central Building Research Institute, Roorkee, Uttarakhand, 247667, India*

ABSTRACT

Phase change materials (PCMs) are an interesting technology due to their high density and isothermal behavior during phase change. Phase change material plays a major role in the energy saving of the buildings, which is greatly aided by the incorporation of phase change material into building products such as bricks, cement, gypsum board, etc. In this study, an experiment has been conducted with three identical small chambers made up of normal, grooved and PCM-treated grooved bricks. Before the inclusion of PCM in grooved bricks, PCM material behavior has been studied by different techniques such as DSC, TG/DTA, SEM, and XRD. Thermal properties and thermal stability were investigated by differential scanning calorimeter (DSC) and thermogravimetric analyzer (TGA) respectively. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) were used to determine the microstructure and crystalloid phase of the PCM before and after the accelerated thermal cycling test (0, 60, 120). These three identical model rooms built were exposed at a temperature just above 40 °C with a heater. When the maximum outdoor temperature was 40-41 °C, then the temperature of the PCM-treated grooved chamber was 32-33 °C. The PCM-treated wall was tested and compared with a conventional and grooved wall. The difference between the PCM-treated grooved chamber and the untreated one was 8-9 °C. PCM-treated bricks provided more efficient internal heat retention in summer when the outside temperature increased.

Keywords: Phase change material; Building temperature; Brick; Fatty acid; Cementitious materials

1. Introduction

Phase change materials are one of alternative resources for renewable energy. These materials are going to be used in building materials to delay the temperature curve in residential houses. In the

*CORRESPONDING AUTHOR:
Srinivasarao Naik B, CSIR-Central Building Research Institute, Roorkee, Uttarakhand, 247667, India; Email: srinivas@cbri.res.in

ARTICLE INFO
Received: 28 January 2023 | Revision: 20 April 2023 | Accepted: 6 May 2023 | Published Online: 17 May 2023
DOI: https://doi.org/10.30564/jaeser.v6i2.5542

CITATION
Pawar, N., Qureshi, Y., Agarwal, R., et al., 2023. Study on Phase Change Material in Grooved Bricks for Energy Efficiency of the Buildings.' Journal of Architectural Environment & Structural Engineering Research. 6(2): 22-32. DOI: https://doi.org/10.30564/jaeser.v6i2.5542

COPYRIGHT
Copyright © 2023 by the author(s). Published by Bilingual Publishing Group. This is an open access article under the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License. (https://creativecommons.org/licenses/by-nc/4.0/).

market, plenty of phase change materials are available [1,2]. Generally, these materials are fatty acids, hydrates, and waxes [3,4]. PCM can improve thermal properties such as thermal conductivity, specific heat, and heat capacity of building materials/components [5]. Most researchers are continuing efforts on phase change materials to decrease energy demand in buildings [6-14]. Ravikumar and Srinivasan applied a phase change material into the room and compared to reinforced concrete, withering course. When withering course was laid along with reinforced concrete and withering course with PCM laid roof the heat entering the room was reduced by 46.88% and 71.16% [15]. Shilei et al. have conducted an experiment with the incorporation of PCM in wallboard and tested thermal properties of PCM with differential scanning calorimetry [16]. Pasupathy and Velraj have studied the thermal performance of an inorganic eutectic PCM-based thermal management system for thermal management in residential buildings [17]. Jin et al. analyzed a new double-layer PCM and two layers have different temperatures applied to the floor. They compared the floor without PCM, energy released by floor with PCM in peak period increased by 41.1% and 37.9% during heating and cooling when the heat of fusion of PCM was 150 kJ/kg [18]. Lai et al. studied hollow bricks with and without PCM and exposed these bricks to the solar radiation. The temperature difference between treated and untreated hollow brick was about 4.9 °C [19]. Li et al. incorporated PCM in porous network of cement composite by absorption process. Cement acted as supporting material to prevent leakage. The cement and PCM composite have the latent heat of 69.12 kJ/kg with melting temperature of 31.86 °C [20]. Zuo et al. have taken two PCMs and mixed them at different compositions i.e. eutectic. Melting temperature and latent heat of fusion were analyzed by DSC [21]. Ceron et al. have tested experimentally on incorporated PCM in tile and compared with ordinary tile. They observed that temperature difference between normal and PCM tile was 4-10 °C. They concluded that PCM was the possible solution of optimizing energy efficiency in construction [22]. In the summer season, building demands more energy because lack of advanced materials and people want live in thermal comfort zone. Researchers and technologists are attempting sophisticated materials such as extremely porous materials, vacuum insulation materials, phase change materials, etc. to reduce energy consumption in buildings. Among the advanced materials PCMs are the possible solution for reducing energy demand in the building at peak hour requirements. In this present study, PCM is incorporated into grooved brick to evaluate temperature profile and the energy efficiency of the bricks to address the above problems confronting the buildings. **Table 1** summarizes the findings of temperature/energy demand reductions afforded by the PCM with relevant literature review.

Table 1. Comparison of temperature reduction using PCM in building materials.

References	Findings
Shi et al. [23]	Energy savings can reach 10% or more throughout the winter.
Lee et al. [24]	Heat flux reductions were 29.7% and 51.3% and at the west and south wall respectively.
Kuznik and Virgone [25]	PCM room temperature is reduced to 4.2 °C.
Evers et al. [26]	Mean heat flow reduced by 1.2% and 9.2% per day.
Sharma et al. [27]	Cooling load decreased by 35.4%. Heating load reduction was 12.8% per autumn.
Mandilaras et al. [28]	The highest temperature is decreased in concrete wall to 4 °C.
Kong et al. [29]	The postponement times for maximum and minimum temperature peaks are increased to 3 hours for samples.
Cabeza et al. [30]	The highest temperature decreased by 1 °C and temperature was delayed by 6 hours.
Castell et al. [31]	Peak temperature reduced by 1 °C.
Principi and Fioretti [32]	Heat flux reduced by 25% and prolonged by 6 hours.
Banu et al. [33]	Energy saved by 79%.

Table 1 continued

References	Findings
Lai et al. [34]	The mean peak reduction was 29.1% and total reduction in heat flux was 16.3%.
Hichem et al. [35]	The temperature of the interior wall was decreased by 3.8 °C and the heat flux was lowered by 82.1%.
Ahmed et al. [36]	The highest room temperature was lowered by 2.2 °C.
Kuznik et al. [37]	Delay the heat flux was about 100 minutes.
Tiago et al. [8]	The temperature was reduced to 5 °C and approximately 3 hours delayed entering heat in the room.
Kara and Kurnucx [38]	14% of the test room's annual heat flux reduced with PCM.
Heim and Clarke [39]	Heat load reduced by up to 90% in summer season.
Kong et al. [29]	1-2 °C reduced in PCM room and wall temperature delayed to 2-3 hours.
Diaconu [40]	10 kWh of energy savings was observed in PCM incorporated system.

2. Materials and methods

The grooved bricks and normal bricks were purchased from the local brick industry of Roorkee. The PCM i.e. fatty acid (C12) purchased from Pioner Inorganics, Delhi. The details of fatty acid, which is used as PCM and their properties are presented in **Table 2**. Calibrated Chromal-Alumel (Type K) thermocouples, plastic cups, and digital temperature measurement were used in this experiment.

Table 2. Properties of PCM.

Properties	Values
PCM	fatty acid
Melting point (°C)	40
Latent heat of fusion (kJ/kg)	227.1
Thermal conductivity (W/m•K)	0.127
Density (kg/m^3)	942.7
Specific heat (kJ/kg•K)	2.3

3. Analysis of phase change materials

3.1 Differential scanning calorimeter (DSC)

The thermal properties of PCM were tested by DSC (**Figure 1**). DSC measurements were performed using a DSC7 thermal analysis system supplied by Perkins-Elmer, USA. DSC runs were carried out at a heating of 5 °C/min under constant stream of Argon atmosphere. The sample weight for PCM is approximately 2.5-10 mg [41]. The melting point temperature of PCM corresponds to the initial temperature obtained by drawing a line on the highest slope point of the upper edge. The melting point and latent heat of fusion of PCM are 40 °C and 227 kJ/kg.

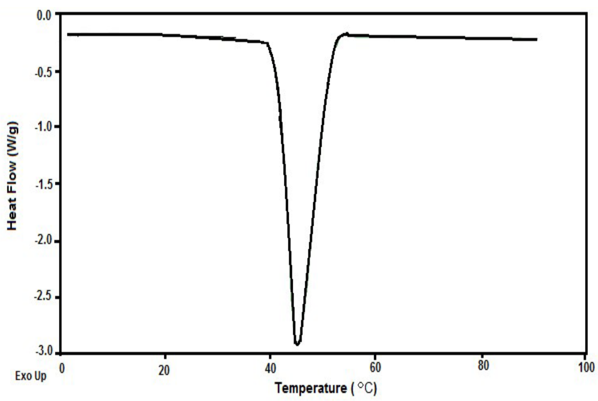


Figure 1. DSC curve of fatty acid, heating rate 5 °C/min.

3.2 Accelerated thermal cycle test

Accelerated thermal cycling tests were performed to investigate changes in melting temperature and latent heat of PCM. Thermal cycle test referred to heating up to the melting point of PCM provided in **Table 1** and then cooled to until PCM completely gets solid i.e. below the melting point. The above procedure is carried out continuously up to 60 and 120 cycles in thermal cycle chamber. After 60 and 120 cycles, DSC was performed to evaluate the melting point and latent heat of PCM. The obtained results were presented in **Table 3**.

Table 3. Melting point and heat of fusion of fatty acid after thermal cycle test.

S.No	No of Cycles	Melting Point (°C)	Heat of fusion (kJ/kg)
1	0	40	227.1
2	60	40	227
3	120	40	277

From **Table 3**, it has been observed that there are no significant values changed after 60 and 120 cycles (Zuo et al., 2011).

3.3 Thermal stability of phase change material (TGA)

The thermal stability test was performed in Thermal Gravimetric Analysis (TGA) from ambient to 40 °C (8-10 mg) in constant nitrogen vapor in the atmospheric pressure at a heating rate of 5 °C/min (**Figure 2**).

From the **Figure 2**, there is no significant weight loss observed even after 60 and 120 cycles.

3.4 Scanning electron microscopy (SEM) of PCM

The carbon tape was adhered on stub. The PCM sample was placed on carbon tape. The PCM samples were coated with gold sputter coater for conducting the PCM samples. Morphology was examined by scanning electron microscopy (SEM, OXFORD-7000F, LEO Inc. UK) to observe microstructural changes after 0, 60, and 120 cycles of PCM. The morphology of PCM changed at each cycle. This is because in each cycle phase changes i.e. solid to liquid vice versa. During these cycles, rearrangement of molecules is placed (**Figure 3**). The changes of morphology won't affect the thermal properties of PCM.

3.5 X-ray diffraction analysis of PCM

The XRD was used to observe mineralogical changes in PCM samples after 0, 60 and 120 cycles. The PCM samples were flattened on glass slide. The glass slide was kept in X-ray diffraction (XRD, Rigaku, Japan) and then XRD was operated from 0 to 60 degrees at a rate of 3 degrees/min. The peaks contained after the 0 cycle of PCM, the same intensity peaks were observed in both cycles i.e. 60 and 120 cycles. From **Figure 4**, it has been observed that there are no additional peaks.

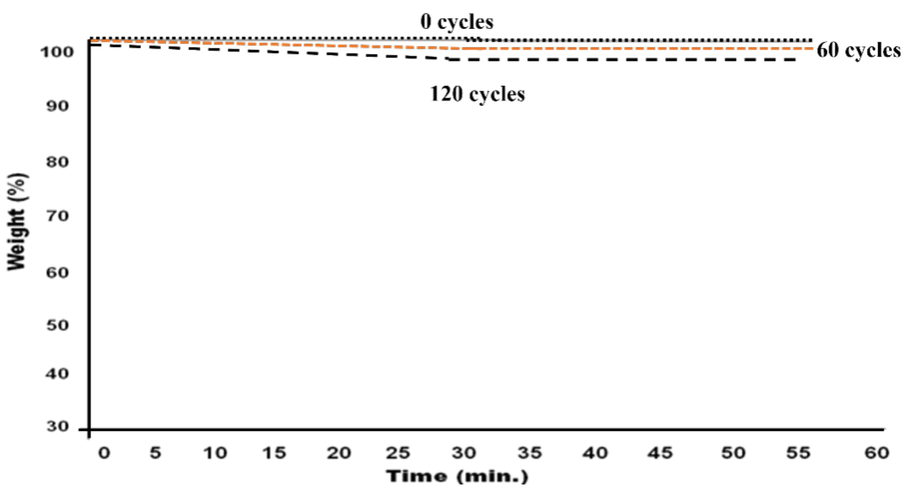
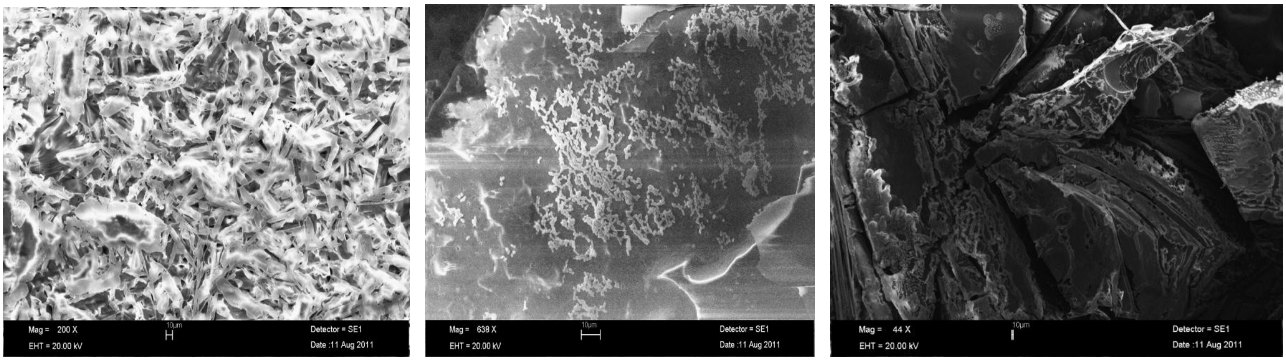


Figure 2. TGA curve of fatty acid, heating rate 5 °C/min.



(A) (B) (C)

Figure 3. Morphology of PCM (A) 0 cycle (B) 60 cycle (C) 120 cycle.

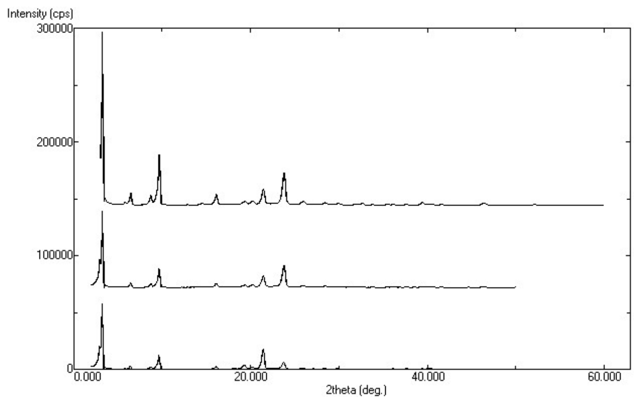


Figure 4. XRD curves of PCM.

4. Experimental

4.1 Thermo physical properties of PCM

Thermal conductivity and specific heat are the two important parameters for analyzing the energy efficiency in buildings. To determine these two properties, the following empirical equations were used. Specific heat of PCM (Cp) 2.27 J/kg•K estimated from the ROWLINSON-BONDI equation [42].

$$\rho_1 = \frac{\rho_0}{[1 + \beta(T_1 - T_2)]} \quad (1)$$

$$k = 3.56 \times 10^{-5} \times C_p(\rho^4/M)^{1/3} \quad (2)$$

Based on the above Equations (1) and (2) thermal conductivity and density of PCM were determined. The obtained data are compared with theoretical data in **Table 4**.

There are no such significant values observed in the theoretical and experimental values. These equations can be used in the modeling of prototype buildings.

4.2 Methodology

An experiment has been conducted in a room size 662 cm × 432 cm × 700 cm with two identical walls that were ordinary, grooved and PCM-treated (**Figure 5**). The grooved and PCM incorporated brick walls were compared with ordinary wall. The walls were exposed just above 40 °C with the help of heater. The calibrated thermocouples were installed on top and bottom of the wall and measured temperature profile during 12 h. After that, the same experiment was repeated with two identical chambers constructed in a room i.e. grooved and PCM-treated.

In this experiment effect of masses (1 kg to 5 kg of PCM) varied in the grooved brick. The additional thermocouples were placed in the PCM contained chamber and measured phase change temperature from the solid to liquid and vice versa. Based on outside and inside of temperature profile of all the chambers determined heat flux of the chamber using governing equation.

Table 4. Thermal and physical properties of phase change material.

Compound	Theoretical PCM	Exp. PCM
Melting Point (°C)	----	40
Heat of Fusion (kJ/kg)	----	227
Density (kg/m^3)	941.7	942.1
Thermal Conductivity(W/m °C)	0.13	0.127
Specific heat(J/g °C)	2.27	2.286

Bricks arrangement with PCM

PCM Chamber

Figure 5. Experimental setup.

5. Results and discussion

5.1 Effect of temperature on PCM thermal conductivity

Figure 6 shows thermal conductivity vs temperature when the temperature was increased thermal conductivity of PCM decreases determined according to Equation (2). Generally, thermal conductivity has descending order in material i.e. solid > liquid > gases. At 40 °C, PCM transition from a solid to a liquid state, and during this transition, PCM thermal conductivity drops. When temperature increases up to 50 and 60 °C, the thermal conductivity of PCM decreases. However, there is no such huge changes occurred in **Figure 6** as temperature changes.

5.2 Thermal analysis of ordinary brick wall

An experiment has been conducted on three walls that were normal, grooved, and incorporated PCM wall. Thermocouples were connected top and bottom surface of each wall. To increase the surface temperature just above 40 °C heater was lit on onside of the wall and generated temperature profiles were on 12 hours basis (7 a.m. to 7 p.m.). The top and bottom surfaces of a typical brick wall were shown to vary in temperature from 7 a.m. to 7 p.m., respectively, in **Figure 7**. The temperature difference within normal brick wall was quite moderate. Heat transfer takes place through the wall by conduction. Top surface of the wall temperature reached its highest point (40 °C), then the bottom surface temperature of the wall was 39 °C. Due to the wall's heat resistance, there is a 1 °C temperature difference observed between the top and bottom surfaces of the wall.

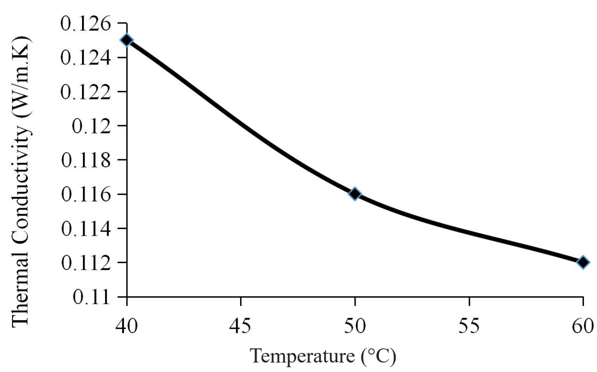


Figure 6. Temperature effect on thermal conductivity.

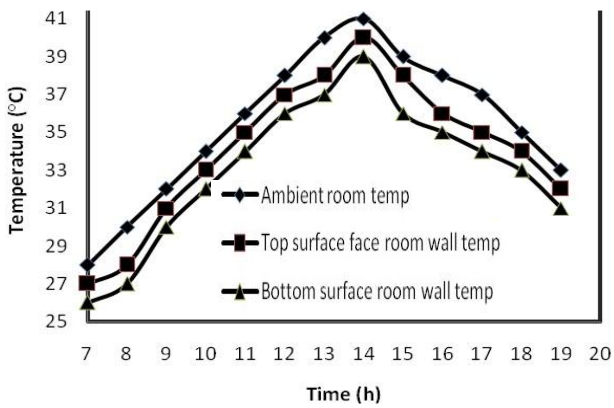


Figure 7. Temperature profile of normal brick.

5.3 Thermal analysis of grooved wall

Figure 8 depicts the top and bottom surfaces of the grooved wall's surface temperature changes from 7 a.m. to 7 p.m. From 7 a.m. to 9 p.m., there was a rather small temperature change inside the untreated bricks. The top and bottom surfaces of the bricks differed in temperature by one hour. When the wall's top surface temperature reached its peak (40 °C), the wall's bottom surface temperature was 38 °C, resulting in a temperature difference of around 2 °C because of the wall's thermal insulation capacity (which here refers to air in the center of the cylindrical holes). The temperature inside the grooved wall increased steadily with the outside temperature.

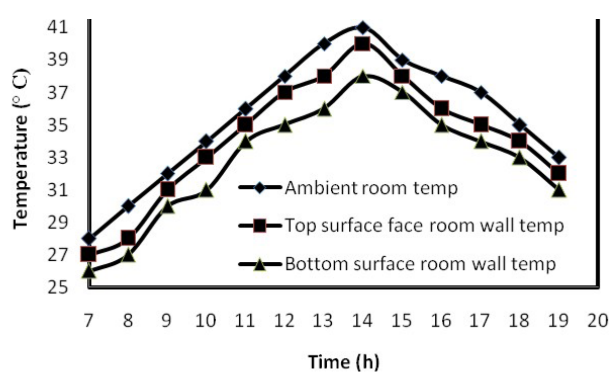


Figure 8. Temperature profile of grooved brick.

5.4 Thermal analysis of incorporated PCM wall

Figure 8 depicts the top surface and bottom surface temperatures of the PCM-treated wall from 7 a.m. to 7 p.m., respectively. Due to the presence of PCM in the wall, solid-liquid state phase shifts accounted for more of the PCM wall's thermal behavior. As heat delivered through the brick, as shown in **Figure 8**, its temperature increased to 40 °C. The PCM starts to melt as a result of heat transmission from the top surface of the bricks into the plastic cups. The brick between the PCM tubes also served as a heat conductor. The temperature of the wall's top surface reached its highest point (40 °C), while the wall's bottom surface reached 36 °C, with a temperature difference of roughly 3 to 4 °C between the two walls.

5.5 Comparison of thermal analysis of ordinary, grooved and incorporated PCM rooms

An experiment has been conducted with three identical chambers that were ordinary, grooved and incorporated PCM chambers. The size of each chamber was given in Section 5. The grooved brick chamber was filled with PCM. These three chambers were constructed in a room and used heater (Maharaja, Whiteline) to increase the ambient temperature of room and chambers were covered with insulation panel. Thermocouples were placed in each chamber and connected to digital temperature controller as shown in **Figure 5**. When ambient temperature profile varies correspondingly normal, grooved and incorporated PCM temperature varied. The ambient temperature at 40 °C, the normal room temperature was 39 °C, grooved room temp was 37 °C, and the incorporated PCM was 30-31 °C with time lag difference. The difference between normal and grooved chamber was 2 °C and difference between normal and incorporated PCM chamber was 8-9 °C. The difference between grooved and normal brick chamber was 1 °C (**Figure 9**). The temperature difference is more than the rest of brick chambers due to PCM absorbing more heat in the form latent heat of fusion and it resists the heat from outside to inside of the chamber.

5.6 Mass effect on incorporated PCM room

An experiment has been conducted with variation of different mass (1 kg to 5 kg) in PCM chamber.

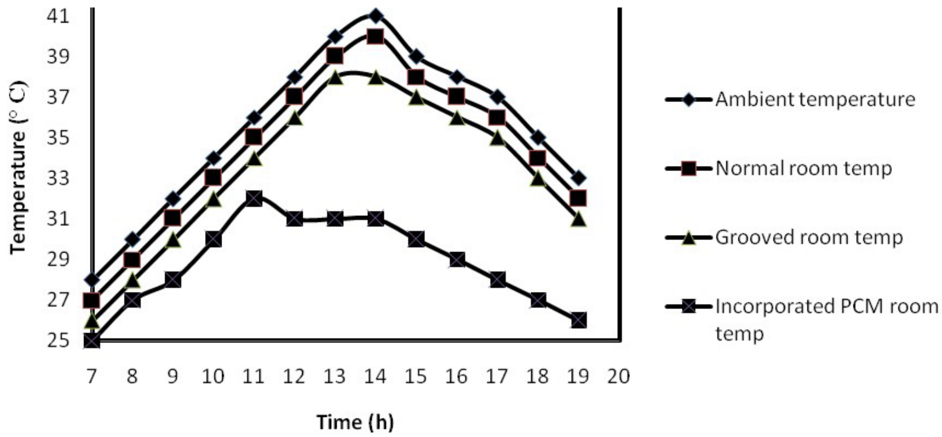


Figure 9. Temperature profile of different chambers.

The incorporated PCM chamber was exposed at 40 °C. The temperature difference of each dosage was determined with the help of data logged system. **Figure 10** shows that when mass of PCM is increased temperature difference range increased (2-11 °C) but time lag was increased due to meting out of phase change (solid to liquid) increased with respect to mass effect i.e. 1 kg to 5 kg.

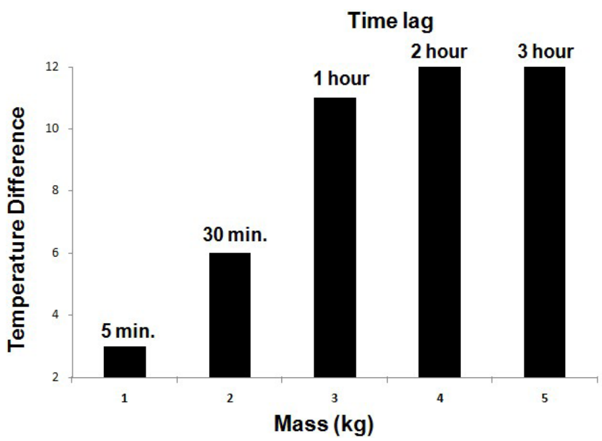


Figure 10. Effect of mass on incorporated PCM with respect to time.

When the mass is increased 1 kg, 2 kg, 3 kg, 4 kg and 5 kg corresponding to time lags are 5 min, 30 min, 1 hour, 2 hours, and 3 hours respectively. When the mass increased 1 kg, 2 kg, 3 kg, 4 kg and 5 kg corresponding to temperature difference are 3 °C, 6 °C, 11 °C, 12 °C, 12 °C respectively. At 5 kg PCM is not melted completely.

5.7 Thermal analysis of PCM

When the experimental room was exposed to the heater, and then generated temperature profile of PCM patterns (Solid to liquid vice versa). When heater was on, the temperature of PCM increased during the time 7-13 hours (**Figure 11**), this is called charging period of PCM in which PCM melts after sensible and heat is absorbed. After one hour heater was off, the temperature is decreased due to PCM going to turns its phase from liquid to solid, is called discharging period during the time 14-19 hours and absorbed heat is released to both sides of the chamber (inside and outside).

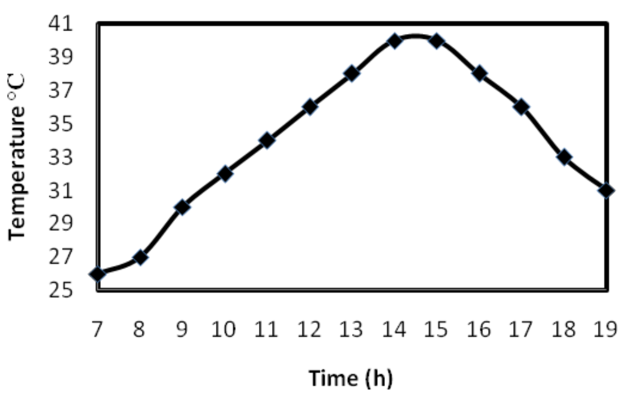


Figure 11. Temperature profile of PCM.

5.8 Heat flux entering the room

Figure 12 makes it abundantly evident that PCM applied on the brick is superior to regular, grooved brick. Heat entering the room can be decreased if PCM is mounted on the wall. Grooved and PCM walls reduce heat transfer by 49.1% and 87.3%, respectively, when compared to the standard wall. The reduction in net heat transmission to grooved walls was determined to be 38.9%. The heat flux is decreased due to absorption. Heat is more in PCM chamber than the rest of the chambers due to ordinary chamber observing the heat in the form of sensible heat, grooved brick observing the heat in the form of sensible and conventional heat, where PCM chamber absorbs the heat in the form of latent heat i.e. latent heat > sensible heat.

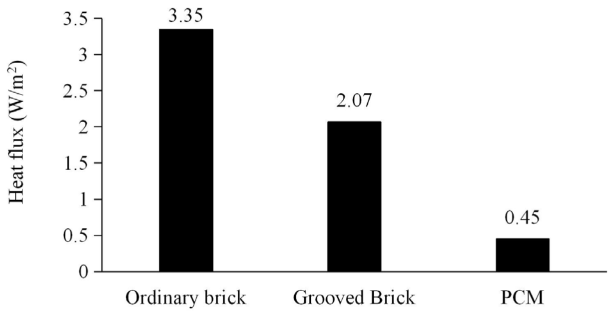


Figure 12. Heat flux entering into the room.

6. Conclusions

To reduce the energy consumption of the buildings selected a phase change material of fatty acid having the melting point of 40 °C and latent heat of fusion 227 kJ/kg. Phase change material has good thermal stability in terms of no weight loss and no changes in its melting temperature and latent heat of fusion. No Change in morphology and microstructure of PCM in its each cycle were 60 and 120. Phase change material was incorporated in grooved wall and compared with normal and grooved wall. The temperature difference of normal and PCM wall of top surfaces was equal but bottom surfaces were 2-3 °C. An experiment has been conducted in three identical rooms with normal, grooved and PCM incorporated grooved bricks. The temperature difference of normal and PCM incorporated grooved bricks room was 8-9 °C and grooved and PCM incorporated grooved bricks room was 6-8 °C at peak hour. This type of fatty acid has the potential for cool storage. PCM-treated in grooved bricks chamber had better insulation effect than ordinary and grooved bricks chamber.

Author Contributions

All authors contributed equally in terms of preparing this manuscript and performing experiments.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

The authors are thankful to the Director, CSIR-CBRI for providing infrastructural facilities and financial support.

References

[1] Mahdaoui, M., Hamdaoui, S., Msaad, A.A., et al., 2021. Building bricks with phase change material (PCM): Thermal performances. Construction and Building Materials. 269, 121315.

[2] Cabeza, L.F., Castell, A., Medrano, M., et al., 2010. Experimental study on the performance of insulation materials in Mediterranean construction. Energy and Buildings. 42(5), 630-636.

[3] Saeed, T., 2022. Influence of the number of holes and two types of PCM in brick on the heat flux passing through the wall of a building on a sunny day in Medina, Saudi Arabia. Journal of Building Engineering. 50, 104215.

[4] Dellagi, A., Ayed, R., Bouadila, S., et al. (editors), 2022. Study of the thermal behavior of a heated brick containing a phase change material. 2022 13th International Renewable Energy Congress (IREC); 2022 Dec 13-15; Hammamet, Tunisia. New York: IEEE. p. 1-5.

[5] Soares, N., Costa, J.J., Gaspar, A.R., et al., 2013. Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency. Energy and Buildings. 59, 82-103.

[6] Memon, S.A., 2014. Phase change materials

integrated in building walls: A state of the art review. Renewable and Sustainable Energy Reviews. 31, 870-906.

[7] Vicente, R., Silva, T., 2014. Brick masonry walls with PCM macrocapsules: An experimental approach. Applied Thermal Engineering. 67(1-2), 24-34.

[8] Silva, T., Vicente, R., Soares, N., et al., 2012. Experimental testing and numerical modelling of masonry wall solution with PCM incorporation: A passive construction solution. Energy and Buildings. 49, 235-245.

[9] Gobinath, S., Senthilkumar, G., Beemkumar, N., 2018. Comparative study of room temperature control in buildings with and without the use of PCM in walls. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 40(14), 1765-1771.

[10] Tunçbilek, E., Arıcı, M., Krajčík, M., et al., 2022. Impact of nano-enhanced phase change material on thermal performance of building envelope and energy consumption. International Journal of Energy Research. 46(14), 20249-20264.

[11] Arıcı, M., Bilgin, F., Nižetić, S., et al., 2020. PCM integrated to external building walls: An optimization study on maximum activation of latent heat. Applied Thermal Engineering. 165, 114560.

[12] Tunçbilek, E., Arıcı, M., Krajčík, M., et al., 2020. Thermal performance based optimization of an office wall containing PCM under intermittent cooling operation. Applied Thermal Engineering. 179, 115750.

[13] Tunçbilek, E., Arıcı, M., Bouadila, S., et al., 2020. Seasonal and annual performance analysis of PCM-integrated building brick under the climatic conditions of Marmara region. Journal of Thermal Analysis and Calorimetry. 141, 613-624.

[14] Arıcı, M., Bilgin, F., Krajčík, M., et al., 2022. Energy saving and CO_2 reduction potential of external building walls containing two layers of phase change material. Energy. 252, 124010.

[15] Ravikumar, M., Srinivasan, P.S.S., 2008. Phase change material as a thermal energy storage material for cooling of building. Journal of Theoretical & Applied Information Technology. 4(6).

[16] Shilei, L., Guohui, F., Neng, Z., et al., 2007. Experimental study and evaluation of latent heat storage in phase change materials wallboards. Energy and Buildings. 39(10), 1088-1091.

[17] Pasupathy, A., Velraj, R., 2008. Effect of double layer phase change material in building roof for year round thermal management. Energy and Buildings. 40(3), 193-203.

[18] Jin, X., Zhang, X., 2011. Thermal analysis of a double layer phase change material floor. Applied Thermal Engineering. 31(10), 1576-1581.

[19] Lai, C.M., Chiang, C.M., 2006. How phase change materials affect thermal performance: Hollow bricks. Building Research & Information. 34(2), 118-130.

[20] Li, H., Liu, X., Fang, G., 2010. Preparation and characteristics of n-nonadecane/cement composites as thermal energy storage materials in buildings. Energy and Buildings. 42(10), 1661-1665.

[21] Zuo, J., Li, W., Weng, L., 2011. Thermal performance of caprylic acid/1-dodecanol eutectic mixture as phase change material (PCM). Energy and Buildings. 43(1), 207-210.

[22] Cerón, I., Neila, J., Khayet, M., 2011. Experimental tile with phase change materials (PCM) for building use. Energy and Buildings. 43(8), 1869-1874.

[23] Shi, X., Memon, S.A., Tang, W., et al., 2014. Experimental assessment of position of macro encapsulated phase change material in concrete walls on indoor temperatures and humidity levels. Energy and Buildings. 71, 80-87.

[24] Lee, K.O., Medina, M.A., Raith, E., et al., 2015. Assessing the integration of a thin phase change material (PCM) layer in a residential building wall for heat transfer reduction and management. Applied Energy. 137, 699-706.

[25] Kuznik, F., Virgone, J., 2009. Experimental assessment of a phase change material for wall building use. Applied Energy. 86(10), 2038-

2046.

[26] Evers, A.C., Medina, M.A., Fang, Y., 2010. Evaluation of the thermal performance of frame walls enhanced with paraffin and hydrated salt phase change materials using a dynamic wall simulator. Building and Environment. 45(8), 1762-1768.

[27] Sharma, A., Tyagi, V.V., Chen, C.R., et al., 2009. Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews. 13(2), 318-345.

[28] Mandilaras, I., Stamatiadou, M., Katsourinis, D., et al., 2013. Experimental thermal characterization of a Mediterranean residential building with PCM gypsum board walls. Building and Environment. 61, 93-103.

[29] Kong, X., Lu, S., Huang, J., et al., 2013. Experimental research on the use of phase change materials in perforated brick rooms for cooling storage. Energy and Buildings. 62, 597-604.

[30] Cabeza, L.F., Castellon, C., Nogues, M., et al., 2007. Use of microencapsulated PCM in concrete walls for energy savings. Energy and Buildings. 39(2), 113-119.

[31] Castell, A., Martorell, I., Medrano, M., et al., 2010. Experimental study of using PCM in brick constructive solutions for passive cooling. Energy and Buildings. 42(4), 534-540.

[32] Principi, P., Fioretti, R., 2012. Thermal analysis of the application of pcm and low emissivity coating in hollow bricks. Energy and Buildings. 51, 131-142.

[33] Banu, D., Feldman, D., Hawes, D., 1998. Evaluation of thermal storage as latent heat in phase change material wallboard by differential scanning calorimetry and large scale thermal testing. Thermochimica Acta. 317(1), 39-45.

[34] Lai, C.M., Chen, R.H., Lin, C.Y., 2010. Heat transfer and thermal storage behaviour of gypsum boards incorporating micro-encapsulated PCM. Energy and Buildings. 42(8), 1259-1266.

[35] Hichem, N., Noureddine, S., Nadia, S., et al., 2013. Experimental and numerical study of a usual brick filled with PCM to improve the thermal inertia of buildings. Energy Procedia. 36, 766-775.

[36] Ahmed, M., Meade, O., Medina, M.A., 2010. Reducing heat transfer across the insulated walls of refrigerated truck trailers by the application of phase change materials. Energy Conversion and Management. 51(3), 383-392.

[37] Kuznik, F., Virgone, J., Johannes, K., 2011. In-situ study of thermal comfort enhancement in a renovated building equipped with phase change material wallboard. Renewable Energy. 36(5), 1458-1462.

[38] Kara, Y.A., Kurnuç, A., 2012. Performance of coupled novel triple glass and phase change material wall in the heating season: An experimental study. Solar Energy. 86(9), 2432-2442.

[39] Heim, D., Clarke, J.A., 2004. Numerical modelling and thermal simulation of PCM-gypsum composites with ESP-r. Energy and Buildings. 36(8), 795-805.

[40] Diaconu, B.M., 2011. Thermal energy savings in buildings with PCM-enhanced envelope: Influence of occupancy pattern and ventilation. Energy and Buildings. 43(1), 101-107.

[41] Srinivasaraonaik, B., Singh, L.P., Tyagi, I., et al., 2020. Microencapsulation of a eutectic PCM using in situ polymerization technique for thermal energy storage. International Journal of Energy Research. 44(5), 3854-3864.

[42] Green, D.W., Southard, M.Z., 2019. Perry's chemical engineers' handbook. McGraw-Hill Education: New York.

BILINGUAL PUBLISHING GROUP

Journal of Architectural Environment & Structural Engineering Research

https://journals.bilpubgroup.com/index.php/jaeser

ARTICLE

Assessing the Role of Environmental Factors in the Transmission of Infectious Diseases in Communal Spaces

Seyyed Mohammadmahdi Hosseinikia[1*]***, Negar Khiabanchian***[2]***, Hadi Rezaei Rad***[3]

[1] *Architecture Department, Tabriz Islamic Art University, Tabriz, 5164736931, Iran*

[2] *Architecture Department, ACECR, Branch of Hamedan, Hamedan, 6517618399, Iran*

[3] *Urban Planning Department, Buali Sina University, Hamedan, 6516738695, Iran*

ABSTRACT

Communal spaces provide different facilities for users while they are the primary place for the spread of diseases, especially respiratory. Transmission is possible through human behaviors, the way they communicate with each other and breathe in an environment by airborne pathogenic particles. Experts from various fields have gained valuable experience and achievements regarding how to prevent these diseases by means of environmental factors. Due to the spread of the corona virus in the past years, environmental planners and designers seriously considered the need to review the design and use of spatial components. This study provides a framework for decision making and design of communal spaces based on how environmental components can be effective in preventing the spread of respiratory diseases such as coronavirus and influenza. The research method used in this article is logical reasoning combined with ANP method and focus group discussion. According to the results of this research, indoor air quality plays the most crucial role in preventing the transmission of viruses (contagious respiratory diseases) based on expert groups.

Keywords: Well building; Healthy building; Contagious diseases respiratory; Air borne transmission

1. Introduction

As humans, we live in space and are surrounded by, both public and private. There is no escape from it. In times of need, we can only change the living space and go from place to place. Quarantine is usually the last place we live and if we get infected. The reason is clear; the place where the least use

*CORRESPONDING AUTHOR:

Seyyed Mohammadmahdi Hosseinikia, Architecture Department, Tabriz Islamic Art University, Tabriz, 5164736931, Iran; Email smmkia@yahoo.com

ARTICLE INFO

Received: 5 April 2023 | Revision: 28 April 2023 | Accepted: 6 May 2023 | Published Online: 22 May 2023

DOI: https://doi.org/10.30564/jaeser.v6i2.5626

CITATION

Hosseinikia, S.M., Khiabanchian, N., Rad, H.R., 2023. Assessing the Role of Environmental Factors in the Transmission of Infectious Diseases in Communal Spaces. Journal of Architectural Environment & Structural Engineering Research. 6(2): 33-44. DOI: https://doi.org/10.30564/jaeser.v6i2.5626

COPYRIGHT

Copyright © 2023 by the author(s). Published by Bilingual Publishing Group. This is an open access article under the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License. (https://creativecommons.org/licenses/by-nc/4.0/).

and traffic takes place and important protocols are implemented. Research has often forgotten the factor of the space in which man lives and is closer to it. The amount of space usage and connection with its components in various spaces is different. As an intelligent component with special features, the virus exists everywhere. How people encounter space on the one hand, and the effect that space and its components such as surface, dimensions, material, etc. have on the virus, all play a decisive role in the spread of the virus among humans.

The topic of occupant health in public buildings is an emerging area for both academic research and industry practices. The World Health Organization (WHO) defines health as "a state of complete physical, mental and social well-being" [1]. Physical well-being is defined as the appropriate functioning of our bodies and our ability to resist illness. Mental well-being includes more than merely the absence of mental illness; it is comprised of mental resilience, contentment, confidence, and peace of mind. Finally, social well-being is the ability to build meaningful relationships with others; it is determined by an individual's sense of belonging, and social engagement [2]. One of the threats that societies face today is the spread of infectious diseases in communal spaces. There are several ways of transmitting respiratory pathogens. Spread or transmission can be through close contact with humans or by human touch [2,3]. The most common way of spreading respiratory infectious diseases is through respiratory droplets when an infected person coughs or sneezes. These tiny droplets can infect a healthy person by sitting on the face (mouth, nose, ears, and eyes) or hands [4]. Contagious diseases respiratory can remain on different surfaces for a long time, which is one of the important reasons for the transmission [2].

1.1 Airborne transmission

The use of Disinfectants decimates microorganisms of viruses or bacteria on internal layers or inert surfaces by acting as an antimicrobial mechanism. Disinfectants are not always impressive against all kinds of microorganisms like bacterial spores as sterilization, which kills all types of life by the use of extreme physical or chemical procedures [5]. Many researches have been conducted on the effect of environmental factors and the form of spaces on the airborne transmission of disease particles, mostly due to the importance and epidemic of SARS virus (COVID) in the study of this virus. Many indoor spaces have a high occupant density, but do not provide adequate fresh air [6], which increases the infection risk through airborne transmission. The transmission by airborne route was considered to greatly contribute to some reported outbreak events. For example, the SARS-CoV-2 spread among the members of the Skagit Valley Chorale during a weekly rehearsal eventually making 53 out of 61 members infected. Such a severe spread was highly suspected to be caused by the airborne transmission [7]. The outbreak event that happened in a Guangzhou restaurant was likely caused by recirculated air, which carried infectious aerosols emitted by an index case [8,9]. A retrospective analysis of these two outbreak events also supported the airborne transmission of SARS-CoV-2 [10]. The outbreaks in a tour coach in Hunan province [11], a communal space in Seoul [12] and a tour coach in Zhejiang province [13] also indicated the possibility of airborne transmission. It is increasingly clear and accepted that airborne transmission is an important contributor to the rapid and long-distance spreading of SARS-CoV-2 [14]. Indoor air quality (IAQ) control strategies can be applied to reduce the infection risk of COVID-19 through airborne transmission [15,16]. Improving indoor ventilation systems, using air cleaning technologies, and wearing masks can enhance the IAQ and decrease the infection risk immensely. These strategies have been introduced and discussed in other published papers [17,18] and recommended by WHO [19], U.S. CDC [20,21] and ASHRAE [22]. A well-known mathematical model for estimating the infection risk through airborne transmission is the Wells-Riley model [23,24]. It assumes well-mixed air and a steady-state infectious particle concentration in a confined space.

1.2 Temperature & light

Various research has been done in the field of different environmental conditions and their relationship with the transmission of viruses and respiratory pathogens. In this context, these studies can be mentioned: In a study, the persistence of SARS-CoV-2 in environmental conditions was measured at different temperatures. The virus is very stable at 4 °C, but sensitive to heat at 4 degrees Celsius, only approx. 0.7 infectious reduction logging units Title on day 14. With an increase in the temperature to 70 degrees Celsius, the virus deactivation time is reduced to 5 minutes [25]. The microbe that causes tuberculosis, Mycobacterium Tuberculosis is called tuberculosis, which affects the lungs in most cases it makes, but it can influence other parts of the body as well. Tuberculosis bacillus is very sensitive to sunlight as a result good and dark places become more and more. In general, TB is a socio-economic disease and everywhere there is a population that gathers a lot under one roof and has proper nutrition and hygiene not to worry and live in poverty, they are seen more often. Housing situation plays a significant role in people's illness, houses are dark, and unsanitary grounds for choosing their inhabitants prepared for tuberculosis [26].

1.3 Surfaces

A comparative study of SARS-CoV-2 and SARS-CoV-1 viruses is done and a comparative study of both viruses shows that SARS-CoV-2 and SARS-CoV-1 have significant sustaining time on different surfaces. This research showed that the persistence of the virus on the surface is directly related to their gender. In this way, the longest shelf life is related to plastic with 72 hours, then steel with 48 hours shelf life, and the lowest copper with 2 hours shelf life [27]. Due to the fact that infectious respiratory diseases are transmitted through the transmission of pathogens in the air between sick and healthy people, studies on the airborne transmission of viruses are discussed. In seminal papers from 1930, Wells proposed the concept of droplets and droplet nuclei that has dominated thinking about airborne infection over the ensuing decades. Wells commented that larger droplets, governed by Stokes' law, would fall quickly to the ground, while smaller droplet nuclei, formed from droplets that evaporated and left behind solid residue, would stay airborne for longer periods of time. Since then, studies in the field of aerosol science have shown that exhalation and various exhalatory activities, e.g. singing, variably generate thousands of small par-tickles (of multiple size modes) that can travel well beyond 6 feet and accumulate in poorly ventilated indoor spaces [28].

From the review of previous studies on the effective components in the transmission of airborne infectious diseases, three important factors and indicators are extracted (**Figure 1**).

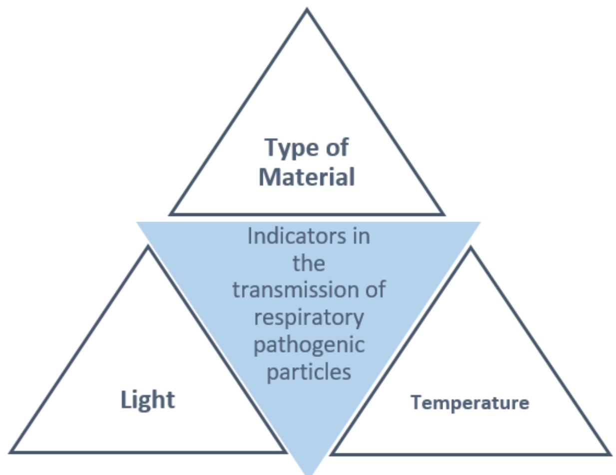


Figure 1. Primarily clustering of important indicators in the transmission of respiratory pathogens from previous studies.

1.4 Well building

Due to the fact that a healthy building is a subset of a good building, the well standard model is used to provide other indicators of a healthy building. These components can play a role in the transmission of airborne particles of infectious respiratory diseases.

WELL Building Standard: Delos Living LLC is an American-based organization that says its mission is 'to build a better world'. It suggests that it transforms the indoor environment by placing health and 'wellness' at the center of design and construction decisions through research, consulting, and real estate development, and by offering innovative solutions for the built environment. The standard is based on seven years of research in partnership with scientists, doctors, and architects exploring the connection between the buildings where people spend their time, and the health and well-being impact those buildings have on their occupants. It is third-party certified by Green Business Certification Inc. (GBCI), which administers the Leadership in Energy and Environmental Design (LEED) program (Delos Living LLC, 2020) [29].

According to the WELL building standard (**Figure 2**), the following components are defined and Spaces can become WELL certified by achieving a defined score in each of seven categories:

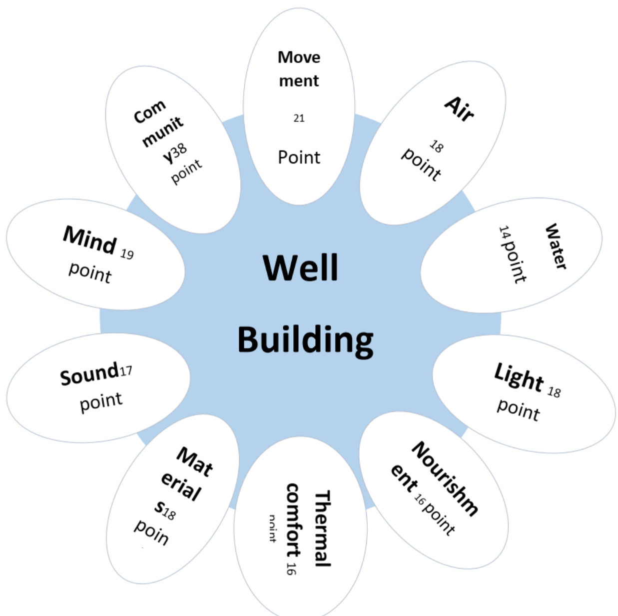


Figure 2. Well Building Standard V2—Concepts and Features, Delos Living LLC [29].

The project can pursue no more than 12 points per concept and no more than 100 points across the ten concepts. 10 additional points are available in the innovation concept (innovative credits).

1.5 Healthy buildings

The term "healthy buildings" is emerging in the literature; researchers have previously focused on "sick buildings," or the "Sick Building Syndrome" (SBS) to address "Building Related Illness" (BRI) [30]. Clearly, the idea of designing places to support resident health has only been recently adopted. A "healthy building" is defined as a built structure that promotes the positive well-being of individuals [31].

Considering that a healthy building is considered a subset of a good building, the components of a healthy building will be presented in order to finally reveal the effective indicators in the airborne transmission of respiratory disease particles. Despite the importance of healthy buildings, rather than avoiding sick buildings, we do not have a clear and commonly accepted definition of what "healthy building" means to building professionals and occupants (**Figure 3**). Moreover, designers do not have a routine process to integrate the fundamental definitions of health offered by the WHO, as explained earlier, in buildings.

A healthy building may be better defined as a building, including all of its systems, that promotes and sustains the health of its occupants, as a state of complete physical, mental and social well-being. As a result of emerging environmental concerns (e.g., climate change, pollution), demographic shifts (e.g., aging population), lifestyle changes (e.g., global epidemics of stress, longer working hours), the role of building professionals and researchers in healthy buildings will be highlighted. It can be said that the components obtained from previous research, the indicators of good building and the components of the healthy building, each play a role in the transmission of airborne particles of respiratory diseases from different dimensions.

According to what has been stated, the question of this research is: What criteria should be considered to increase the communal space resilience against contagious diseases respiratory? How can a process facilitate the selection of criteria be proposed by forming a discussion group with the experts' choice?

The premise of this research is that using both FGD① and analytical network process among the spatial indicators of architecture in the transmission of infectious respiratory diseases, he identified the most important factors in order. Many researches have been conducted in the field of infectious diseases in various fields of medicine, environmental health, environmental design, architecture and urban planning, and there is a lot of accumulated knowledge

① Focus Group Discussion

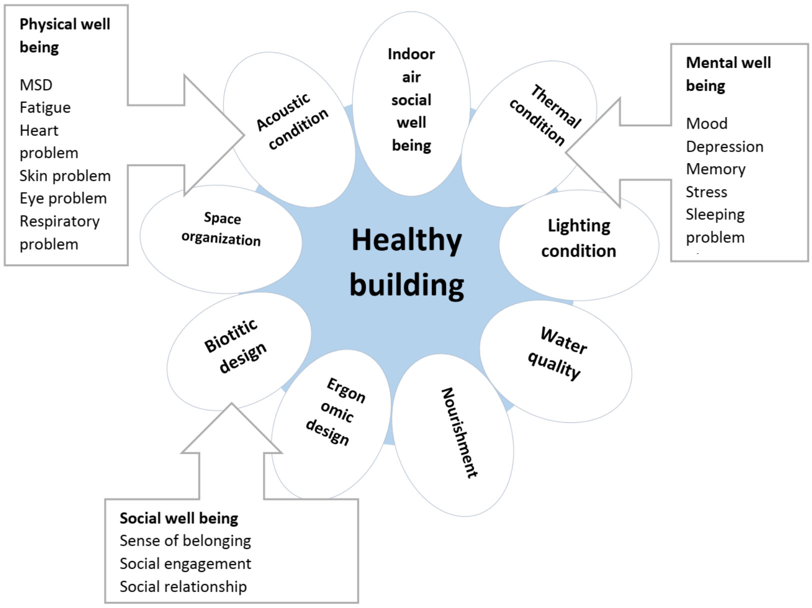


Figure 3. Air quality and healthy buildings concept [32].

related to this issue. Based on this and according to the purpose of the research, which found the spatial component as one of the most effective agents in the transmission of airborne particles of infectious diseases, the conceptual process model of the research is presented (**Figure 4**).

2. Materials and methods

The research method used in this article is logical reasoning combined with ANP② method and focus group discussion. This is a practical method when desiring to solve real-world issues [33]. The analysis of indicators and their prioritization has been done by Mat-Lab program. The method of data collection is field and library and the research tool is the analytical network process. According to the scope of calculations and accuracy in the computational process, the Mat-Lab program is used to form the process and perform calculations. This study has two main phases so that collect and weigh qualitative criteria to help explain and build upon the quantitative results. The study encompassed a quantitative component (analytical network process) and a qualitative component (focus group discussions). ANP method is used in various fields of science, including engineering, management, business and science; to help decision makers make good choices [34]. The purposes of using such methods are evaluating, choosing, ranking and sorting alternatives. FGD is a way of gathering data that involves engaging a small group of (expert) people 'focused' on a particular topic or set of issues [35]. Also the group consists of two doctors, two environmental health experts, two urban planners, two architects, and two environment designers who had experience working in communal spaces of Hamedan city and dealing with coronavirus patients. The most significant applications of the discussion group method are: 1) Obtaining an information background with existing and potential characteristics of individuals and groups in areas related to the goal. 2) In-depth discovery and search and expertise concerning the general needs of groups as well as information are hidden in the thoughts and ideas of the people. 3) Estimating opinions in thought combinations are related to how to achieve social needs [36].

Considering that the members of the group are all residents of Hamadan province, so, their observations of the type and extent of the spread of infectious diseases, including the coronavirus, in this city will have an impact on the results of this study.

The analytical network process begins with identifying and prioritizing decision elements. These

② analytical network process

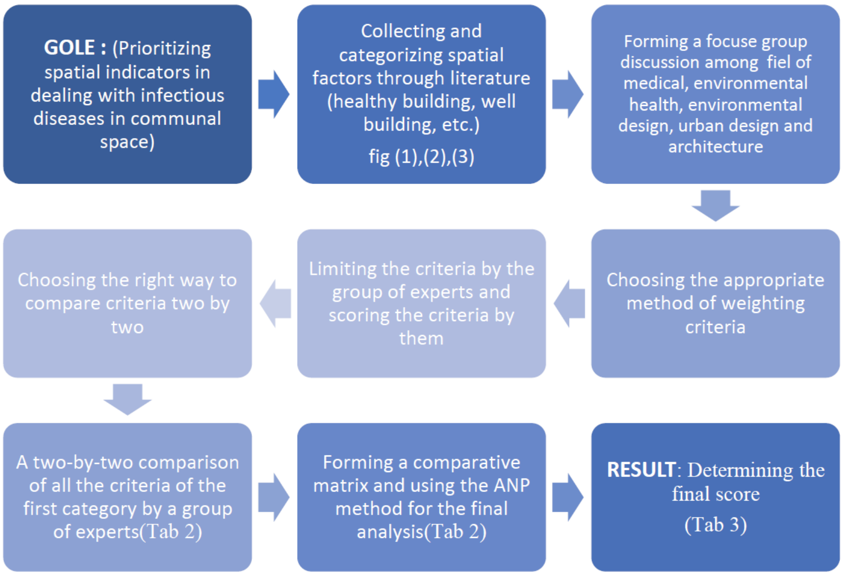


Figure 4. Study design process.

elements include goals, criteria, characteristics and possible options used in prioritization. The existence of structure is because the elements of decision-making (options and decision-making criteria) can be summarized at different levels (**Table 1**).

Table 1. Degree of preference in ANP [37].

Score (degree of preference)	Description	Explanation
1	Equal importance	Two criteria are equally important
3	Slightly more important	Two criteria are equally important
5	more important	Experience shows that i is more important than j
7	Much more important	Experience shows that the importance of i is much more than j
9	Absolute importance	Absolutely is more important than j
2, 4, 6, 8	Intermediate preferences	

3. Case study

In the study of the statistics of infection and deaths caused by corona disease in Hamedan province, from the beginning of the epidemic of this virus to May 2, 2021, about 37,812 people were infected with coronavirus in Hamedan province, and among them, 15,330 patients were hospitalized, and this number was 5,618 in Hamedan city for whom that has been infected with this virus and hospitalized. The number of deaths from the coronavirus in the province has reached 1,951 people since the beginning of the outbreak until the mentioned date [38], which shows the importance of managing and re-examining the strategies for dealing with it, including spatial factors affecting its spread.

4. Findings and discussion

This finding clarifies that each of the spatial indicators has a role in the spread of viruses and their transmission from the perspective of experts in various fields of medicine, environmental health, environment design and architecture. The indicators were gathered in the literature section and downsized by focus group discussion. They prioritized the ANP method by experts in fields related to the purpose of the research (**Table 3**). Each of these factors has a determining effect on the probability of infectious and respiratory pathogenic particle transmission. Their combination with other spatial indicators in the context of space along with factors such as the use of space has a significant effect on the probability of translocation (**Table 2**).

Table 2. Related criteria and sub-criteria, on an example of Matrix of two-by-two weight comparison of criteria derived from the average weighing by experts, authors.

Numb	Criteria	Explicate
1	Spatial use	Permanent, temporary
2	The user of space	All habitant, children, adults, …
3	Spatial dimension	Space length, Space width, Space height
4	Depth of space	away from the original space, Main and secondary space
5	Spatial distance	The distance between center of space
6	Spatial community	Public transport, private transport, social activity…
7	Type of surface material	Antibacterial and antiviral materials, Using metals such as silver, brass, zinc, copper, Stones such as marble, travertine, turquoise, azure, etc. Not using steel, plastic, etc. brick, Stone, ceramic, Floor Covering, Parquet, Mosaic, Antibacterial and antiviral materials
8	Air quality	Natural ventilation, Fan, air conditioner, Ventilator
9	Space lighting	Direct sunlight, Direct Southern sunlight, Direct Eastern sunlight , Western front, Northern front
10	Space coloring	Red and dark on the floor, Red and dark on the wall
11	Vertical communication	Elevator, Residential and commercial complex
12	Construction technologies	Floor heating, air conditioning, Air curtain system, X virus, Automatic doors, Positive Air Pressure system
13	Crowding	Face to face, social distance,
14	circulation	Air flow, windows, handle and automatic door
15	Space temp	Natural sunlight, type of heating and cooling devices, air conditioning

Table 2 continued

Criteria		1 Spatial use	2 The user of space	3 Spatial dimension	4 Depth of space	5 Spatial distance	6 Spatial communication	7 Type of surface materials	8 Air quality	9 space lighting	10 Space coloring	11 Vertical communication	12 Construction technologies	13 Crowding	14 circulation	15 Space temp
1	Spatial use	1	1/3	1/3	1/3	1	1/5	3	1/5	3	7	3	1/3	1/5	1/3	1/3
2	The user of space	3	1	3	1/3	1	1/3	7	1/5	3	9	5	1	1/7	3	1/5
3	Spatial dimension	3	1/3	1	3	3	1/3	3	1/5	5	9	7	3	1/3	5	1/3
4	Depth of space	3	3	1/3	1	3	1/3	3	1/3	5	9	7	3	1/3	3	1/3
5	Spatial distance	1	1	1/3	1/3	1	1/3	3	3	3	7	5	3	1	1/3	1
6	Spatial communication	5	3	3	3	3	1	5	1	3	7	5	3	1	3	3
7	Type of surface material	1/3	1/7	1/3	1/3	1/3	1/5	1	1/5	1/3	3	1/3	1/5	1/7	1/5	1//3
8	Air quality	5	5	5	3	1/3	1	5	1	5	7	5	5	3	5	9
9	space lighting	1/3	1/3	1/5	1/5	1/3	1/3	3	1/5	1	3	3	1	1/5	1/3	3
10	Space coloring	1/7	1/9	1/9	1/9	1/7	1/7	1	1/7	1/3	1	1	1/3	1/5	1/3	1
11	Vertical communication	1/3	1/5	1/7	1/7	1/5	1/5	3	1/5	1/3	1	1	1/3	1/5	1/3	1/3
12	Construction technologies	3	1	1/3	1/3	1/3	1/3	5	1/5	1	3	3	1	1/3	3	3
13	Crowding	5	7	3	3	1	1	7	1/3	5	5	5	3	1	5	3
14	circulation	3	1/3	1/5	1/3	3	1/3	5	1/5	3	3	3	1/3	1/5	1	1
15	Space temp	3	5	3	3	1	1/3	3	1/9	1/3	1	3	1/3	1/3	1	1

Matrix of two-by-two weight comparison

Each space has its unique features such as length and width, height, depth of ambient and natural light, the amount of ventilation, the surface material, and most importantly, its use and the amount of its use the level and lifespan of the virus vary on different surfaces and colors. Natural light, fresh air, the material of the surfaces, each has different effects on the persistence of the virus and the possibility of its transmission. These cases may have been unimportant and unnecessary for people before. Today, most health recommendations consider one or more of these factors and how people deal with them. In general, these indicators can be presented and weighted at the same time using the series analysis method (**Table 2**).

Depending on their character, application, physical characteristics, such as the type of surfaces, the amount of equipment used, and the transition that takes place, spaces can prevent the transmission of the virus or increase its transmission rate exponentially. It is the shared living space that includes people, which has a huge impact on the behavior of the Infectious and respiratory pathogenic particles (virus), their durability, how it moves, and ultimately the possibility of transmitting to another person. The total score is calculated by MATLAB software by comparing the indicators with each other, which was previously determined by FGD. Therefore, the quantitative values of the impact and final score of the spatial indicators have been obtained according to the process mentioned in **Figure 4** in **Table 3**.

Given the fact from **Table 3**, based on the purpose, spatial ventilation is ranked first. The next is awarded to the spatial communication, crowding, spatial dimension, space temp, depth of space, the use of space, spatial distance and type of surface material, respectively.

The strength of this study is the use of the opinions of experts in different fields and its analysis by MATLAB software. By bringing this different expertise together, more effective solutions can be provided because each of them looks at the issue from their own point of view and the sum of these views is more than their individual opinions. One of the most important limitations of this article was the lack of statistical information, especially location-based statistics regarding the effective factors in the spread of infectious diseases in communal spaces.

Table 3. Ranking of criteria based on the effect on Infectious and respiratory pathogenic particle transmission, authors.

Importance	Criteria	Final score
1	Air quality	0.215
2	Spatial communication	0.154
3	Crowding	0.142
4	Spatial dimension	0.129
5	Space temp	0.112
6	Depth of space	0.111
7	The user of space	0.089
8	Spatial use	0.057
9	Spatial distance	0.042
10	Direct natural lighting	0
10	Space coloring	0
10	Vertical communication	0
10	Construction technologies	0
10	Circulation	0
10	Type of surface material	0

5. Conclusions

Nowadays, the issue of infectious diseases has become one of the principal problems in societies, in such a way that with every pandemic, many social activities in communal spaces face problems, and many people in these spaces get infected with those diseases. The World Health Organization (WHO) defines health as "a state of complete physical, mental and social well-being". This study tries to determine the indicators related to physical and social areas and examine the effect of each of them on preventing the spread of infectious diseases and as a result achieving a healthy building. The surrounding environment in communal spaces has many capacities, and the right decision about the use and changing them can help in the face of infectious diseases. In other words, different fields of knowledge have different views on environmental capacities, and taking advantage of the personal experiences of specialists in separate scientific fields can be an optimal way to deal with these conditions. The results of this research are based on the quantitative method and using both FGD and analytical network processes. In this study, spatial criteria extracted from the literature review were evaluated and finally, the most important ones were selected by experts, those who somehow had the experience of dealing with infectious diseases, including the coronavirus, in Hamadan city. According to this process, the degree of importance and significant difference of the results shows that the factor of air quality can have a very high effect. The "Air Quality" in communal spaces is the main criterion for the transmission of pathogenic respiratory particles (**Table 3**). This method can play an important role in finding the most effective factors in the environment of the public building by considering the effect of all criteria in the analytical network process. This process will play an effective role in making decisions and designing communal spaces that can deal with the spread of airborne particles of infectious diseases. According to the logical reasoning approach of this research, although the group of experts has determined and weighted the indicators based on their experiences in Hamadan city, the results of this study can be generalized to other cities as well. As a result, due to the high efficiency and relatively low costs of taking advantage of clean air, such as using natural air by leaving openings or filtration, it is possible to reduce the amount of transmission of diseases through airborne particles.

Authors Contributions

This research was done collaboratively by all the authors listed on the first page.

Conflict of Interest

There is no conflict of interest.

References

[1] Novel Coronavirus (2019-nCoV): Situation Report, 13 [Internet]. World Health Organization; 2020. Available from: https://apps.who.int/iris/handle/10665/330778

[2] Chan, J.F.W., Yuan, S., Kok, K.H., et al., 2020. A familial cluster of pneumonia associated with the 2019 novel coronavirus indicating person-to-person transmission: A study of a family cluster. The Lancet. 395(10223), 514-523. DOI: https://doi.org/10.1016/s0140-6736(20)30154-9

[3] Ijaz, M.K., Brunner, A.H., Sattar, S.A., et al., 1985. Survival characteristics of airborne human coronavirus 229E. Journal of General Virology. 66(12), 2743-2748.

[4] Ansari, S.A., Springthorpe, V.S., Sattar, S.A., et al., 1991. Potential role of hands in the spread of respiratory viral infections: Studies with human parainfluenza virus 3 and rhinovirus 14. Journal of Clinical Microbiology. 29(10), 2115-2119.

[5] Novel Coronavirus (2019-nCoV): Situation Report, 12 [Internet]. World Health Organization; 2020. Available from: https://apps.who.int/iris/handle/10665/330777

[6] Division of Oral Health—Infection Control Glossary [Internet]. U.S. Centers for Disease Control and Prevention [cited 2019 Apr 9]. Available from: https://www.cdc.gov/oralhealth/infectioncontrol/glossary.htm

[7] Zhao, L., Liu, J., 2020. Operating behavior and corresponding performance of mechanical ventilation systems in Chinese residential buildings. Building and Environment. 170, 106600.

[8] Miller, S.L., Nazaroff, W.W., Jimenez, J.L., et al., 2021. Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event. Indoor Air. 31(2), 314-323.

[9] Li, Y., Qian, H., Hang, J., et al., 2021. Probable airborne transmission of SARS-CoV-2 in a poorly ventilated restaurant. Building and Environment. 196, 107788.

[10] Lu, J., Gu, J., Li, K., et al., 2020. COVID-19 outbreak associated with air conditioning in restaurant, Guangzhou, China, 2020. Emerging Infectious Diseases. 26(7), 1628.

[11] Buonanno, G., Morawska, L., Stabile, L., 2020.

Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: Prospective and retrospective applications. Environment International. 145, 106112.
DOI: https://doi.org/10.1016/j.envint.2020.106112
[12] Luo, K., Lei, Z., Hai, Z., et al., 2020. Transmission of SARS-CoV-2 in public transportation vehicles: A case study in Hunan Province, China. Open Forum Infectious Diseases. 7(10), ofaa430.
[13] Park, S.Y., Kim, Y.M., Yi, S., et al., 2020. Coronavirus disease outbreak in call center, South Korea. Emerging Infectious Diseases. 26(8), 1666-1670.
[14] Shen, Y., Li, C., Dong, H., et al., 2020. Community outbreak investigation of SARS-CoV-2 transmission among bus riders in eastern China. JAMA Internal Medicine. 180(12), 1665-1671.
[15] Balachandar, S., Zaleski, S., Soldati, A., et al., 2020. Host-to-host airborne transmission as a multiphase flow problem for science-based social distance guidelines. International Journal of Multiphase Flow. 132, 103439.
DOI: https://doi.org/10.1016/j.ijmultiphaseflow.2020.103439
[16] Zhang, J., 2020. Integrating IAQ control strategies to reduce the risk of asymptomatic SARS CoV-2 infections in classrooms and open plan offices. Science and Technology for the Built Environment. 26(8), 1013-1018.
DOI: https://doi.org/10.1080/23744731.2020.1794499
[17] Morawska, L., Tang, J.W., Bahnfleth, W., et al., 2020. How can airborne transmission of COVID-19 indoors be minimised? Environment International. 142, 105832.
DOI: https://doi.org/10.1016/j.envint.2020.105832
[18] Dai, H., Zhao, B., 2020. Association of the infection probability of COVID-19 with ventilation rates in confined spaces. Building Simulation. 13, 1321-1327.
DOI: https://doi.org/10.1007/s12273-020-0703-5
[19] Coronavirus Disease (COVID-19), Ventilation and Air Conditioning [Internet]. WHO; 2021 [cited 2020 Dec 3]. Available from: https://www.who.int/news-room/q-a-detail/coronavirus-disease-covid-19-ventilation-and-air-conditioning
[20] Manufacturing Workers and Employers [Internet]. U.S. Centers for Disease Control and Prevention; 2020 [cited 2020 Dec 29]. Available from: https://search.bvsalud.org/global-literature-on-novel-coronavirus-2019-ncov/resource/en/grc-739919
[21] Operating Schools during COVID-19: CDC's Considerations [Internet]. U.S. Centers for Disease Control and Prevention; 2020 [cited 2020 Dec 23]. Available from: https://stacks.cdc.gov/view/cdc/92308
[22] Filtration/Disinfection [Internet]. ASHRAE, 2020 [cited 2020 Sep 5]. Available from: https://www.ashrae.org/technical-resources/filtration-disinfection
[23] Wells, W.F., 1955. Airborne contagion and air hygiene: An ecological study of droplet infections. JAMA. 159(1), 90.
[24] Riley, E.C., Murphy, G., Riley, R.L., 1978. Airborne spread of measles in a suburban elementary school. American Journal of Epidemiology. 107(5), 421-432.
[25] Chin, A.W.H., Chu, J.T.S., Perera, M.R.A., et al., 2020. Stability of SARS-CoV-2 in different environmental conditions. The Lancet. 1(1).
DOI: https://doi.org/10.1016/S2666-5247(20)30003-3
[26] Global Tuberculosis Control: Surveillance, Planning, Financing [Internet]. World Health Organization; 2004. Available from: https://www.who.int/publications/i/item/9789241563141
[27] Suman, R., Javaid, M., Haleem, A., et al., 2020. Sustainability of coronavirus on different surfaces. Journal of Clinical and Experimental Hepatology. 10(4), 386-390.
[28] Wells, W.F., 1934. On air-borne infection. Study II. Droplets and droplet nuclei. American Journal of Hygiene. 20, 611-18.
[29] Well Rating System 5 Minute Guide [Internet]. Green Material Library; 2021[cited 2023 Apr 20]. Available from: https://ongreening.com/well-rating-system-5-minute-guide/
[30] Infection Prevention and Control during Health Care When Novel Coronavirus (nCoV) Infection

is Suspected [Internet]. WHO; 2020. Available from: https://www.who.int/publications/i/item/10665-331495

[31] Otter, J.A., Donskey, C., Yezli, S., et al., 2016. Transmission of SARS and MERS coronaviruses and influenza virus in healthcare settings: The possible role of dry surface contamination. Journal of Hospital Infection. 92(3), 235-250.

[32] Awada, M., Becerik-Gerber, B., Hoque, S., et al., 2021. Ten questions concerning occupant health in buildings during normal operations and extreme events including the COVID-19 pandemic. Building and Environment. 188, 107480.

[33] McPherson, S., Reese, C., Wendler, M.C., 2018. Methodology update: Delphi studies. Nursing Research. 67(5), 404-410. DOI: https://doi.org/10.1097/NNR.0000000000000297

[34] Research Tools: Focus Group Discussion [Internet]. ODI Global Advisory; 2009 [cited 2023 Apr 20]. Available from: https://odi.org/en/publications/research-tools-focus-group-discussion/

[35] Ansari, M., Bemanian, M.R., Mahdavi, N.M., et al., 2011. Locating natural tourism sites based on the principles of landscape architecture (combined application of FGD focus group discussion and AHP hierarchical analysis process). Urban Management. 10(29), 7-22.

[36] Mohammad, T., 2021. Corona Took the Lives of 13 Other People in Hamadan Province, IRNA, Islamic Republic of Iran News Agency, Hamadan province, May 4, 2021 [Internet]. Available from: www.irna.ir/news/84315820/

[37] Behzadian, M., Kazemzadeh, R.B., Albadvi, A., et al., 2010. PROMETHEE: A comprehensive literature review on methodologies and applications. European Journal of Operational Research. 200(1), 198-215.

[38] Wilkinson, S., 2015. Focus groups. Qualitative psychology: A practical guide to research methods. Sage: London.

BILINGUAL PUBLISHING GROUP

Journal of Architectural Environment & Structural Engineering Research

https://journals.bilpubgroup.com/index.php/jaeser

ARTICLE

Survival Analysis Using Cox Proportional Hazards Regression for Pile Bridge Piles Under Wet Service Conditions

Naiyi Li [*], ***Kuang-Yuan Hou, Yunchao Ye, Chung C. Fu***

The Bridge Engineering Software & Technology Center, Civil & Environmental Engineering, University of Maryland, College Park, Maryland, 20742, United States

ABSTRACT

This paper studies the deterioration of bridge substructures utilizing the Long-Term Bridge Performance (LTBP) Program InfoBridge™ and develops a survival model using Cox proportional hazards regression. The survival analysis is based on the National Bridge Inventory (NBI) dataset. The study calculates the survival rate of reinforced and prestressed concrete piles on bridges under marine conditions over a 29-year span (from 1992 to 2020). The state of Maryland is the primary focus of this study, with data from three neighboring regions, the District of Columbia, Virginia, and Delaware to expand the sample size. The data obtained from the National Bridge Inventory are condensed and filtered to acquire the most relevant information for model development. The Cox proportional hazards regression is applied to the condensed NBI data with six parameters: Age, ADT, ADTT, number of spans, span length, and structural length. Two survival models are generated for the bridge substructures: Reinforced and prestressed concrete piles in Maryland and reinforced and prestressed concrete piles in wet service conditions in the District of Columbia, Maryland, Delaware, and Virginia. Results from the Cox proportional hazards regression are used to construct Markov chains to demonstrate the sequence of the deterioration of bridge substructures. The Markov chains can be used as a tool to assist in the prediction and decision-making for repair, rehabilitation, and replacement of bridge piles. Based on the numerical model, the Pile Assessment Matrix Program (PAM) is developed to facilitate the assessment and maintenance of current bridge structures. The program integrates the NBI database with the inspection and research reports from various states' department of transportation, to serve as a tool for condition state simulation based on maintenance or rehabilitation strategies.

Keywords: Survival analysis of bridge structures; Cox proportional hazards regression; Bridge rehabilitation and maintenance; Bridge substructure protection; National bridge inventory; Simulation of bridge substructure condition state

*CORRESPONDING AUTHOR:

Naiyi Li, The Bridge Engineering Software & Technology Center, Civil & Environmental Engineering, University of Maryland, College Park, Maryland, 20742, United States; Email: henry1412af@gmail.com

ARTICLE INFO

Received: 1 May 2023 | Revision: 19 May 2023 | Accepted: 28 May 2023 | Published Online: 30 May 2023

DOI: https://doi.org/10.30564/jaeser.v6i2.5690

CITATION

Li, N.Y., Hou, K.Y., Ye, Y.Ch., et al., 2023. Survival Analysis Using Cox Proportional Hazards Regression for Pile Bridge Piles Under Wet Service Conditions. Journal of Architectural Environment & Structural Engineering Research. 6(2): 45-58. DOI: https://doi.org/10.30564/jaeser.v6i2.5690

COPYRIGHT

Copyright © 2023 by the author(s). Published by Bilingual Publishing Group. This is an open access article under the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License. (https://creativecommons.org/licenses/by-nc/4.0/).

1. Introduction

Deterioration of bridge structures plays an essential role in maintaining the functionality of transportation networks as aging infrastructure becomes more prevalent nowadays. Bridges are unique because there are few substitutions to them when a failure occurs. Hence, any obstruction during a bridge's operational life will create major losses. Due to the complexity of bridge deterioration, prediction models derived using analytical methods struggle to provide accurate predictions of the deterioration process. Since large-scale datasets became available, engineers can perform statistical analysis with the aid of evolving computational power. In addition, deterministic models are gradually being replaced by probabilistic approaches, which account for uncertainties. Hence, a probabilistic-based model is preferred over a deterministic model in the prediction of a bridge condition rating.

Bridges under wet service conditions generally deteriorate faster than those on land. In a wet environment, the piles are the most vulnerable components of a bridge. Yet it is a critical part of the bridge integrity, especially in terms of seismic resistance [1-3]. Michael and Sagues concluded that in marine environments, bridge piles are highly susceptible to server localized corrosion [4]. The condition rating of a bridge can be considered as individual incidents throughout the lifespan of the bridge, and the defects in structural integrity can be viewed as hazards [5]. The Cox proportional hazards regression is widely used in clinical trials that describe the survival rate, hazard rate, and cumulative survival function [6]. In bridge studies, the survival function outlines the deterioration of bridges or bridge components over the lifespan of the structure [5]. Missing data in bridge inventory records can also be accounted for by survival models [7,8]. The deterioration of bridge structures can be modeled as a Markov process with discrete time, with the stochastic characteristic of bridge deterioration maintained [9,10]. The transition probability is key to the Markov chain. In bridge maintenance, the transition probability is the probability of a bridge component, will transition into the next condition rating. It is calculated by dividing the total number of bridge components in a particular condition state in the year prior by the number of bridge components in the same condition state in the current year [11].

Using modern computers and advanced programs, large-scale statistical analysis can investigate the deterioration trend of bridge structures with customized parameters deemed relevant by the user. Such an approach allows researchers to acquire probabilistic models for both a large area and a specific region [12]. The parameters can also be adjusted to reflect critical factors that may not be predominant in a larger-scale model.

The scope of this research is to study the deterioration of bridge substructures using the Long-Term Bridge Performance (LTBP) Program InfoBridge™ [13], and bridges with reinforced or prestressed concrete (RC/PC) columns/piles are chosen. The dataset is obtained from the National Bridge Inventory (NBI) [14] for bridge information from 1992 to 2020. This study primarily focuses on the bridges in the state of Maryland, with three additional northeast regions also included to facilitate the survival analysis, particularly for bridges in wet service conditions. The NBI dataset was condensed to only include items considered to be reverent to the deterioration model. The Cox proportional hazards regression was selected as the statistical tool to develop the survival model that reflects the deterioration of bridge piles. Results of the survival analysis are used to construct two Markov chains for visualization and prediction of pile deterioration.

The stakeholders of bridge structures rely on a robust and comprehensive bridge management system to secure the serviceability and longevity of the bridges [15]. However, there is a lack of existing studies in developing a tool for the assessment and prediction of bridge piles under wet service conditions. Robert et al. discovered that prestressed concrete piles deteriorate in marine environments as the jackets deteriorate, exposing prestressing strands and tie reinforcement that exhibit heavy corrosion due to high levels of chloride [16]. The challenge of monitoring pile deterioration is that the process is gradual and continuous throughout the lifespan of the structure. When deterioration becomes visible, the piles are severely compromised. Moreover, major corrosion can be hidden by jackets designed to protect the piles, and the deterioration of jackets can also boost the corrosion of the reinforcing steel. Therefore, there is a need for an automatic, robust, and reliable tool for assessing the integrity of piles. The tool needs to be easily implemented and user-friendly and can be applied to different regions as the service condition of the bridge structures dramatically affects the deterioration of piles.

A total of 979 bridges in the state of Maryland were chosen to be the primary focus of this study, complemented by bridges in the state of New York, North Carolina, Virginia, Delaware, and the District of Washington to expand the sample size. The goal of the study is to perform a survival analysis of bridge piles under wet service conditions and develop a pile assessment tool for simulating future pile conditions based on maintenance and rehabilitation strategies. Users can easily implement the computer program to assist in decision-making.

2. Materials and methods

2.1 Cox proportional hazards regression model

The deterioration of bridge substructures is controlled by various factors, such as geological location, usage, soil, and service condition [5]. The deterioration of bridge substructures is similar to that of clinical trial studies. In clinical trial studies, a certain outcome, for instance, death, is associated with various parameters in the treatment. The Cox proportional hazards regression model [6] is one of the most popular regression techniques in survival analysis. The model calculates the hazard rate given the subject has survived for a certain amount of time. The Cox proportional hazards regression is based upon three fundamental assumptions:

1) The survival times between each distinct individual are independent.

2) The predictors and the hazards share a multiplicative relationship.

3) The hazard ratio is constant over time.

The general expression of the Cox proportional hazards regression can be written as:

$$h(t) = h_0(t)\exp(b_1X_1 + b_2X_2 ++ b_pX_p) \quad (1)$$

where h(t) represents the hazard at time t, and X is the predictor and independent variable that affects the hazard rate over time t. $h_0(t)$ is the baseline hazard when all the parameters are equal to zero. The relevance of the predictors is quantified by the regression coefficients, b.

The hazard ratio relates the hazard ratio at time t and the individual item X and can be written as:

$$HR(X_i) = \frac{h(X_i,t)}{h_0(t)} = \exp[\sum_{i=1}^{p} X_{ij}b_j] \quad (2)$$

The Cox proportional hazards regression model is semi-parametric, meaning that the shape of the baseline hazard function is not assumed. The hazard ratio of the Cox proportional regression model provides a clear sign of the association between the predictor variable and the hazard rate. The hazard ratio of a variable can be calculated as $\exp(b_i)$, and the interpretation can be summarized below:

1) If hazard ratio > 1, increase in hazard.

2) If hazard ratio < 1, decrease in hazard.

3) If hazard ratio = 1, no effect on hazard.

Since the hazard rate is related to the survival rate, the survival rate at time t can be derived as:

$$S_{xi}(t) = S_0(t)^{HR(X_i)} \quad (3)$$

To complete the regression, the cumulative hazard function is calculated as:

$$H(t,X) = \int_0^t h(t,X)dt = e^{(Xb)}\int_0^t h_0(t)dt = e^{(Xb)}H_0(t) \quad (4)$$

Thus, the cumulative survival function can be calculated as follows [8]:

$$S(t,X) = e^{-H(t,X)} = e^{-e(Xb)H_0(t)} = [e^{-H_0(t)}]^{e(Xb)} = [S_0(t)]^{e(Xb)} \quad (5)$$

The cumulative survival function can be used to calculate the transition probability to construct a Markov chain. The Markov chain defined in this study has a time interval of one year [5]. Hence, the transition probabilities describe the probabilities of a bridge substructure remaining in one condition for a year, as shown by Mishalani and Madanat [11]. The transition probabilities are calculated as:

$$P_{kk}(t, X) = \frac{S_k(t+\Delta t,X)}{S_k(t,X)} = \frac{S_k(t+1,X)}{S_k(t,X)} \quad (6)$$

where Δt = 1 year.

The transition probabilities between substructure condition states can be modeled using a Markov chain [9,10]. It is assumed that the deterioration of the bridge substructure only goes in one direction: from a better state to a worse state. The process is irreversible without repair or rehabilitation. Once the bridge substructure rating reaches the failure state, it will remain in the failure state. The Markov chain uses the NBE condition state format, with an artificial condition state CS5 added solely for mathematical reasons. The Markov chain adopted in this research is illustrated in **Figure 1**.

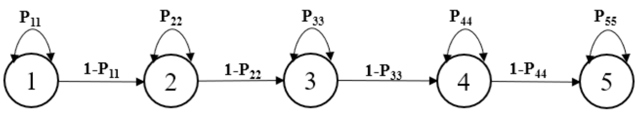


Figure 1. Markov chain for deterioration of bridge substructures.

2.2 Survival analysis of bridge structures

The general approach of this study adopts the mythology presented by the research report published by Goyal et al. [1]. Using LTBP Infobridge™ [13]. bridges with RC/PC columns/piles are selected. Then, two survival analyses were performed based on the filtered data from New York, North Carolina, Maryland, and Virginia. The first analysis focuses on 979 bridges in the state of Maryland. All 979 bridges are constructed with RC/PC columns/piles. The number of Maryland's bridges with prestressed concrete piles in wet service conditions is relatively small to represent the entire population. Hence, additional states (NY, NC, and VA) in the northeast are included to facilitate the second survival analysis where the hollow prestressed concrete pile is adopted in wet service conditions.

The NBI dataset provides bridge information for all states starting from 1992, which makes it the most comprehensive dataset on LTBP Infobridge™ [13]. Meanwhile, the National Bridge Element (NBE) [14] is a great complementary tool to the NBI dataset, as NBE offers detailed information on specific bridge elements. Items in the NBE dataset represent the condition of the primary structural component of a bridge and can be used as indicators in the assessment of the overall condition rating of the structure. However, unlike the NBI dataset, some bridges' NBE datasets are not provided in the LTBP Infobridge™ database. In Maryland, only 1,972 bridges have NBE data among all 5,430 bridges. In this study, the NBE dataset is used as a filter to identify bridges that meet the criteria of this research. The locate the bridges with reinforced or prestressed columns/piles and bridges with RC/PC columns/piles in wet service condition, the following NBE items are used in **Table 1**.

Table 1. National bridge element items.

Item number	Description
204	Prestressed Concrete Column
205	Reinforced Concrete Column
226	Prestressed Concrete Pile
227	Reinforced Concrete Pile

In the NBI dataset, item 92B (underwater inspection) is used to select bridges that are under wet service conditions, including lakes, rivers, bay areas, and oceans. The items listed in **Table 2** are processed and converted into parameters that serve as predictors for the Cox proportional hazards regression. Among them, item 60 (substructure condition) is the target output of the model. Hence, the purpose of the regression is to study the association of the variables with the substructure condition. Then, the condensed NBI data was processed to prepare the parameters for the Cox proportional hazards regression.

Table 2. Nation bridge inventory items for Cox proportional hazards regression.

NBI item number	Description
27	Year built (age of the bridge)
29	Average daily traffic
45	Number of spans in main unit
46	Number of approach spans
48	Length of maximum span
49	Structure length
109	Average daily truck traffic (%)

Per MDOT State Highway Administration, the NBI substructure condition rating is converted into the NBE condition state format before processing Cox proportional hazards regression, with one additional condition state (CS5: failure) added. The added condition state is only necessary for mathematical reasons in the Markov chain developed in the latter section. The conversion follows the instruction of the MDOT State Highway Administration and is displayed in **Table 3**. The NBI condition ratings are based on the recording and coding guide by the Federal Highway Administration [17]. When a bridge is in condition rating 9 to 8, there is no defect. In ratings 7 to 6, minor defects become visible. At 5, the main structural components are in good condition while they may exhibit slight deterioration in certain areas, such as section loss, cracks, and scour. Starting from rating 4 the bridge shows advanced section loss and deterioration and will quickly enter critical conditions. In practice, bridges reaching a condition rating of 4 or below demand immediate attention and rehabilitation effort.

Table 3. Nation bridge element items.

NBI condition rating	NBE condition rating
9-8	CS1
7-6	CS2
5	CS3
4 or less	CS4
failure	CS5 (failure)

With the condensed NBI dataset established, a series of scripts were created in MATLAB to perform the Cox proportional hazards regression. The MATLAB scripts are streamlined: First, import bridge data from 1992 to 2020; next, select bridges that meet the research criteria using structural number/ID; then, perform data cleaning and prepare the NBI data for regression; finally, perform Cox proportional hazards regression to obtain cumulative survival function, calculate transition probability and construct the Markov chain. An example of the condensed data in MATLAB is shown in Appendix A for bridge number 100000210108014.

To prepare the data for regression, censoring information, and data normalization need to be included. Censoring is crucial for acquiring an accurate model since it is not always possible when the event is completely observed. In this study, a bridge may exhibit substructure condition state 7 in the year 1992. There is no definitive information of when did this bridge reach substructure condition state 7, and for exactly how long has the bridge been in that condition state, since the NBI record starts in the year 1992. Because of the reconstruction or repair of the bridge, the natural deterioration process is interrupted. Hence, substructure condition state 7 for this bridge is censored. While only the fully observed substructure condition states remain effective, data normalization is required to limit the bias of predictor variables in terms of their impact on the event of interest. For instance, the value of average daily traffic usually contains a larger number compared to that of the age of the structure; the value of span length is also considerably greater than that of the number of spans. Parameters with large fluctuations will also introduce bias without proper treatment. The regression may be biased without balancing and normalizing these parameters. Hence, the parameters are normalized into a standard 1 to 10 scale before being processed by the Cox proportional hazards regression model.

3. Results

3.1 Results of survival analysis of Maryland bridges with RC/PC columns and piles

Two survival analyzes were performed using the Cox proportional hazards model. The first case generates the cumulative survival function for 979 bridges in Maryland with RC/PC columns and piles. The second case calculates the cumulative survival function for the same type of bridges in wet service conditions in New York, Maryland, Virginia, and North Carolina. The following data visualizations are based on results for Maryland bridges. **Figure 2** shows the occurrence of each rating of the substructure condition.

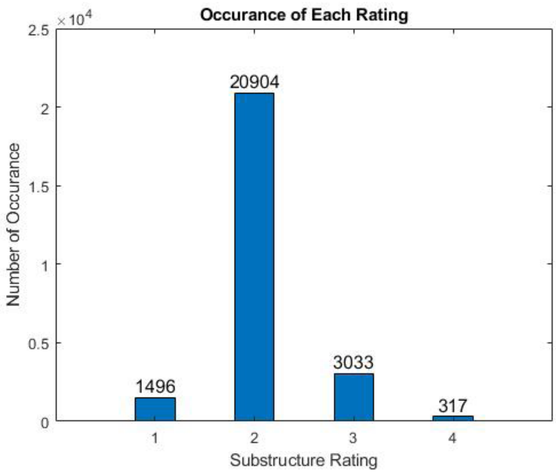


Figure 2. Occurrence of each substructure condition rating.

Based on the graphs above, most of the bridges in Maryland stay in substructure condition rating CS2 (20904), while CS4 has the least occurrence (317) over the past 29 years. The NBI dataset was fitted by the Cox proportional regression, and four cumulative survival functions are generated. The cumulative survival function reflects the probability of the bridge substructure staying in a specific condition rating each year. Likewise, it can also be interpreted as the percentage of bridge substructures remaining in a condition state at a year. At CS1, the deterioration rate of the substructure is considerably faster as the cumulative survival function displays a faster drop. This observation shows that a new bridge exhibits an accelerated deterioration rate when the substructure is still in the best condition ratings. The substructure condition ratings of bridges constructed with reinforced or prestressed concrete columns/piles stabilize in CS2 and CS3. A bridge structure will spend most of its service life in these two condition states, where the deterioration of the substructure remains steady. Conversely, the deterioration rate accelerates rapidly in CS4. Under substructure condition rating CS4, the substructure is considered in "poor" condition. As deterioration accumulates over the life span, the substructure experiences an increased rate of drop in structural integrity, as shown by the steeper slope and sudden drop in the cumulative survival function. Overall, the substructure condition rating exhibits an accelerated deterioration rate in CS1 and CS4 and stabilizes during CS2 and CS3. cumulative survival function of the bridges over 29 years are plotted in **Figure 3**.

The hazard ratio of each predictor variable was calculated and shown in **Table 4**. The hazard ratios give a direct indication of the association between the predictor variables and the substructure condition rating. If the hazard ratio is greater than one, that

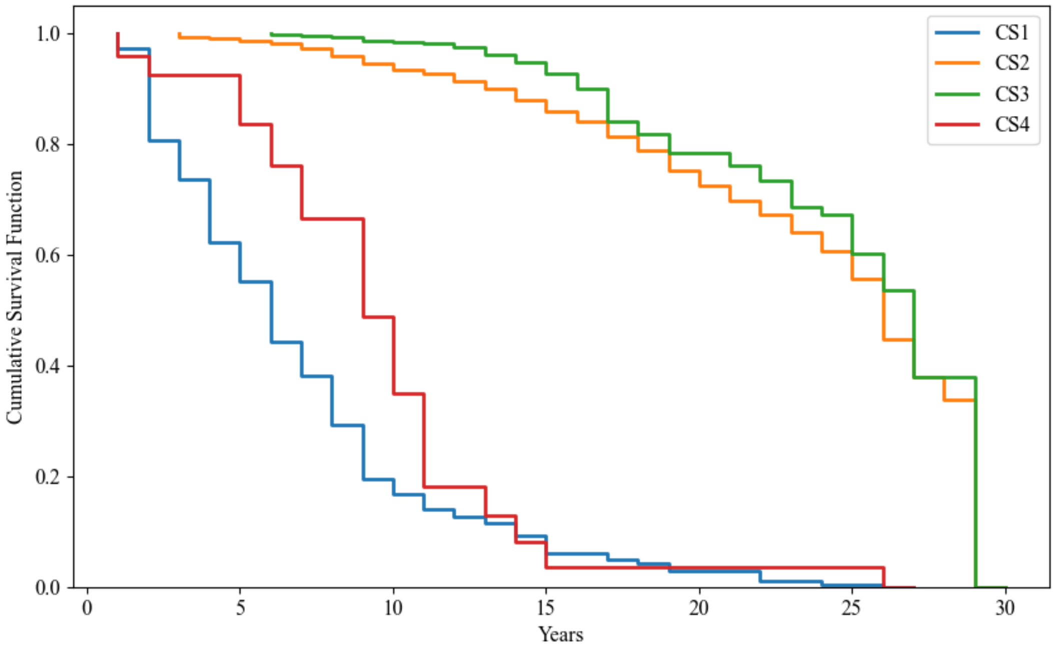


Figure 3. Cumulative survival function for Maryland bridge.

translates to an increase in hazard; when the hazard ratio is smaller than one, it shows a reduction in hazard. The value of the hazard ratio reflects the increase in hazard when the predictor variable increases by one unit, and vice versa. Note that for bridges under wet service conditions, the dataset does not distinguish seawater and freshwater because this classification is not available in the National Bridge Inventory data portal. Hence, results for bridges in wet service conditions are based on the general condition where the bridge is water-crossing. For instance, if the age of the bridge increase by one unit, there is an increase of 2.5% in hazard at CS1. The hazard ratios contradict the four condition states. At CS1, an increase in age, ADT, number of spans, and ADTT results in an increase in hazard, while longer maximum length and structure length result in a hazard reduction. At CS2, the structure length is the only variable that offers a hazard reduction, and the reduction is greater than that in CS1. At CS3, the maximum span length becomes the only variable with a hazard ratio smaller than one, however, it has almost no effect on the deterioration rate. At CS4, the number of spans and ADTT are identified as the only two variables with a hazard ratio greater than one, while others are smaller than one.

Table 4. Hazard ratios of predictor variables for Maryland bridge.

Parameter	CS1	CS2	CS3	CS4
Age	1.025689	1.06883	1.075101	0.811192
ADT	1.030079	0.913986	1.053165	0.643571
Number of spans	1.168937	1.318656	1.158964	1.785335
Max span length	0.980824	1.357925	0.284489	0.975701
Structure length	0.843096	0.609547	1.41E-06	0.739896
ADTT	1.036217	1.04808	0.930124	1.832976

The transition probability is calculated based on the cumulative survival function according to Equation (6). Under the NBE condition status rating, the Markov chain was developed to account for the transition from CS1 to CS5, with CS5 being an artificial condition state solely for mathematical purposes. The Markov chain for Maryland bridges is shown in **Figure 4**. Based on the results, there is a 77.7% of chance that a Maryland bridge will remain in CS1 for a year and a 22.3% of chance to transition into CS2. Then, it has a 96% of chance staying in CS2 and a 4% of chance deteriorating into CS3. Next, the bridge has a 95.7% of chance remaining in CS3 for another year, and a 4.3% of chance degrading into CS4. Finally, at CS4, the structure has a 76.1% of chance remaining in CS4 and a 23.9% of chance of failure. Once the structure reaches failure (CS5), it cannot transition into any other condition state. The Markov chain also reflects the same trend observed in the cumulative survival functions: the deterioration rate accelerates at CS1 and CS4 but stabilizes at CS2 and CS3.

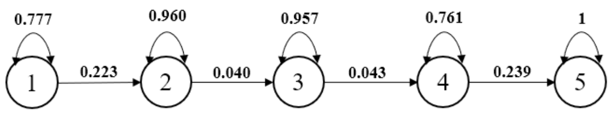


Figure 4. Markov chain for Maryland bridge.

3.2 Results of survival analysis of bridge structures with pre-stressed piles/columns

The survival analysis based on bridges constructed with pre-stressed piles/columns was carried out similarly. To obtain an adequate amount of bridge structures within regions where water-induced deterioration may be an issue, the sample comprises 330 bridges from New York, Virginia, Maryland, and North Carolina. The results are shown in **Figures 5 and 6**.

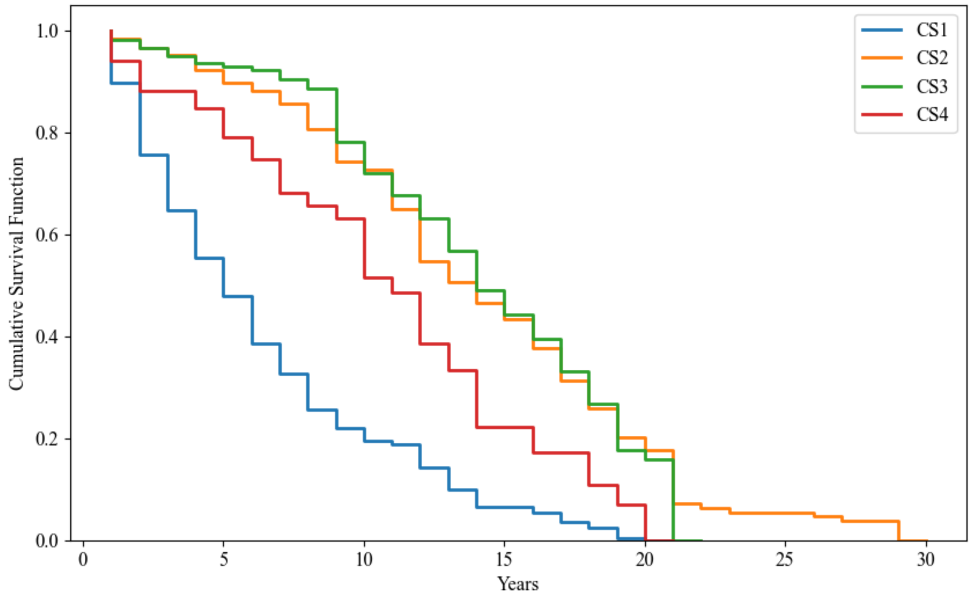


Figure 5. Cumulative survival function for bridge with pre-stressed piles/columns.

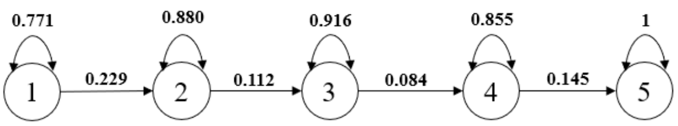


Figure 6. Markov chain for bridges with pre-stressed piles/columns.

3.3 Pile assessment matrix program (PAM)

Overview

To facilitate the simulation of bridge piles based on rehabilitation and maintenance strategies, the Pile Assessment Matrix Program (PAM) was developed to offer users an accessible tool to model the condition rating of piles in the future to assist in decision-making. PAM is constructed to incorporate the NBI database with research reports for state DOTs, forming a framework for pile condition rating simulation. To ease accessibility, the program is developed using Visual Basic for Applications so the users can simply operate the program in MS Excel. The workflow of PAM is presented in **Figure 7**.

The current version of PAM has integrated the NBI dataset of Maryland up to the year 2020, with the corresponding survival rates generated based on the same dataset. Hence, the numerical model is region-specific. As the NBI dataset gets updated each year, users can easily update the program database by adding the latest dataset to the program. There are two options regarding the preset for survival rates of bridge piles: One based on the reinforced/prestressed concrete bridges and the other based on the prestressed concrete bridges with hollow cross sections. The user can choose the appropriate option based on the bridge inventory being managed. In addition, the user is free to enter their survival rates carried out from other studies. Though the program is primarily a simulation tool for forecasting pile condition ratings, it also serves as a condensed database for the bridge inventory system. The user can access the bridge's age, length, longest span length, number of spans, number of approach spans, annual average daily traffic, and the total number of piles of a bridge by entering the structure ID. The general steps for using PAM can be summarized in **Figure 8**.

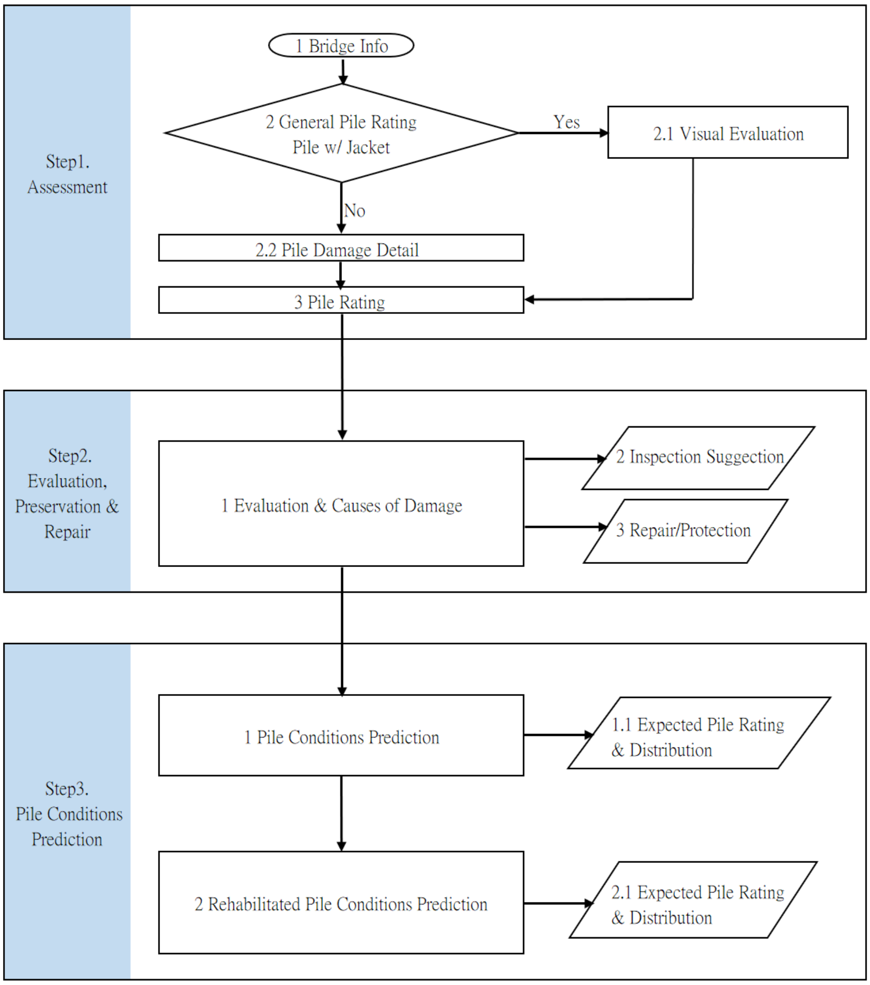


Figure 7. Flowchart of workflow in PAM.

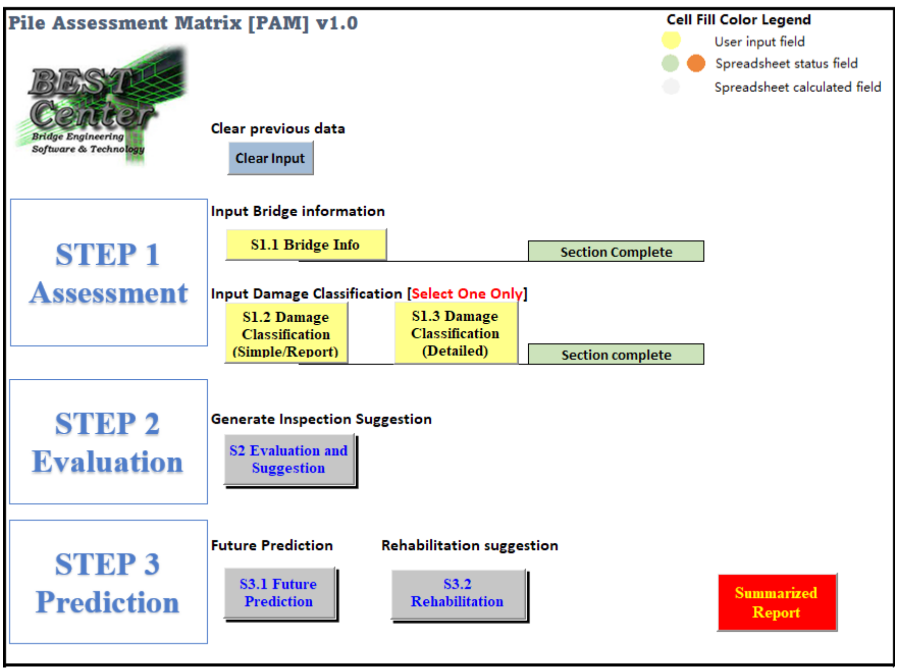


Figure 8. General steps in PAM.

Assessment of pile condition using PAM

Users can enter information regarding the current condition of the bridge pile based on inspection reports. There are two options for describing the pile conditions. The simplified method has the user entering the number of piles in each condition state, and the detailed approach enables more data entries on the pile conditions, including the overall condition of the bents and deterioration of specific categories.

Evaluation and recommendation

Based on the pile conditions, PAM can offer recommendations on potential location and cause of pile damage. These suggestions are based on various reports from DOTs across the U.S. **Table 5** and **Figure 9** show the reference guide for the potential cause of damages. Suggestions on the following inspection are also generated to focus on vulnerable components that may require immediate attention for repair.

Prediction of pile condition

The key functionality of PAM is to simulate the pile condition ratings based on the initial pile condition and maintenance strategies. The transition probabilities between condition ratings are calculated during the survival analysis. But the user has the freedom to specify the transition probabilities manually to suit the specific use case. As shown in **Figure 10**, PAM will estimate the percentage of piles in each condition rating and calculate the future values based on the specified time interval. The expected ratings are also listed for reference. A series of pie charts will be generated at the end of the simulation to visualize the change in pile conditions over time (shown in **Figure 11**). Likewise, simulation of the pile conditions also allows inputs regarding rehabilitation. The transition probability will adjust based on the rehabilitation implemented. **Figure 12** shows a summary report of a simulation.

Table 5. Common deteriorations.

Symptoms	Damage	Cause
Cracking w/rusted stains	Loss and exposed material	Corrosion of reinforcing steel
Longitudinal cracking above water level	Loss of material & exposure in splash and tidal zone	Freeze/Thaw
Softening of concrete	Loss and exposed material	Sulfate attack
Cracking	Loss and exposed material	Chemical reaction of aggregates with water
Hairline cracking and spall at the top of the pile	Loss and exposed material	Overloaded structure
Hairline circumferential cracks	Loss and exposed material	Overloaded structure
Exposed foundations	Loss of foundation soil & exposed footing	Erosion due to bridge scour or major flooding
Localized major cracking	Exposed material, impact damage, large section loss	Abnormal events (earthquakes, ship collisions, etc.)

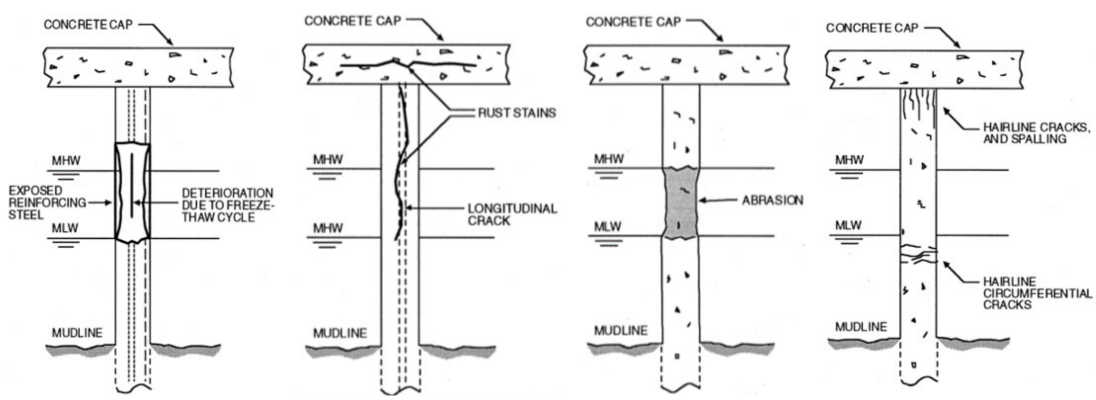


Figure 9. The common cause of damage.

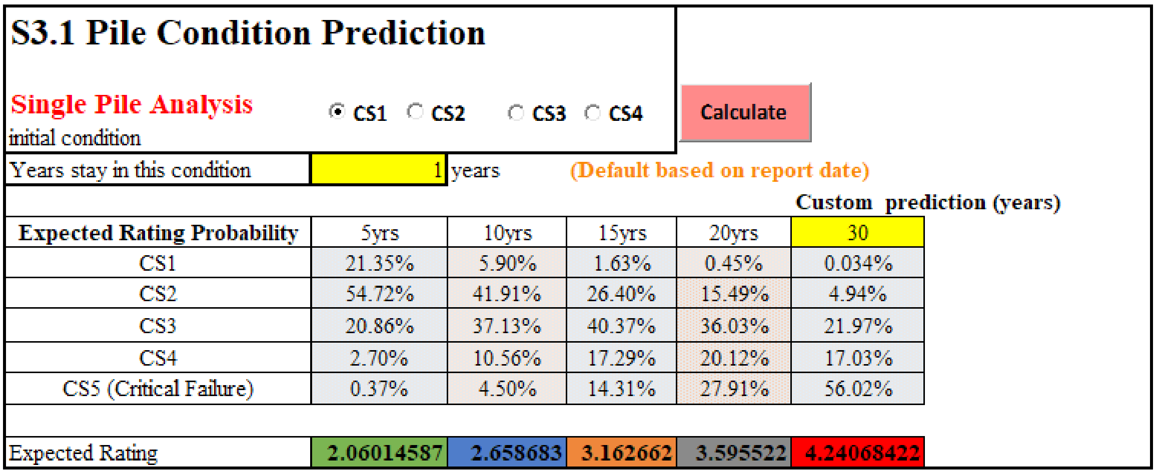


Figure 10. Estimated percentage of pile ratings.

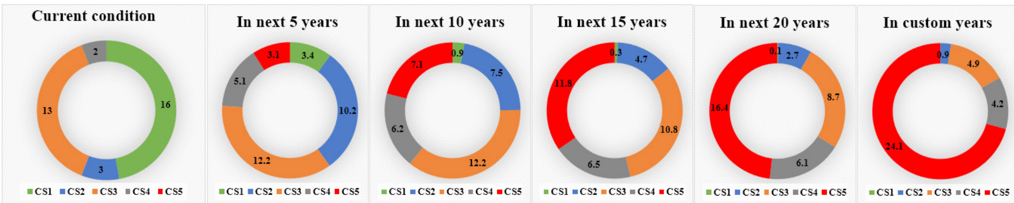


Figure 11. Change of pile ratings over time.

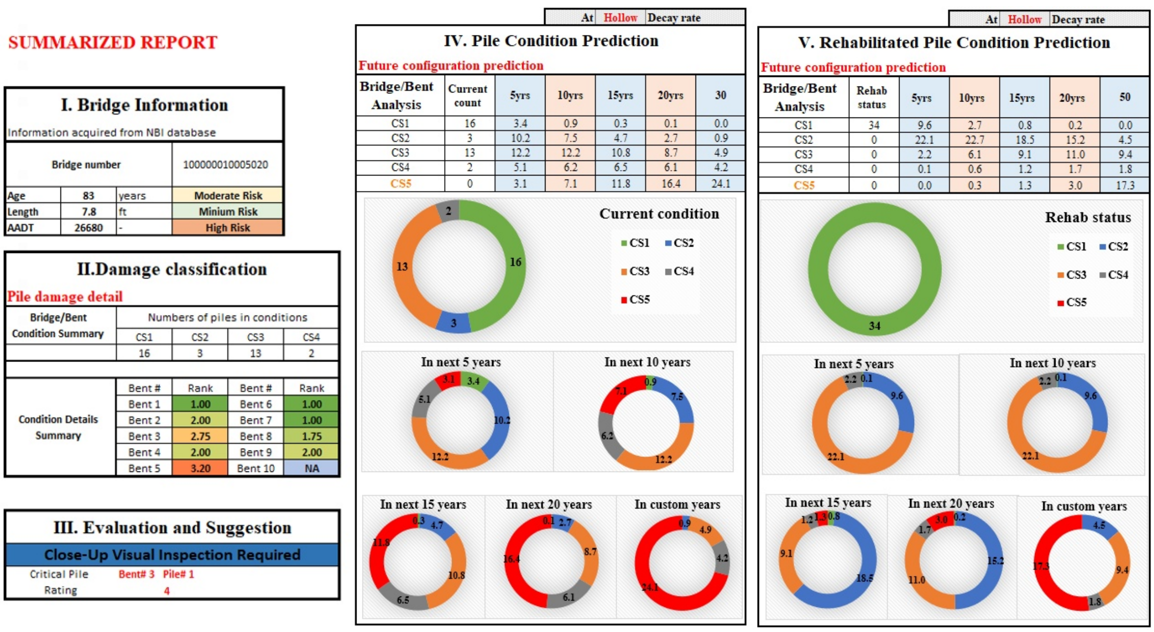


Figure 12. Summary report on pile condition simulation.

4. Discussion

Survival analysis carried out by the Cox proportional hazards regression model offers flexibility for users to generate various models based on specific criteria. The choice of predictor variables can be defined based on the project, and the dataset can also be chosen to reflect the structural deterioration in a certain region. For this study, there are six predictor variables included in the regression. The collection of predictor variables can always be expanded as deemed necessary. Whereas a larger number of predictor variables does not guarantee improvement in the accuracy as irrelevant data may introduce noise into the sample. Hence, further statistical analysis can be performed to identify any predictor variables that are not important. Results in this study might be improved by performing an in-depth analysis of the statistical correlation of the predictor variables and identifying the best subset for the algorithm.

The deterioration rate of newly built bridges with substructure condition state CS1 is faster than expected. One potential explanation is not all bridges are built with encapsulation of the columns or piles. In certain situations, pile jackets are installed after repair, or substantial damage has been found on the substructures. This effect can be observed with bridges in wet service conditions when a 68.3% probability is calculated compared to 77.7% of the general case. Bridges in wet service conditions are more susceptible to damage such as corrosion, spalling, and chloride contamination.

5. Conclusions

Two survival analyses were accomplished using the NBI, NBE dataset, and the Cox proportional hazards regression model. Two sets of cumulative survival functions were plotted to reflect the deterioration process of bridges constructed with reinforced RC/PC columns/piles. The associated Markov chains were developed based on the transition probabilities calculated from the cumulative survival function. The Markov chains are used as a probabilistic basis for a separate program forecasting the bridge substructure condition states. The key findings of this research are summarized below:

1) The deterioration of bridge substructures with RC/PC columns/piles can be modeled using Cox proportional hazards regression. The condition states of the bridge piles are treated as individual incidents, similar to those in medical trials.

2) The choice of predictor parameters affects the results. Though the NBI database offers a wide range of bridge parameters, only a portion of them is significant concerning the efficiency and accuracy of the survival analysis. When selecting the predictor variables, only the most relevant parameters are included, based on the specific subject on which the survival analysis is performed. For instance, the direction of traffic may not be important when calculating the survival rate of the piles.

3) The deterioration rates of bridge substructures with reinforced or prestressed columns/piles are fastest during the best or worst condition states (CS1 and CS4) but stabilize in the intermediate condition states (CS2 and CS3). That is, when the piles are in pristine condition, they tend to deteriorate faster as the material is settling into the surrounding environment and numerous chemical reactions are initiated. As the fresh materials interact with the environment, the deterioration starts to slow down, and the outer portion of the piles will start to show visible cracks without major damage. At last, deterioration of the piles accelerates again when they are in the worst condition state because at this point most of the protections have been consumed and the structure is severely exposed to the surrounding environment, promoting faster reactions between the materials and moisture contents.

4) In wet service conditions, bridge substructures experience an accelerated deterioration rate. This is mostly caused by chloride-induced reactions between the piles and water.

5) The Pile Assessment Matrix (PAM) is a computer program designed to facilitate the assessment and simulation of bridge piles under wet service conditions. The program is region-specific as the survival rates are dependent on the geological locations of the bridges. The user can use the default setting if the target bridge inventory is similar to those of Maryland. Otherwise, the user can manually specify the survival rates based on the particular use case. The main functionality of PAM is to simulate the pile conditions in the future and offer potential causes of deterioration and recommendations for future inspection.

Author Contributions

Naiyi Li—Collecting and organizing data, and performing survival analysis.

Kuang-Yuan Hou—Collecting and organizing data, and developing an assessment program.

Yunchao Ye—Developing an assessment program.

Chung C. Fu—Collaborating and guiding research efforts, interacting with funding agencies.

Conflict of Interest

There is no conflict of interest.

Funding

This research receives funding from the Maryland Department of Transportation State Highway Administration.

References

[1] An-jie, W., Wan-li, Y., 2020. Numerical study of pile group effect on the hydrodynamic force on a pile of sea-crossing bridges during earthquakes. Ocean Engineering. 199, 106999. DOI: https://doi.org/10.1016/j.oceaneng.2020.106999

[2] Tu, W., Gu, X., Chen, H.P., et al., 2021. Time domain nonlinear kinematic seismic response of composite caisson-piles foundation for bridge in deep water. Ocean Engineering. 235, 109398. DOI: https://doi.org/10.1016/j.oceaneng.2021.109398

[3] Ding, Y., Ma, R., Shi, Y.D., et al., 2018. Underwater shaking table tests on bridge pier under combined earthquake and wave-current action. Marine Structures. 58, 301-320. DOI: https://doi.org/10.1016/j.marstruc.2017.12.004

[4] Walsh, M.T., Sagüés, A.A., 2016. Steel corrosion in submerged concrete structures—Part 1: Field observations and corrosion distribution modeling. Corrosion. 72(4), 518-533. DOI: https://doi.org/10.5006/1945

[5] Goyal, R., 2015. Development of a survival based framework for bridge deterioration modeling with large-scale application to the North Carolina bridge management system [PhD thesis]. Charlotte: The University of North Carolina.

[6] Cox, D.R., 1972. Regression models and life-tables. Journal of the Royal Statistical Society: Series B (Methodological). 34(2), 187-202. DOI: https://doi.org/10.1111/j.2517-6161.1972.tb00899.x

[7] Lemeshow, S., May, S., Hosmer Jr, D.W., 2011. Applied survival analysis: Regression modeling of time-to-event data. John Wiley & Sons: New York.

[8] Greene, W.H., 1997. Econometric analysis. Prentice Hall, Inc.: Upper Saddle River.

[9] Butt, A., Shahin, M.Y., Feighan, K.J., et al., 1987. Pavement performance prediction model using the Markov process. Transportation Research Record 1123: Pavement Management and Weigh in Motion. Transportation Research Board: Washington, DC.

[10] Jiang, Y., Saito, M., Sinha, K.C., 1988. Bridge performance prediction model using the Markov chain. Transportation Research Record. 1180, 25-32.

[11] Madanat, S., Mishalani, R., Ibrahim, W.H.W., 1995. Estimation of infrastructure transition probabilities from condition rating data. Journal of Infrastructure Systems. 1(2), 120-125. DOI: https://doi.org/10.1061/(asce)1076-0342(1995)1:2(120)

[12] Rens, K.L., Nogueira, C.L., Neiman, Y.M., et al., 1999. Bridge management system for the city and county of Denver. Practice Periodical on Structural Design and Construction. 4(4), 131-136.

[13] LTBP InfoBridge™ [Internet]. U.S. Department of Transportation Federal Highway Administration. Available from: https://infobridge.fhwa.dot.gov/

[14] National Bridge Inventory [Internet]. U.S. Department of Transportation Federal Highway Administration. Available from: https://www.fhwa.dot.gov/bridge/inspection/

[15] Cavalline, T.L., Whelan, M.J., Tempest, B.Q., et al., 2015. Determination of Bridge Deterioration

Models and Bridge User Costs for the NCDOT Bridge Management System [Internet]. Available from: https://trid.trb.org/view/1405296

[16] Moser, R., Holland, B., Kahn, L., et al., 2011. Durability of Precast Prestressed Concrete Piles in Marine Environment: Reinforcement Corrosion and Mitigation [Internet]. Available from: https://rosap.ntl.bts.gov/view/dot/20616

[17] Federal Highway Administration, 1995. Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges [Internet]. Available from: https://www.fhwa.dot.gov/bridge/mtguide.pdf

BILINGUAL PUBLISHING GROUP

Journal of Architectural Environment & Structural Engineering Research
https://journals.bilpubgroup.com/index.php/jaeser

ARTICLE

Preliminary Study of Agricultural Waste as Biochar Incorporated into Cementitious Materials

***Achal Pandey*[1]*, Srinivasarao Naik B*[3]*, Shishir Sinha*[1,2*]*, B. Prasad*[1]**

[1] *Chemical Engineering Department, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, 247667, India*
[2] *Central Institute of Petrochemicals Engineering & Technology, Chennai, Tamil Nadu, 600032, India*
[3] *CSIR-Central Building Research Institute, Roorkee, Uttarakhand, 247667, India*

ABSTRACT

Incorporating small amounts of biochar into cementitious materials has partial effects on the environment. In this present study, rice husk was collected as agricultural biomass from a local area of Roorkee Uttarakhand, which contains siliceous material to a significant extent. Biochar was prepared from agricultural waste in a muffle furnace at a temperature of 500 °C for 90 min and ground to a fineness of less than 10 µm. Prior to incorporation into building envelopes such as mortar and concrete, a basic study on cement pastes is essentially required. For this purpose, different dosages of biochar such as 0, 3%, 5% and 10% wt. were replaced with cement in cementitious materials. Physical properties such as water absorption, density and porosity were investigated. Furthermore, mechanical and thermal properties such as compressive strength and thermal conductivity were studied. Advanced tools like field emission scanning electron microscopy (FESEM), X-ray diffraction (XRD) and thermogravimetric analyzer (TGA) were used to identify the hydration products. As the dosages increased in the cement matrix, the physical properties of sample were increased and porosity decreased. The compressive strength of biochar incorporated cement paste improved according to 0, 3%, 5% and 10% wt. It further reveals that as the dosage increased, the thermal conductivity of the samples decreased significantly. Moreover, the sustainable assessment showed that biochar could reduce embodied carbon, embodied energy and strength efficiency substantially over the control sample. A satisfactory result was obtained at 5% wt. and 10 % wt. of biochar. The overall result revealed that biochar up to 10% wt. can be incorporated into mortar and concrete due to better results than the control mix.

Keywords: Rice husk; Silicious material; Biochar; Cement; Hydration

*CORRESPONDING AUTHOR:
Shishir Sinha, Chemical Engineering Department, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, 247667, India; Central Institute of Petrochemicals Engineering & Technology, Chennai, Tamil Nadu, 600032, India; Email: shishir@ch.iitr.ac.in

ARTICLE INFO
Received: 25 April 2023 | Revision: 20 May 2023 | Accepted: 26 May 2023 | Published Online: 5 June 2023
DOI: https://doi.org/10.30564/jaeser.v6i2.5695

CITATION
Pandey, A., Naik, B.S., Sinha, S., et al., 2023. Preliminary Study of Agricultural Waste as Biochar Incorporated into Cementitious Materials. Journal of Architectural Environment & Structural Engineering Research. 6(2): 59-79. DOI: https://doi.org/10.30564/jaeser.v6i2.5695

COPYRIGHT
Copyright © 2023 by the author(s). Published by Bilingual Publishing Group. This is an open access article under the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License. (https://creativecommons.org/licenses/by-nc/4.0/).

1. Introduction

Increased CO_2 emissions from cement industries are one of the most critical hazards to the atmosphere in recent times. The rise of industrial development radically increased CO_2 discharges day by day [1,2]. Human activity has contributed significantly to this increase in energy production for manufacturing industries. Construction-related industries, among other production activities, have contributed significantly to global CO_2 emissions [3]. Only 7% of the world's CO_2 emissions come from the production, processing, and manufacturing processes used in cement production [4]. Research has been carried out all around the world to provide effective solutions to reduce CO_2 emissions from the cement production industries [5]. The impact of alternative bio-based components and life cycle assessment (LCA) and the impact of alternative bio-based components in cement manufacturing were also investigated [6]. The addition of bio-based materials and cellulosic materials degrade the cement properties and delay the hydration process respectively [7,8]. Converting these biobased materials to biochar is a successful technique because of its superior thermal and mechanical properties, sustainability, and capacity to lower CO_2 emissions [9]. The thermal and mechanical qualities of cement-based products are influenced by the quantity of biochar used, its origin, preparation method, and particle size [10]. In comparison to other incineration techniques, pyrolysis produces biochar, a stable carbon-rich material that releases less CO_2 into the environment. The circumstances under which biochar is produced have a significant impact on its quality. The yield of pyrolysis products as well as their physicochemical and microstructural characteristics are influenced by variables such as pyrolysis temperature range, pressure, heating rate, and residence duration [11]. The variety of biomass feedstock chosen determines the physicochemical optimal-bonding variation of biochar, including surface area, pore size, cation exchange capacity and water retention capacity [12]. Formation of hydrogen bonds between water molecules and having OH groups on biochar surfaces, biochar contains highly porous substance with a significant surface area [13]. Biochar is prepared by fast and slow pyrolysis methods. The combustion process in the absence of oxygen leads to the degradation of biomass in various phases depending on the chemistry and composition of the raw feedstock. Biomass consists mostly of cellulose, hemicellulose, and lignin. The proportion of hemicellulose, lignin and cellulose in the biomass determines how much fixed carbon the biochar contains. Biochar with a pore width of less than 30 mm was the most effective at holding water, and biochar with micropore sizes between 5 and 30 mm was found to be the most active particle in absorbing and holding moisture. High propensity for water absorption in biochar with pores of 5-6 μm diameter [14,15]. Nowadays, biochar is used as soil remediation, carbon sequestration, filler in polymeric materials, conversion purposes and energy storage purposes, etc. [16]. The addition of higher dosage of biochar to cement matrix led to fluidity, demand of superplasticizer and reduction of free water [17]. Ahmad et al. [18] reported that less bamboo biochar was required to improve the compressive strength of the cement composite. Gupta and Kua [19] evaluated the yield stress and plastic viscosity of biochar-cement composites, finding that coarse biochar had a bigger impact on the flowability and viscosity of cement paste than fine biochar. Additionally, it was revealed that micro biochar particles excelled macroporous biochar in terms of early strength (1-day and 7-day) and water tightness. Recent studies have found that the best filler percentage for biochar derived from food and wood waste was 2% since it increased compressive strength the most [20]. Akhtar and Sarmah [21] studied three different forms of biochar such as rice husk, paper and pulp sludge, and chicken litter. No matter which type of biochar was utilised, the study showed that adding biochar to concrete reduced its compressive strength. However, the type of biochar used determines how much the compressive strength of concrete is reduced [22]. They found that adding biochar reduced the compressive strength of cement-based materials, yet cement samples made with biochar effectively reached to

12.5 MPa minimum compressive strength needed to prepare mortar for structural usage after 28 days. The higher reduction in cement content caused by higher biochar dosages, mechanical strength is lowered. This results in a significantly reduced production of the hydration product. However, cementitious composites' mechanical strength may be increased by adding biochar at lower replacement amounts [23]. According to Ahmad et al. [18], adding 0.08 wt% of inert bamboo charcoal particles to mortar might increase its flexural strengths and toughness by 66% and 103%, respectively. Using five different ratios (0, 1, 3, 5, and 10% wt.), the biochar added to the cement before being combined with water and sand. The mortar's thermal conductivity was decreased by the addition of biochar. For instance, the addition of 1% wt., 3% wt., 5% wt., and 10 wt% of biochar decreased by 16%, 22%, 30%, and 39%, respectively, in comparison to the reference mortar [24]. The thermal performance of cement pastes containing sugarcane bagasse biochar has been reported to have decreased significantly. The heat conductivity dropped by 30% and 45%, respectively, in the 6% biochar-cement composites after 90 and 28 days of curing respectively [25]. The samples with 1 and 2% biochar by weight showed the highest decrease in thermal conductivity, reporting 0.208 to 0.230 W/(m.K), and specifically, 0.192-0.197 W/(m.K) for cementitious materials [26]. The porosity of the matrix and Inter Transitional Zone (ITZ) are improved by biochar, which typically has D90 and D50 between 9 µm and 5 µm and was very efficient in reducing the capillary water absorption rate [27]. Tasdemir [28] demonstrated, when compared to the control mix, the initial sorptivity of commercial wood, Singapore wood biochar and 5% wt. coconut were reduced by 38%, 29% and 28% respectively. Most of the research found that adding fine fillers to cementitious composites refines the matrix's pores and increases ITZ [28]. According to certain research, the amount of biochar incorporated, the w/b ratio, the pyrolytic temperature, and the size of the biochar all have an impact on the reduction in water absorption. A considerable quantity of capillary holes is introduced into the matrix by an increase in the percentage of biochar and the w/b ratio, which causes the open porosity and moisture transportation of cementitious material to increase [29]. The addition of biochar at low concentrations (0.1-0.5 wt%) has been described to reduce water absorption of recycled aggregate, which was due to high porosity. This was attributed to the biochar's ascendant filler effect, which creates compact matrix with fewer voids for water absorption [30]. The primary features provided to the mortar to prevent moisture evaporation and shrinkage are the water absorption and retention capabilities of biochar. The moisture transfer qualities of cement mortar are greatly influenced by the water retention capacity of the biochar. Although less polar functional groups in the biochar produced at high temperatures cause it to lose its hydrophilicity, the consequence of increased porosity at elevated temperatures controls the retaining water capacity. The biochar's ability to retain water is influenced by several elements, including morphology, porosity, pore size, and pore connectivity [31,32].

In this study, rice husk was converted into biochar at a temperature of 500 °C without the presence of oxygen. In order to assess the biochar and biochar in the cement matrix, sophisticated tools are used. With dosages of 0%, 3%, 5%, and 10%, the produced biochar is substituted for cement. Investigations were made into the physical, mechanical, and thermal characteristics of biochar used in cement paste. In-depth research was done on the morphology of incorporated biochar cement paste.

2. Materials and methods

2.1 Materials used in the experiment

Rice husk was purchased from a local source in Roorkee. The binder (OPC, Ultra-tech) was acquired from local market of Roorkee, Uttarakhand. The materials such as cement and biochar composition were presented in **Table 1**.

Table 1. Chemical composition of biochar and ordinary portland cement.

Oxides	Biochar(%)	Ordinary portland cement (%)
CaO	1.9	61.05
SiO_2	89.17	22.23
Al_2O_3	0.98	6.01
Fe_2O_3	1.12	2.19
SO_3	0.89	2.15
MgO	---	3.09
Na_2O	---	0.51
K_2O	3.2	0.12
MnO	0.11	0.16
P_2O_5	1.2	0.045
LOI	---	0.081

2.2 Preparation biochar from rice husk biomass

350 g of rice husk is combusted in a muffle furnace at a temperature of 500 °C for 90 min at a ramp rate of 5 °C/min. A ball mill was used to compress the biochar for fine particles. A particle size analyzer (PSA) was used to measure the size of the biochar particles. The average particle distribution of biochar was 6.4 µm (**Figure 1** and **Table 3**). It was used as a substitute for cement in the experiment. Elemental composition was measured using the method of ultimate analysis and their values are given in **Table 2**.

Table 2. Ultimate analysis of biochar.

Element	Percentage
C	61.05
H	0.53
N	2.47
S	0.13
O	35.82

Table 3. Physical properties of cement and biochar.

Cement	
Density (kg/m^3)	3155
Blaine fineness (m^2/kg)	383
Mean Particle size (µm)	19.63
Biochar	
Density (kg/m^3)	340
Mean Particle size (µm)	6.4
pH	10.7
Yield	47%

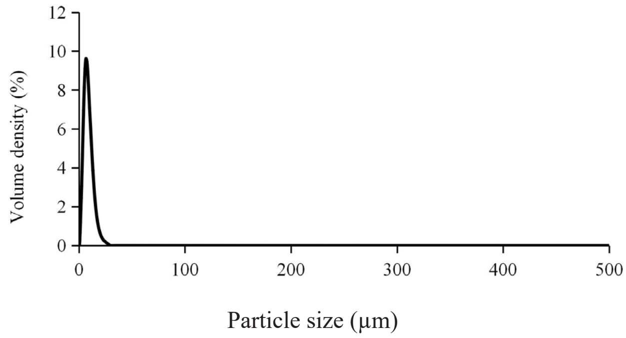


Figure 1. Particle size distribution of biochar (500 °C, 90 min and 5 °C/min).

2.3 Cement samples with rice husk biochar

At a water-to-binder (w/c) ratio of 0.5, cement was mixed with different concentrations of biochar (0%, 3%, 5% and 10%). The combination ratio of cement and biochar were presented in **Table 4**. These combinations were poured into a 25 mm × 25 mm × 25 mm mold. After a day, the samples were immersed in plain water. Water absorption, density, porosity, compressive strength, thermal conductivity, and characterization were made after 28 days.

Table 4. Mix proposition of cement paste.

w/c : 0.5	
Cement (%)	**Biochar (%)**
100	0
97	3
95	5
90	10

3. Physical properties of cement cubes with rice husk biochar

3.1 Water absorption

After 28 days, the cement with biochar samples was dried in an electric oven and adjusted to 100 °C for 24 hours. The samples were removed from the electrical oven after 24 hours, allowed to cool to room temperature, and their dry weights were calculated (W_d). The dried samples were immersed in normal water for 24 hours. Each sample was cleaned with a dry cloth to remove the remaining surface moisture before weighing while wet (W_w). The following method was used to calculate the percentage of water absorption of cement paste.

$$\text{Water absorption (\%)} = \frac{Ww - Wd}{Wd} \times 100 \quad (1)$$

where, W_d is oven dried sample weight (g), W_w is wet samples weight.

3.2 Porosity and density

The density of biochar-incorporated cement paste samples was determined according to the mass and volume of the samples. The dimensions of the samples were measured with the help of a digital caliper accurate to 0.01 mm for four samples and the results were averaged for each dimension [33]. The cement with biochar samples was dried at 100 °C for 24 hours and subsequently for 28 days. The weight of dried samples (W_d) was calculated after 24 hours. The samples were dried, then soaked for 24 hours and then boiled for 5 hours. After cooling for 5 hours at room temperature, the cement with biochar samples was cleaned with a dry cloth to eradicate any external moisture from the boiled samples. After boiling, the weights of the samples were calculated (W_b). After cooling the cement with biochar samples were halted in water and the suspended weight of the samples was calculated (W_s).

$$\text{Porosity (\%)} = \frac{Wb - Wd}{Wb - Ws} \times 100 \quad (2)$$

where W_b is the sample weight after boiling, and W_s is the sample suspended weight [34].

3.3 Compressive strength of biochar-incorporated cement paste

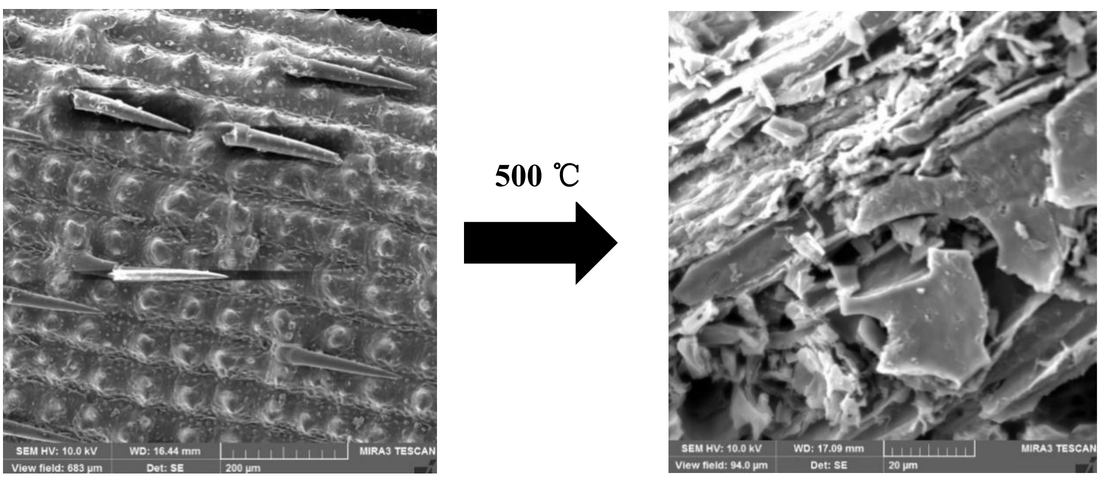
Specimens of cement cubes were prepared according to Section 2.3. Testometric UTM 50kN was used to evaluate the compressive strength of cement paste samples with biochar after 28 days.

4. Characterization of biochar-incorporated cement paste

4.1 Field emission scanning electron microscopy (FESEM)

With the help of field emission scanning electron microscopy (Make: TESCAN, Model: MIRA 3), the morphology of the biochar-incorporated materials was examined in vacuo. Samples were mounted on carbon tape adhered to a stub after being coated with gold using an Electron Microscope Sciences gold sputter coater (model: K550X). The stub was inserted into the FESEM apparatus to examine the material microstructure.

The morphology of rice husk biochar was presented in **Figure 2**. The biochar appears intermittent shape and non-uniform surfaces with various



(a) Rice husk (b) Bio Char

Figure 2. Morphology of (a) Rice husk (b) Bio Char.

heterogeneous porous arrangements. The porous arrangements depend on the method of combustion, biomass, heating rate and volatile content.

4.2 X-ray diffraction

The materials were pulverised, and then spread onto a glass slide. The sample on a glass slide was introduced into an X-ray diffraction equipment (Make: Rigagu, Model: D5110) and operated between the 2:5-80 range at a speed of 3 theta/min.

The XRD of rice husk biochar was presented in **Figure 3**. At elevated temperature, cellulose crystalline was changed due to the emergence of atoms in the carbon substance. The deficiency of crystalline intensity peaks informed that; the rice husk biochar is a semi-amorphous in nature (**Figure 3**) [35].

4.3 Thermogravimetric analysis

Under nitrogen atmosphere, flow rate 3.6 sccm/min, and continuous heating temperature 5 °C/min, the weight loss of raw rice husk was determined using STA PT 1600 model. After 28 days, the hydration products were determined between ambient to 1000 °C. When calcium hydroxide dissociates during cement hydration, water is released. This water loss between 380 and 520 °C can be translated to portlandite and is estimated using the equations below.

$$\%CH_{dx} = 4.11 \times dx_{(400-500\ °C)} \quad (3)$$

where CH_{dx} and dx (400-500 °C) is the content of calcium hydroxide and the weight loss in the decarboxylation zone, respectively.

The chemically bound water (W_b) in the sample is determined using the following equation:

$$W_b = W_{dh} + W_{dx} + 0.41\,(W_{dc}) \quad (4)$$

where, W_{dh} (105-400 °C) is the percentage weight loss of dehydration, W_{dx} (400-500 °C) is percentage weight loss of dihydroxylation, W_{dc} (500-900 °C) is the percentage weight loss of decarbonation. The empirical factor 0.41 was employed to change in percentage weight loss of decarbonation of water. The percentage degree of hydration is determined using Equation (5) [36]:

$$\alpha\,(\%) = \frac{W_b}{0.24} \times 100 \quad (5)$$

The TGA of rice husk biochar was presented in **Figure 4**. There are two stages of mass loss observed at different temperatures. Mass loss is observed between 100 and 125 °C due to moisture content. Another one is 200 to 410 °C due to combustible and non-combustible gases. The moisture content in rice husk is about 6.84%. The second stage of weight loss is about 62.3%.

4.4 Thermal conductivity

A hot disk TPS 1500 instrument (ISO 22007-2) [37] was used to analyze the thermal performance of the samples under ambient conditions. After 28 days, the surface of the samples was flattened for effective contact with the temperature sensors. A temperature sensor was placed between the flat specimens. Working conditions were provided by inbuilt software to determine the thermal conductivity of the specimens.

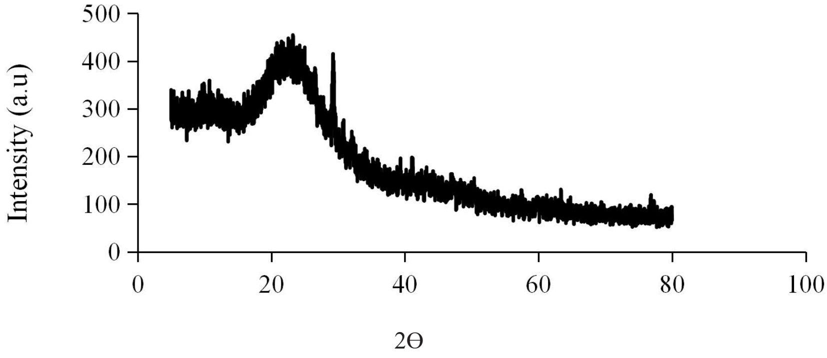


Figure 3. XRD pattern of biochar (500 °C, 90 min and 5 °C/min).

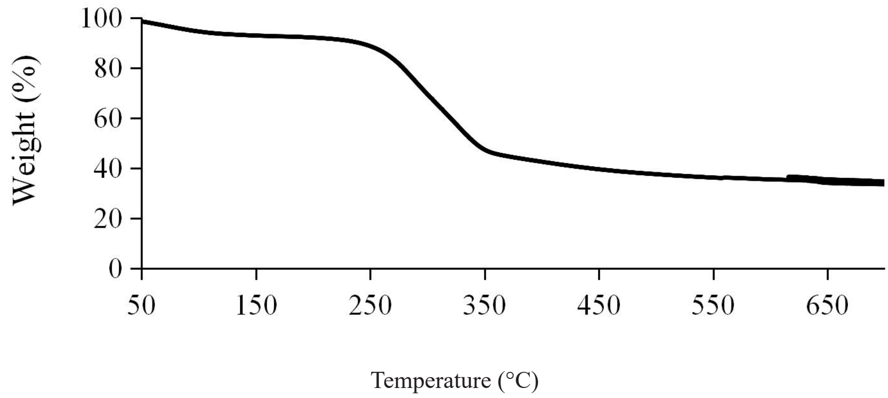


Figure 4. TGA of rice husk (500 °C, 90 min and 5 °C/min).

5. Results and discussions

5.1 Initial and final setting of samples

The initial and final setting time of cement and cement containing biochar are shown in **Figure 5**. The initial and final setting time for cement is found to be 35 min and 560 min respectively. The replacement of different dosages of biochar led to a decrease in the initial and final setting times (30 min and 527 for 3%, 26 min and 480 min for 5% and 28 min and 520 min for 10%). The obtained results revealed that as the dosage of biochar accelerates initial and final setting time and cement hydration.

5.2 Compressive strength of samples

Mechanical strengths of the different dosages of rice husk biochar-incorporated samples were shown in **Figure 6**. The results revealed that the compressive strength of various dosages of biochar incorporated samples was first increased by 3% wt. and 5% wt. and then decreased by 10% of biochar than 5% of biochar but increased than the control. Compressive strength of samples enhanced by 13.6%, 19.2%, and 16.06% as compared to the control mix corresponding to 3%, 5% and 10% respectively. The improvement of a maximum proportion of C-S-H in the samples up to 5% wt. of biochar is attributed to the cement samples. This is turned out due to the density difference between raw materials such as cement and biochar. The compressive strength of the sample at 10% wt. of biochar is higher than 3% wt. of biochar. On the other hand, finer particles of biochar are placed between cement particles, which densified the cement paste [27,38,39].

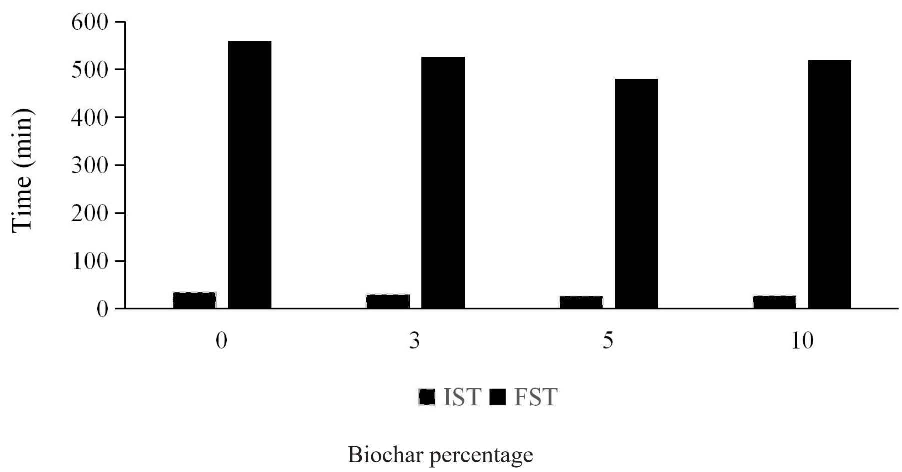


Figure 5. Compressive strength of biochar incorporated cement paste.

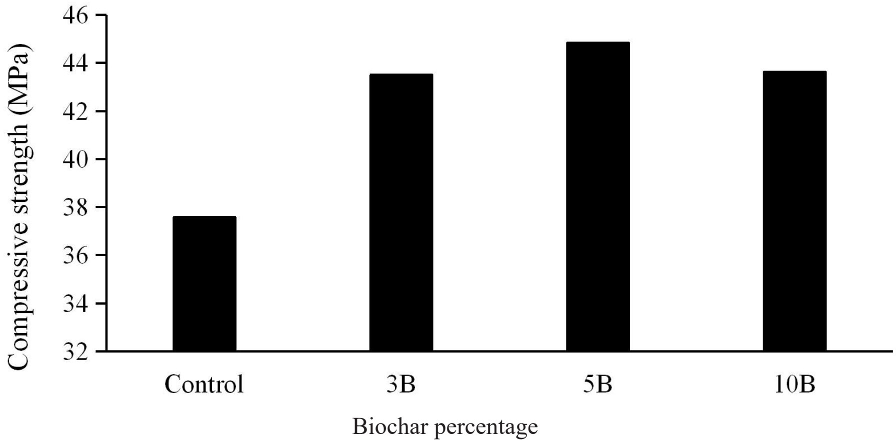


Figure 6. Compressive strength of biochar incorporated cement paste.

5.3 Porosity and density

The porosity and density of samples were determined according to ASTM C 642 [35]. The obtained results were shown in **Figure 7** and **Figure 8**. The porosity of the samples is decreased than the control mix as amount of rice husk biochar increases. The porosity of control mix is observed at 11.42%. The maximum reduction of porosity is examined at 5% wt. of biochar. 10.9%, 8.3% and 10.24 % of porosity reduced than the control mixes subsequent to 3%, 5% and 10% (**Figure 7**). From **Figure 7**, it has been investigated that, the porosity of 10% wt. of samples was further reduced than the 3% wt. of sample. It means that rice husk biochar enhances the packaging density of cement matrix. Density is the physical property of cementitious materials. Densities of samples are increased as the amount of biochar increases (**Figure 8**). The density of the sample is 1.98 g/cm^3. The maximum density of the sample is examined at 5% wt. of biochar. 2.04 g/cm^3, 2.18 g/cm^3 and 2.1 g/cm^3 enhanced than the control mixes subsequent to 3%, 5 % and 10 % respectively (**Figure 8**). It means that as porosity is reduced, density of samples is increased (**Figure 7** and **Figure 8**).

5.4 Water absorption

The water absorption of various dosages of biochar-incorporated samples was investigated according to ASTM C 642 [35]. The water absorption of the samples is decreased as compared to the control mix as amount of rice husk biochar increases. The water absorption of control mix is examined at 22.5%. The maximum reduction of water absorption is examined at 5% wt. of biochar. Following 3%,

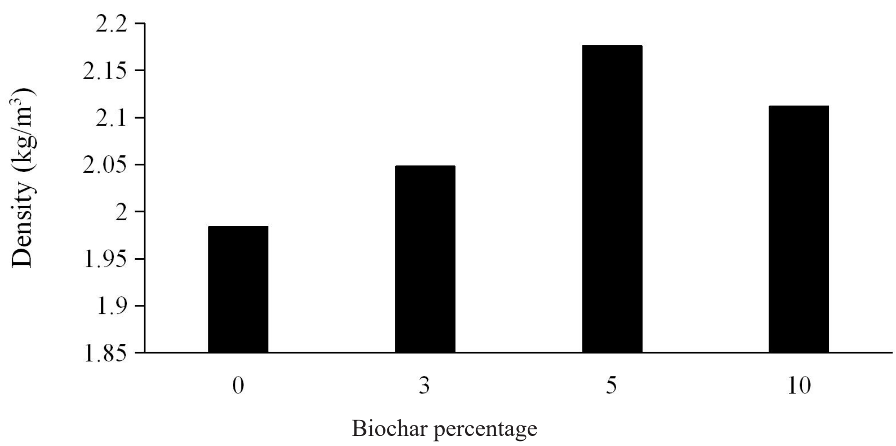


Figure 7. Density of biochar incorporated cement paste.

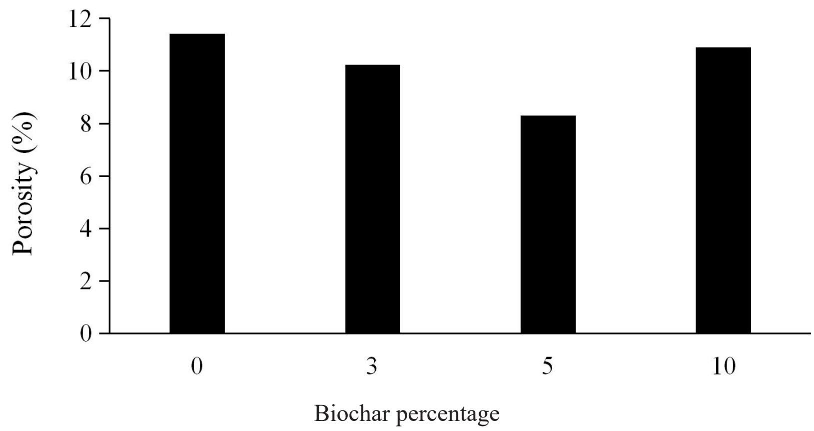


Figure 8. Water absorption of biochar incorporated cement paste.

5%, and 10%, there was a 17.2%, 14.2%, and 16.6% decrease in water absorption compared to the control mixes (**Figure 9**). In **Figures 7 and 8**, where porosity is decreased and density is raised, there is a reduction in water absorption due to these changes.

5.5 Morphology of samples

The morphology of various dosages of biochar-incorporated samples were shown in **Figure 10**. The hydration products in various dosages of biochar-incorporated samples increased as biochar content increased. The more compacted hydration products such as C-S-H, $Ca(OH)_2$ and ettringite are observed at 5% of biochar (**Figure 10C**). It means that the replacement of biochar with cement promoted hydration. The porous structure of the biochar also facilitated in the formation of hydration products and heterogeneous precipitation. Because of the filler effect and dense particle packing in the paste matrix, the compressive strength of the sample was increased by up to 10 wt.% [40]. The C-S-H concentration of cement paste is lower when 3% biochar is added than when 10% biochar is introduced. In addition, van der Waals' gravity-assisted biochar particle aggregation in cement mixtures containing biochar (as a cement replacement) with 5% of biochar leads to lower hydration production in the mixtures, larger pores and cracks near the ITZ macroscopic mechanical properties [20].

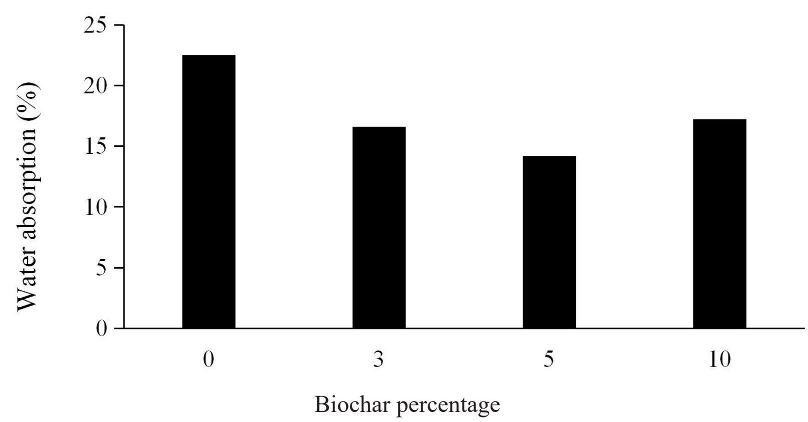
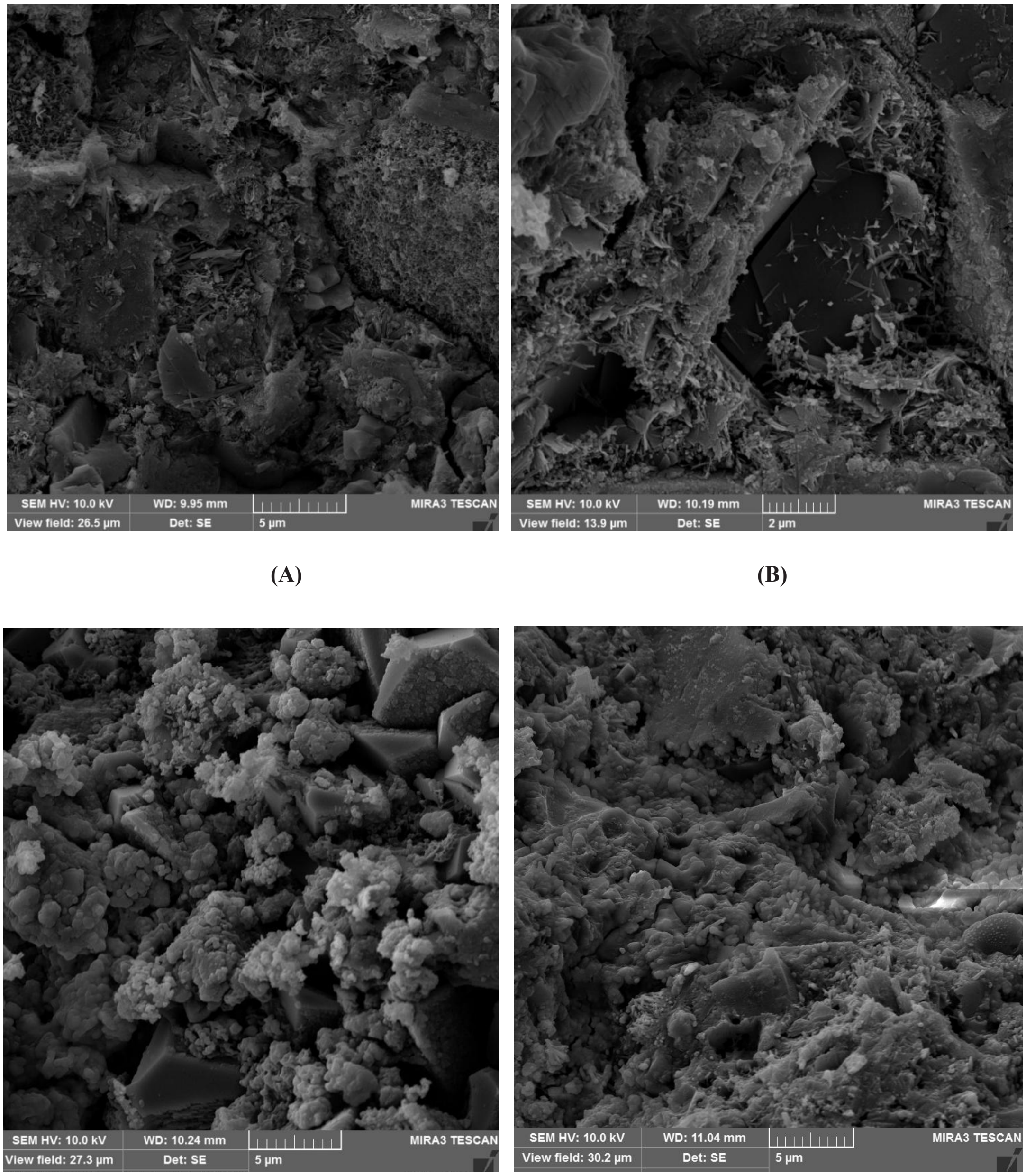


Figure 9. Water absorption of biochar incorporated cement paste.



(A) **(B)**

(C) **(D)**

Figure 10. Morphology (FESEM) of biochar incorporated cement paste (A) 0% (B) 3% (C) 5% (D) 10%.

5.6 XRD analysis of samples

The hydration products of crystalline phases such as Calcium silicate (CS1 and CS2), C-S-H, Calcium hydroxide (CH) and Calcite (C), are observed in **Figure 11** corresponding to different peaks. The results showed that adding biochar increased the number of hydration products. In cement pastes containing 3%, 5% and 10% biochar, the CH peak at 2ϴ = 17.9° is greater than that in normal paste sample. However, as the biochar dosage increased from 3% to 10%, it was found that the amount of CH decreased. Compared to the control sample, the intensity of C-S-H peak (2ϴ = 31.9°) was increased by biochar from 3% to 10%. The C-S-H peak, however, is a lesser amount developed than with 3% of biochar. As seen in **Figure 11**, the C-S-H concentration is decreased in the cement sample

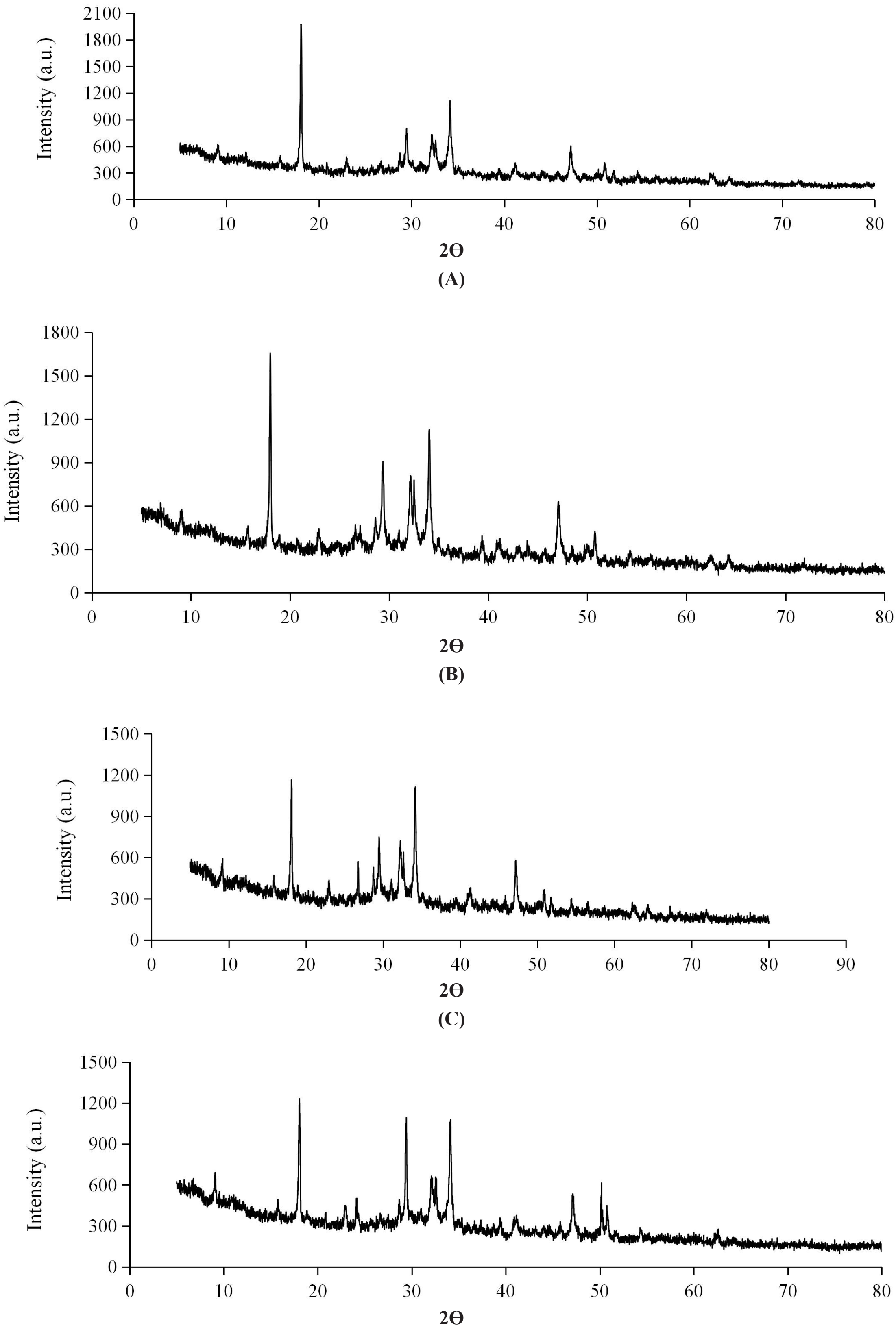


Figure 11. Mineralogical (XRD) of biochar incorporated cement paste (A) 0% (B) 3% (C) 5% (D) 10%.

when compared to 5% biochar. Most calcite (C) peaks were evident at angles of 28.3° and 37.2°. The peaks in the XRD spectra of calcium carbonate are more prominent than those of calcium hydroxide. As a result, cement pastes are expected to contain more calcite. Biochar addition significantly increased C intensity at 2Θ = 28.3° and 37.2°. Promoted calcite is one of the essential elements for the hardness of cement composite [41].

5.7 TGA analysis of samples

The weight loss of various dosages of biochar incorporated samples were shown in **Figure 12**. The effect of the first mass loss peak on the breakdown of C-A-H and C-S-H gels is observed in TGA curves from **Figure 12**. Endothermic peaks below 200 °C are brought about by the dehydration of CSH and ettringite phases. In thermographs, calcium silicate hydrate is identified by the loss of water in the range of 120-150 °C. The hydration products such as Calcium aluminate hydrates (C-A-H), calcium silicate hydrates (C-S-H) gel (105-400 °C), calcium hydroxide (C-H) (400-500 °C), and calcium carbonate (CC) (500-900 °C) are found at various temperature ranges. The addition of biochar (BC) resulted in an increased peak at 105-540 °C, demonstrating that the addition of biochar increased the generation of hydration products. The hydration products and degree of hydration were calculated using Equations (3), (4), and (5) [42,43]. The values for each are shown in **Table 5**. The CH concentration reduced as the biochar dose increased, but the C-S-H content increased from 0 to 10% of the biochar [44]. The degree of hydration is determined using Bhatty's Equation (5). The degree of hydration is increased as biochar content is increased (**Figure 13**) from 49.4% to 55.5%. The maximum degree of hydration of sample is examined at 5% wt. The more hydration products in biochar with cement sample is due to the increment of the degree of hydration [45].

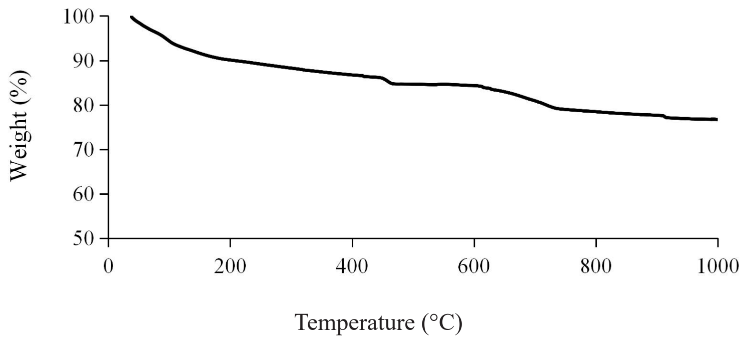
5.8 Thermal conductivity of samples

The Thermal conductivity of various dosages of biochar-incorporated samples was investigated according to (ISO 22007-2) [37]. The Thermal conductivity of the samples is decreased as compared to the control mix as amount of rice husk biochar increases. The thermal conductivity of the control mix is examined at 1.17 W/m.K. The maximum reduction of the thermal conductivity is examined at 5% wt. of biochar. Following 3%, 5%, and 10%, there was a 1.05 W/m.K, 0.86 W/m.K, and 0.93 W/m.K decrease in thermal conductivity compared to the control mixes (**Figure 14**). It is also necessary to look at dynamic heat transmission in building materials with added biochar. A study on dynamic heat transfer found that biochar has low heat reactivity [46]. This is because cement containing biochar has lower thermal conductivity than cement without. In addition, it was found that the main reason for the reduced thermal conductivity was the increased porosity of the biochar by releasing volatiles.

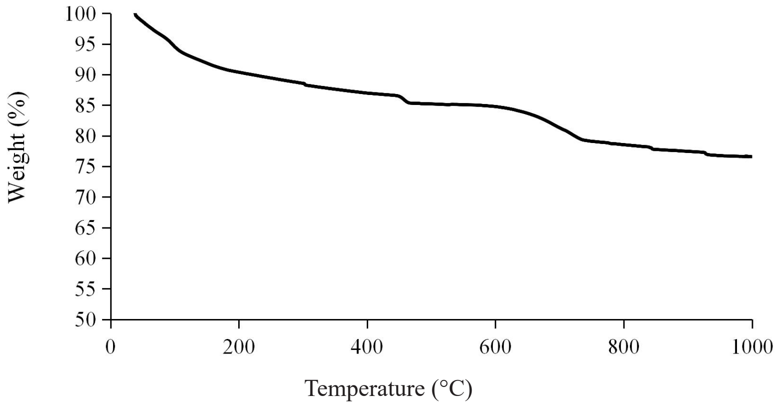
The obtained data are compared with the existing literature review and their observations were given in **Table 6** for a better understanding of the experimental results.

Table 5. Investigation of hydration products using TGA analysis.

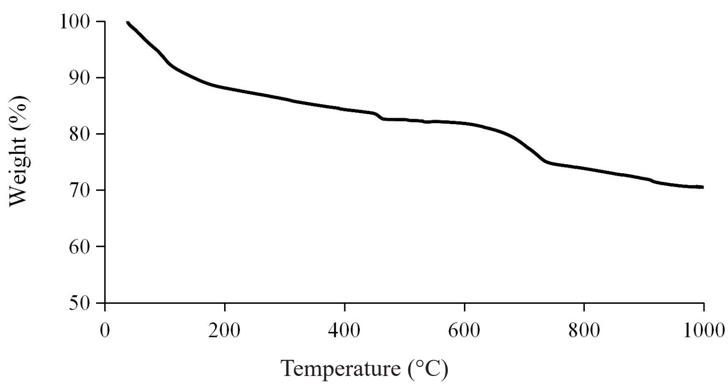
Dosage of Biochar	105-400 °C (W_{dh})	400-500 °C (W_{dx})	500-900 °C (W_d)	W_b	α (%)
0%	6.9	2.1	7.0	11.9	49.4
3%	7.16	1.7	7.8	12.1	50.4
5%	8.3	1.8	10.5	14.4	60
10%	7.8	2.6	7.5	13.4	55.8



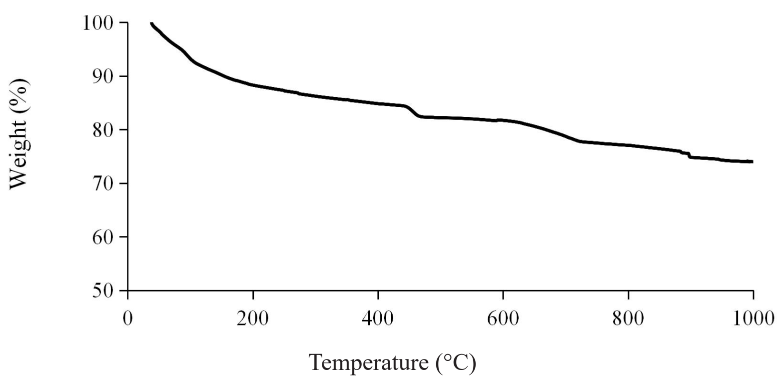
(A)



(B)



(C)



(D)

Figure 12. TGA analysis of biochar incorporated cement paste (A) 0% (B) 3% (C) 5% (D) 10%.

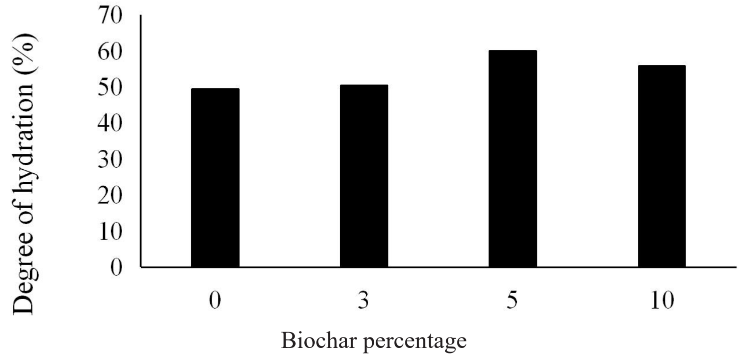


Figure 13. Degree of hydration of biochar incorporated cement paste.

Table 6. Comparison of biochar incorporated cement based materials with present work.

Feedstock	Pyrolysis conditions	Biochar used as	Dosage	Main consequences	References
Mixture of woodchips of local forest	900 °C	Filler	1%, 2.5%	Reduction of compressive strength with increasing biochar	[23]
Hardwood	500 °C	Cement replacement	5-20%	Comparable compressive strength with 5% of biochar as replacement	[47]
Rice husk	450 °C	Silica fume replacement	0.1-0.75%	Water absorption reduction 17%, enhancement of mechanical strength increased optimum dosage of biochar	[30]
Rice husk	500 °C	Cement replacement	40%	Acceleration of cement hydration, 15-20% higher compressive strength retention by mortar exposed to 450 °C	[48]
Wheat Straw	650 °C	MgO + ADP replacement	0.5, 1, 1.5%	Mechanical properties enhanced with biochar.	[49]
Wood saw dust	300-500 °C	Filler	1, 2, 5, 8%	Development of early age e strength	[20]
Wood saw dust	300-500 °C	Filler	2%	Higher degree of hydration by pre-soaked biochar, Improvement of strength and water tightness	[50]
Wood saw dust	500 °C	Cement replacement	2, 5, 8%	Increase of hydration degree	[27]
Peanut shells	850 °C,	Filler	0.025, 0.05, 0.08, 0.2, 0.5, 1%	Increase in electromagnetic radiation shielding	[51]
Standardized biochar, Pyrolyzed polyethylene beads (CNBs) and coconuts shells	750-850 °C	Nano/Micro-filler	0.5, 1%	Flexural strength and fracture energy	[52]
Rice husk biochar	**500** °C	**Replacement with cement**	**0, 3, 5 and 10%**	**Significant results obtained upto 10% replacement**	**Present study**

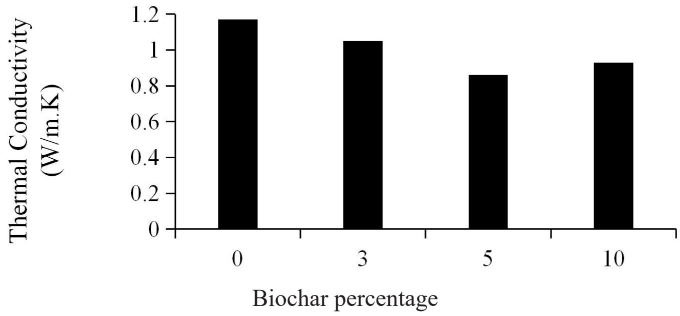


Figure 14. Thermal conductivity of biochar incorporated cement paste.

6. Life cycle assessment of Biochar incorporated cement paste samples

6.1 Estimation of CO_2 emission

The raw materials of CO_2 emission of OPC and water were adopted from the available literature. Carbon emission of rice husk biochar (RHBC) is determined based on specific assumptions such as transportation, processing of RHBC and 1 m^3 of cement paste for each sample. The collection of Rice husk has mentioned in materials and methods section. The RHBC farm is located roughly 5 km from the lab where the casting and testing were done. The RHBC is transported using a heavy vehicle (HV) with a 1000 kg load capacity. Also, it is predicted that the ball milling of 1000 kg of RHBC will use approximately 169.7 kWh of power. According to the CO_2 benchmark database for the Indian power sector and the factors for road transport emissions specific to India, the CO_2 emission factor per kWh of electricity used in January 2023 is 0.79 $kgCO_2/kWh$ and 0.148 $kgCO_2/km$ for CUVs [53]. The amount of carbon in 1 kg of each type of cement paste RHBC is 0.135 kg. For each type of cement paste, embodied GHG ECO_2e and embodied energy EE are calculated based on the manufacture of 1 kg using the control and RHBC methods, as shown in the equation below.

$$ECO_2e = \Sigma CO_{2i} \times m_i \quad (6)$$

$$EE = \Sigma E_i \times m_i \quad (7)$$

CO_{2i} is the coefficient of embodied carbon, E_i is the coefficient of embodied energy coefficient per unit mass of component i, and m_i resembles to the mass of cement paste component i per kg of cement paste [54,55]. The raw materials used to produce EE are derived from various sources as shown in **Table 8**. Moreover, the production of RHBC is involved in transport and ball milling. As shown in **Tables 7 and 9**, the estimated carbon footprint based on these aspects was 0.135 $kgCO_2/kg$. As a result of introducing RHBC into the cement paste, the embedment rate was significantly reduced. The inclusion of RHBC in cement as a replacement, the difference in ECO_2e for the different replacements. **Figure 15** shows that the use of RHBC in cement paste significantly reduces the carbon content of the mixture. A mixed cement paste contains 3%, 5%, and 10% carbon, which is 6%, 15%, and 17%, respectively [56,57].

Table 7. CO_2 emission factors for raw materials used in cement paste [58,59].

Cement	0.82
Water	0.0013
Biochar	0.135

Table 8. Embodied energy for raw materials used in cement paste.

Cement	5.5
Water	0.0017
Biochar	1.82

6.2 Embodied energy

Figure 16 illustrates the various embodied energy and RHBC percentages. It can be seen that the control solution produced significantly less EE than the other mixes. With RHBC values of 0, 3, and 5, as well as 10%, the amounts of EE are 6.71, 6.58, 6.49, and 6.26 MJ/kg, respectively. EE has decreased

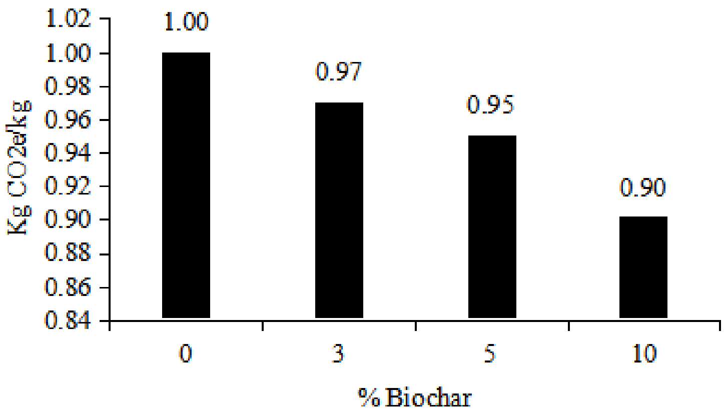


Figure 15. Embodied carbon and eco-strength efficiency of cement paste at different percentage of biochar.

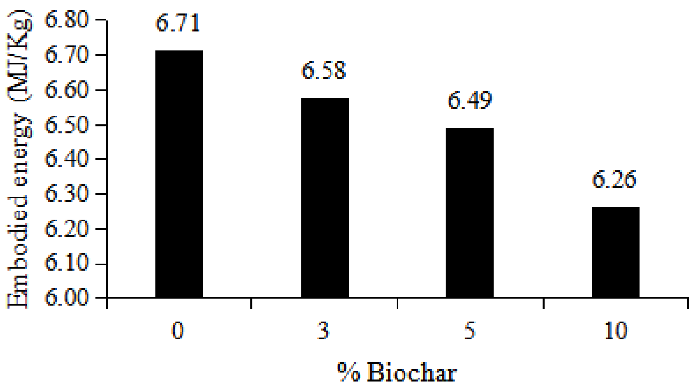


Figure 16. Embodied energy of cement paste at different percentage pf biochar.

by 1.93%, 3.27%, and 6.7% in comparison to the control sample. These findings show that partial RH replacement with cement lowers EE.

6.3 Estimation of eco-strength efficiency

Total CO_2 emissions vary depending on the RHBC combinations. Therefore, it is essential to concentrate on both material reduction and its impact on compressive strength in addition to the decrease of carbon content. Equation (8) is used to create environmental strength indicators [56].

$$Eco - strength\ efficiency = \frac{compressive\ strength\ of\ samples\ after\ 28 days}{Total\ emboided\ carbon\ of\ sapmples} \quad (8)$$

As shown in **Figure 17**, the 0% RHBC control sample has an efficiency of 0.0376 MPa/kg CO_2-eq. kg within 28 days. **Figure 17** can show that the environmental strength performance of the RH replaced cement is increased at all levels compared to the control mortar. It may be due to the increase in strength of all mixed RHBC cement past sample after 28 days. By replacing OPC with 3%, 5%, and 10%, the efficiency of ecological intensity increased by 18.18%, 29.7%, and 28.26% respectively. As mentioned earlier, the RHBC replaced cement paste sample can be used for high compressive strength. However, it is important to focus on reducing the content of components by replacing the level of OPC and embodied carbon, as well as reducing the efficiency of environmental durability [60]. Although the RHBC contributes little to the reduction of CO_2 emissions, it ensures the protection of natural resources and can be used to develop environmentally friendly and energy-efficient mortars for the cement industry to promote sustainable development.

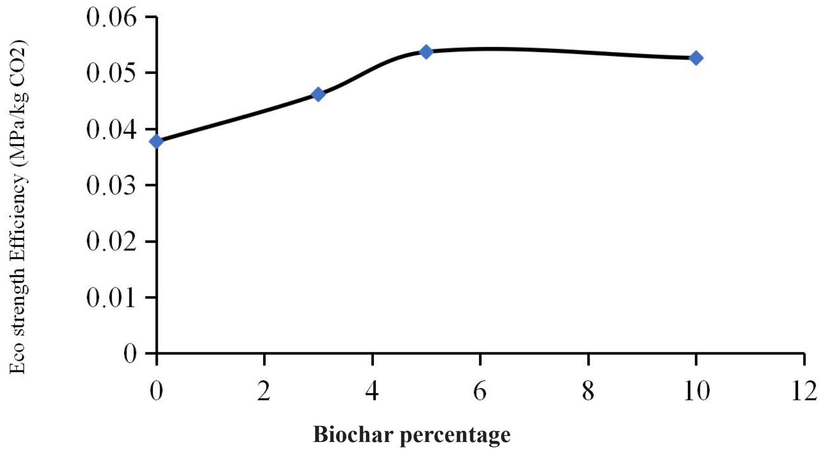


Figure 17. Eco strength efficiency with biochar.

6.4 Cost assessment of rice husk biochar

The RHBC used in this study is untreated community waste sourced directly from industry. The resulting ash is disposed of on land, and RHBC's processing costs are relatively lower than those of cement Therefore, the cost of grinding, and CNSA shipments will be taken into account in this study. From **Table 9**, the total power consumption for grinding RHBC for and 1000 kg ball mill is 169.7 kWh. The cost of 169.7 units consumed to grind and ball mill 1000 kg of RHBC is Rs. 1201.00*/1000 kg. If 1000 kg of RHBC is transported over a distance of 5 km, the shipping cost of CNSA is 408.19*/1000 kg. Therefore, the total cost of CNSA is Rs. 1609*/kg. Calculating the amount of cement per m^3 of cement with a mixing. **Table 9** shows the total cost of mixing 1 m^3 of cement.

7. Conclusions

This study substituted high doses of biochar in cementitious materials to reduce the use of cement in construction materials. For further incorporation into building envelopes, the mechanical, thermal and physical, performance of biochar with cement paste was investigated. The hydration products in the cement matrix were investigated using state-of-the-art equipment.

The biochar was successfully prepared under pressurised condition in muffle furnace. The particle size of biochar is observed at 6.4 µm after grinding in a ball mill. Further, 0, 3%, 5%, and 10% of biochar were replaced with cement. The initial and final setting time of cement with biochar is decreased as the replacement of biochar increased and it meets IS : 4031 (part-5)-1988.

The compressive strength of biochar with cement paste is increased as biochar dosage increased. The maximum compressive strength (44.85 Mpa) of the specimen was observed at 5% wt. of biochar. At 10% wt. of biochar, the superior strength (43.64 Mpa) was observed than control mix (37.6 Mpa). The porosity of specimen is decreased as biochar dosage increased. The maximum reduction of porosity of the specimen was observed at 5% wt. of biochar. At 10% wt. of biochar, the significant porosity of

Table 9. CO_2 emission factor for rice husk.

Energy requirements for 1000 kg of Rice husk		**Transportation of 1000 kg of Rice husk**		**Total emission (kg CO_2/kg CNSA)**
Total electrical Consumption (kg/CO_2/kWh)	Emission Factor	Distance (km)	Emission factor (kg CO_2/km)	
169.7	0.79	5	0.148	0.135

the specimen was reduced strength than the control mix. The density of specimen is increased as biochar dosage increased. The maximum density of biochar with cement was observed at 5% wt. of biochar. At 10% wt. of biochar, the density of specimen was increased than the control mix. As the dosage of biochar increased in the cement matrix, the water absorption decreased due to change in porosity of specimen.

After 28 days, the morphology of specimen was observed with the help of FESEM. The results revealed that biochar enhances the cement hydration products up to 5% wt. There is no significant reduction of hydration observed at 10% wt. The formation of more calcium hydroxide and calcium carbonate because of using biochar particles in replacement of cement was confirmed by XRD and TGA results. The improvement in C-S-H was observed after the addition of 3%, 5%, and 10% wt. biochar to cement pastes that already contained biochar was initially attributed to the filler effect of biochar, which creates a nucleation site for cement hydration products. The obtained results also demonstrated that rice husk biochar encouraged the hydration products in cement matrix. Agricultural-based biochar is a sustainable substitute for lowering the cement requirement in building envelope cement-based materials. For all replacement levels of biochar, the sustainability assessment reveals a significant decrease in the embodied carbon, energy, and overall carbon footprint. For all of the mixes, the biochar blended cement sample's eco-strength efficiency was significantly lower than that of the control mortar. Also, the cost analysis of the cement sample mixes showed that using biochar as an accelerator may be done affordably.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Mensah, R.A., Shanmugam, V., Narayanan, S., et al., 2021. Biochar-added cementitious materials—A review on mechanical, thermal, and environmental properties. Sustainability. 13(16), 9336.

[2] Lindsey, R., 2023. Climate Change: Atmospheric Carbon Dioxide [Internet]. Climate. gov. Available from: https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

[3] Gupta, S., Kua, H.W., Low, C.Y., 2018. Use of biochar as carbon sequestering additive in cement mortar. Cement and Concrete Composites. 87, 110-129.

[4] Lüthi, D., Le Floch, M., Bereiter, B., et al., 2008. High-resolution carbon dioxide concentration record 650,000-800,000 years before present. Nature. 453(7193), 379-382.

[5] Boesch, M.E., Hellweg, S., 2010. Identifying improvement potentials in cement production with life cycle assessment. Environmental Science & Technology. 44(23), 9143-9149.

[6] Sierra-Beltran, M.G., Jonkers, H.M., Schlangen, E., 2014. Characterization of sustainable bio-based mortar for concrete repair. Construction and Building Materials. 67, 344-352.

[7] Wu, F., Yu, Q., Liu, C., 2021. Durability of thermal insulating bio-based lightweight concrete: Understanding of heat treatment on bio-aggregates. Construction and Building Materials. 269, 121800.

[8] Wei, J., Meyer, C., 2015. Degradation mechanisms of natural fiber in the matrix of cement composites. Cement and Concrete Research. 73, 1-16.

[9] Das, O., Sarmah, A.K., Bhattacharyya, D., 2015. Structure-mechanics property relationship of waste derived biochars. Science of the Total Environment. 538, 611-620.

[10] Maljaee, H., Madadi, R., Paiva, H., et al., 2021. Incorporation of biochar in cementitious materials: A roadmap of biochar selection. Construction and Building Materials. 283, 122757.

[11] Zahed, M.A., Salehi, S., Madadi, R., et al., 2021. Biochar as a sustainable product for remediation of petroleum contaminated soil. Current Research in Green and Sustainable Chemistry. 4, 100055.

[12] Zhao, M.Y., Enders, A., Lehmann, J., 2014. Short-and long-term flammability of biochars. Biomass and Bioenergy. 69, 183-191.

[13] Shafizadeh, F., 1982. Introduction to pyrolysis of biomass. Journal of Analytical and Applied Pyrolysis. 3(4), 283-305.

[14] Shafie, S.T., Salleh, M.M., Hang, L.L., et al., 2012. Effect of pyrolysis temperature on the biochar nutrient and water retention capacity. Journal of Purity, Utility Reaction and Environment. 1(6), 293-307.

[15] Lehmann, J., 2007. Bio-energy in the black. Frontiers in Ecology and the Environment. 5(7), 381-387.

[16] Sizmur, T., Quilliam, R., Puga, A.P., et al., 2016. Application of biochar for soil remediation. Agricultural and Environmental Applications of Biochar: Advances and Barriers. 63, 295-324.

[17] Mindess, S., Young, J.F., Darwin, D., 2003. Concrete, 2nd Edition. Prentice-Hall: Upper Saddle River.

[18] Ahmad, S., Khushnood, R.A., Jagdale, P., et al., 2015. High performance self-consolidating cementitious composites by using micro carbonized bamboo particles. Materials & Design. 76, 223-229.

[19] Gupta, S., Kua, H.W., 2019. Carbonaceous micro-filler for cement: Effect of particle size and dosage of biochar on fresh and hardened properties of cement mortar. Science of the Total Environment. 662, 952-962.

[20] S. Gupta, S., Kua, H.W., Dai Pang, S., 2018. Biochar-mortar composite: Manufacturing, evaluation of physical properties and economic viability. Construction and Building Materials. 167, 874-889.

[21] Akhtar, A., Sarmah, A.K., 2018. Novel biochar-concrete composites: Manufacturing, characterization and evaluation of the mechanical properties. Science of the Total Environment. 616, 408-416.

[22] Roy, K., Akhtar, A., Sachdev, S., et al., 2017. Development and characterization of novel biochar-mortar composite utilizing waste derived pyrolysis biochar. International Journal of Scientific and Engineering Research. 8(12), 1912-1919.

[23] Sirico, A., Bernardi, P., Belletti, B., et al., 2020. Mechanical characterization of cement-based materials containing biochar from gasification. Construction and Building Materials. 246, 118490.

[24] Yang, S., Wi, S., Lee, J., et al., 2019. Biochar-red clay composites for energy efficiency as eco-friendly building materials: Thermal and mechanical performance. Journal of Hazardous Materials. 373, 844-855.

[25] Rodier, L., Bilba, K., Onésippe, C., et al., 2019. Utilization of bio-chars from sugarcane bagasse pyrolysis in cement-based composites. Industrial Crops and Products. 141, 111731.

[26] Świerczek, L., Cieślik, B.M., Konieczka, P., 2018. The potential of raw sewage sludge in construction industry—a review. Journal of Cleaner Production. 200, 342-356.

[27] Gupta, S., Krishnan, P., Kashani, A., et al., 2020. Application of biochar from coconut and wood waste to reduce shrinkage and improve physical properties of silica fume-cement mortar. Construction and Building Materials. 262, 120688.

[28] Tasdemir, C., 2003. Combined effects of mineral admixtures and curing conditions on the sorptivity coefficient of concrete. Cement and Concrete Research. 33(10), 1637-1642.

[29] Du, H., Gao, H.J., Dai Pang, S., 2016. Improvement in concrete resistance against water and chloride ingress by adding graphene nanoplatelet. Cement and Concrete Research. 83, 114-123.

[30] Akhtar, A., Sarmah, A.K., 2018. Strength improvement of recycled aggregate concrete through silicon rich char derived from organic waste. Journal of Cleaner Production. 196, 411-

423.

[31] Weber, K., Quicker, P., 2018. Properties of biochar. Fuel. 217, 240-261.

[32] Dixit, A., Gupta, S., Dai Pang, S., et al., 2019. Waste Valorisation using biochar for cement replacement and internal curing in ultra-high performance concrete. Journal of Cleaner Production. 238, 117876.

[33] Cuthbertson, D., Berardi, U., Briens, C., et al., 2019. Biochar from residual biomass as a concrete filler for improved thermal and acoustic properties. Biomass and Bioenergy. 120, 77-83.

[34] ASTM C642-21 Standard Test Method for Density, Absorption, and Voids in Hardened Concrete [Internet]. Available from: https://www.astm.org/c0642-21.html

[35] Tan, K., Pang, X., Qin, Y., et al., 2020. Properties of cement mortar containing pulverized biochar pyrolyzed at different temperatures. Construction and Building Materials. 263, 120616.

[36] Ali, D., Agarwal, R., Hanifa, M., et al., 2023. Thermo-physical properties and microstructural behaviour of biochar-incorporated cementitious material. Journal of Building Engineering. 64, 105695.

[37] ISO 22007-2:2015. Plastics—Determination of Thermal Conductivity and Thermal Diffusivity—Part 2: Transient Plane Heat Source (Hot Disc) Method [Internet]. Available from: https://www.iso.org/standard/61190.html

[38] Pan, S.Y., Adhikari, R., Chen, Y.H., et al., 2016. Integrated and innovative steel slag utilization for iron reclamation, green material production and CO_2 fixation via accelerated carbonation. Journal of Cleaner Production. 137, 617-631.

[39] Moosberg-Bustnes, H., Lagerblad, B., Forssberg, E., 2004. The function of fillers in concrete. Materials and Structures. 37, 74-81.

[40] Li, Y., Zeng, X., Zhou, J., et al., 2021. Development of an eco-friendly ultra-high performance concrete based on waste basalt powder for Sichuan-Tibet Railway. Journal of Cleaner Production. 312, 127775.

[41] Ruan, S., Qiu, J., Yang, E.H., et al., 2018. Fiber-reinforced reactive magnesia-based tensile strain-hardening composites. Cement and Concrete Composites. 89, 52-61.

[42] Monteagudo, S.M., Moragues, A., Gálvez, J.C., et al., 2014. The degree of hydration assessment of blended cement pastes by differential thermal and thermogravimetric analysis. Morphological evolution of the solid phases. Thermochimica Acta. 592, 37-51.

[43] Wang, L., Chen, L., Tsang, D.C., et al., 2020. Biochar as green additives in cement-based composites with carbon dioxide curing. Journal of Cleaner Production. 258, 120678.

[44] Bakolas, A., Aggelakopoulou, E., Moropoulou, A., 2008. Evaluation of pozzolanic activity and physico-mechanical characteristics in ceramic powder-lime pastes. Journal of thermal Analysis and Calorimetry. 92(1), 345-351.

[45] Haha, M.B., Le Saout, G., Winnefeld, F., et al., 2011. Influence of activator type on hydration kinetics, hydrate assemblage and microstructural development of alkali activated blast-furnace slags. Cement and Concrete Research. 41(3), 301-310.

[46] Srinivasaraonaik, B., Sinha, S., Singh, L.P., 2021. Studies on microstructural and thermo-physico properties of microencapsulated eutectic phase change material incorporated pure cement system. Journal of Energy Storage. 35, 102318.

[47] Choi, W.C., Yun, H.D., Lee, J.Y., 2012. Mechanical properties of mortar containing bio-char from pyrolysis. Journal of the Korea Institute for Structural Maintenance and Inspection. 16(3), 67-74.

[48] Gupta, S., Kua, H.W., 2020. Application of rice husk biochar as filler in cenosphere modified mortar: preparation, characterization and performance under elevated temperature. Construction and Building Materials. 253, 119083.

[49] Ahmad, M.R., Chen, B., Duan, H., 2020. Improvement effect of pyrolyzed agro-food biochar on the properties of magnesium phosphate cement. Science of the Total Environment. 718,

137422.

[50] Gupta, S., Kua, H.W., 2018. Effect of water entrainment by pre-soaked biochar particles on strength and permeability of cement mortar. Construction and Building Materials. 159, 107-125.

[51] Khushnood, R.A., Ahmad, S., Restuccia, L., et al., 2016. Carbonized nano/microparticles for enhanced mechanical properties and electromagnetic interference shielding of cementitious materials. Frontiers of Structural and Civil Engineering. 10, 209-213.

[52] Cosentino, I., Restuccia, L., Ferro, G.A., et al., 2019. Type of materials, pyrolysis conditions, carbon content and size dimensions: The parameters that influence the mechanical properties of biochar cement-based composites. Theoretical and Applied Fracture Mechanics. 103, 102261.

[53] Bhawan, S., Puram, R.K., 2022. CO_2 Baseline Database for the Indian Power Sector [Internet]. Central Electricity Authority, Ministry of Power, Government on India, New Delhi, India. Available from: https://cea.nic.in/wp-content/uploads/baseline/2023/01/Approved_report_emission__2021_22.pdf

[54] Selvaranjan, K., Gamage, J.C.P.H., De Silva, G.I.P., et al., 2021. Development of sustainable mortar using waste rice husk ash from rice mill plant: Physical and thermal properties. Journal of Building Engineering. 43, 102614.

[55] Manjunath, B., Ouellet-Plamondon, C.M., Das, B.B., et al., 2023. Potential utilization of regional cashew nutshell ash wastes as a cementitious replacement on the performance and environmental impact of eco-friendly mortar. Journal of Building Engineering. 66, 105941.

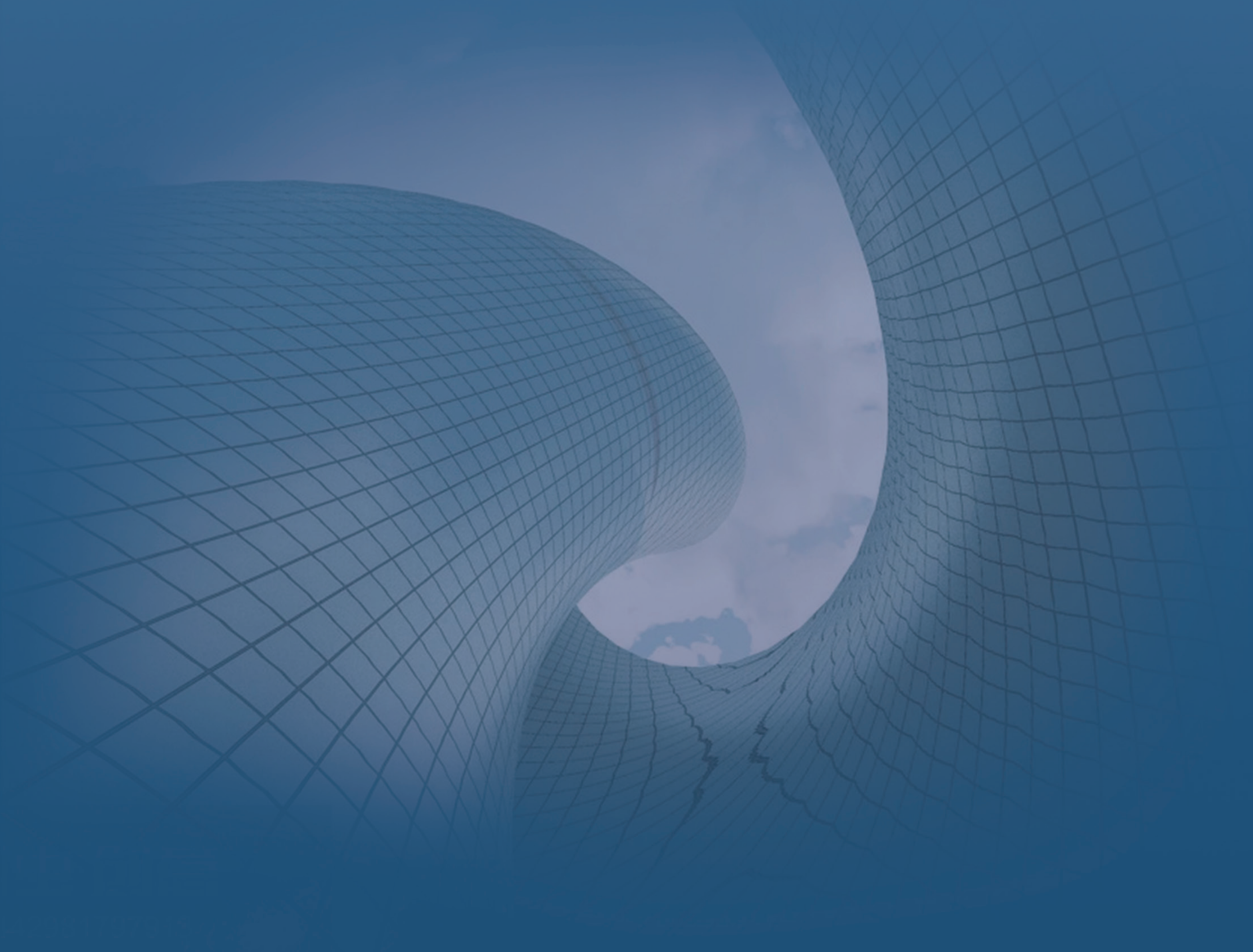
[56] Srikanth, G., Fernando, A., Selvaranjan, K., et al., 2022. Development of a plastering mortar using waste bagasse and rice husk ashes with sound mechanical and thermal properties. Case Studies in Construction Materials. 16, e00956.

[57] Thomas, B.S., Yang, J., Mo, K.H., et al., 2021. Biomass ashes from agricultural wastes as supplementary cementitious materials or aggregate replacement in cement/geopolymer concrete: A comprehensive review. Journal of Building Engineering. 40, 102332.

[58] Turner, L.K., Collins, F.G., 2013. Carbon dioxide equivalent (CO_2-e) emissions: A comparison between geopolymer and OPC cement concrete. Construction and Building Materials. 43, 125-130.

[59] Crawford, R.H., Stephan, A., Prideaux, F., 2019. Environmental Performance in Construction (EPiC) Database [Internet]. Available from: http://www.epicdatabase.com.au/

[60] Caronge, M.A., Tjaronge, M.W., Rahim, I.R., et al., 2022. Feasibility study on the use of processed waste tea ash as cement replacement for sustainable concrete production. Journal of Building Engineering. 52, 104458.



BILINGUAL PUBLISHING GROUP

Tel:+65 65881289

E-mail: contact@bilpublishing.com

Website:https://journals.bilpubgroup.com

2630-5232