Lecture Notes in Civil Engineering

Tehmina Ayub · Khuram Rashid ·
Tariq Jamil · Shashank Bishnoi ·
Joseph Mwiti Marangu *Editors*

Proceedings of the Global Conference on Green Construction Materials and Practices 2025

GCGC 2025, February 5–6, Karachi, Pakistan

Springer

Lecture Notes in Civil Engineering 774

Series Editors

Lecture Notes in Civil Engineering (LNCE) publishes the latest developments in Civil Engineering—quickly, informally and in top quality. Though original research reported in proceedings and post-proceedings represents the core of LNCE, edited volumes of exceptionally high quality and interest may also be considered for publication. Volumes published in LNCE embrace all aspects and subfields of, as well as new challenges in, Civil Engineering. Topics in the series include:

- Construction and Structural Mechanics
- Building Materials
- Concrete, Steel and Timber Structures
- Geotechnical Engineering
- Earthquake Engineering
- Coastal Engineering
- Ocean and Offshore Engineering; Ships and Floating Structures
- Hydraulics, Hydrology and Water Resources Engineering
- Environmental Engineering and Sustainability
- Structural Health and Monitoring
- Surveying and Geographical Information Systems
- Indoor Environments
- Transportation and Traffic
- Risk Analysis
- Safety and Security

To submit a proposal or request further information, please contact the appropriate Springer Editor:

– Pierpaolo Riva at pierpaolo.riva@springer.com (Europe and Americas);
– Swati Meherishi at swati.meherishi@springer.com (Asia—except China, Australia, and New Zealand);
– Wayne Hu at wayne.hu@springer.com (China).

All books in the series now indexed by Scopus and EI Compendex database!

Tehmina Ayub · Khuram Rashid · Tariq Jamil ·
Shashank Bishnoi · Joseph Mwiti Marangu
Editors

Proceedings of the Global Conference on Green Construction Materials and Practices 2025

GCGC 2025, February 5–6, Karachi, Pakistan

Springer

Editors
Tehmina Ayub
Department of Civil Engineering
NED University of Engineering
and Technology
Karachi, Pakistan

Tariq Jamil
Department of Mechanical Engineering
NED University of Engineering
and Technology
Karachi, Pakistan

Joseph Mwiti Marangu
Department of Physical Sciences
Meru University of Science and Technology
Meru, Kenya

Khuram Rashid
Department of Architectural Engineering
and Design
University of Engineering and Technology
Lahore, Pakistan

Shashank Bishnoi
Department of Civil Engineering
Indian Institute of Technology Delhi
New Delhi, Delhi, India

ISSN 2366-2557 ISSN 2366-2565 (electronic)
Lecture Notes in Civil Engineering
ISBN 978-981-95-6591-7 ISBN 978-981-95-6592-4 (eBook)
https://doi.org/10.1007/978-981-95-6592-4

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Preface

The “Global Conference on Green Construction Materials and Practices” (GCGC 2025) was held on February 5 & 6, 2025, at NED University of Engineering and Technology, Karachi, Pakistan. This two-day event was jointly organized by NED University of Engineering and Technology, and the Institution of Engineers Pakistan (Karachi Center), with the objective of bringing together leading experts, researchers, and industry professionals from around the world. The organizers are grateful for the financial contribution from the NRPU Project No. 14074 titled “Development of Cost-Effective Structural Concrete Formulation using Limestone Calcined Clay-Based LC3 Cement Blend with Domestic Resources and its Application in a Pilot Project” awarded to Dr Tariq Jamil in the year 2021.

All submitted papers underwent a peer-review process to ensure high academic and research standards. A total of 20 papers were submitted, out of which 16 were accepted, covering a diverse range of topics, including green materials, sustainable construction practices, and case studies highlighting best practices. The conference addressed the critical issue of the 8% global pollution attributed to building materials, showcasing cutting-edge advancements and innovative solutions to promote sustainability in the construction sector.

GCGC 2025 aimed to foster collaboration and knowledge exchange in sustainable construction and green materials, promoting innovative technologies for sustainable infrastructure. Aligned with UN SDGs 9, 11, and 17, it highlighted resilient infrastructure, sustainable cities, and global partnerships. To ensure ongoing research and collaboration, the conference is planned as a biennial event.

I sincerely appreciate the authors for their valuable contributions and extend my gratitude to all guests for their participation. Their collective efforts played a crucial role in the success of this conference, establishing it as a key platform for advancing sustainable construction and green building materials. We also acknowledge the dedication of the management committee, organizing committee, and international scientific committee, whose contributions were essential in making this event possible.

Tariq Jamil
Secretary, GCGC 2025

GCGC 2025 Conference Committees

Advisory Board

Sarosh Hashmat Lodi	Vice Chancellor, NED UET, Karachi, Pakistan
Muhammad Tufail	Pro-Vice Chancellor, NED UET, Karachi, Pakistan
Sohail Bashir	Chairman, IEP Karachi Centre, Pakistan
Asad-ur-Rehman Khan	Dean, Faculty of Civil & Petroleum Engineering, NED UET, Karachi, Pakistan
Karen Scrivener	Head of Laboratory of Construction Material, EPFL, Lausanne, Switzerland
Chuanlin Hu	Professor at Wuhan University of Technology, Wuhan, China
Shashank Bishnoi	Professor at Indian Institute of Technology (Delhi), India

Organizing Committee

Asad-ur-Rehman Khan (Convener)	Dean, Faculty of Civil & Petroleum Engineering, NED UET, Karachi, Pakistan
Tariq Jamil (Secretary)	Assistant Professor, NED UET, Karachi, Pakistan
Tehmina Ayub (Secretary)	Professor, NED UET, Karachi, Pakistan
Abdul Jabbar Sangi	Chairman, Department of Civil Engineering, NED UET, Karachi, Pakistan
Khuram Rashid	Professor, University of Engineering and Technology, Lahore, Pakistan
Muhammad Noman	Assistant Professor, International Islamic University, Islamabad, Pakistan
Muhammad Bilal	Project Manager GetInnovative4Impact, NED UET, Karachi, Pakistan
Muhammad Danyal Sheikh (Editorial Assistant)	Research Assistant, NED UET, Karachi, Pakistan

Editors of Conference Proceedings

Tariq Jamil (Corresponding Editor)	Assistant Professor, NED UET, Karachi, Pakistan
Tehmina Ayub	Professor, NED UET, Karachi, Pakistan
Khuram Rashid	Professor, University of Engineering and Technology, Lahore, Pakistan
Shashank Bishnoi	Professor at Indian Institute of Technology (Delhi), India
Joseph Mwiti Marangu	Director, Institute of Cement and Concrete, MUST, Meru, Kenya

Contents

Conference Track I: Green Materials

Acid Activation of Low Grade Clay to Develop LC^3

Miral Fatima[1], Khuram Rashid[1](✉), and Arif Bashir[2]

[1] Department of Architectural Engineering and Design, University of Engineering and Technology, Lahore, Pakistan
khuram_ae@uet.edu.pk
[2] D.G.Khan Cement Co. Ltd. Nishat House, Lahore, Pakistan

Abstract. Efforts to reduce global carbon emissions have intensified, leading to the exploration of alternatives to ordinary Portland cement (OPC). Limestone Calcined Clay Cement (LC^3) has emerged as a promising candidate. This study was centered on the development of LC^3 through the activation of low-grade kaolinite clay by acid. The low kaolinite clay was initially calcined at 800 °C for 2 h. Afterward, LC^3 was prepared by reducing OPC by 25% (LC^3-25). Then LC^3 mortar was prepared and oxalic acid was introduced in powder and liquid forms, as an admixture, with varying molar concentrations (1M and 2M). In contrast, calcined clay was chemically activated with an oxalic acid solution, after which LC^3 mortar was developed. For comparison, control specimens of OPC mortar were also prepared. All types of specimens were tested under compression on 7 and 28 days. The findings revealed that LC^3 holds significant potential as a viable alternative to OPC. Furthermore, the thermo-chemical activation of clay, facilitated by the oxalic acid treatment showed 9% more strength than OPC at 7 days and almost similar strength at 28 days with a difference of only 3%.

Keywords: LC^3 · Low-grade kaolinite clay · Chemical activation · Acid treatment · Strength

1 Introduction

The construction industry must address the urgent challenge of reducing CO_2 emissions, particularly in cement production, which has a significant carbon footprint. Exploring sustainable alternatives is essential for this effort. Traditionally, materials like fly ash and slag, classified as supplementary cementitious materials (SCMs), have been used to replace ordinary Portland cement (OPC) partially [1]. However, the availability of these materials depends on other industries, and the varying quality of their source materials can greatly influence the properties of the resulting cement.

Recently, limestone calcined clay cement (LC^3) has gained attention as a promising alternative to OPC [2]. LC^3 is a ternary blend made by replacing a certain percentage of OPC with calcined clay and limestone in 2:1. The properties of LC^3 are dependent on the properties of the clay used, particularly its kaolinite content. Research suggests that clays with a kaolinite content of over 40% are ideal for achieving comparable properties

T. Ayub et al. (Eds.): GCGC 2025, LNCE 774, pp. 3–10, 2026.
https://doi.org/10.1007/978-981-95-6592-4_1

to OPC [3]. However, low-grade clays with less kaolinite require some activation to enhance their reactivity [4, 5]. While calcination has proven effective for high-kaolin clays, the activation of low-grade clays remains an area that is still being explored. Recent research explores methods such as mechanical grinding and acid or alkaline activation to enhance the performance of low grade clays [6, 7]. The potential of combining calcination with other techniques is being investigated and the results have demonstrated that co-calcination can be effective for treating medium to low-grade clays [8]. These treatments make the clay structure amorphous and remove impurities like Fe and Mg, increasing its silica content and boosting hydration reactivity in cement systems. Hydrochloric or sulphuric acid has been used widely for acid treatment of clays [9], but alternatives are to be explored due to its volatile nature and high cost. It has been reported that oxalic acid offers a more efficient and sustainable alternative to sulfuric acid for phosphate extraction, requiring lower quantities and has organic nature. This highlights the potential of organic acids for clay activation, providing a cost-effective and impactful solution.

In this context, the present study aims to explore strategies for improving the strength of LC^3. Specifically, it examines the effects of treating low-grade clays with oxalic acid in various forms to enhance the strength of mortar. By focusing on this approach, the study hopes to contribute to the development of more sustainable construction materials that meet the industry's evolving needs.

2 Experimental Methodology

2.1 Materials

For preparation of LC^3, clay was obtained from a quary nearby DG cement plant HUB, Pakistan. Kaolinite content of clay was determined by Quantitative X-ray diffraction (QXRD) and found to be 21%. X-ray flourescence (XRF) analysis showing composition of its oxides is presented in Table 1. Thermogravimetric analysis (TGA) showed dehydroxylation even after 700 °C. Limestone was also obtained from DG cement plant, in pulverized form. Oxalic acid was obtained in form of white grains from local chemical market and colourless solution was obtained upon preparing its molar solution. OPC and river Ravi sand were used in this study for preparing mortar. Sand was sieved through Sieve No. 16 in order to obtain fine sand.

Table 1. XRF analysis of raw materials

Constituent	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3
Clay	50.5	17.6	11.6	1.4	1.7	1.2	1.8	0.1
OPC	20.2	4.9	3.0	64.1	1.9	0.3	0.7	2.9
Limestone	16.2	3.9	2.4	39.1	0.8	0.2	0.7	0.1

2.2 Clay Activation and Specimen Preparation

The raw clay was calcined in a Muffle Furnace to enhance pozzolanic reactivity, heated at 10 °C per minute to 800 °C, and held for 2 h to ensure mineral transformation for LC^3 production. Oxalic acid was added to LC^3–25 mortar as a 2M powder and 1M solution to enhance strength. Following the incorporation of oxalic acid as a plasticizer, the calcined clay underwent a more intensive chemical treatment involving the dipping of calcined clay in 1M oxalic acid solution for 3 h. The treated clay was then deionized with water and dried until moisture-free. Specific nomenclature used in this study is presented in Fig. 1.

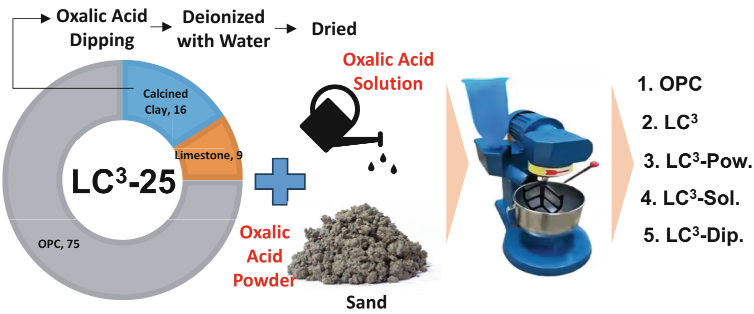


Fig. 1. Type of specimen prepared in this work.

As a control specimen, OPC mortar was prepared according to ASTM guidelines (ASTM C109). The mix design adhered to a cement-to-sand ratio of 1:2.75. The water-to-binder ratio was precisely maintained at 0.485 to ensure consistency and comparability with the LC^3 mortar. The OPC mortar mix served as a baseline for evaluating the performance enhancements achieved with the LC^3 mortar. The LC^3-25 mortar was designed with a blend of calcined clay and limestone in a ratio of 2:1. Six samples of each mortar type were prepared to assess the compressive strength at two curing periods: 7 days and 28 days. All mortar specimens were subjected to wet curing until testing age.

3 Results and Discussion

3.1 Influence of Age on Strength of OPC and LC3

Figure 2 illustrates the compressive strength development of OPC and LC^3 at both 7 and 28 days. At the 7-day, OPC exhibited a compressive strength that was 5% higher than that of LC^3, highlighting the rapid hydration rate characteristic of OPC. This early strength development in OPC is due to its fast-reacting clinker phases, which enable a quicker gain in compressive strength. By 28 days, the strength difference between OPC and LC^3 increased to 11%, indicating that OPC continues to gain strength at a slightly faster rate. The comparable strength performance of LC^3 at both ages suggests that LC^3's hydration and strength gain may be slower than OPC initially but, it remains competitive over time. This trend highlights the potential for LC^3 to continue gaining strength beyond 28 days, with likely strength improvements up to 90 days. This prolonged strength gain in LC^3 is due to its pozzolanic and filler effects, which contribute to strength development over a more extended period.

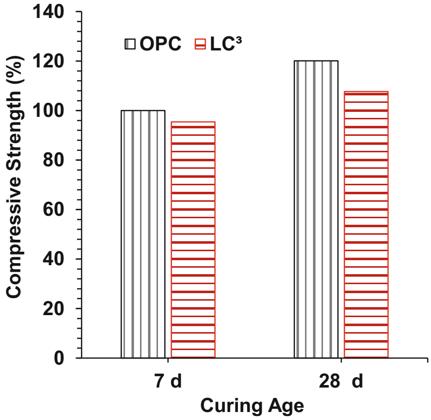


Fig. 2. Strength comparison of OPC and LC^3 at 7 and 28 days.

3.2 Influence of Oxalic Acid on Mortar

At 7 days, the strength of LC^3-Pow., which incorporates 2M oxalic acid in powder form, decreased drastically to 102% of the strength of LC^3 (Fig. 3). In contrast, the strength of LC^3-Sol., with 1M oxalic acid added in solution form, showed a significant reduction of 43% compared to LC^3 (Fig. 3). This suggests that the 1M solution form is more effective than the 2M dry powder addition, as the latter may inhibit optimal strength development due to excessive crystallization (formation of calcium oxalate crystals) or uneven dispersion with the hydration process.

By 28 days, the performance of both modified mixes improved considerably (Fig. 3). The strength of LC^3-Pow. Specimen increased, resulting 28% lesser than that of LC^3, while LC^3-Sol. was now 21% weaker than the standard LC^3 mix. Notably, LC^3 itself exhibited a 12% increase in strength from 7 to 28 days. More significantly, LC^3-Pow. Demonstrated a remarkable strength gain of 78%, and LC^3-Sol. experienced a 33% increase compared to their respective strengths at 7 days. This trend can be attributed to the effective role of the 1M solution form, which may enhance the reactivity of the clay and improve the microstructure by facilitating better bonding within the matrix. These findings underscore the potential for tailored admixtures to enhance the performance of LC^3 mortars, particularly the advantageous effects of the 1M solution form.

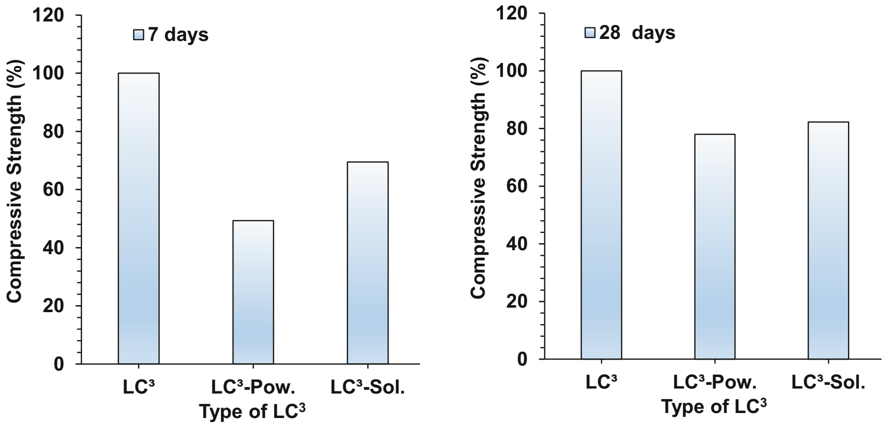


Fig. 3. Compressive strength of LC^3 with and without oxalic acid.

3.3 Influence of Oxalic Acid on Clay Reactivity

Figure 4 illustrates the influence of clay treated with oxalic acid through the dipping process on the strength of the resulting LC^3 mortar. At 7 days, Dip-LC^3 exhibited a notable strength increase of 16% compared to the standard LC^3, demonstrating the positive impact of the chemical treatment on early-age performance. This initial strength gain can be attributed to the enhanced reactivity of the clay due to the removal of impurities and the exposure of more reactive sites [10], which facilitates the formation of calcium silicate hydrate (C-S-H) during hydration. By 28 days, Dip-LC^3 continued to show improvement, achieving a 7% increase in strength relative to LC^3.

In contrast, the overall strength gain of LC^3 was 12% from 7 to 28 days, while the strength increase for Dip-LC^3 during the same period was limited to just 5%. This disparity suggests that while the dipping treatment effectively enhances early strength, its influence may diminish over time. The initial benefits may result from the rapid formation of reactive phases [11], but as the hydration process progresses, the rate of reaction may slow down, indicating a potential need for optimization in the treatment process to sustain strength development throughout the curing period.

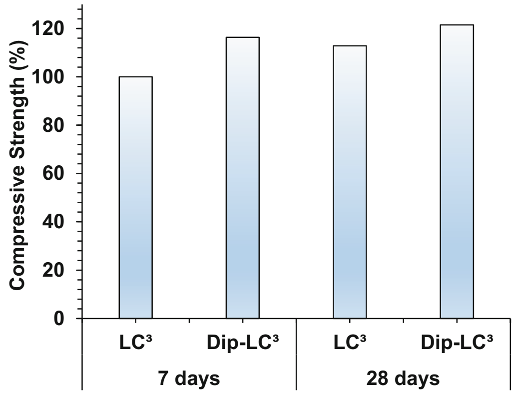


Fig. 4. Compressive strength of sample type, C and D at 7 and 28 days.

3.4 Comparative Assessment

Figure 5 compares the strength of OPC with control LC^3 with other types of blends prepared. At 7 days, the strength of OPC was 4% more than that of LC^3 and 9% lesser than Dip-LC^3. At 28 days, the strength of OPC was 11% more than LC^3 while only 3% more than Dip-LC^3. OPC and LC^3 gained strength from 7 to 28 days at increases of 20% and 13%, respectively, while Dip-LC^3 experienced only a 5% increase over the same period.

Strength differences stem from calcination and chemical treatment. At 800 °C, clay decomposes into reactive phases like metakaolin, which react with calcium hydroxide from cement hydration to form C-S-H gel. This improves mortar densification and mechanical strength.

In the case of Dip-LC^3, treatment with oxalic acid further increases the reactivity of the calcined clay by removing impurities and amorphous phases from the particle surfaces. This exposure allows for more reactive sites to participate in pozzolanic reactions, enhancing the formation of C-S-H. Additionally, oxalic acid dissociates into oxalate and hydrogen ions, which can chelate metal ions present in the clay, forming stable metal-oxalate complexes [12].

However, while Dip-LC^3 may initially show improved strength due to these factors, its performance can be affected by the solubility of calcium oxalate. If calcium oxalate films dissolve, this may hinder the formation of a robust microstructure, impacting long-term strength gain [13, 14]. Thus, the mechanisms driving strength development in Dip-LC^3 reflect a complex interplay between increased reactivity from chemical treatment and potential limitations due to the solubility of resultant compounds. Figure 6 represents the relation between 7 day and 28 day compressive strength of all blends. All specimens showed strength gain from 7 to 28 days, as expected and a good correlation was observed, with coefficient of determination (R^2) value of 0.91 (Fig. 6). The regression analysis was carried out and the following relationship (Eq. (1)) has been extracted for all types of blends. Where $f'_{c,28}$ and $f'_{c,7}$ are 28 and 7 days compressive strength, respectively. This equation, based on multiple blends, predicts average strength trends but does not fully capture blend-specific variations.

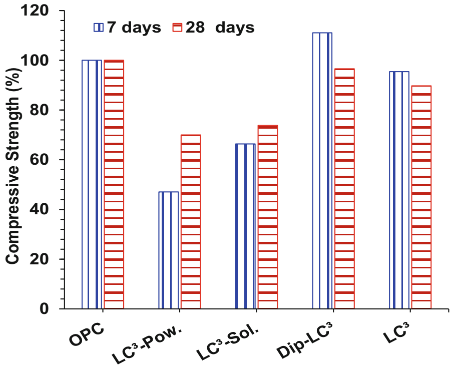


Fig. 5. Comparison of all blends.

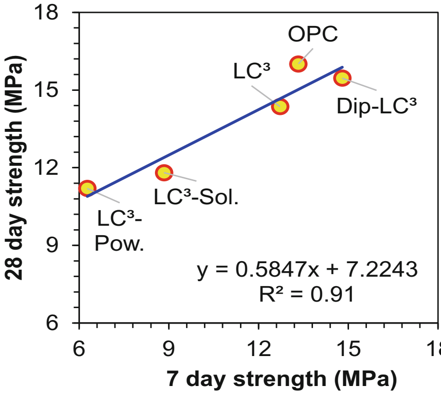


Fig. 6. Relation between 7-day and 28-day strength of all blends.

$$f'_{c,28} = 7.2 + 0.59 f'_{c,7} \quad (1)$$

4 Conclusions and Recommendations

The study comprehensively compares the compressive strength development between OPC, LC^3, and LC^3 treated with oxalic acid through various methods. The following conclusions can be drawn from the present study;

1. At 7 days, OPC exhibited a 5% higher strength than LC^3, which increased to 11% by 28 days. Although OPC demonstrated faster early strength development, LC^3 showed a 13% strength gain from 7 to 28 days, indicating potential for longer-term performance enhancements.
2. The 2M oxalic acid in powder form (LC^3-Pow.) initially led to a decrease in strength at 7 days, but a significant increase was observed by 28 days, suggesting a delayed but robust impact on the mortar's strength. The 1M solution (LC^3-Sol.) initially resulted in a substantial reduction in strength. However, a significant recovery was observed by 28 days.
3. The dipping process led to an initial 16% increase in strength at 7 days (Dip-LC^3), but the strength gain diminished over time, with only a 7% increase by 28 days which suggests that oxalic acid concentration needs to be optimized.
4. The comparative assessment shows that while LC^3 and its treated variants initially lag behind OPC, they close the gap significantly over time. Dip-LC^3, in particular, shows superior early strength due to enhanced reactivity from oxalic acid treatment.

References

1. Alqahtani, F.K., Rashid, K., Zafar, I., Iqbal Khan, M., Ababtain, A.A.: Production of sustainable green mortar by ultrahigh utilization of fly ash: Technical, economic and environmental assessment. Construct. Build. Mater. **281** (2021)

2. Scrivener, K., Martirena, F., Bishnoi, S., Maity, S.: Calcined clay limestone cements (LC3). Cem. Concr. Res. **114**, 49–56 (2018)
3. Zunino, F., Scrivener, K.: Increasing the kaolinite content of raw clays using particle classification techniques for use as supplementary cementitious materials. Construct. Build. Mater. **244** (2020)
4. Blouch, N., Rashid, K., Ju, M.: Exploring low-grade clay minerals diving into limestone calcined clay cement (LC3): characterization − hydration – performance. J. Clean. Product. **426** (2023)
5. Blouch, N., Rashid, K., Zafar, I., Ltifi, M., Ju, M.: Prioritization of low-grade kaolinite and mixed clays for performance evaluation of Limestone Calcined Clay Cement (LC3): multicriteria assessment. Appl. Clay Sci. **243**, 107080 (2023)
6. Bu, M., Yang, Q., Wang, P., Dong, B., Hou, D., Wang, Y.: Dissolution behaviors and mechanisms of metakaolin in acidic activators. Cement Concrete Res. **178** (2024)
7. Khalifa, A.Z., et al.: Advances in alkali-activation of clay minerals. Cement Concrete Res. **132** (2020)
8. Borno, I.B., Nair, N., Ashraf, W.: Alkali thermal fusion: a prospective route to enhance the reactivity of low-grade clay and utilize as supplementary cementitious material (SCM), Cement Concrete Compos, **147** (2024)
9. Komadel, P.: Acid activated clays: materials in continuous demand. Appl. Clay Sci. **131**, 84–99 (2016)
10. Deng, L., et al.: Effects of calcination and acid treatment on improving benzene adsorption performance of halloysite. Appl. Clay Sci. **181** (2019)
11. Mohammed, S., Elhem, G., Mekki, B.: Valorization of pozzolanicity of Algerian clay: optimization of the heat treatment and mechanical characteristics of the involved cement mortars. Appl. Clay Sci. **132–133**, 711–721 (2016)
12. Lin, S.-M., et al.: The synergistic mechanisms of citric acid and oxalic acid on the rapid dissolution of kaolinite. Appl. Clay Sci. **196** (2020)
13. Singh, N.K., Mishra, P.C., Singh, V.K., Narang, K.K.: Effects of hydroxyethyl cellulose and oxalic acid on the properties of cement. Cem. Concr. Res. **33**(9), 1319–1329 (2003)
14. Baba, A.A., Raji, M.A., Abdulkareem, A.Y., Ghosh, M.K., Bale, R.B., Adeyemi, C.O.: Dissolution kinetics potential of a biotite-rich kaolinite ore for industrial applications by oxalic acid solution. Min. Metall. Explor. **36**(6), 1091–1099 (2019)

Impact of Kaolin and Alumina-Silica Ratio on Cement Strength

Saqib Nawaz Khan[1], Tariq Jamil[2], Muhammad Danyal Sheikh[2(✉)], Ali Faruque[1], Syed Fakhar Abbas[1], and Abdur Rehman[1]

[1] Cherat Cement Company Limited, Karachi, Pakistan
{saqib.nawaz,ali.faruque,fakhar.abbas,abdur.rehman}@gfg.com.pk
[2] NED University of Engineering and Technology, Karachi, Pakistan
{tariqjamil,danyalsheikh}@neduet.edu.pk

Abstract. In Pakistan, blended cements are relatively rare, with most supplementary cementitious materials (SCMs) incorporated directly during concrete production. However, rising demand and the limited availability of high-quality SCMs have prompted cement manufacturers to investigate alternative options for blended cements to cater to the construction sector's requirements. Recent advancements in Limestone Calcined Clay Cement (LC3) have attracted the interest of Cherat Cement Company Limited. The company conducted extensive surveys in the northern regions of Pakistan, collecting 15 clay samples from various locations. The chemical composition and kaolinitic content of the clays were analysed using X-ray fluorescence (XRF) and the furnace protocol method, respectively. To assess the performance of LC3, compressive strength tests were conducted. Comparative samples of control specimens were prepared and tested under identical conditions for benchmarking. Fine calcined clay samples of varying grades were blended with cement to produce LC3. The results indicated that 9 out of the 15 LC3 samples demonstrated superior compressive strength compared to their OPC counterparts at 28 days. Conversely, the remaining 6 samples exhibited only a modest strength deficit, averaging 12%, demonstrating their close potential for optimization to match or exceed OPC standards. The main finding of the study is that all 9 high-performing samples, regardless of kaolinitic content, had an A-S ratio between 0.7 and 1.3, with the best compressive strength achieved at an optimal ratio close to 1. It has also been observed that low-kaolinite clay with an adequate amount of CaO content exhibits good strength development in cement.

Keywords: Kaolinitic Clays · Limestone Calcined Clay Cement (LC3) · Strength Validation

1 Introduction

Concrete has been a necessary element of construction, with global production reaching 10 billion cubic meters annually, a figure expected to remain steady [1]. Ordinary Portland Cement (OPC), serves as its primary binder in concrete. Cement demand closely

T. Ayub et al. (Eds.): GCGC 2025, LNCE 774, pp. 11–18, 2026.
https://doi.org/10.1007/978-981-95-6592-4_2

aligns with GDP and population growth, driving industries to scale up production. However, the sector contributes approximately 8–10% of global CO_2 emissions, posing significant environmental challenges [2, 3].

Alternative materials like fly ash, silica fume, and slag have shown promise in reducing OPC reliance, but their availability remains a challenge [4]. Reserves of clay are available in abundant quantities, making it a sustainable and cost-effective solution when combined with limestone to produce Limestone Calcined Clay Cement (LC3), which contains 50% clinker, 30% calcined clay, 15% limestone, and 5% gypsum [5]. Clays containing up to 40% kaolinite are suitable for making LC3. LC3 demonstrates properties that are comparable to or surpass those of OPC, with greater durability and economic benefits, attracting commercial interest [6].

Pakistan is gifted with abundant mineral resources, including substantial reserves of kaolin clay, as highlighted in a study [7, 8]. These deposits present a significant opportunity for the production of LC3 cement, offering a viable pathway to substantially reduce the carbon dioxide footprint of the cement industry [5]. Research indicates that a kaolinite concentration range of 40% to 75% in clay is optimal, shows good results in both compressive strength and durability tests [9, 10]. However, limited data on these clays and inadequate exploration of suitable deposits remain critical research gaps, posing challenges to the large-scale production of LC3 cement. Addressing these gaps could unlock immense potential for sustainable cement production in Pakistan.

This study aims to collect clay samples from regions near a factory to assess their kaolinite content using furnace protocol method, thereby reducing carbon emissions and transportation costs. The chemical composition of the clays was analysed using X-ray Fluorescence (XRF) to gain insights into their chemistry. Additionally, compressive strength tests were conducted at 2 and 28 days to evaluate the mechanical performance of the samples. A detailed analysis was then carried out to investigate the influence of chemical composition on compressive strength.

2 Materials and Methods

2.1 Raw Materials

Fifteen clay samples were extracted from various regions of northern Pakistan. The chemical composition of raw materials from X-ray fluorescence is given in (Table 1). Control and LC3 Cement was used for mortar preparation. CEN reference sand used to prepare mortar was obtained from Leucate, France. The Swiss Federal Institute of Technology (EPFL) provided a protocol for determining the kaolinite concentration in clay was used to calculate the kaolin percentage [11]. Three alumina crucibles placed in a muffle furnace maintained at a temperature of 850 °C to remove any redundant. Clay was then crushed in a laboratory jaw crusher “Retsch BB 200” to a product size of 1mm and was finely ground in a manual pulverizing mill “Herzog HSM”. The fine material was passed through a size 90 microns standard sieve conforming to DIN ISO 3310–1. The percentage of kaolinite content in the clays is further discussed in the Results and Discussion section. The chemical analysis of cement, and clays was determined by XRF in (Table 1).

Table 1. Chemical composition of raw materials

Code	Chemical Composition (%)				
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO
CC-1	38.8	26.5	18.3	3.9	0.0
CC-2	26.2	50.3	1.2	0.7	0.1
CC-3	52.5	28.9	1.5	1.4	0.2
CC-4	38.8	44.9	0.8	1.1	0.3
CC-5	44.8	36.3	0.0	0.7	0.5
CC-6	50.3	36.7	0.0	0.9	0.5
CC-7	44.3	32.0	8.5	0.9	0.6
CC-8	35.7	35.1	16.9	0.7	0.3
CC-9	28.7	37.2	21.8	0.7	0.2
CC-10	36.1	31.4	23.1	1.5	0.3
CC-11	45.3	23.0	3.6	5.6	0.4
CC-12	33.1	32.1	9.6	3.3	1.2
CC-13	50.2	40.9	1.5	0.6	0.0
CC-14	39.5	25.0	5.2	11.7	2.0
CC-15	61.6	16.3	5.0	3.7	1.0
Control Cement	18.4	4.2	3.0	60.8	1.9
Low Grade Limestone	18.1	3.1	2.5	40.0	0.6

2.2 Mix Composition

A total of 30 mixes were prepared for this study. Fifteen mixes were made using LC3 with clay samples from CC1 to CC15, and for each LC3 mix, a corresponding OPC mix was also prepared for comparison. The water-cement ratio was maintained at 0.5, with a cement-to-sand ratio of 1:3, and the detailed composition of the mixture is provided in Table 2. Cement mortar samples were mixed using an automatic mortar mixer, "ELE 039-0045/06" by Matest. Test specimens were prepared on a jolting table, "E-130" by Matest, and conditioned in a humidity cabinet, "SFC2C/RH," maintained at a temperature of 20 °C with a relative humidity of 90%.

Table 2. Weight of OPC and LC3 blends

Materials	Mortar	
	OPC (g)	LC3 (g)
Total Binder	450	450
OPC	450	247.5
Calcined Clay	0	135
Limestone	0	67.5
Water-Binder Ratio	0.5	0.5
Water	225	225
Fine Aggregate	1350	1350

Table 3. Result of Kaolin and A-S Ratio

Code	Kaolin (%)	A-S Ratio
CC-1	41.1	0.68
CC-2	82.9	1.92
CC-3	41.5	0.55
CC-4	66.9	1.15
CC-5	90.6	0.81
CC-6	55.7	0.73
CC-7	49.7	0.72
CC-8	62.9	0.98
CC-9	63.0	1.30
CC-10	63.0	0.87
CC-11	53.9	0.51
CC-12	55.5	0.97
CC-13	44.3	0.81
CC-14	17.3	0.63
CC-15	41.5	0.26

2.3 Experimental Test Method

A reference cement with each LC3 cement blend was used to prepare prismatic mortar specimens' size of 40 mm x 40 mm in cross-section and 160 mm in length. At 2, and 28 days cured mortar specimens were tested on a compression test machine 'Matest E160PD' applying a uniform load of 2.4 KN/second. Taken the best possible measures to perform the compressive strength test strictly following the guidelines of PS-232-2015 [12]. Consistency, setting times and soundness was also conducted on all five samples following PS-232-2015 [12].

3 Result and Discussion

3.1 Kaolin Content of Clays

Among the 15 pure clay samples tested, those with a higher alumina-to-silica ratio (indicating higher alumina levels) exhibited greater kaolinite content. Notably, 3 out of the 15 samples had an A-S ratio greater than 1. The silica (SiO_2) content in the clay samples ranges from 62% to 26%, while the alumina (Al_2O_2) content varies from 50% to 16%. Lime (CaO) content ranges from 0.7% to 12%. Low-kaolinitic clays are identified by their high silica content and extremely low alumina-to-silica (A-S) ratios.

One sample, CC5, stands out with a kaolinite content of up to 90%, despite its black color and high silica content; it has low ferrous content. No sample was found with an A-S ratio below 0.26, and nearly all had kaolinite content exceeding 40%, excluding one sample CC14. This sample had an A-S ratio of 0.63, low kaolinite content, a white color, and a noticeable CaO presence (Table 3).

3.2 Compressive Strength

Compressive strength measurements for LC3-based and OPC-based mortars were recorded at 2 and 28 days, with the results illustrated in Fig. 1. At 2 days, all LC3 variants exhibited lower strength compared to OPC, with an average reduction of 31% across all samples. The highest early strength was observed in sample CC9, which demonstrated only a 17% reduction compared to OPC. This better early performance compared to other clays is likely attributed to its optimal A-S ratio, which is crucial for gel formation and Portlandite consumption [13]. Conversely, the lowest 2-day strength was observed in a CC15 sample which has the highest silica content among all samples, with a reduction of nearly 46% corresponding to OPC sample.

By 28 days, LC3 mortars outperformed OPC in 9 out of 15 samples, with these 9 samples showing an average strength increase of 10% over OPC. However, 6 LC3 samples failed to achieve the targeted strength, averaging 12% lower compressive strength compared to OPC. The highest strength increment at 28 days was observed in sample CC4, with an increase of up to 21%, whereas the lowest strength was recorded in sample CC15, with a reduction of 30% compared to its OPC counterpart.

A noteworthy observation was made for sample CC14. Despite having the lowest kaolinitic content (17%), its compressive strength reached 41.5 MPa, only 9% lower than its OPC counterpart. This high strength is likely due to the elevated CaO content in the sample. Sample CC15 is a prime example in this study, despite having an eligible content of kaolinite (41.5%). However, due to its high silica content and low A-S ratio, the compressive strength could not reach the targeted strength.

The findings suggest that, regardless of high kaolinite content, the A-S ratio significantly influences compressive strength. For instance, sample CC2, with 82.9% kaolinitic content, failed to achieve the target strength due to its high A-S ratio. The optimal A-S ratio for achieving desirable compressive strength ranges between 0.7 and 1.3. Deviations from this range adversely affect the results. Additionally, the high CaO content in certain clay, as seen in CC14, also contributes positively to compressive strength.

The cluster of points inside the box shown in Fig. 2, where the A-S ratio ranges from 0.7 to 1.3, has achieved the targeted strength of 42.5 MPa. This demonstrates the validity of the study and the impact of the alumina-silica ratio on the compressive strength of mortar.

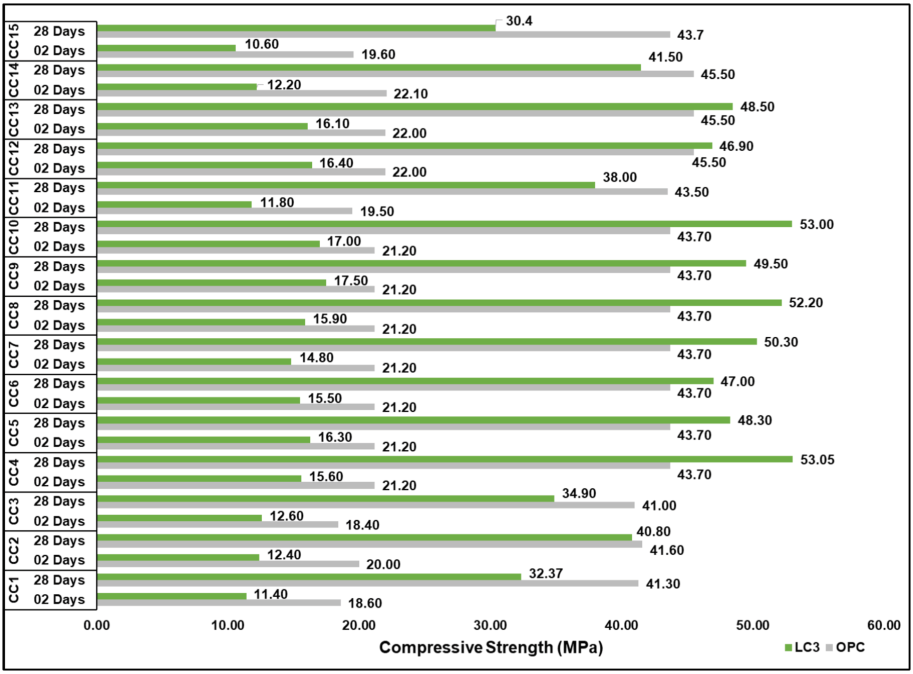


Fig. 1. Results of compressive strength of OPC and LC3 cement-based mortar samples on 2, and 28 days of curing.

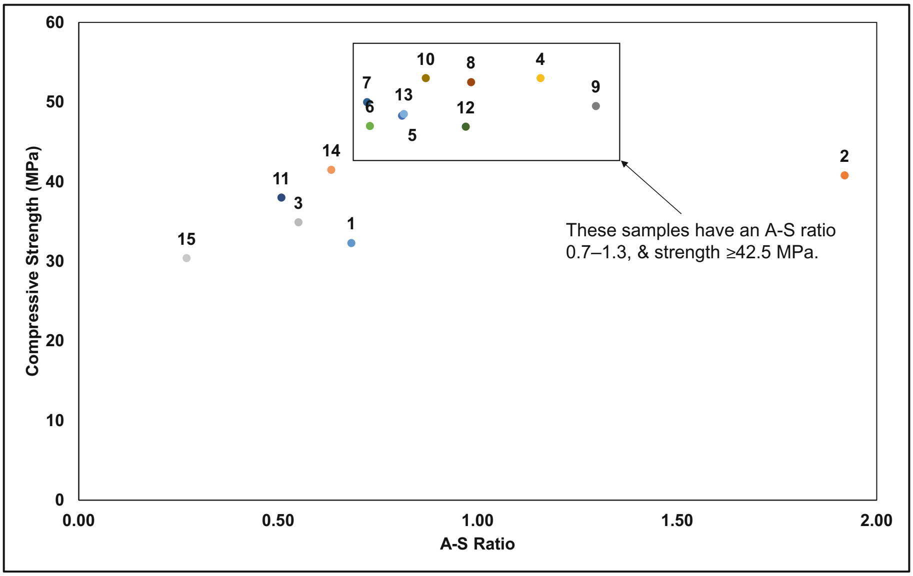


Fig. 2. Effect of alumina-to-silica ratio on compressive strength of mortar

4 Conclusion

In this study, various clay samples were collected from different regions of Pakistan to produce Limestone Calcined Clay Cement (LC3). Characterization tests were conducted to assess their chemical composition and kaolinitic content using the furnace protocol method. Additionally, compressive strength tests were performed to evaluate the performance of the cement. The conclusions drawn from this study are as follows:

1. Clays with a higher alumina-to-silica (A-S) ratio, particularly those exceeding 1, exhibited elevated kaolinite content, with values exceeding 60%. In contrast, low-kaolinitic clays were characterized by high silica levels and significantly low A-S ratios.
2. High kaolinitic content positively influenced compressive strength results. However, the alumina-to-silica ratio also played a critical role, suggesting that an optimized A-S ratio could further enhance strength properties.
3. A balanced A-S ratio in the range of 0.7 to 1.3, with an optimal value near 1, demonstrated the best performance, yielding adequate results in terms of compressive strength.
4. The presence of an adequate amount of CaO was observed to enhance compressive strength, even in clays with low kaolinitic content, as demonstrated by sample CC14.

References

1. Alexander, M., Bentur, A., Mindess, S.: Durability of concrete: design and construction. CRC Press (2017)

2. Van Ruijven, B.J., et al.: Long-term model-based projections of energy use and CO2 emissions from the global steel and cement industries. Resour. Conserv. Recycl. **112**, 15–36 (2016)
3. Huntzinger, D.N., Eatmon, T.D.: A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies. J. Clean. Prod. **17**(7), 668–675 (2009)
4. Unep, A., I.R.R. ASSESSMENT: the rise of environmental crime. UNEP, Nairobi (2016)
5. Sheikh, M.D., et al.: Comparative study on LC3-50 with OPC concrete using raw materials from Pakistan. Adv. Mater. Sci. Eng. **2023**(1), 5503670 (2023)
6. Reddy, V.A., et al.: Comparison of limestone calcined clay cement and ordinary Portland cement for stabilization/solidification of Pb-Zn smelter residue. Environ. Sci. Pollut. Res. 1–12 (2022)
7. Ismail, S., et al.: Physico-chemical characteristics of Nagar Parkar kaolin deposits, Thar Parkar district, Sindh, Pakistan. J. Himalayan Earth Sci. **48**(1) (2015)
8. Hussain, S.M.F., et al.: Initial search for low grade clay in Pakistan for producing LC3 ecofriendly cement. Low-carbon Mater. Green Construct. **1**(1), 15 (2023)
9. Kalipcilar, I., et al.: Sustainability of cement-stabilised clay: sulfate resistance. In: Proceedings of the Institution of Civil Engineers-Engineering Sustainability. Thomas Telford Ltd (2016)
10. Ayub, T., et al.: Effect of glass powder on the compressive strength and drying shrinkage behavior of OPC-and LC3-50-based cementitious composites of various strengths. Adv. Mater. Sci. Eng. **2024**(1), 8860083 (2024)
11. Fernandez Lopez, R.: Calcined clayey soils as a potential replacement for cement in developing countries. EPFL (2009)
12. Authority, P.S.Q.C.: PS-232–2015 (R): Specification for Cement. Karachi, Pakistan (2014)
13. Blouch, N., Rashid, K., Ju, M.: Exploring low-grade clay minerals diving into limestone calcined clay cement (LC3): characterization– hydration– performance. J. Clean. Prod. **426**, 139065 (2023)

Utilizing Waste Marble Powder as a Partial Cement Substitute: Enhancing Sustainability in Concrete Production

Muhammad Ubair Javed[1](✉), Hashir[2], Asfand Ahmed[2], and Muhammad Ali[1]

[1] The Islamia University, Bahawalpur 63100, Punjab, Pakistan
ubairce2024@gmail.com
[2] Quaid-E-Awam University of Engineering, S&T, Nawabshah 67450, Sindh, Pakistan

Abstract. The construction industry faces growing challenges related to carbon emissions and resource depletion, largely driven by the extensive use of cement. This study investigates the potential of waste marble powder (WMP), derived from the marble processing industry, as a partial replacement for cement in concrete production. Three types of marble powders—White Marble, Badal Gray Marble, and Granite Marble—were assessed for their impact on concrete's workability and compressive strength. Concrete specimens were prepared with WMP replacements ranging from 0% to 40% and evaluated using slump tests for workability and compressive strength tests over curing periods of 7, 28, and 90 days. Results indicated that Granite Marble Powder achieved the highest compressive strength (37.1 MPa at 20% replacement), attributed to its high silica content and enhanced pozzolanic activity. Badal Gray Marble Powder demonstrated a balance between strength (32.56 MPa at 20% replacement) and workability, making it a versatile choice for general applications. White Marble Powder improved workability but exhibited lower strength, limiting its use to non-structural applications. The findings underscore WMP's viability as a sustainable cementitious material, offering environmental and economic benefits through reduced cement consumption, landfill waste, and carbon emissions. This research aligns with circular economy principles, promoting eco-friendly construction practices.

Keywords: Waste Marble Powder (WMP) · Sustainable Cement Substitute · Carbon Emissions Reduction

1 Introduction

Global environmental problems are significantly influenced by construction practices, with cement manufacturing alone accounting for approximately 7% of global CO_2 emissions [1]. The process of producing cement, essential for concrete, generates emissions through energy consumption and limestone transformation. As global infrastructure development continues to expand, the resulting increase in cement production exacerbates environmental strain, emphasizing the need for scientific alternatives to mitigate its impact [2].

T. Ayub et al. (Eds.): GCGC 2025, LNCE 774, pp. 19–26, 2026.
https://doi.org/10.1007/978-981-95-6592-4_3

Concrete, a composite of cement, aggregates, water, and sometimes admixtures, is fundamental to modern construction due to its versatility and durability [3]. However, its environmental footprint is concerning, as each ton of cement produced emits nearly one ton of CO_2, contributing to climate change [4]. This has driven researchers to explore supplementary cementitious materials (SCMs) to reduce cement use, cut emissions, and conserve resources.

Transforming marble industry waste into a supplementary material offers a sustainable solution, addressing both the environmental challenges of cement production and the waste management issues of marble processing. The polishing and cutting of marble generate significant waste, often dumped into natural environments, causing ecological harm and health risks. Using waste marble powder (WMP) as a partial cement substitute targets these dual challenges, paving the way for sustainable construction practices [5].

This study evaluates locally sourced WMP for its feasibility as a partial cement replacement in concrete. By examining the mechanical performance and durability of concrete containing WMP, the optimal replacement percentage for maintaining workability and compressive strength can be identified. Different marble powders, such as white marble, gray marble, and granite powder, offer varied effects due to their unique chemical compositions, making them suitable for diverse applications.

Using WMP to replace conventional cement provides significant environmental and economic benefits. It reduces the carbon footprint of concrete by lowering cement usage, minimizes landfill waste, and mitigates resource depletion. This innovative approach aligns with global trends in sustainable material use, contributing to circular economy principles and promoting environmentally responsible construction solutions.

2 Methodology

The research methodology ensures an exhaustive assessment of waste marble powder (WMP) potential for partial cement substitution in concrete production. Waste marble powder evaluation proceeded through stages of material selection to result analysis while implementing international standards to maintain dependable test results.

2.1 Materials Used

Cement

The cement used in this research is DG Cement, a commonly available 53 grade Ordinary Portland Cement (OPC) in Pakistan.

Fine Aggregate

The fine aggregate used is locally sourced Sakhi Sarwar sand, which passes through a 4.75 mm sieve. The sand meets the requirements for clean, durable fine aggregate.

Coarse Aggregate

Coarse aggregates are crushed stone aggregates with a maximum size of 20 mm, sourced from the local market.

Waste Marble Powder

The waste marble powders were sourced from a marble factory in Bahawalpur and included white marble powder, Badal gray marble powder, and granite powder, each characterized by distinct chemical compositions as shown in the Table 1. These powders were analyzed to determine their specific chemical constituents, such as calcium carbonate ($CaCO_3$) and silica (SiO_2), which are crucial for their performance as supplementary cementitious materials (SCMs).

Table 1. Chemical composition of marble powders

Component	White Marble Powder (%)	Badal Gray Marble Powder (%)	Granite Powder (%)
$CaCO_3$	84.4	54.5	1.5
SiO_2	2.31	24.5	75
Al_2O_3	3.5	11.5	12
MgO	4	1.2	–
Fe_2O_3	0.07	–	4

2.2 Experimental Methods

Sample Preparations

Concrete samples were prepared by replacing cement with waste marble powder at varying percentages of 0%, 10%, 20%, 30%, and 40% by weight. For each replacement level, cylindrical concrete specimens measuring 100 mm in diameter and 200 mm in height were cast. The mix design followed a ratio of 1:1.5:3 (cement: fine aggregate: coarse aggregate) with a constant water-to-cement (w/c) ratio of 0.46 to ensure consistent workability across all mixes. Details are provided in Table 2.

The materials were mixed in a standard mechanical mixer to achieve uniformity, and the fresh concrete was placed into cylindrical molds in three layers, each compacted with a tamping rod to remove air voids. After casting, the molds were covered with damp burlap and allowed to cure at room temperature for 24 h before being demolded. Following demolding, the specimens were submerged in a curing tank filled with water to ensure proper hydration for periods of 7, 28, and 90 days.

Testing Procedures

Two primary tests were conducted to evaluate the properties of the concrete: the slump test for workability and the compressive strength test. The workability of each concrete mix was assessed using the slump cone test as per ASTM C143. The compressive strength of concrete specimens was tested according to ASTM C39 at intervals of 7, 28, and 90 days.

Table 2. Mix Proportions and Sample Details

Replacement %	W/C Ratio	Mix Ratio
0%	0.46	1:1.5:3
10%	0.46	1:1.5:3
20%	0.46	1:1.5:3
30%	0.46	1:1.5:3
40%	0.46	1:1.5:3

3 Results and Discussion

The study evaluated the properties of both fresh and hardened concrete, specifically focusing on workability and compressive strength. The research examined three types of marble powders: White Marble, Badal Gray Marble, and Granite Marble.

3.1 Workability

The workability of concrete mixes was assessed using the slump test in accordance with ASTM C143 standards. Table 3 summarizes the slump test results for normal concrete (M20) and concrete mixes with varying percentages of WMP replacement.

Table 3. Slump Test Results at W/C = 0.46

Concrete Type	0%	10%	20%	30%	40%
M20 Normal Concrete	45 mm	45 mm	45 mm	45 mm	45 mm
White Marble Concrete	0 mm	50 mm	60 mm	72 mm	50 mm
Badal Gray Marble Concrete	0 mm	60 mm	70 mm	80 mm	60 mm
Granite Marble Concrete	0 mm	45 mm	55 mm	60 mm	50 mm

The results indicate a general increase in slump values with higher percentages of WMP replacement, peaking at 30%, followed by a decline. This trend is attributed to the finer particle size and spherical morphology of WMP, which enhance the packing density of the concrete mix and improve the flowability of the cement paste [6]. However, beyond 30% replacement, excess WMP leads to reduced cohesion and increased water demand, negatively affecting workability.

Badal Gray Marble Concrete demonstrated the highest slump value (80 mm) at 30% replacement, indicating superior workability. White Marble Concrete achieved moderate workability (72 mm) at 30% replacement. Granite Marble Concrete exhibited the lowest slump value (60 mm) at 30% replacement.

3.2 Compressive Strength

The compressive strength of concrete mixes was evaluated at 7, 28, and 90 days in accordance with ASTM C39 standards. Results for normal concrete and WMP-based concrete are presented below (Table 4).

White Marble Concrete

Table 4. Compressive Strength of M20 and White Marble Concrete

Concrete Type	7 Days (MPa)	28 Days (MPa)	90Days (MPa)
M20 Normal Concrete	21	24	26
10% White Marble Concrete	24.9	27.31	29.43
20% White Marble Concrete	19.9	22.5	25.3
30% White Marble Concrete	16	21	23.9
40% White Marble Concrete	14.5	19	22

White Marble Concrete achieved its highest compressive strength (29.43 MPa) at 90 days with 10% replacement, indicating this as the optimal replacement level. Beyond 10%, the compressive strength decreased due to the dilution of cementitious material caused by excessive WMP [6].

Badal Gray Marble Concrete

Table 5. Compressive Strength of M20 and Badal Gray Marble Concrete

Concrete Type	7 Days (MPa)	28 Days (MPa)	90 Days (MPa)
M20 Normal Concrete	21	24	26
10% Badal Gray Concrete	23.4	28.9	30.6
20% Badal Gray Concrete	24.5	29.7	32.56
30% Badal Gray Concrete	21.34	23.5	25.7
40% Badal Gray Concrete	19.4	21.43	23.67

Badal Gray Marble Concrete achieved its peak compressive strength (32.56 MPa) at 90 days with 20% replacement. This improvement is attributed to its balanced chemical composition, which includes an optimal combination of calcium carbonate ($CaCO_3$) and silica (SiO_2), facilitating enhanced cementitious reactions [7] (Table 5).

Table 6. Compressive Strength of M20 and Granite Marble Concrete

Concrete Type	7 Days (MPa)	28 Days (MPa)	90 Days (MPa)
M20 Normal Concrete	21	24	26
10% Granite Concrete	25.4	29.8	35.2
20% Granite Concrete	26.8	35.7	37.1
30% Granite Concrete	21.6	23.5	25.4
40% Granite Concrete	18.5	21.6	23.5

Granite Marble Concrete

Granite Marble Concrete exhibited the highest compressive strength among all mixes, reaching 37.1 MPa at 20% replacement after 90 days. This superior performance is attributed to its high silica (SiO_2) content, which significantly enhances pozzolanic activity and the formation of calcium silicate hydrates (CSH) [8]. However, beyond 20% replacement, the strength declined due to excessive dilution of the cement matrix (Table 6).

3.3 Comparison of Strength and Workability

Three marble powders reveal distinct differences in their impact on the strength and workability of concrete, highlighting their suitability for different applications. Granite Marble Concrete stood out by achieving the highest compressive strength, reaching 37.1 MPa at 20% replacement after 90 days. However, this high strength came at the cost of workability, as the reduced cohesion and increased particle friction in the mix limited its flowability, making it less suitable for applications where high workability is essential [8] (Fig. 1).

Badal Gray Marble Concrete offers a balanced performance, combining moderate strength and good workability. At a 20% replacement level, it achieves a compressive strength of 32.56 MPa, which is lower than Granite Marble Concrete but significantly higher than normal concrete. Its balanced calcium carbonate ($CaCO_3$) and silica (SiO_2) content contribute to its versatility. Calcium carbonate improves flowability, while silica enhances strength by promoting CSH formation during hydration. This makes it ideal for general construction projects requiring both strength and ease of use [9].

In contrast, White Marble Concrete has moderate workability but lower compressive strength, peaking at 29.43 MPa at a 10% replacement level. Its high calcium carbonate content gives it a fine, smooth texture, improving flowability. However, its low silica content limits pozzolanic reactivity, restricting strength development. As a result, it is better suited for decorative or non-structural applications, such as countertops or interior finishes, where aesthetics and workability are prioritized over strength [10].

Granite Marble Concrete excels in strength due to its high silica content and pozzolanic activity, making it the strongest among the three. However, its angular particles reduce workability, making it harder to handle [11]. This makes it ideal for structural

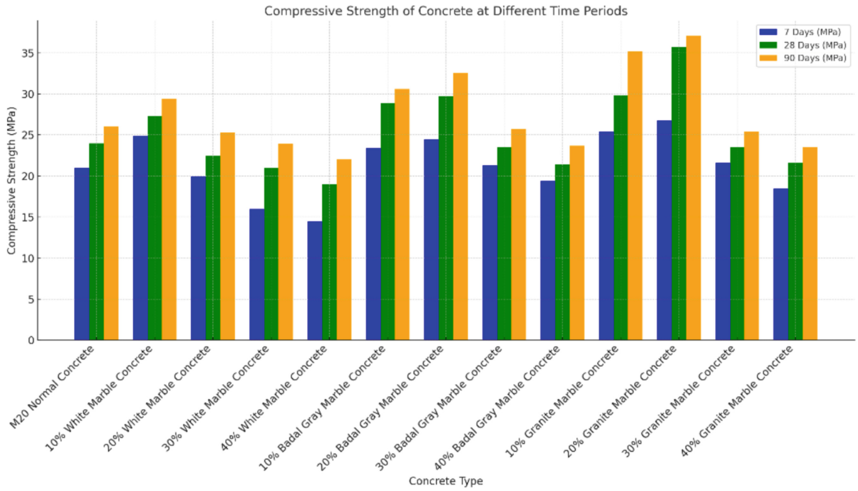


Fig. 1. Compressive strength of concrete

projects, such as foundations or load-bearing walls, where high strength is critical. While it lacks the workability of Badal Gray or White Marble Concrete, its superior strength makes it a top choice for demanding structural applications [12].

4 Conclusion

This study demonstrates the efficacy of utilizing waste marble powder (WMP) as a partial cement replacement in concrete production, presenting a sustainable solution to address environmental challenges associated with cement manufacturing and marble industry waste. Among the three marble powders tested, Granite Marble Powder emerged as the most promising option for structural applications, achieving the highest compressive strength due to its elevated silica content and superior pozzolanic activity. However, its reduced workability highlights its suitability for load-bearing applications requiring high strength rather than high flowability.

Badal Gray Marble Powder provided a balanced performance, offering moderate strength and workability, making it ideal for diverse construction projects where these properties are equally important. White Marble Powder, with its smoother texture and high calcium carbonate content, enhanced workability but demonstrated limited strength development, restricting its use to decorative or non-load-bearing applications.

References

1. Habert, G., et al.: Environmental impacts and decarbonization strategies in the cement and concrete industries. Nat. Rev. Earth Environ. **1**(11), 559–573 (2020)
2. Makul, N.: Modern sustainable cement and concrete composites: Review of current status, challenges and guidelines. Sustain. Mater. Technol. **25**, e00155 (2020)
3. Li, Z., et al.: Advanced concrete technology. Wiley (2022)

4. Belaïd, F.: How does concrete and cement industry transformation contribute to mitigating climate change challenges? Resources Conserv. Recycl. Adv. **15**, 200084 (2022)
5. Sathe, S., Patil, S., Bhosale, Y.N.: Investigation of strength, durability, and microstructure properties of concrete with waste marble powder as a partial replacement of cement. World J. Eng. (2024)
6. Prakash, B., et al.: Exploring the potential of waste marble powder as a sustainable substitute to cement in cement-based composites: a review. Constr. Build. Mater. **401**, 132887 (2023)
7. Abbas, M.M., Muntean, R.: Marble powder as a sustainable cement replacement: a review of mechanical properties. Sustainability **17**(2), 736 (2025)
8. BEng, L.M.: Precipitated Calcium Carbonate as Sustainable Supplementary Cementitious Material to Reduce the Environmental Impact of Portland Cement. University of Aberdeen (2021)
9. Chavhan, P.J., Bhole, S.: To study the behaviour of marble powder as supplementry cementitious material in concrete. Int. J. Eng. Res. Appl. **4**(1), 377–381 (2014)
10. Wang, Y., et al.: Mechanical behavior of concrete prepared with waste marble powder. Sustainability **14**(7), 4170 (2022)
11. Asadi Shamsabadi, E., et al.: Performance of concrete with waste granite powder: the effect of superplasticizers. Appl. Sci. **8**(10), 1808 (2018)
12. Basaran, B., et al.: Effects of waste powder, fine and coarse marble aggregates on concrete compressive strength. Sustainability **14**(21), 14388 (2022)

Utilization of Stone Waste Powder as Partial Replacement of Precursors in Alkali-Activated Lightweight Aggregate Concrete

Sohail Ahmad, Muhammad Noman(✉), Muhammad Muneeb Nawaz, and Sartaj Khan

Department of Civil Engineering, International Islamic University, Islamabad, Pakistan
muhammad.noman@iiu.edu.pk

Abstract. Alkali-activated concrete (AAC) has emerged as a viable low-carbon alternative to Portland cement; however, the scarcity of conventional precursors such as fly ash (FA) and granulated blast furnace slag (GBFS) poses challenges to its scalability. This study explores the utilization of waste powders from the stone processing industry, including marble waste powder (MWP), granite waste powder (GWP), and pumice waste powder (PWP), as sustainable precursors for alkali-activated lightweight aggregate concrete (AAC-LWAC). Locally available lightweight pumice stones were used to replace the normal coarse aggregates, and the FA precursor was replaced with waste powders in proportions ranging from 25% to 100%. X-ray diffraction analysis was conducted to investigate the characterization and reactivity of the powders. Furthermore, the mechanical properties of the resulting materials were evaluated to determine the compressive strength, modulus of elasticity, and stress-strain relationships. The results showed that at lower replacement levels (25–50%), lightweight pumice waste powder (LPWP) concrete exhibited superior performance among the studied waste powders, achieving strength close to the control sample and demonstrating better ductility and strain capacity, particularly at 50% replacement. In contrast, at higher replacement levels (75–100%), all powders showed significant reductions in strength and stiffness. Granite & Marble waste powder concretes were acceptable at lower replacement levels but are more suited for non-structural or insulating uses where high mechanical performance is not critical.

Keywords: Alkali-activated · Lightweight · Waste Powder · Aggregate

1 Introduction

The cement industry profoundly affects the environment, causing about 8% of the global carbon dioxide emissions, roughly equal to 4.4 billion tons per year [1]. About 40% of the emissions result from fuel burning and electricity consumption, while the remaining 60% come from the decomposition of CaCO3, producing free CO_2 [2].

Among recent advancements, alkali-activated concrete (AAC) has emerged as a potential solution, offering comparable performance to traditional cement while significantly reducing CO_2 emissions. However, as a relatively new material with limited

T. Ayub et al. (Eds.): GCGC 2025, LNCE 774, pp. 27–35, 2026.
https://doi.org/10.1007/978-981-95-6592-4_4

research, further scientific investigation is needed to fully explore its feasibility across various scales and reliably predict its performance. A critical challenge lies in the availability of precursors like fly ash (FA) and granulated blast furnace slag (GBFS) [3]. While slag can replace clinker by 70–90%, its global supply accounts for only 5% of clinker production [4]. Fly ash availability is slightly higher, but its properties are inconsistent [4], and its supply is declining due to advancements in cleaner energy production processes and a global shift away from coal-based industries. Furthermore, weather conditions can disrupt the availability of both fly ash and GBFS, worsening supply challenges.

Natural stone powders, such as marble powder, granite powder, and pumice stone powder, are byproducts of stone cutting and grinding processes, presenting both opportunities and challenges. Approximately 20–30% of stone blocks are converted into powder during processing [5], generating billions of tons of waste globally yearly. While these materials have potential applications in construction, art, and landscaping, they pose significant health risks due to the crystalline silica they contain, which can cause respiratory diseases such as silicosis and lung cancer when inhaled. Additionally, improper disposal of these powders can lead to environmental issues, including waterways, soil, and air contamination, thereby impacting ecosystems. Managing large quantities of waste powder further complicates storage and disposal for industries.

Incorporating stone processing by-products, such as granite, marble, and pumice powders, into lightweight aggregate concrete (LWAC) can further enhance its environmental and structural benefits. These waste powders, with their silica and alumina content, can serve as precursors in alkali-activated LWAC, enabling efficient waste management while improving material performance. This integration addresses the challenges of precursor scarcity and aligns with efforts to reduce the environmental footprint of concrete production.

This study explores the potential of utilizing waste powders from the stone processing industry, specifically marble, granite, and pumice powders, as sustainable precursors for alkali-activated lightweight aggregate concrete (AAC-LWAC). Despite stone powders' significant potential in AAC applications, a notable gap exists in understanding their mechanical performance and suitability as reliable precursors in lightweight concrete. The findings of this study are expected to demonstrate the practical viability of stone powder-based AAC-LWAC as a low-carbon, resource-efficient material, offering a sustainable solution for the construction industry.

2 Experimental Work

2.1 Materials

The pumice stone used in this study was sourced from volcanic mines in the Chagai district of the Baluchistan province. The stones were light in weight, with an average density of 1150 kg/m^3, and were characterized by their white color and porous structure.

The waste powders, including Marble Waste Powder (MWP), Granite Waste Powders (GWP), and Pumice Waste Powder (PWP), were obtained from the local stone processing industry. To ensure uniformity, the waste powders were dried in the oven for 24 h at a constant temperature of 105 °C. The dried waste powders were sieved through No. 200, confirming the maximum size of 75 μm. The X-ray Diffraction (XRD) analysis of the dust is presented in detail in Sect. 3.1. The physical and chemical properties of the waste powders used in this study are presented in Table 1.

The alkali activator (AA) consisted of a 12-molar sodium hydroxide (NaOH) solution and a sodium metasilicate (Na_2SiO_3) solution. The sodium metasilicate was used in a ratio of 2:1 by mass relative to NaOH. The NaOH solution was prepared by dissolving NaOH in water at a ratio of 1:1. Similarly, the sodium metasilicate solution included water in a ratio of 1:2 by mass of sodium metasilicate. These solutions were combined in the specified proportions to achieve the desired silica-to-alumina ratio and ensure effective activation of the precursors. The activators were prepared 24 h before the casting of the specimens.

Table 1. The physical & chemical properties of waste powders

Property	MWP	GWP	PWP
Physical Properties			
Color	White to light grey	Pink to grey	White
Texture	Smooth, fine	Coarse, granular	Porous, fine
Specific Gravity	2.64	2.72	0.8–1.0
Bulk Density (kg/m^3)	1232	1418	600–900
Water Absorption (%)	0.15	0.16	30–60
Chemical Properties			
SiO_2 (%)	4	68	72.1
CaO (%)	53	3	1.7
Al_2O_3 (%)	<1	13	12.8
Fe_2O_3 (%)	<0.5	3.5	1.5
MgO (%)	0.78	0.72	0.6
K_2O (%)	<0.2	4.3	3.1
Na_2O (%)	<0.1	2.25	3.2
LOI (%)	41	0.75	6

2.2 Sample Preparation

The mix design for the alkali-activated concrete (AAC) was developed based on methods reported in the literature [6, 7], with modifications to accommodate the use of lightweight aggregate. The detailed proportions of the mix are presented in Table 2. The precursor-to-coarse aggregate ratio was maintained at 1:3, the precursor-to-fine aggregate ratio at 1:2, and the AA-to-precursor ratio at 1:2. The alkali activator (AA), sand, and coarse lightweight aggregate (LWA) were mixed in a ratio of 1:2:4 by volume. Due to the pumice aggregate's high absorption capacity, the trial mixes' workability was low; therefore, additional water and a superplasticizer were introduced to improve the mix. The extra water content corresponded to a water-to-precursor ratio of 0.42, including the water used to prepare the alkali activator. The total weight of the fresh concrete was 1521 kg/m^3. Once the AA-LWAC mixture was prepared, it was cast into cylindrical moulds 100 mm in diameter and 200 mm in height. The samples were left in the moulds for 48 h before being transferred to an electric oven, where they were cured at a constant temperature of 60 °C for 72 h.

In this experimental study, 14 mix proportions were designed. The fly ash content in the AAC was replaced in the ratios of 25%, 50%, 75%, and 100% by GWP, LWP, and PWP. A reference mixture (CS) was prepared with no lightweight aggregates to compare the result. Three specimens were prepared for each test, making 32 concrete specimens with the average value of the three considered.

Table 2. Mix design for AA-LWAC

Material	Dust/FA	Fine Agg	C. Agg	NaOH	Na_2SiO_3	Water	s.p
Mass (kg/m^3)	214.5	457.6	651	35.75	71.5	89.38	2.15

2.3 Experimental Procedure

After curing, the samples were wrapped in plastic and placed in the laboratory for another 56 days at an average temperature of 25 ± 5 °C. The samples were further tested for their compression strength in the deformation-controlled universal testing machine (UTM) using the standard loading rates specified by the ASTM C39 [8]. The deformation of the samples was measured with the linear variable differential transducers (LVDT) attached to the UTM. The displacement of the plates was controlled using the 100 mm LVDT. The results from the load-deformation were used to determine the stress-strain relationships, modulus of elasticity, and stiffness.

3 Results and Discussion

3.1 XRD Results

The results of X-ray diffraction (XRD) analysis in Fig. 1 identified crystalline and amorphous phases of FA, PWP, MWP, and GWP, providing insight into their mineralogical compositions and potential suitability for AA-LWAC. FA exhibits a highly amorphous structure with high silica and alumina content, which is critical for forming aluminosilicate gels during alkali activation. Crystalline phases like quartz, mullite, and calcite in FA are less reactive but contribute to its geopolymer precursor role. PWP shows significant quartz (SiO_2), albite ($NaAlSi_3O_8$), and zeolites, enhancing reactivity and mechanical properties in AAC. In the case of MWP, the XRD pattern reveals a high calcite content characteristic of marble, which impacts carbonation resistance and texture, though its environmental implications require further study. GWP's quartz, feldspar, and mica enhance AAC's reactivity, durability, and mechanical performance. These materials demonstrate promise as sustainable alternatives in alkali-activated concrete, though further research on their long-term performance and environmental impact is essential. The properties of these minerals suggest that the materials can be effectively used in alkali-activated concrete, especially in applications requiring durability and sustainability.

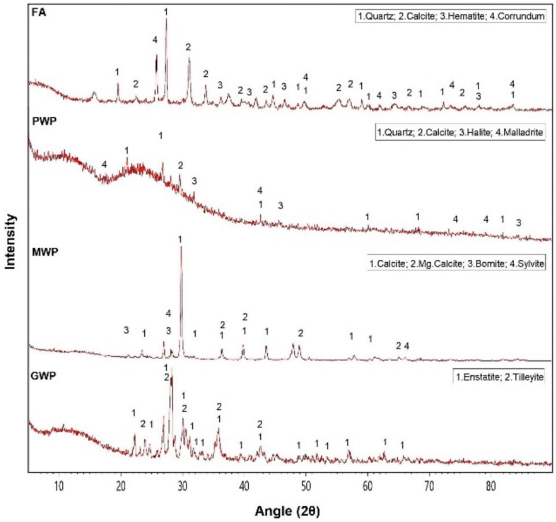


Fig. 1. XRD for Precursors in AA-LWAC

3.2 Effects on Ultimate Compressive Strength

The compressive strength of the control sample (CS) with normal cement and coarse aggregate was 22.48 MPa, which was expected given the design mix. When the coarse aggregates were replaced with lightweight pumice stones, the compressive strength of the replaced sample (LCS) was 14.27 MPa, showing a reduction of 36.5%. This is expected because lightweight aggregates have higher porosity and lower density, reducing the overall strength. Replacing the cement with alkali activators, including 100% FA (LFA100), further reduced the strength to 13.56 MPa, which is 39.6% less than the CS. The minimal strength difference between LFA100 and LCS (0.71 MPa or 5%) reflects the highly amorphous structure of FA, which enhances its alkali-activation potential but may not fully compensate for the loss of cement's binding properties [9, 10].

At 25% replacement, LGWP maintains relatively high strength (12.51 MPa), with only a 7% reduction from LFA100 (see Fig. 2), due to the high silica content in granite waste powder (GWP) aiding alkali activation. However, strength drops sharply at 50–100% replacements (39.5–65.0%) as reduced reactivity from quartz and feldspar affects structural integrity. GWP is optimal at ≤25% replacement; beyond this, it is unsuitable for load-bearing applications.

Due to its high calcite content, MWP acts primarily as a filler, resulting in significant strength reductions (38.3–81.3%) across all replacement levels. The limited reactivity of calcite and phases like dolomite further hampers performance, making MWP unsuitable for structural use.

In contrast, LPWP exhibits superior performance, with only an 8.6% strength reduction at 25% replacement. Even at higher levels (50–100%), LPWP outperforms LGWP and MWP due to its high silica and alumina content and zeolite presence, which enhance reactivity in the alkali-activation process, making it ideal for AA-LWAC applications.

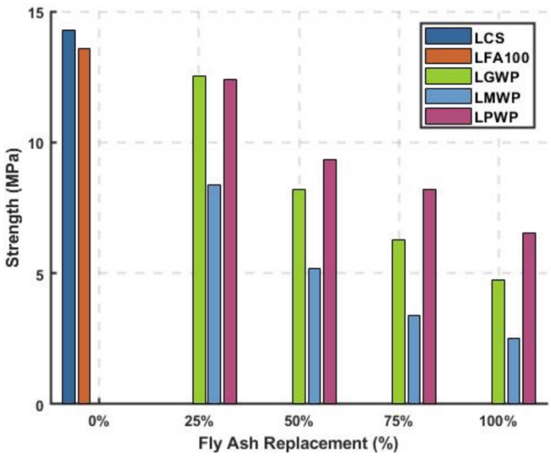


Fig. 2. Ultimate Compressive Strength of AA-LWAC with replacement of FA precursor with waste stone dust

3.3 Effects of Dust Replacement on Stress-Strain Curves

The descending portion of the stress-strain curves shown in Fig. 3 highlights the post-peak behavior of the materials, which is critical for assessing ductility and energy absorption. At 25% replacement, LGWP, LMWP, and LPWP exhibited gradual stress declines, indicating ductile failure modes due to sufficient gel formation and cohesion. Increasing replacement levels (50–75%) caused steeper post-peak slopes, reflecting a transition to brittle behavior driven by weaker interfacial bonds and reduced hydration products. At 100% replacement, all mixes demonstrated highly brittle failure with abrupt stress drops, attributed to inadequate gel phase formation or weak microstructures.

Low replacement levels (25%) in LMWP and LPWP resembled the control mix, benefiting from improved packing density and stress redistribution capacity. However, higher replacement levels diminished these properties, indicating a shift toward brittleness. LPWP100's porous microstructure and LMWP100's weaker matrix further amplified brittle behavior. These findings underline the suitability of low replacement levels for applications requiring ductility and energy dissipation, while higher replacements compromise structural performance.

The secant stiffness of a material can be evaluated using the secant modulus typically determined from the slope of the stress-strain curve connecting the origin to 40% of the ultimate strength. The slope of the stress-strain curve from the origin to 40% of the ultimate strength was taken as secant stiffness. This study presents the secant modulus for different samples at various replacement levels (see Fig. 3d) in percentage form relative to the LCS taken as 100%.

As can be seen in Fig. 3d, at 0% replacement level, the LCS shows the highest secant modulus and the highest stiffness compared to other samples. As the replacement level increases, the various waste powders' secant modulus decreases, reflecting a reduction in material stiffness [11, 12]. Among the waste powders, LGWP shows the most significant drop in secant modulus as the replacement level increases, with values decreasing from 81.7% at 25% replacement to 36.5% at 100% replacement, providing a significant loss of stiffness at higher replacement levels. This substantial loss of stiffness highlights the fragility of the material's microstructure at higher replacement levels. Similarly, LMWP shows a gradual decrease in stiffness, with values dropping from 68.0% at 25% replacement to 38.2% at 100% replacement. In contrast, LPWP demonstrates more consistent stiffness values, with a moderate decline from 77.5% at 25% replacement to 51.1% at 100% replacement. This stability in stiffness reaffirms LPWP's enhanced matrix properties due to its chemical composition, making it a viable choice for AA-LWAC applications that demand both strength and ductility.

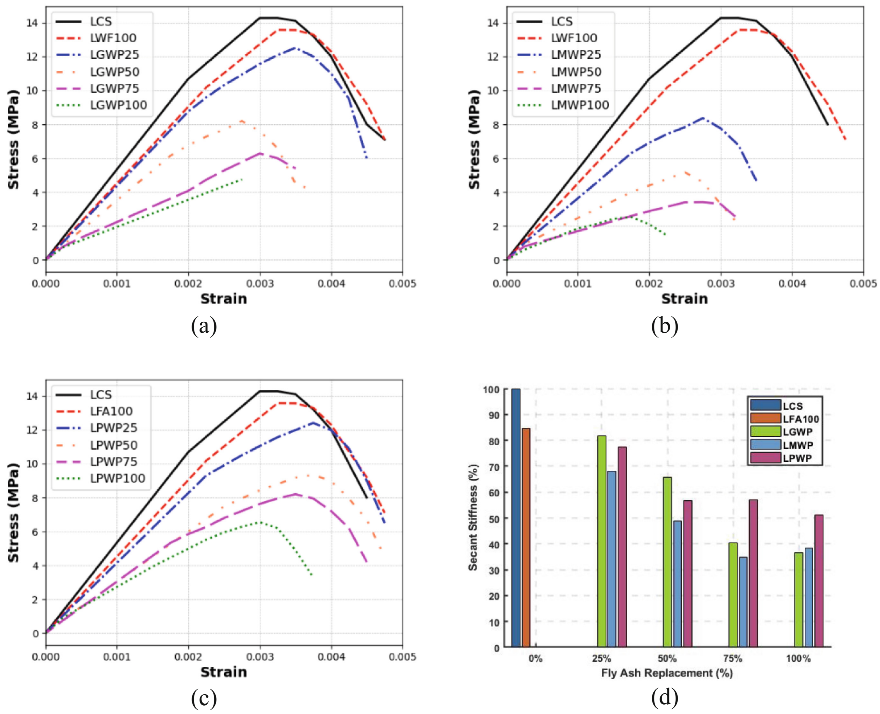


Fig. 3. Stress-strain behavior at various replacement levels. (a) Replacements with GWP, (b) Replacements with MWP, (c) Replacement with PWP, & (d) Relative secant stiffness at varying percentages of waste powders.

4 Conclusion

This study evaluated the mechanical performance of AA-LWAC using GWP, MWP, and PWP as partial replacements for FA as a precursor of AAC. Key findings are:

1. LPWP at 25–50% replacement showed superior compressive strength, close to the control sample. However, all powders exhibited reduced strength at 75–100% replacement, with LPWP performing better overall.
2. LPWP displayed better strain capacity and ductility, particularly at 50% replacement (ultimate strain: 0.0035). LGWP showed comparable strength but lower ductility (ultimate strain: 0.0027). Higher replacement levels reduced ductility for all powders.
3. Secant stiffness decreased with increasing replacement levels. LPWP maintained moderate stiffness, making it more suitable for lightweight, non-load-bearing applications. LGWP and LMWP showed significant stiffness reductions at higher replacements.
4. LPWP balanced strength, ductility, and stiffness, making it suitable for moderate-strength applications. LGWP and LMWP are better for non-structural or insulating purposes.
5. These waste powders reduce cement use and carbon emissions, with LPWP ideal for lightweight structures like partition walls, precast elements, and insulation panels.

References

1. Belaïd, F.: How does concrete and cement industry transformation contribute to mitigating climate change challenges? Resour. Conserv. Recycl. Adv. **15**, 200084 (2022). https://doi.org/10.1016/j.rcradv.2022.200084
2. Sharma, M., Bishnoi, S., Martirena, F., Scrivener, K.: Limestone calcined clay cement and concrete: a state-of-the-art review. Cem. Concr. Res. **149**, 106564 (2021). https://doi.org/10.1016/j.cemconres.2021.106564
3. Dacić, A., Kopecskó, K., Fenyvesi, O., Merta, I.: The obstacles to a broader application of alkali-activated binders as a sustainable alternative—a review (2023). https://doi.org/10.3390/ma16083121
4. Scrivener, K.L., John, V.M., Gartner, E.M.: Eco-efficient cements: potential economically viable solutions for a low-CO2 cement-based materials industry. Cem. Concr. Res. **114**, 2–26 (2018). https://doi.org/10.1016/j.cemconres.2018.03.015
5. Yurdakul, M.: Natural stone waste generation from the perspective of natural stone processing plants: an industrial-scale case study in the province of Bilecik, Turkey. J. Clean. Prod. **276**, 123339 (2020). https://doi.org/10.1016/j.jclepro.2020.123339
6. Sun, B., Sun, Y., Ye, G., De Schutter, G.: A mix design methodology of blast furnace slag and fly ash-based alkali-activated concrete. Cem. Concr. Compos. **140**, 105076 (2023)
7. Lian, C., Wang, Y., Liu, S., Hao, H., Hao, Y.: Experimental study on dynamic mechanical properties of fly ash and slag based alkali-activated concrete. Constr. Build. Mater. **364**, 129912 (2023). https://doi.org/10.1016/j.conbuildmat.2022.129912
8. ASTM C39: ASTM C39/C39M-20, Standard test method for compressive strength of cylindrical concrete specimens. In: Annual Book of ASTM Standards. West Conshohocken, PA (2020)
9. Pacheco-Torgal, F., Labrincha, J., Leonelli, C., Palomo, A., Chindaprasit, P.: Handbook of alkali-activated cements, mortars and concretes. Elsevier (2014)
10. Tataranni, P., Besemer, G.M., Bortolotti, V., Sangiorgi, C.: Preliminary research on the physical and mechanical properties of alternative lightweight aggregates produced by alkali-activation of waste powders (2018). https://doi.org/10.3390/ma11071255

11. Sara, R., Nuno, C., António, V. da F., Cristiana, F.: stiffness behavior of soil stabilized with alkali-activated fly ash from small to large strains. Int. J. Geomech. **17**, 4016087 (2017). https://doi.org/10.1061/(ASCE)GM.1943-5622.0000783
12. Chen, P., Wang, Z., Cao, S., Rong, X., Shi, Z., Wang, H.: Study on axial compressive stress-strain relationship of alkali-activated slag lightweight aggregate concrete. Constr. Build. Mater. **364**, 129991 (2023). https://doi.org/10.1016/j.conbuildmat.2022.129991

Investigating the Effect of Aggregate Size on the Heat of Hydration in Conventional and Low Carbon Concrete

Abdul Ahad Hashmi, Usman Allah Buksh, Nashmiyah Shaikh, Muhammad Danyal Sheikh, and Tariq Jamil(✉)

NED University of Engineering and Technology, Karachi, Pakistan
{hashmi4407022,buksh4405828,shaikh4401416}@cloud.neduet.edu.pk, {danyalsheikh,tariqjamil}@neduet.edu.pk

Abstract. This research compares Ordinary Portland Cement (OPC) and Limestone Calcined Clay Cement (LC3) to study their heat of hydration and strength characteristics by varying aggregate sizes. Four samples of each cement type were tested, with different coarse aggregate sizes used in each specimen. Among the four specimens, three had simple aggregate sizes of 1/2 in., 3/8 in., and 3/4 in., while the remaining one was consisted of combination with 30% 3/8 in. and 70% 1/2 in. The heat of hydration was measured using an isothermal calorimeter to evaluate the impact of aggregate size and grading differences. Cylindrical specimens, as per ASTM C39, were also prepared for each cement type using the same mix design to assess compressive strength. These cylinder samples were tested to validate the heat of hydration curves. The study provides insights into how aggregate size and grading influence the heat of hydration and compressive strength for OPC and LC3 cements. By comparing the two cement types under different conditions, the research aims to establish a clearer understanding of the relationship between heat of hydration and compressive strength, offering valuable information for practical applications in construction.

Keywords: Concrete · Heat of Hydration · Aggregate Gradation

1 Introduction

The heat of hydration, a key indicator of the hydration process, reflects the chemical reactions between cement particles and water. This reaction releases heat and directly affects the setting time, early-age strength, and potential cracking due to thermal stress. By studying the heat of hydration, valuable insights can be obtained into the hydration kinetics and the thermal behavior of different cement types under varying conditions [1].

In the past, there were no specific instruments available to accurately measure the heat of hydration of concrete samples. There is a study available that has done this work, but they designed the instrument themselves, which cannot be validated, and its results cannot be considered highly accurate [2]. This made it difficult to study how

T. Ayub et al. (Eds.): GCGC 2025, LNCE 774, pp. 36–43, 2026.
https://doi.org/10.1007/978-981-95-6592-4_5

cement reacts with water and releases heat during the hydration process. However, with the development of calorimeters, such as the Calmetrix instrument, it is now possible to measure the heat of hydration directly [3]. These instruments measure heat release and generate curves, making it easier to analyse concrete hydration. This enables the assessment of the heat of hydration in concrete. This study aims to evaluate the impact of aggregate gradation on the heat of hydration.

Cement plays a vital role in construction due to its ability to bind materials and provide strength and durability to structures. Among the widely used cement types, Ordinary Portland Cement (OPC) is known for its consistent performance. However, OPC emits a significant amount of carbon dioxide during production, making it less sustainable and contributing to environmental challenges [4]. As a sustainable alternative, Limestone Calcined Clay Cement (LC3) was developed. LC3 is made using limestone, calcined clay, and gypsum—materials that are abundant in Pakistan [5]. This innovative cement offers a much lower carbon footprint while providing comparable mechanical properties to OPC [6]. The performance of these cementitious materials is significantly influenced by their hydration behavior, which directly impacts their strength, durability, and long-term stability [7].

The primary objective of this study is to compare the behavior of OPC and LC3 concrete under controlled conditions, specifically focusing on the impact of varying aggregate sizes on hydration and strength. The results of this research aim to contribute to a better understanding of the potential applications and performance of LC3 as a sustainable alternative to OPC in construction.

2 Materials and Methods

2.1 Raw Materials

The Ordinary Portland Cement (OPC) used in this study was a general-purpose 53 Grade cement, selected for its higher strength. To produce LC3-65, clay with 75% kaolinite content was utilised. The calcined clay for this project was sourced from an industrial facility in Nagarparkar, Tharparkar, Sindh. Research indicates that kaolinite undergoes partial dehydroxylation at 600 °C, with complete dehydroxylation occurring from 700 °C onwards [8]. Consequently, calcining clay at 800 °C enhances its reactivity. In this study, the clay was heated at 800 °C for one hour in an electric furnace. Limestone, primarily composed of calcium carbonate ($CaCO_3$), plays a crucial role in LC3-65. Limestone unsuitable for clinker production can be incorporated into LC3-65, provided it has a low calcite content and contains dolomite and quartz as impurities. In LC3-50, the limestone content remains at 10%. Additionally, LC3-65 contains 5% gypsum. The chemical composition of the LC3-65 cement blend is presented in Table 1. Both coarse and fine aggregates used in this research were locally sourced. No plasticizer was incorporated in the study.

Table 1. Chemical Composition of OPC and LC3-65

Code	Chemical Composition (%)				
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO
OPC	17.6	4.3	4.2	62.3	1.7
LC3-65	22.5	12.3	2.7	49.2	0.05

2.2 Mix Composition

This study involved the testing of 8 specimens based on the cement used. These specimens were divided into two groups. The first group was prepared using Ordinary Portland Cement (OPC), while the second group was made using Limestone Calcined Clay Cement (LC3). The detailed composition of LC3-65 is provided in Table 2. Each group contained five specimens, differentiated by varying aggregate sizes, as outlined in Table 2. A consistent mix design ratio of 1:2:4 was used for all specimens, with the water-to-cement ratio maintained at 0.55. No admixture was used in this study; however, due to the high water demand of clay, the w/c ratio was maintained at a higher level [9].

Table 2. Weight (%) of OPC & LC3

Materials (g)	OPC	LC3-65
OPC	35.714	24.285
Calcined Clay	0	7.142
Limestone	0	3.572
Gypsum	0	0.715
Water	19.64	19.64

2.3 Experimental Test Method

A 250 g mixture was prepared for each specimen, out of which 200 g were carefully measured and placed into a plastic container. The specimens were then placed into the "I-Cal 2000 HP Calorimeter (Model AO113163)", Fig. 1. Data was recorded every 1 min over 24 h at a constant temperature of 20 °C to monitor the heat of hydration.

The mix compositions, detailed in Table 2, were also used to prepare 8 cylindrical reference specimens, each measuring 150 mm in diameter and 300 mm in height, following guidelines of ASTM C39 [10], Fig. 2. These cylinders were cured for 28 days and tested for compressive strength using a compression testing machine (Table 3).

Fig. 1. Calmetrix I-CAL 2000 HPC and Specimens

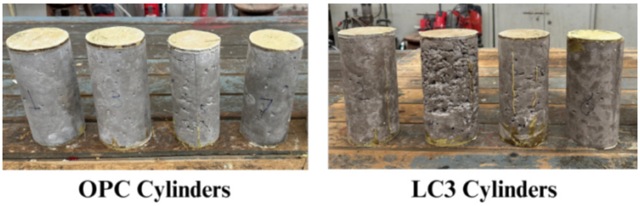


Fig. 2. OPC and LC3 Cylinders

Table 3. Specimen and Cylinder Summary

Specimen Code	Cylinder Code	Type	Aggregate Size
CS-1/2	CC-1/2	OPC	1/2 in.
CS-3/8	CC-3/8	OPC	3/8 in.
CS-3/8-1/2	CC-3/8-1/2	OPC	30% 3/8 in. & 70% 1/2 in.
CS-3/4	CC-3/4	OPC	3/4 in.
LS-1/2	LC-1/2	LC3-65	1/2 in.
LS-3/8	LC-3/8	LC3-65	3/8 in.
LS-3/8-1/2	LC-3/8-1/2	LC3-65	30% 3/8 in. & 70% 1/2 in.
LS-3/4	LC-3/4	LC3-65	3/4 in.

3 Results and Discussion

3.1 Heat of Hydration of Specimens

The results of the heat of hydration show that with an increase in aggregate size, the heat of hydration decreases. For OPC specimens, the highest heat of hydration is found in CS-3/8 (0.079803 W), followed by CS-1/2 (0.051476 W) and CS-3/4 (0.042689 W), with the lowest value in CS-3/8-1/2 (0.039314 W). LC3 specimens follow the same trend, where LS-3/8 has the highest heat of hydration at 0.059598 W and LS-3/8-1/2 has the lowest at 0.027964 W. Smaller aggregates provide more surface area for hydration, leading to higher heat release, while the interlocking effect in combined gradation limits heat dissipation, resulting in the lowest heat of hydration. Additionally, OPC specimens consistently exhibit higher heat of hydration than their LC3 counterparts across all gradations, confirming that LC3 is a low-heat cement, as previously reported in studies[11] (Figs. 3 and 4).

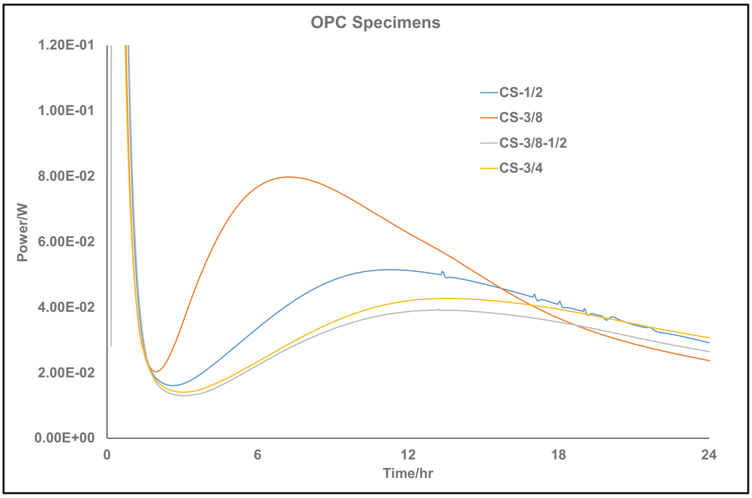


Fig. 3. Heat of hydration of OPC-based concrete specimens

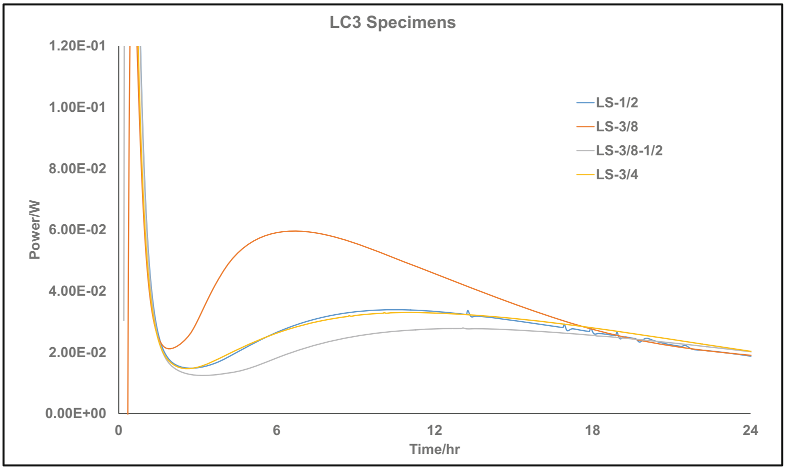


Fig. 4. Heat of hydration of LC3-based concrete specimens.

3.2 Compressive Strength of Cylinders

The compressive strength results for the OPC cylinders reveal that the CC-3/8-1/2 (2395.84 psi) has the highest strength, followed by CC-3/8 (2337.35 psi), CC-1/2 (2039.88 psi), and then CC-3/4 (1801.98 psi). The same pattern is observed in LC3 cylinders, with LC-3/8-1/2 (2350.76 psi) exhibiting the highest strength, followed by a decline in the remaining mixes: LC-3/8 (2105.90 psi), LC-1/2 (1979.35 psi), and LC-3/4 (1759.58 psi). In both cement types, as aggregate size increases, compressive strength decreases because the larger pore spaces reduce the packing efficiency. OPC cylinders were consistently stronger than LC3 cylinders at all gradations, suggesting basic differences in the hydration process and bonding (Fig. 5).

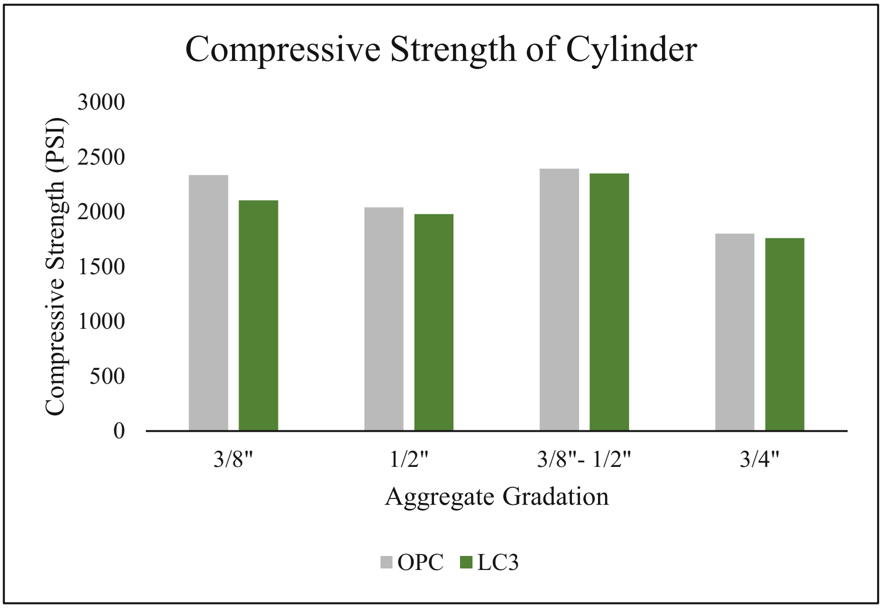


Fig. 5. Compressive strength of cylinder with aggregate gradation

3.3 Discussion of Trends

The observed trend of decreasing heat of hydration with increasing aggregate size is explained by the relationship between surface area and hydration reactions. Smaller aggregates (e.g., CS-3/8) provide a larger surface area for reaction which lead to more hydration, leading to greater heat release. Conversely, larger aggregates (e.g., CS-3/4) limit the reaction area and result in lower heat of hydration. The combination gradation CS-3/8-1/2 exhibits the lowest heat release due to its high interlocking effect, which restricts heat dissipation during the first 24 h. However, the heat release may increase gradually over time as the reaction progresses, which can be further analyzed in future studies. Such a trend can be seen throughout both OPC and LC3 samples.

The compressive strength obtained is highest when the aggregate interlocking is denser, and voids are reduced in CC-3/8-1/2 and LC-3/8-1/2. The compressive strength values of OPC and LC3 decreased as the aggregate size increased because large pores spaces have the tendency to break the inner structures.

The matching trends between OPC specimens and cylinders support the assumption that higher heat of hydration corresponds to higher compressive strength. For instance, CS-3/8, which indicates the highest heat of hydration, matches with CC-3/8, which attained the targeted compressive strength. Other than the combination gradation, the trend is valid, which means that increased hydration results in stronger cement bonding and greater strength.

The LC3 specimens and cylinders also show a relationship between heat of hydration and compressive strength. For example, LS-1/2, which exhibits higher heat of hydration compared to LS-3/4, corresponds to LC-1/2 achieving higher compressive strength than LC-3/4. This evidence confirms the assumption made that higher heat of hydration in the specimens indicated higher compressive strength within the corresponding cylinder.

4 Conclusion

This study confirms the initial assumption that heat of hydration can be quite effectively used as an indicator for predicting the compressive strength of concrete specimens, reducing requirements for extensive compressive strength testing. Observed trends demonstrate that specimens with higher heat of hydration generally correspond to cylinders with higher compressive strength, thus supporting the validity of this relationship for both OPC and LC3 concretes. More importantly, the different sizes of aggregate show a repeating pattern: as the aggregate size is increased, the heat of hydration decreases, and compressive strength decreases. This is because coarser aggregates have lesser surface area for hydration reactions to take place and larger pore spaces resulting in less strength and heat outputs. The gradation of combined aggregate always outperforms individual gradations due to increased interlocking effects, indicating that optimized aggregate combinations can enhance strength and thermal efficiency in concrete. Additionally, LC3 specimens and cylinders consistently exhibit slightly lower heat of hydration and compressive strength compared to their OPC counterparts, indicating that LC3 performs less efficiently in terms of strength development under the conditions of this study.

References

1. Schindler, A.K., Folliard, K.J.: Heat of hydration models for cementitious materials. ACI Mater. J. **102**(1), 24 (2005)
2. Tan, Y., Tang, K.: Evaluate the effect of coarse aggregates on cement hydration heat and concrete temperature modelling using isothermal calorimetry. Heliyon **10**(19) (2024)
3. Huang, L., et al.: Non-destructive test system to monitor hydration and strength development of low CO2 concrete. Constr. Build. Mater. **408**, 133774 (2023)
4. Habert, G., et al.: Environmental impacts and decarbonization strategies in the cement and concrete industries. Nat. Rev. Earth Environ. **1**(11), 559–573 (2020)
5. Hussain, S.M.F., et al.: Initial search for low grade clay in Pakistan for producing LC3 ecofriendly cement. Low-Carbon Mater. Green Constr. **1**(1), 15 (2023)
6. Sheikh, M.D., et al.: Comparative study on LC3-50 with OPC concrete using raw materials from Pakistan. Adv. Mater. Sci. Eng. **2023**(1), 5503670 (2023)
7. Ayub, T., et al.: Effect of glass powder on the compressive strength and drying shrinkage behavior of OPC-and LC3-50-based cementitious composites of various strengths. Adv. Mater. Sci. Eng. **2024**(1), 8860083 (2024)

8. Werling, N., et al.: Rehydroxylation of calcined swellable clay minerals at ambient conditions. Appl. Clay Sci. **247**, 107113 (2024)
9. Moghul, S., Zunino, F., Flatt, R.J.: Flow loss in superplasticized limestone calcined clay cement. J. Am. Ceram. Soc., e20344 (2024)
10. ASTM: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. ASTM: West Conshohocken, PA 19428-2959, United States (2021)
11. Vaasudevaa, B., Dhandapani, Y., Santhanam, M.: Performance evaluation of limestone-calcined clay (LC2) combination as a cement substitute in concrete systems subjected to short-term heat curing. Constr. Build. Mater. **302**, 124121 (2021)

Conference Track II: Sustainable Construction

State-of-the-Art Review on Utilizing Ferrochrome Ash, Red Mud, and Granulated Blast Furnace Slag as Sustainable Cement Replacements in Green Concrete

Syed Hussain Ali Zaidi[1(✉)], Syed Asghar Abbas[1], Syed Muhammad Bilal Haider[2], Dongkeun Lee[3], and Muhammad Aun Abbas[4]

[1] Department of Civil Engineering, NED University of Engineering and Technology, Karachi, Pakistan
zaidi14964@gmail.com
[2] Civil Engineering Division, CPH Consulting LLC, Sanford, FL, U.S.A.
[3] Southern University and A&M College, Baton Rouge, LA 70813, U.S.A.
[4] Faculty of Engineering and Green Technology, Universiti Tunku Abdul Rahman, Petaling Jaya, Malaysia

Abstract. The construction industry heavily relies on Portland cement, contributing to CO_2 emissions and environmental degradation. This study explores using industrial byproducts—Ferrochrome Ash (FCA), Red Mud (RM), and Ground Granulated Blast Furnace Slag (GGBFS)—as sustainable partial cement replacements in green concrete. These materials enhance durability, reduce embodied carbon, and improve resistance to harsh environments. While FCA and RM enhance microstructure and lower sorptivity, GGBFS improves workability and reduces permeability. Optimal mix designs are crucial to balance strength and shrinkage risks. This review highlights the environmental, economic, and performance benefits of these materials, supporting circular economies and Sustainable Development Goals. Future research directions are discussed to enhance their feasibility.

Keywords: Green Concrete · Sustainable Development Goals (SDG) · CO2 emissions · Red Mud · GGBFS · Ferrochrome Ash · Portland Cement Replacements

1 Introduction

Concrete is the most commonly used material in the construction industry due to its various applications [1]. Currently, the world consumes about 12–15 billion tons of concrete annually [2, 3]. Cement production, making up 5–20% of concrete, is rising globally, with China leading, followed by India [4]. Around half of the world's cement production is used to make approximately 30 billion tons of concrete [5]. Concrete production has a major environmental impact due to high energy use and greenhouse gas emissions, especially from Portland cement [6] (Fig. 1).

T. Ayub et al. (Eds.): GCGC 2025, LNCE 774, pp. 47–54, 2026.
https://doi.org/10.1007/978-981-95-6592-4_6

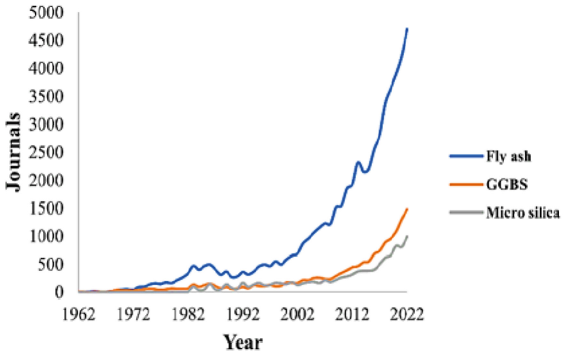


Fig. 1. Trend of waste material usage in cement [5]

Researchers are developing SCMs from industrial waste, considering social, economic, and environmental factors to conserve natural resources and reduce construction-related carbon emissions [5, 7]. The rising trend of journal publishing using different supplemental cementitious materials reflects that the usage of these supplementary cementitious materials has significantly grown over the past few decades, fly ash being the most viable material used as a replacement [5]. The construction industry heavily consumes materials, energy, and water, significantly impacting climate change, health, and well-being [8]. Furthermore, construction has had a significant environmental impact, including waste generation, CO_2 emissions, land use changes, biodiversity loss, and climate change [9]. In light of this, cutting edge ideas including carbon trading, low-carbon environments, low-carbon economies, and low carbon living have become essential to the global development plan [10].

This study explores the use of Ferrochrome Ash (FCA), Red Mud (RM), and Ground Granulated Blast Furnace Slag (GGBFS) as sustainable alternatives to Ordinary Portland Cement (OPC) in concrete, evaluating their properties, limitations, and feasibility.

2 Comparison of FCA, Red Mud and GGBFS as Green Alternatives in Concrete

This study explores the potential of utilizing industrial byproducts such as FCA, RM, and GGBFS offer a sustainable solution for concrete by partially replacing OPC, these materials reduce embodied CO_2 emissions, and enhance durability, and promote efficient waste management, paving the way for a greener and more sustainable future.

2.1 Production of Materials

The ferrochrome industry is essential to stainless steel production, as ferrochrome is responsible for providing the alloy with its corrosion-resistant properties [11]. Global ferrochrome production is 6.5–9.5 million tons annually, growing at 2.8–3%, with 1–1.2 million tons of solid waste generated per ton produced [12]. RM is a highly alkaline waste byproduct generated from alumina refineries typically produced through the Bayer or sintering processes involved in alumina extraction [13]. The disposal of large quantities of RM is very difficult and leads to land, air and water pollution [14]. It is because RM has a strong alkaline nature and includes numerous hazardous substances such as metals and radioactive materials [15, 16]. Globally, around 500 million tons of GGBFS is produced annually [17]. Rapid cooling prevents large crystal formation, resulting in granular material with ~95% non-crystalline calcium-aluminum silicates. The slag is then dried, ground in a ball mill, and processed into GGBFS [18].

2.2 Chemical Compositions and Physical Properties

RM typically contains a number of chemical substances, including Na_2O, CaO, Fe_2O_3, and Al_2O_3. These substances also include SiO_2, TiO_2 [19, 20]. The chemical compositions of FCA were characterized by X-Ray Fluorescence (XRF) analysis [11]. X-ray diffraction pattern of GGBFS shows that it is composed of Ca, Al, and silica-rich minerals [21, 22].The detailed comparison is shown in Table 1.

Table 1. Chemical Compositions of RM, FCA & GGBFS

Comp	S-P RM	B-P RM	CB-S RM	FCA	GGBFS
CaO	45–49	3–9	43.8–46.8	3.14	24.12
Al_2O_3	4–7	12–22	5.5–7.5	10.91	20.40
SiO_2	22–23	4–20	20.2–20.5	19.1	36.3
TiO_2	2.6–3.0	0.2–10	6.2–7.5	–	0.73
Na_2O	2.5	3–10	2.7–3.0	2.46	0.38
K_2O	0.3–0.4	–	0.4–0.7	11.42	1.02
Fe_2O_3	6–10	35–36	6.2–7.5	23.60	8.08
MgO	1.3–1.6	–	–	23.60	24.12
References		[19, 20]		[11]	[11, 22]

FCA has a specific gravity of 2.24, a density of 2.24 g/cm^3, fineness of 571 m^2/kg, and a pH of 9.79, indicating fine particle distribution and alkaline nature; it is typically grey in color [23]. GGBFS exhibits a specific gravity of 2.8, density of 2.8 g/cm^3, with a characteristic whitish-grey appearance [24–26]. Bayer-process RM has a particle size of 14.8 µm, density of 2.7 g/cm^3, and specific gravity of 2.64, while sintering-process RM has particles (28.5 µm), higher density (3.26 g/cm^3), and lower specific gravity (2.47), with a pH of 10.43, and are brown in color [19, 23].

2.3 Environmental Impact (EI) of Red Mud, FCA, GGBFS

To reduce the environmental impact of concrete, adopting green practices like recycling waste materials and using alternatives like GGBFS, FCA, and RM as partial cement replacements is key to producing green concrete [27, 28]. It was found that replacing

20% of cement with RM resulted in a lower carbon footprint of around 470 CO_2-eq (Kg.m-3/MPa), compared to 555 CO_2-eq (Kg.m-3/MPa) when using 0% replacement [21]. It was found that the mixture with 100% OPC yields 920 kg CO_2 of embodied carbon dioxide (ECO_2eq), whereas the mixture with 100% GGBFS replacement yields 271 kg CO_2 of embodied carbon dioxide. [29] conducted an LCA of concrete with FCA replacement showed that replacing 20% of cement with FCA reduces CO2 emissions from 341.333 kg to 292.454 kg CO2 eq.

2.4 Effect of RM, FCA and GGBFS on Workability of Concrete

FCA's larger particle size, spherical shape, and packing effect reduce concrete workability, especially at higher concentrations and with lime, due to early hydration [30, 31]. RM, while improving compactness, decreases workability due to its finer particle size, higher water absorption, and increased volume, which negatively affect flowability, limiting its use in high-workability applications [27, 28]. GGBFS improves workability by filling voids, but at replacement levels over 40%, flowability plateaus, requiring superplasticizers to maintain slump [31, 32].

Table 2. Effect of Sulphate Attack on FCA, Rm & GGBFS

Material	Test Condition	Effect of Sulfate Attack	References
FCA	Immersion in 1% magnesium sulfate solution for 28, 91, and 180 days	Reduced strength loss compared to control mix	[30, 33]
RM	Immersion-drying cycles with Na2SO4 solution for 5 and 10 cycles	Increasing FCA content decreases strength loss due to improved homogeneity and decreased sorptivity	[34, 35]
GGBFS	Immersion in water and MgSO4 solution for 90 days	Variation in compressive strength response to sulfate attack	[36]

2.5 Effect Due to Sulphate Attack

The response of concrete to sulfate attack varies significantly depending on its composition and the type of sulfate exposure. Studies have revealed that magnesium sulfate $MgSO_4$ degrades hydrated calcium compounds in concrete. However, mixes incorporating fly ash (FA) and lime exhibit enhanced resistance to sulfate attack due to reduced sorptivity and improved pore structure [30, 33]. Concrete with RM initially gains strength from Alumina Ferric Tri-Sulphate (Aft) formation, improving compactness. However, excessive AFt later causes cracking and strength loss [34, 35]. GGBFS enhances sulfate resistance by forming C-S-H and a protective $Mg(OH)_2$ layer, delaying damage, but prolonged exposure can cause cracking from secondary ettringite and gypsum formation [36]. The results of sulphate attack are shown in Table 2.

2.6 Effect on Shrinkage of Concrete

The influence of alternative materials on drying shrinkage varies significantly across studies. According to ASTM C596, Alkali Activated Material (AAM) prisms with FCA showed reduced shrinkage strains (5.2–11.6%) as FCA content increased to 30%, attributed to unreacted FCA particles acting as barriers [37]. RM in concrete mixtures also reduced drying shrinkage due to its porous nature, retaining and gradually releasing water, with greater reductions observed as RM content increased [38]. In GGBFS concrete, shrinkage strains increased with replacement levels (20%, 40%, and 60%), showing 14.1%, 28.0%, and 48.7% higher strain at 180 days due to finer particles, enhanced pozzolanic reactions, and higher water absorption, leading to autogenous shrinkage and lower modulus of elasticity [39]. Overall, GGBFS's faster hydration and lower strength intensified shrinkage compared to other materials.

2.7 Effect on Sorption of Concrete

Sorptivity, indicating concrete's near-surface pore system continuity, measures water absorption due to capillary suction. [40] show that sorptivity decreases with 0–40% FCA and 7% lime replacing OPC, as lime hydration densifies the microstructure, reducing voids. RM replacement also lowers sorptivity by filling capillary pores with C-S-H, creating a dense matrix and enhancing durability [41, 42]. For GGBFS concrete, [43] reported Sorptivity trends varied with replacement levels: 50% GGBFS reduced sorptivity, while 70% GGBFS initially increased it but significantly decreased it by 91 days due to fewer capillary pores. High GGBFS content improved water resistance and long-term durability.

FCA, RM, and GGBFS are sustainable OPC alternatives that reduce CO_2, enhance durability, and improve workability, though high replacements may affect shrinkage and workability. Together, they provide eco-friendly solutions for the construction industry's environmental impact.

3 Limitations and Future Recommendations

RM improves early strength at 10% replacement but reduces workability and strength at higher levels due to limited hydration. GGBFS enhances durability and reduces carbon emissions but slows early strength and increases shrinkage at higher levels. FCA boosts early strength but lowers workability; when combined with lime, it reduces sorptivity and shrinkage, resisting sulfate attacks. Optimal replacements: 10% RM, up to 40% GGBFS, and 20% FCA with lime.

Future research should optimize RM, GGBFS, and FCA combinations to balance their limitations. Experimental studies should explore higher replacement levels and their synergy with pozzolanic materials like fly ash, rice husk, and nano-silica to enhance strength and durability. Pilot studies are needed to validate findings and ensure practical application in construction.

References

1. Mukhti, J.A., Kee, S.-H.: Chloride-induced damage monitoring of reinforced concrete using ultrasonic pulse wave-based machine learning. In: Ismail, A., Zulkipli, F.N., Fitriadhy, A., Ahmad, S.Z.A.S., Öchsner, A. (eds.) Exploring Diversity in Engineering and Technology for Knowledge and Innovation. ASM, vol. 215, pp. 237–246. Springer, Cham (2024). https://doi.org/10.1007/978-3-031-64330-9_21
2. Aliabdo, A.A., Abd Elmoaty, A.E.M., Aboshama, A.Y.: Utilization of waste glass powder in the production of cement and concrete. Constr. Build. Mater. **124**, 866–877 (2016)
3. Dobiszewska, M., et al.: Utilization of rock dust as cement replacement in cement composites: an alternative approach to sustainable mortar and concrete productions. J. Build. Eng. **69**, 106180 (2023)
4. Survey, U.S.G.: Mineral commodity summaries 2022. Mineral Commodity Summaries (2022)
5. Rakesh Kumar Reddy, R., Yaragal, S.C., Sagar Srinivasa, A.: One-part eco-friendly alkali-activated concrete – an innovative sustainable alternative. Constr. Build. Mater. **408** (2023)
6. Bajpai, R., et al.: Environmental impact assessment of fly ash and silica fume based geopolymer concrete. J. Clean. Prod. **254**, 120147 (2020)
7. Barbhuiya, S., Bhusan Das, B., Adak, D.: Roadmap to a net-zero carbon cement sector: strategies, innovations and policy imperatives. J. Environ. Manag. (2024)
8. Alawneh, R., et al.: Assessing the contribution of water and energy efficiency in green buildings to achieve United Nations Sustainable Development Goals in Jordan. Build. Environ. **146**, 119–132 (2018)
9. Mastrucci, A., et al.: Life cycle assessment of building stocks from urban to transnational scales: a review. Renew. Sustain. Energy Rev. **74**, 316–332 (2017)
10. Labaran, Y.H., Mathur, V.S., Farouq, M.M.: The carbon footprint of construction industry: a review of direct and indirect emission. J. Sustain. Constr. Mater. Technol., 101–115 (2021)
11. Mishra, J., et al.: Synthesis and characterization of a new class of geopolymer binder utilizing ferrochrome ash (FCA) for sustainable industrial waste management. Mater. Today Proc. (2020)
12. Acharya, P.K., Patro, S.K.: Effect of lime and ferrochrome ash (FA) as partial replacement of cement on strength, ultrasonic pulse velocity and permeability of concrete. Constr. Build. Mater. **94**, 448–457 (2015)
13. Venkatesh, C., Chand, M.S.R., Nerella, R.: A state of the art on red mud as a substitutional cementitious material. Annales de Chimie: Science des Materiaux **43**(2), 99–106 (2019)
14. Alam, S., Das, S.K., Rao, B.H.: Strength and durability characteristic of alkali activated GGBS stabilized red mud as geo-material. Constr. Build. Mater. **211**, 932–942 (2019)
15. Ortega, J.M., et al.: Effects of red mud addition in the microstructure, durability and mechanical performance of cement mortars. Appl. Sci. **9**(5) (2019)
16. Samal, S., Ray, A.K., Bandopadhyay, A.: Proposal for resources, utilization and processes of red mud in India — a review. Int. J. Miner. Process. **118**, 43–55 (2013)
17. Sithole, N.T., et al.: Alternative cleaner production of sustainable concrete from waste foundry sand and slag. J. Clean. Prod. **336** (2022)
18. Kumar, R., Samanta, A.K., Roy, D.K.S.: Characterization and development of ecofriendly concrete using industrial waste – a review. J. Urban Environ. Eng. **8**(1), 98–108 (2014)
19. Patangia, J., et al.: Study on the utilization of red mud (bauxite waste) as a supplementary cementitious material: pathway to attaining sustainable development goals. Constr. Build. Mater. **375**, 131005 (2023)
20. Wang, S., et al.: Comprehensive utilization status of red mud in China: a critical review. J. Clean. Prod. (2021)

21. Chethan, K.B., Yaragal, S.C., Das, B.B.: Ferrochrome ash – its usage potential in alkali activated slag mortars. J. Clean. Prod. **257** (2020)
22. Xu, D., et al.: Effects of GGBFS on hydration and carbonation process, microstructure, and mechanical properties of NHL-based materials. J. Build. Eng. **60**, 105149 (2022)
23. Sharma, M., et al.: Effect of silica fume and red mud on mechanical properties of ferrochrome ash based concrete. Mater. Today Proc. **60**, 55–61 (2022)
24. Nishanth, L., Patil, D.N.N.: Experimental evaluation on workability and strength characteristics of self-consolidating geopolymer concrete based on GGBFS, flyash and alccofine. Mater. Today Proc. **59**, 51–57 (2022)
25. Pradhan, P., et al.: Variation in fresh and mechanical properties of GGBFS based self-compacting geopolymer concrete in the presence of NCA and RCA. Mater. Today Proc. **62**(P12), 6348–6358 (2022)
26. Sahraei Moghadam, A., Omidinasab, F., Moazami Goodarzi, S.: Characterization of concrete containing RCA and GGBFS: mechanical, microstructural and environmental properties. Constr. Build. Mater. **289** (2021)
27. Chavan, S.P., et al.: An investigational study on properties of concrete produced with industrial waste red mud. Mater. Today Proc. (2020)
28. Hou, D., et al.: Sustainable use of red mud in ultra-high performance concrete (UHPC): design and performance evaluation. Cem. Concr. Compos. **115** (2021)
29. Acharya, P.K., Patro, S.K.: Evaluation of environmental disturbance indicator using functional performance and life cycle assessment of ferrochrome waste concrete. J. Build. Eng. **65** (2023)
30. Acharya, P.K., Patro, S.K.: Utilization of ferrochrome wastes such as ferrochrome ash and ferrochrome slag in concrete manufacturing. Waste Manag. Res. **34**(8), 764–774 (2016)
31. Patra, R.K., Mukharjee, B.B.: Influence of incorporation of granulated blast furnace slag as replacement of fine aggregate on properties of concrete. J. Clean. Prod. **165**, 468–476 (2017)
32. Ahmad, J., et al.: Effects of steel fibers (SF) and ground granulated blast furnace slag (GGBS) on recycled aggregate concrete. Materials **14**(24) (2021)
33. Yunus, E., Asrah, H., Rizalman, A.N.: Strength and sorptivity of eco-processed pozzolan concrete under chloride and sulphate exposure. Int. J. Adv. Res. Eng. Innov., 32–43 (2020)
34. Hua, S., et al.: Effects of fibers on mechanical properties and freeze-thaw resistance of phosphogypsum-slag based cementitious materials. Constr. Build. Mater. **121**, 290–299 (2016)
35. Yan, P., et al.: Influence of red mud on the engineering and microstructural properties of sustainable ultra-high performance concrete. Constr. Build. Mater. **396** (2023)
36. Melais, F.Z., Achoura, D., Ghorbel, E.: Durability of mortars containing blast furnace slags used as a partial substitute of Portland cement exposed to external sulfate attacks. J. Mater. Environ. Sci **2021**(6), 837–852 (2021)
37. Omur, T., et al.: Characterization of ferrochrome ash and blast furnace slag based alkali-activated paste and mortar. Constr. Build. Mater. **363** (2023)
38. Liu, R.X., Poon, C.S.: Utilization of red mud derived from bauxite in self-compacting concrete. J. Clean. Prod. **112**, 384–391 (2016)
39. Lee, K.M., et al.: Autogenous shrinkage of concrete containing granulated blast-furnace slag. Cem. Concr. Res. **36**(7), 1279–1285 (2006)
40. Acharya, P.K., Patro, S.K.: Strength, sorption and abrasion characteristics of concrete using ferrochrome ash (FCA) and lime as partial replacement of cement. Cement Concr. Compos. **74**, 16–25 (2016)
41. Qureshi, H.J., et al.: A study on sustainable concrete with partial substitution of cement with red mud: a review. Materials (2022)

42. Venkatesh, C., Nerella, R., Chand, M.S.R.: Role of red mud as a cementing material in concrete: a comprehensive study on durability behavior. Innov. Infrastruct. Solut. **6**(1) (2021)
43. Siddique, R.: Utilization (recycling) of iron and steel industry by-product (GGBS) in concrete: strength and durability properties. J. Mater. Cycles Waste Manag, pp. 460–467 (2014)

Investigating the Viability of Incorporating Industrial-Waste Additives for Soil Stabilization

Shah Rukh Khan, Muhammad Bilal Khan, Muhammad Muneeb Nawaz, Muhammad Asad Tahir, and Muhammad Noman(✉)

Department of Civil Engineering, International Islamic University, Islamabad, Pakistan
muhammad.noman@iiu.edu.pk

Abstract. Soil stabilization is a process of enhancing the bearing capacity of challenging soil through mechanical or chemical means, which enhances shear strength parameters, which alters the nature of the soil as and when required for the project since the ground soil may not support the imposed structure loads. The available methods to solve this problem are not cost-effective; some are non-sustainable and prove effective only in the long run. This research concentrates on a practical approach for utilizing industrial by-products such as bagasse ash (BA), marble dust (MD), cement kiln dust (CKD), and lime to enhance soil stability, as their disposal poses potential environmental risks. To accomplish this, varying proportions of these waste materials were used to replace soil samples throughout this investigation. Tests for Atterberg limits, modified proctor, shear strength, and unconfined compression were performed on these samples. The findings indicate that the compression strength increases by 53% when 19% of BA and lime are applied in a similar proportion. Additionally, it will decrease the soil's plasticity due to the filler effect of the blended particles. It is noted, however, that CKD provided an optimum moisture content (OMC) of 13.7%. The best ratio identified at the conclusion of this study is 11% of MD, which yielded the highest maximum dry density among all the additives and resulted in a 40% reduction in cost compared to traditional methods.

Keywords: soil improvement · industrial waste additives · shear strength

1 Introduction

Soil stabilization is an essential process of increasing the load-bearing capacity and enhancing the other attributes of the soil, such as strength, compacting, and working qualities for supporting structures and pavements. Most soils, especially those that come under the expansive category, change volumetrically with changes in moisture content, thereby subjecting structures such as buildings, roads, etc. Some standard techniques concerning stabilization include cementation, liming, and fly ash treatment; some of these methods entail high energy utilization and relative greenhouse gas emissions that compromise their sustainability [1]. This has led to calls for fresh approaches to materials handling, especially waste industrial products, because they are environment-friendly, cheap, and have excellent properties [2, 3].

T. Ayub et al. (Eds.): GCGC 2025, LNCE 774, pp. 55–62, 2026.
https://doi.org/10.1007/978-981-95-6592-4_7

Bagasse Ash (BA), Marble Dust (MD), and Cement Kiln Dust (CKD) byproducts that have industrial origins offer intriguing possibilities for the stabilization of soil. BA, a remnant of the sugarcane industry, has high silica content to improve black cotton soil's mechanical properties and can be an adequate substitute for stabilizers [4]. According to the literature, it has been observed that BA can improve the compressive strength and CBR and reduce the cement and lime requirements [5]. MD is a marble industry waste containing calcium carbonate, which enhances the soil's workability and reduces water absorption [6, 7]. Current studies have indicated that using MD can improve the strength of clayey soil, but in large proportions, it weakens the soil strength [8]. In the same way, CKD, a cement industry byproduct, has displayed excellent enhancements on the soil's stress and plasticity because of the pozzolanic qualities [9, 10]. Incorporating CKD into highly compressible soil types will decrease the compression characteristics of the soil while improving the stability of the ground area. Other uses of this industrial waste are as follows in sustainable waste management.

However, some limitations are still observed concerning identifying proper amounts of such materials for various soil types and the conditions of their localization. Therefore, there is a need for further research to determine the effects of its overuse and why the results differ with the type of soil. Nonetheless, applying BA, MD, and CKD in soil stabilization offers a sustainable option that requires further research to be perfected. This study intends to fill this gap by comparing the effect of BA, MD, and CKD on the soil attributes in question along with the aims to establish how these additives improve the nail and soil characteristics. Thus, the goal is to determine the best practice and rate for using different stabilizers and assist in improving the efficiency of soil stabilization methods. Conventional tests like the unconfined compression test and Californian bearing ratio test will be employed to quantify the soil's strength properties for its application and enhancement using an environment-friendly method.

2 Methodology

This research focuses on the soil characteristics at two sites in Pakistan, including Shahen Dam and Chakwal City, for expansion after construction. Hence, some samples were taken to assess their index and strength. BA and lime, inexpensive in Pakistan, were used in this experiment to amend soil in various percentages of 0–20% by weight of soil. The tests included sieve analysis for particle size distribution, hydrometer analysis for identification of soil particles, Atterberg's limits for suitability of the soil, modified compaction test for determination of bearing capacity of the soil, unconfined compression test for the strength of the soil and compaction test by proctor penetrometer and vane shear test for shear strength. The study aims to establish how these additives improve the nail and soil characteristics.

3 Materials

The properties of raw soil and additives are displayed as follows:

3.1 Properties of Un-Treated Soil

The properties of untreated soil are presented in Table 1.

Table 1. Overview of the properties of untreated soil

Property	Quantity	Property	Quantity
Passing #200 Sieve	97%	Maximum Dry Density (MDD) (lb/ft3)	113.1
Clay Content	23%	Optimum Moisture Content (OMC)	13.7%
Liquid Limit	43%	Shear Strength (kN/m^2)	65.65
Plastic Limit	22%	Bearing Capacity (kN/m^2)	337.4
Specific Gravity	2.52		

3.2 Properties of Additives

The XRF result obtained in Table 2 revealed that Bagasse Ash (BA) contains a high silica content of 73%. In comparison, Lime contains high calcium oxide (74.23%), Marble Dust (MD) contains calcium oxide (33.12%), magnesium oxide (17.91%), cement kiln dust (CKD) contains 44.28% calcium oxide, and silica (7.24%). These compositions affect the performance of the given compositions within soil stabilization.

Table 2. Chemical properties of the additives

Oxide (%)	CaO	SiO2	Al_2O_3	Fe_2O_3	MgO	P_2O_5	$CaSO_4$	LOH	LOI
BA	2.8	73	6.7	6.3	3.2	4	–	–	1.1
Lime	74.23	2.14	2.17	1.11	0.74	0.08	22.12	–	–
MD	33.12	3.75	Traces	0.13	17.91	–	–	45.07	–
CKD	44.28	7.24	1.9	4.47	0.82	–	–	–	39.28

4 Results and Discussion

The results are for on-site soil without additives and for on-site mixing of soil with additives. The testing result is displayed as follows:

4.1 Effect on Atterberg Limits and Compaction Characteristics

The introduction of MD, CKD, and BA-lime mixture influenced the soil parameters concerning its moisture capacity, plasticity coefficient, and liquid limit. This is evident in Fig. 1. As observed, increases in the liquid limit with the decrease in the soil's organic content and passing through the minimum at 11% MD indicated that the liquid limit reduced from its initial value of 43% to 34%. However, minor variations in the MD thereafter led to marginal variation in the liquid limit.

Likewise, the incorporation of 15% CKD resulted in an acceptable decrease in the liquid limit to 35%, down from 43%. Apart from this level of CKD inclusion, the values for the liquid limit of the soil hardly changed, indicating a threshold effect. The BA-lime mixture operated similarly, decreasing the liquid limit to 31% with a 15% BA addition. Like the other material, a higher portion of BA-lime mixture modifying did not make any significant difference, hence implying that it was the first introducing portions that had a more profound effect on the properties of the soil.

When evaluating compaction, it was noted that all the additives improved the Maximum Dry Density (MDD) and, at the same time, reduced the Optimum Moisture Content (OMC); depicted in Fig. 2, it was found that the addition of MD that could go as high as 11% of the overall mixture led to an increase in the MDD until a decrement was registered. The same pattern was observed with the MD and BA-lime blends; the MDD achieved its highest value at an 11% MD inclusion level. The maximum MDD values of 127 kN/m^2 were achieved for the BA-lime mixture. In comparison, the MD mixture achieved a slightly lower result of 121.9 kN/m^2. The addition of lime was found to have a positive impact on the density. In addition, there was the realization that while the OMC reduced as the level of additives improved, it increased again with the increase in the level of additives. The findings of this study agree with other studies done for similar industrial-waste additives by Harichane et al. (2011), Ola (1983), and Al-Rawas et al. (2005), where it was established that those by-products work as fillers and lower the Atterberg limits [11–13].

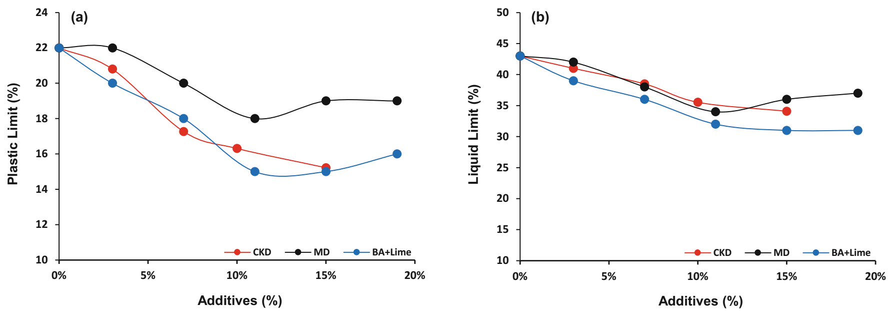


Fig. 1. Effect on Atterberg limits for different percentages of additives in the soil: (a) Plastic limit and (b) Liquid limit

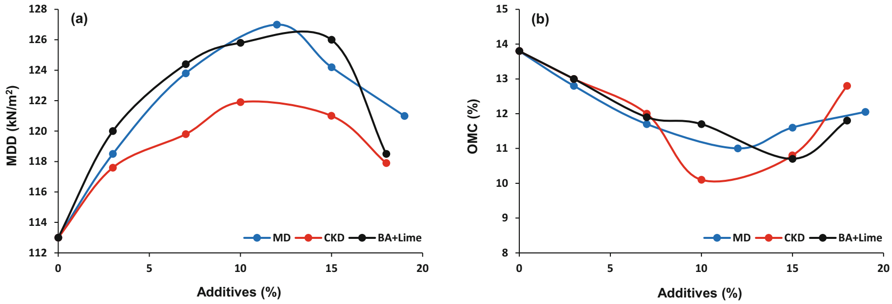


Fig. 2. Effect of different percentages of additives in the soil on (a) MDD and (b) OMC

4.2 Effect on Unconfined Compressive Strength, Shear Strength and Bearing Capacity

This research also evaluated the impact of the waste additives on the unconfined compressive strength of the soil, as represented in Fig. 3, the shear strength, and the bearing capacity, as represented in Fig. 4. The compressive strength improved significantly from 131 kN/m^2 to an appealing 228 kN/m^2 when 19% MD was incorporated into the soil mix. In the same, the incorporation of 19% CKD produced better outcomes, thereby increasing the compressive strength to 229KN/m^2.

Of all the tested mixtures, the BA-lime blend obtained the highest improvement. This increased the proportion mixture to 19%, which greatly increased the concentration of the ability to bond the workpiece while enhancing the compressive strength to 251 kN/m^2. In addition, the increase of field density using all additive samples MD, CKD, and BA-lime also enhanced both shear strength and bearing capacity. In particular, with 19% MD, the bearing capacity from 65.65 kPa up to 114 kPa, and the soil bearing capacity from 337.4 kPa up to 585.93 kPa. The 19% CKD mix similarly showed better results as the shear strength was increased to 114.9 kN/m^2, and the bearing capacity was 590.97 kN/m^2 square, respectively. However, the BA-lime mixture has shown higher results than all other mixtures, where the shear strength increased to 125.5 kN/m^2, and the bearing capacity enhanced to 636.23 kN/m^2.

These statistics are rather persuasive. Therefore, it is suggested that the use of lime and BA together yields the highest improvements in the soil's physical properties, recommending this solution for soil stabilization. The workings of Rao et al. (2008) and Sherwood (1993) support the enhancement of the shear strength properties consequent to additive mixtures based on the revelation that pozzolanic reactions, a better packing of the particles, and the formation of cementitious compounds all contributed to an increase in the bearing strength of the soil [13, 14].

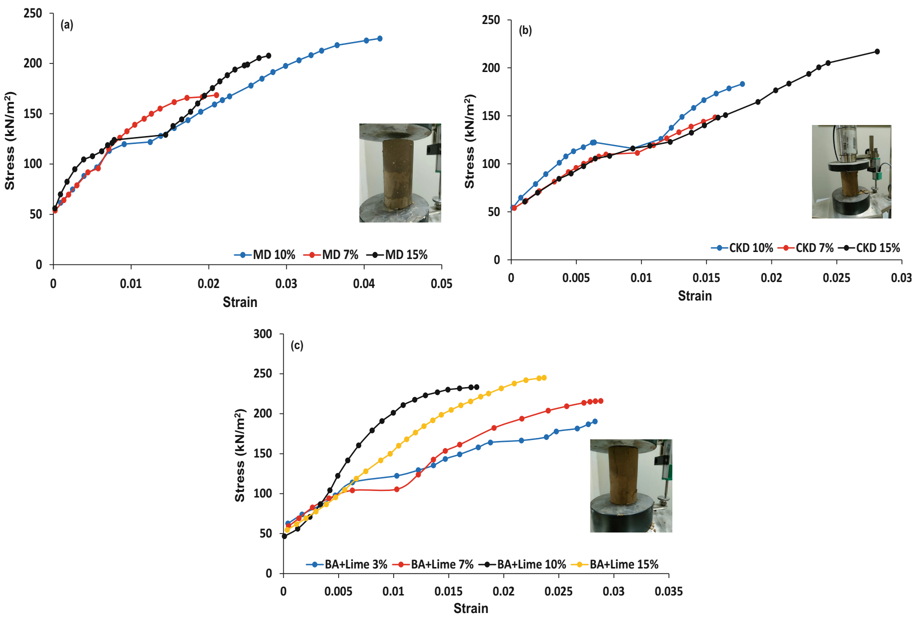


Fig. 3. Axial stress-strain with UCS test at different percentages of additives used in soil: (a) MD (b) CKD (c) Mixture of BA with lime

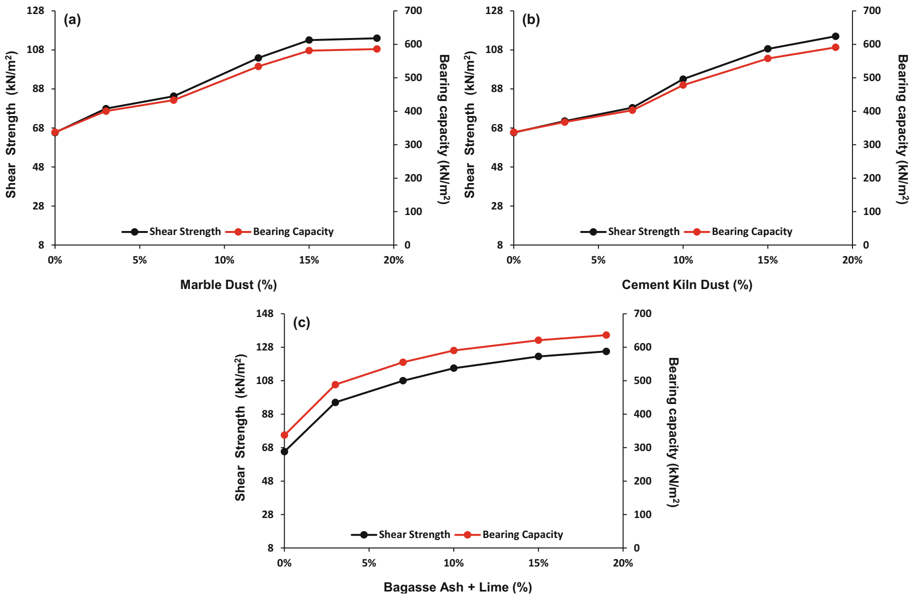


Fig. 4. The shear strength and bearing capacity of the soil with different percentages of additives

5 Conclusions

Based on the thorough examination of the study, the following conclusions can be drawn:

i. The combination of MD, CKD, and BA with lime proves to be more effective in lowering moisture holding capacity, plasticity, and liquid limit compared to the effect of blending ash with lime, which enhances the values of MDD and OMC.
ii. A higher proportion, precisely 19% of MD and CKD, when combined with BA and lime, significantly enhances the soil's compressive strength. This combination meets the criteria for fine texture and high clay content, along with moderate plasticity and substantial shear strength, making it well-suited for use as subgrade materials.
iii. Adding MD, CKD, and a mixture of BA with lime reduces the capacity of moisture holding, plasticity, and liquid limit more effectively than adding ash and lime, which raises the value of MDD and OMC.
iv. When it comes to cost, strength, and sustainability, marble industrial waste is the most appropriate of all the additives used. It costs 40% less than soil replacement. However, adding such materials as MD, CKD, and bagasse ash to lime mixtures significantly affects the characteristics of the soil while helping create a green environment. These additives can decrease the water retaining capacity, workability, and Indian limit of the soil, enhancing the soil's stability and bearing power.

Thus, the results of this work shed light on the advantages of employing industrial byproducts and waste materials for soil stabilization. These could have important implications for the construction industry, especially regarding sustainable and environmentally sensitive construction processes.

References

1. Alzhanova, G.Z., et al.: Development of environmentally clean construction materials using industrial waste. Materials **15** (2022). https://doi.org/10.3390/ma15165726
2. Afrin, H.: A review on different types soil stabilization techniques. Int. J. Transp. Eng. Technol. **3**, 19 (2017). https://doi.org/10.11648/j.ijtet.20170302.12
3. Elsiragy, M.: Geotechnical behaviour of reinforced soft clay by marble dust as a waste material. J. Eng. Res. (2021). https://doi.org/10.21608/erjeng.2021.88123.1023
4. Wang, A., Zhan, Q., Dong, W., Gu, W., Zhou, J., Pan, Z.: Influence of recycled fine aggregate content on properties of soft soil solidified by industrial waste residue. Materials **15**, 1–11 (2022). https://doi.org/10.3390/ma15217580
5. Singh, R., Kumar, S., Sharma, A.: Effect of bagasse ash on strength and durability of black cotton soil. Geotech. Geol. Eng. (2020)
6. Sharma, K., Kumar, A.: Utilization of industrial waste—based geopolymers as a soil stabilizer—a review. Innov. Infrastruct. Solut. **5**, 1–20 (2020). https://doi.org/10.1007/s41062-020-00350-7
7. Thirumalai, R., Babu, S.S., Naveennayak, V., Nirmal, R., Lokesh, G.: A review on stabilization of expansive soil using industrial solid wastes. Engineering **09**, 1008–1017 (2017). https://doi.org/10.4236/eng.2017.912060
8. Meena, M., Prasad, R., Singh, D.: Utilization of marble dust as soil stabilization material. Geotech. Geol. Eng. (2017)

9. Consoli, N.C., Bittar Marin, E.J., Quiñónez Samaniego, R.A., Heineck, K.S., Johann, A.D.R.: Use of sustainable binders in soil stabilization. J. Mater. Civ. Eng. **31** (2019). https://doi.org/10.1061/(asce)mt.1943-5533.0002571
10. Yilmaz, F., Kamiloɫlu, H.A., Şadoɫlu, E.: Soil stabilization with using waste materials against freezing thawing effect. Acta Phys. Pol. A. **128**, 392–394 (2015). https://doi.org/10.12693/APhysPolA.128.B-392
11. Al-Rawas, A.A., Hago, A.W., Al-Sarmi, H.: Effect of lime, cement and Sarooj (artificial pozzolan) on the swelling potential of an expansive soil from Oman. Build. Environ. **40** (2005). https://doi.org/10.1016/j.buildenv.2004.08.028
12. Ola, S.A.: The potentials of lime stabilization of lateritic soils. Eng. Geol. **11** (1977). https://doi.org/10.1016/0013-7952(77)90036-9
13. Rao, S.M., Shivananda, P.: Compressibility behaviour of lime-stabilized clay. Geotech. Geol. Eng. **23**, 309–319 (2005). https://doi.org/10.1007/s10706-004-1608-2
14. Sherwood, P.: Soil stabilization with cement and lime. Her Majesty Stationary Office (1993)

Investigation of Heat of Hydration of Superplasticized Calcined Clay-Based Cement

Talha Raza, Muhammad Danyal Sheikh, Tariq Jamil(✉), Tehmina Ayub, and Asad-ur-Rehman Khan

NED University of Engineering and Technology, Karachi, Pakistan
{danydalsheikh,tariqjamil,tehmina,asadkhan}@neduet.edu.pk

Abstract. Cement production is a significant contributor to global CO_2 emissions, with clinker manufacturing being the primary source. Limestone Calcined Clay Cement (LC^3) has emerged as a sustainable alternative to Ordinary Portland Cement (OPC), reducing emissions by replacing a portion of clinker with calcined clay and limestone. However, its adoption in Pakistan remains limited due to insufficient research on its chemical composition and hydration behavior. This study investigates the heat of hydration of LC^3 using indigenous materials, focusing on the impact of superplasticizers on its setting time, workability, and strength development. LC^3 was produced by blending 50% clinker, 30% calcined clay, 15% limestone, and 5% gypsum. Chemical composition analysis, consistency tests, and compressive strength evaluation were conducted per ASTM standards. The heat of hydration was measured using isothermal calorimeter. Results indicate that LC^3 exhibits lower early-age strength due to reduced CaO content but demonstrates improved long-term performance. The addition of superplasticizers enhanced workability, with polycarboxylate-based superplasticizers accelerating hydration compared to naphthalene-based alternatives. The heat of hydration of LC^3 was lower than that of OPC due to the pozzolanic effect of calcined clay, which reduced free lime availability. This slower hydration process results in a more gradual heat release, minimizing thermal cracking risks. Overall, LC^3 presents a viable low-carbon alternative to OPC, with optimized superplasticizer use improving its mechanical properties. Further research on long-term durability and field applications is recommended to enhance its feasibility for large-scale implementation.

Keywords: Heat of Hydration · Calcined Clay · Sustainable Cement

1 Introduction

A study by the Centre for Research on Energy and Clean Air (CREA) found that CO_2 emissions from fossil fuel consumption in Pakistan have more than doubled in the past two decades, with cement production being a major contributor, responsible for one-third of the increase [1]. Currently, Limestone Calcined Clay Cement (LC^3) offers a sustainable alternative to Ordinary Portland Cement (OPC), reducing CO_2 emissions by up to 40% [2]. The clinker production process is the primary source of emissions, as it

T. Ayub et al. (Eds.): GCGC 2025, LNCE 774, pp. 63–70, 2026.
https://doi.org/10.1007/978-981-95-6592-4_8

requires high temperatures (1400–1500 °C) and releases CO_2 from limestone decomposition. Replacing clinker with supplementary cementitious materials (SCMs) is the most effective way to cut both energy use and carbon emissions.

LC^3 is still relatively new in Pakistan, with limited foundational studies conducted to date. Ongoing research continues to explore its properties and potential applications [3–5]. The major issue with calcined clays is their high water demand, which makes the concrete harsh [6]. Recently, Sheikh et. al., reported that using LC^3 with additives found best results in terms of compressive strength for concrete [3]. The heat produced by cement is caused by cement hydration; any additive used to regulate the rate of hydration will also have an impact on the rate of heat emission. The heat of the hydration reaction is a characteristic of cement concrete in its hardening state [7]. The "heat of hydration (HOH)"—the amount of heat produced when a certain volume of un-hydrated cement hydrates at a specific temperature is commonly used to describe the hydration behavior of cement [8]. Switching out some limestone for calcined clay can significantly improve the bulk of the cement's properties [9].

This study aims to analyze the chemical composition and hydration behavior of LC^3 using different superplasticizers. After production, the chemical composition, consistency, initial and final setting times, and hydration behavior of LC^3 were evaluated, with a particular focus on the impact of water-reducing agents on early-age heat generation during hydration.

2 Material and Methodology

2.1 Raw Materials

LC^3 was produced by blending 15% limestone, 30% calcined clay (kaolinite content: 40%), 50% clinker, and 5% gypsum for improved workability. The calcined clay was sourced from Nagarparkar, while low-calcite limestone with quartz and dolomite impurities was obtained from Memon Goth, Karachi. To regulate workability and cement hardening, gypsum content was adjusted to 2.5%. Chemical composition analysis of the cement and clays was conducted using XRF (Table 1). The superplasticizers used included Sika Viscocrete – 3110, Sikament – NN, Sikament 512-star PK, and Sikament-R4QV, which are high-range water reducers capable of lowering water content by up to 20%. Since calcined clay requires sufficient fineness and water, the proper dosage of superplasticizers was crucial for maintaining workability.

Table 1. Chemical Composition

Oxides	Calcined Clay	Limestone	LC^{3}-50
CaO	2.21	54.58	43.09
SiO2	41.64	0.02	27.36
Al2O3	33.81	0.02	11.96
Fe2O3	0.48	0.05	3.29

(*continued*)

Table 1. (*continued*)

Oxides	Calcined Clay	Limestone	$LC^{3-}50$
MgO	0.35	0.15	3.50
Na2O	0.10	0.01	0.13
K2O	0.06	0.00	0.40
SO3	0.01	0.03	3.64
Others	21.29	45.14	6.55

2.2 Mix Composition

Experiments on LC3 used varying dosages of superplasticizers to enhance workability. The primary mix design, LC^3-50 2:1, consisted of 50% clinker, 30% calcined clay, 15% limestone, and 5% gypsum (Julien, 2019). The numbers in "LC^3-50 2:1" indicate clinker content and the calcined clay-to-limestone ratio. Polycarboxylate ether-based and naphthalene formaldehyde sulphonate-based superplasticizers were tested, modifying paste properties. A water-to-binder ratio of 0.30 was maintained after achieving consistency.

2.3 Experimental Method

Consistency and Setting Time

The normal consistency, initial setting time, and final setting time of cement paste were determined using the Vicat apparatus per ASTM C187-74 [10] and ASTM C191-74 [10]. Consistency was assessed by adjusting water and superplasticizer levels until the paste met specific penetration resistance. Samples with the lowest w/c ratio underwent trial-and-error testing with different superplasticizers. A 1 mm square needle measured the initial setting time at 10-minute intervals, while a needle with an annular attachment recorded the final setting time at 30-minute intervals. The results were averaged from three tests.

Table 2. Mix Design

Superplasticizer	w/c	Dosage of Superplasticizer (%)
Without Superplasticizer	0.35	0.0
Sika Viscocrete – 3110	0.25	0.3
Sikament – NN	0.28	0.3
Sikament 512-star PK	0.26	0.3
Sikament-R4QV	0.28	0.3

Compressive Strength

The mortar compressive strength test was conducted according to ASTM C 109/C109M [11]. Mortar specimens were prepared using cubes 2″ × 2″ (50 mm × 50 mm) having curing periods of 3, 7, and 28 days, with a mix design of (Table 2). Compressive strength was measured at 3, 7, and 28 days, with the final strength determined as the average of the peak stresses from three specimens.

Heat of Hydration

The heat of hydration was measured using an isothermal calorimeter (I-Cal 2000) on fresh paste samples prepared according to the mix design in (Table 2). Before mixing, all materials and containers were preconditioned at the set temperature for 24 h. The cement blend was then mixed with distilled water for 2 min at 1600 rpm. A 100 g sample of the fresh paste was immediately placed in the calorimeter, where data logging continued for 3 days. The recorded data were analyzed to determine heat flow and total heat of hydration per gram of binder.

3 Result and Discussion

3.1 Consistency and Setting Time

The mixes maintained consistent workability by keeping the superplasticizer dosage constant and adjusting the water-to-cement ratio. Naphthalene-based superplasticizers delayed setting times due to their dispersion mechanism slowing hydration, while polycarboxylate-based superplasticizers shortened setting times by enhancing particle dispersion and reducing water demand. Overall, polycarboxylate-based pastes exhibited faster setting and better strength development (Figs. 1 and 2).

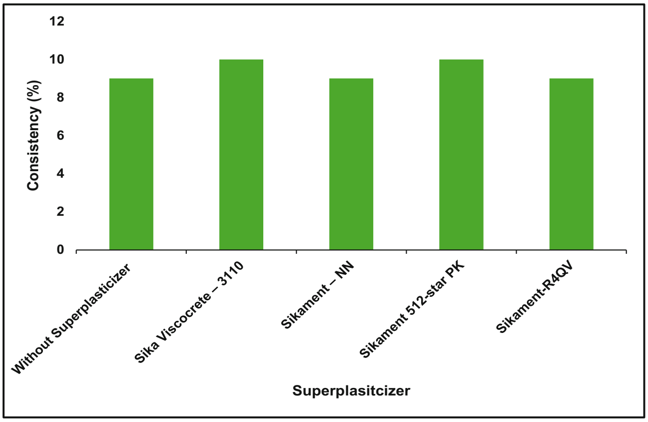


Fig. 1. Results of the Consistency Test

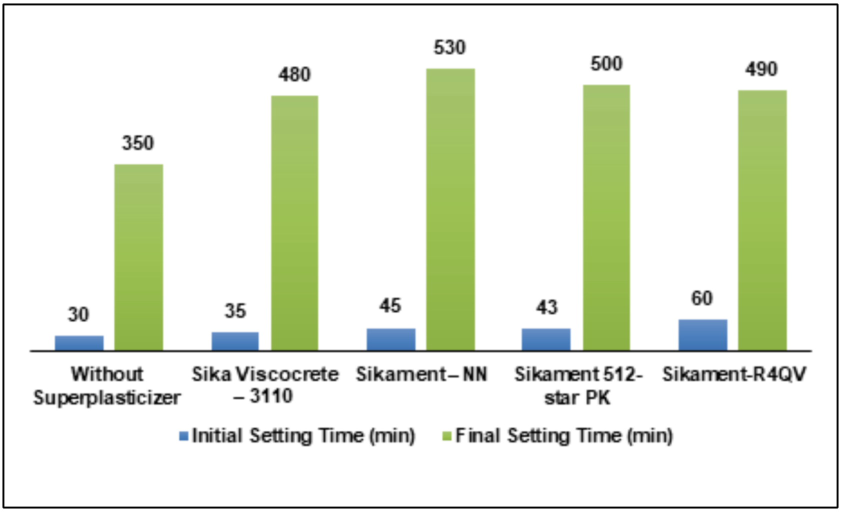


Fig. 2. Results of Setting Time

3.2 Compressive Strength

Figure 4 presents the compressive strength of mortar cubes at different curing ages (3, 7, and 28 days). At 3 days, the strength development was relatively similar across all samples, though polycarboxylate-based pastes exhibited slightly higher early strength than naphthalene-based pastes. By 7 days, the strength of polycarboxylate-based pastes showed a more significant increase, surpassing that of naphthalene-based pastes. At 28 days, the difference became even more pronounced, with polycarboxylate-based pastes achieving higher final strength than their naphthalene-based counterparts.

While increasing gypsum content generally slowed down strength development in LC^3, the 28-day strength of mixes with higher gypsum content still showed improvement in polycarboxylate-based pastes compared to naphthalene-based ones. Across all ages, low-clinker cements exhibited slower strength gain, particularly in the first few days (Fig. 3).

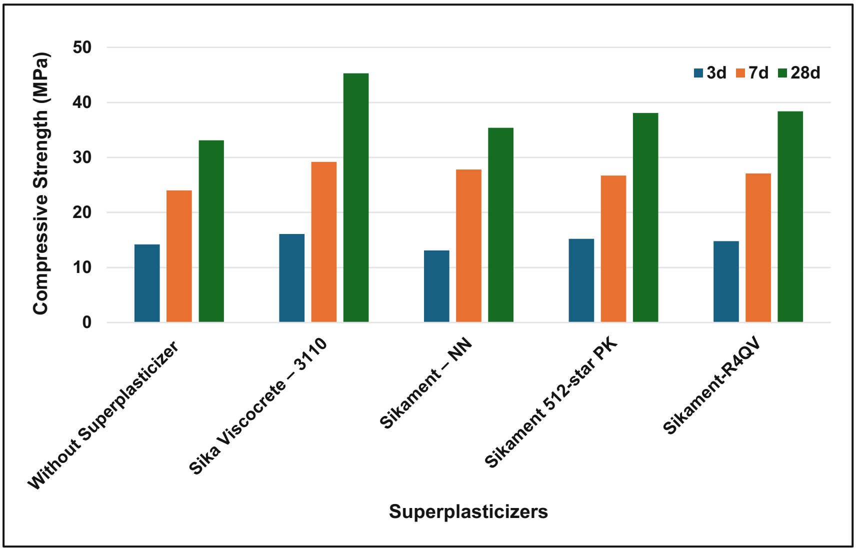


Fig. 3. Result of Compressive Strength Test

3.3 Heat of Hydration

Cement hydration is a multi-phase process with distinct stages. Superplasticizers do not alter hydration mechanisms but affect peak intensity, slow setting, and delay hydration. Microcalorimetric curves (Fig. 4) illustrate these effects.

The dormant period is slightly longer with PCE-based superplasticizers than with naphthalene-based ones. While hydration heat release remains small, the rapid rise in pH and $Ca2^{+}$ ion content delays clinker dissolution. During this phase, the solution saturates with $Ca2^{+}$, but $Ca(OH)_2$ precipitation is slow due to competition with C-S-H formation. Induction time lasts 2–2.5 h for regular cement but extends to 8–11 h with PCE-based superplasticizers and 3–4 h with naphthalene-based ones due to high-range water reduction.

As lime precipitates and silicates deplete in the aqueous phase, hydration accelerates, marking the first setting period. Rapid $Ca2^{+}$ and OH^{-} consumption enhances cement phase dissolution, initially causing slow heat evolution (endothermic $Ca(OH)_2$ precipitation), then a faster rise. The paste stiffens due to interparticle bonding of hydrated silicates and aluminates. Superplasticizers delay setting and hydration, shifting heat flow peaks to 21 h (2 mW/g) for PCE-based and 8 h (1.7 mW/g) for naphthalene-based superplasticizers. SO_42^{-} ions are consumed in ettringite formation due to limited calcium sulfate availability.

Ettringite transforms into mono-sulfate in the fourth phase, often known as the hardening period. The silicate phases' hydration is accelerated by this reaction, which also produces heat. Finally, a coating of hydrates covering the cement grains thickens and slows the hydration process. Superplasticizer is added, which has a larger retarding effect and lowers overall summed heat.

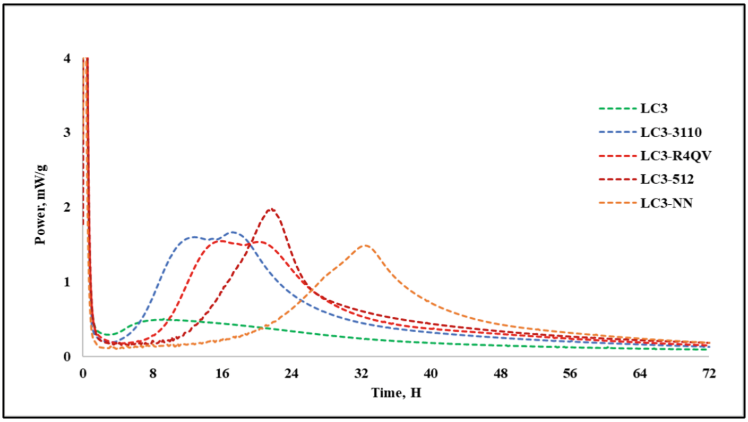


Fig. 4. Results of Heat of Hydration

4 Conclusion

The following are the conclusions drawn from this study:

1. Based on the results of LC^3 chemical composition it is concluded that the content of CaO is lesser which means that LC^3 has less strength in early stages but greater strength in later stages and Al_2O_3 is greater in LC^3 so it creates workability issues and decreases the setting time.
2. Based on the consistency, setting time, compressive strength, and heat of hydration of LC^3 with different types of PCE-based superplasticizers, 'some conclusions are drawn:
   a. Consistency of LC3 affects the workability. Greater consistency results in greater workability. LC3 has workability issues, to counter this different superplasticizer has been added which enhances the workability.
   b. Based on the results of the initial and final setting time tests performed on limestone-calcined clay cement (LC^3) with different types of superplasticizers with 0.3% dosage, it is concluded that LC^3 exhibits a slower setting time. The addition of calcined clay affects the cement paste's reaction kinetics and slows the LC3's setting time.
   c. LC^3 has distinct proportions of C_3S and C_2S as a result. At later stages, LC^3 performs better in terms of compressive strength. It is observed that the compressive strength of LC^3 containing Sikament Viscocrete 3110 is high as compared to all the other superplasticizers.
   d. Investigating LC3 hydration with various superplasticizers confirms its lower heat release. Calcined clay reduces free lime, while PCE-based superplasticizers show no adverse effects. The reaction occurs gradually, generating less heat.

References

1. Uddin, A., et al.: Circular economy and its implementation in cement industry: a case point in Pakistan. Sci. Total. Environ. **898**, 165605 (2023)

2. Kanagaraj, B., et al.: Limestone calcined clay cement (LC3): a sustainable solution for mitigating environmental impact in the construction sector. Resour. Conserv. Recycling Adv. **21**, 200197 (2024)
3. Sheikh, M.D., et al.: Comparative study on LC3-50 with OPC concrete using raw materials from Pakistan. Adv. Mater. Sci. Eng. **2023**(1), 5503670 (2023)
4. Hussain, S.M.F., et al.: Initial search for low grade clay in Pakistan for producing LC3 ecofriendly cement. Low-Carbon Mater. Green Constr. **1**(1), 15 (2023)
5. Ayub, T., et al.: Effect of glass powder on the compressive strength and drying shrinkage behavior of OPC-and LC3-50-based cementitious composites of various strengths. Adv. Mater. Sci. Eng. **2024**(1), 8860083 (2024)
6. Nehdi, M.: Clay in cement-based materials: critical overview of state-of-the-art. Constr. Build. Mater. **51**, 372–382 (2014)
7. Awal, A.A., Hussin, M.W.: Effect of palm oil fuel ash in controlling heat of hydration of concrete. Procedia Eng. **14**, 2650–2657 (2011)
8. Neville, A.M.: Properties of Concrete. Longman (1995)
9. Antoni, M., et al.: Cement substitution by a combination of metakaolin and limestone. Cem. Concr. Res. **42**(12), 1579–1589 (2012)
10. ASTM: C187-04 Standard Test Method for Normal Consistency of Hydraulic Cement. ASTM: West Conshohocken, PA 19428-2959, United States (2009)
11. ASTM: C191–08 Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle. West Conshohocken, PA 19428-2959, United States (2009)

A Novel Approach to Reduce Smog by Proposing Alternative to Bricks in Construction

Souman Khalid[1], Khadija Mawra[1], Khuram Rashid[1](✉), and Arif Bashir[2]

[1] Department of Architectural Engineering and Design, University of Engineering and Technology, Lahore, Pakistan
khuram_ae@uet.edu.pk

[2] Director (Technical & Operations), DG Khan Cement Co. Ltd. Nishat Group, Lahore, Pakistan

Abstract. Brick is a primary building material in developing countries, but its manufacturing is energy-intensive and causes smog hazards. Therefore, alternate concrete wall panels have been proposed in this work, which can provide better qualities and benefits than conventional fired-clay bricks (CB). Five constructional units – CB, Ordinary Portland Cement (OP), Fly Ash (FP), OPC with thermopore (OPT), and Fly Ash with thermopore (FPT) – were evaluated. The panel size (600 × 300 × 125 mm) was selected by balancing the weight carried by one labor and tested under uniaxial compression for evaluating structural performance. Afterward, an estimation was carried out for a sample room of size 4.6 × 4.6 m for all five units. For the CB room, the English bonding technique was used, while hinge jointing was proposed for the construction of walls with panels. Furthermore, a financial analysis was conducted using an interest rate of 11% and a discount factor of 12%. The estimations, which also considered 1% annual Operation and Maintenance (O&M) costs and uniform rental revenue simulated for 25 years, yielded Benefit-Cost Ratios (BCR) and Net Present Values (NPV) for each case. The results demonstrate that wall panels offer significant advantages over CB in terms of higher compressive strength, lower construction costs, and enhanced durability and also present an economically feasible solution. Notably, FPT emerged as the most cost-effective alternative to brick masonry, making it a promising solution for the construction industry. This study provides valuable insights for policy-makers, builders, and researchers seeking sustainable and economically viable construction materials and methods.

Keywords: Wall masonary · Concrete panel · Thermopore · Financial feasibility

1 Introduction

Pakistan, a low-income developing country, is striving to provide affordable housing to its citizens. In this industry, clay burnt brick is a widely used building material, which is, however, highly environmentally antagonistic of 1.5 trillion fired-clay bricks produced worldwide annually, 87% are only being produced in Asia. Conventional brick masonry has various drawbacks including longer construction durations, high quality deviations, and environmental harms of brick manufacturing including smog and air pollution [1,

T. Ayub et al. (Eds.): GCGC 2025, LNCE 774, pp. 71–78, 2026.
https://doi.org/10.1007/978-981-95-6592-4_9

2]. Pakistan is facing severe smog annually, with AQI reaching above 1000 in different cities. As a result, efforts are being made to propose alternative masonry materials with potential benefits and fewer environmental concerns.

A recent national research developed a fly ash and rice-husk based geopolymer brick that somehow addresses conventional bricks' environmental issues by only requiring 60 °C temperature instead of the high burning required in brick kilns that lead to smog [3, 4]. Moreover, sustainable development goal (SDG) 11.1, aims at the provision of safe, sustainable, and affordable houses to all, for which recently a lot of research has been carried out to make sustainable models for financing houses. A few other research studies concluded that the building materials cost is a main hindrance to affordable housing in developing countries, leading to the adaptation of alternative materials for construction technologies [5]. Not much research has been carried out to propose a plan for affordable housing by decreasing construction costs and duration and increasing the use of sustainable materials in construction at a larger scale without compromising the basic parameters/performance of the housing units.

Load-bearing wall panels made from the Mean Mix Designs (MMD) approach have been recently introduced in the construction industry with cost and environmental effectiveness [6]. These load-bearing wall panels can also be used for affordable houses with lesser construction costs, rapid erection, additional space, and better environmental properties. This study aims to provide a comprehensive financial analysis for OPC-Con and FA-Con-based wall panels in practical application. The study first develops concrete panels of OPC and FA with and without thermophore insulation layer, along with their bonding mechanism as masonry units. Their mechanical performance was evaluated experimentally and financial analysis was carried out for their feasibility for affordable housing.

2 Methodology

A comparison of traditional burnt clay brick with OPC-based and FA-based concrete blocks was carried out regarding mechanical and financial performance. The steps of sample preparation and mechanical and financial analyses are explained in subsequent sections.

2.1 Materials and Sample Preparation

The cement for this study was procured from a local manufacturer (D.G. cement), the sand used was Lawrencpur sand, and the aggregate used was Sargodha crush. While FA was obtained from Sahiwal coal power plant. The mix design for casting OPC and FA panels was 1:2.4:2.9 from the mean mix design approach [6]. The quantities of the raw material used for both types of concrete mix are listed in Table 1. The concrete panels sized 600 × 300 × 125 mm were cast with OPC and FA in two types of cross-sections; solid rectangular and with thermopore sheet in the center, as shown in Fig. 1. The inner cavity was created by placing a thermopore in the center of the casting mould by leaving 50 mm from the boundaries of the mold on all sides. Hence, the thermopore sheet of 500 × 200 × 25 mm was placed at the center as shown in Fig. 1.

Table 1. Mix quantities of OPC and FA-based concrete panels

Constituents (kg)	OP	FA	OPT	FPT	Rate (PKR/kg)	Rate (USD/kg)
Cement	8.24	5.90	7.50	5.38	26	0.092
Sand	18.48	17.60	16.83	16.04	3.3	0.012
Aggregate	24.14	21	22	19.13	3.8	0.013
Water	4.51	4.20	4.11	3.83	1	0.004
Fly ash	-	2.40	-	2.19	5	0.018
Superplasticizer	-	0.22	-	0.20	175	0.614
Thermopore	-	-	1.10*	1.10*	6.7**	0.024**

* square foot (sft); ** per square foot (sft)

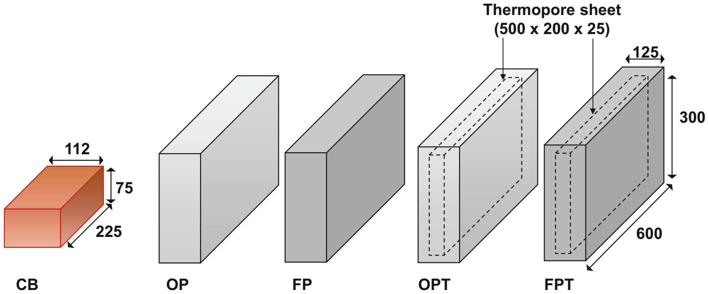


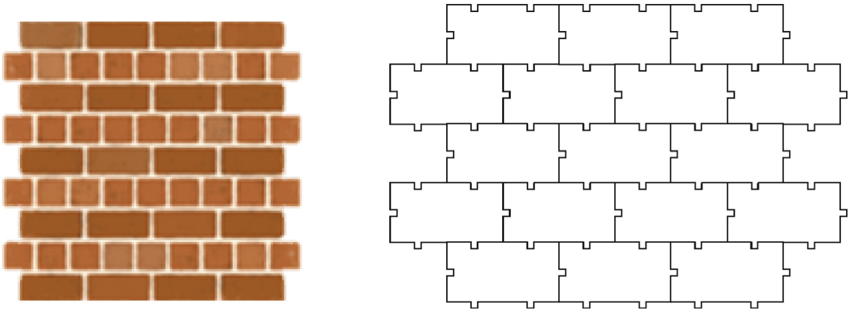
Fig. 1. Five masonry units developed in the study (all dimensions in mm).

2.2 Compressive Strength

To evaluate the compressive strength parameter, the cast panels were cured and tested for compressive strength as per the standard uniaxial compression test procedure. The compressive strength of common class A brick (225 × 112 × 75 mm) (Fig. 1) was considered as per ASTM C62 and a comparison was made with test results of concrete panels. Overall, five material alternatives are considered in this study, as enlisted in Fig. 1.

2.3 Compressive Strength

For conducting financial analyses, a case of room construction was considered. For which, wall masonry bonding was considered for both CB and panel construction. For CB construction, the most commonly used interlocking / bonding pattern is through the English bonds. For FA panel walls, interlocking was done through hinges at each side for effective bonding as illustrated in Fig. 2.



(a) English bond brick masonry (b) Panel masonry with hinge system bonding

Fig. 2. Interlocking techniques for masonry types.

2.4 Financial Analysis

The financial benefits/losses of using the five types of alternatives in wall masonry were assessed by considering constructing a room of size 4.6 m × 4.6 m × 3 m with them. A net present value and benefit-to-cost ratio were evaluated for the five cases of construction. For both techniques, major components required are cash outflows (costs), cash inflows (benefits), and the discount (d = 12%) and inflation rates (i = 11%). A cashflow representation for a period of 25 years is shown in Fig. 3 and the components are discussed in the subsequent sections.

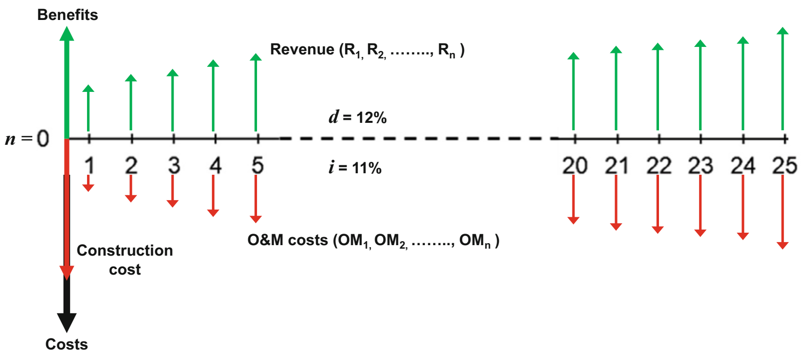


Fig. 3. Cash inflows and outflows of the 25 years financial analysis

The total costs (C) are the sum of initial construction cost (I) and present value of annual O&M expenses (PV_{OM}) of 25 years at year 0 discounted at d. The construction cost of the prescribed room with the five masonry materials was calculated based on per unit cost of masonry material (CB, OP, FP, OPT, FPT), quantities of each, plastering, and the labor cost. The per unit cost of panels was based on raw material quantity in the volume of each panel and the Lahore-based labor rates according to Market Rates System notified on 4th January 2024 by the Government of Punjab. The brick price was considered PKR 17/brick as per market quotations available in Lahore. Then 1% of the construction cost was considered to be the O&M expenses which are further inflated at 11% 'i' every year (Eq. (1)). The discounted present value @ 12% of annual O&M costs was given by Eq. (2). The total cost is given as the sum of initial construction cost (I) and PV_{OM} as given in Eq. (3). Secondly, the total benefits (B) were taken as the present value of all revenues (PVR) generated by renting out the room at local rent rate of 10,500 per year and increased yearly by an i of 11%. The yearly increase in revenue is given by Eq. (4). And the present value of all revenues is given mathematically by Eq. (5) by incorporating a discounted factor of 12%.

$$OM_n = OM_{n-1}(1+i)^n(1) \tag{1}$$

$$\mathrm{PV}_{\mathrm{OM}} = \sum \frac{OM_{1\to n}}{(1+d)^n} \tag{2}$$

$$C = I + PV_{OM} \tag{3}$$

$$R_n = R_{n-1}(1+i)^n \tag{4}$$

$$\mathrm{B} = \mathrm{PV}_{\mathrm{R}} = \sum \frac{R_{1\to n}}{(1+d)^n} \tag{5}$$

From the calculated total costs and benefits, the net present value (NPV) was calculated is a measure of financial feasibility of an alternative in construction. It is given by the difference between total benefits (B) and total costs (C) given as Eq. (6). A positive value of NPV establishes the beneficence of an alternative to being selected. The second indicator of financial assessment was benefit-to-cost ratio. It is given by the ratio of total benefits ($\mathrm{PV_R}$) to total costs (C) given as Eq. (7). A value of greater than 1 means the alternative is acceptable and beneficial.

$$\mathrm{NPV} = \mathrm{PV_R} - \mathrm{C} \tag{6}$$

$$\frac{B}{C} = \frac{\mathrm{PV_R}}{C} \tag{7}$$

3 Results and Discussion

3.1 Masonry Strength Compliance

The utility of panels/blocks in masonry structures greatly depends upon the material's compressive strength. All 4 types of panel blocks surpassed the compressive strength of CB (12 MPa) and therefore found fit for use in the housing industry. The OP showed a maximum compressive strength of 18.3MPa which is 52.5% higher than the traditional brick. FP gave strength 17.4 MPa, while FPT (with thermopore) showed the lowest compressive strength among the laboratory-made panels (13.3 MPa), which was still 10.5% greater than the bricks used for local residential units (Fig. 4).

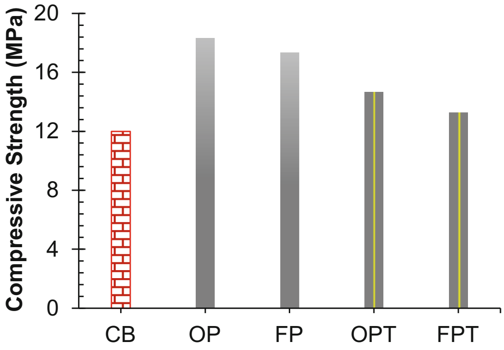


Fig. 4. Compressive strengths for 5 types of bricks/panels.

3.2 Cost and Benefits

The construction cost of the five alternatives depended on the per unit cost of each masonry unit and their quantities. The per unit price of concrete panels was comparatively higher than the common brick (PKR 17/0.06 USD). Whereas the OP and FP cost around PKR 371 (1.31 USD) and PKR 344 (1.21 USD), respectively. OPT and FPT had slightly lower prices due to less concrete volume, PKR 346 (1.22 USD) and PKR 321 (1.13 USD), respectively. However, the total construction cost of panels came out to be lower than the CB as shown in Fig. 5. This was due to lesser quantity of panels required as compared to bricks, owing to their larger size. A total of 5372 number of bricks were required for construction whereas only 290 panels. A similar comparison was anticipated for O&M expenses as well because O&M were 1% of the respective construction cost. The total costs at the start of the room construction with five masonry alternatives consisting the construction cost and the present value of cumulative O&M costs for all years are shown in Fig. 5. It is clearly seen that using the wall panels is overall beneficial than the traditional construction with burnt clay bricks as CB case reports the highest initial construction cost and O&M expenses. Among the concrete panels, the use of FPT panels comes out as the best alternative depicting lowest total costs valuing only 352 thousand PKR including an initial construction cost of 174 thousand PKR and 178 thousand PKR as cumulative O&M cost. The results reveal that the addition of FA lowers the cost of concrete due to FA being a cheap material compared to cement. On the other hand, the benefits for all cases remained constant since the rental revenue for all cases was same valued 1201 thousand PKR (4,228 USD).

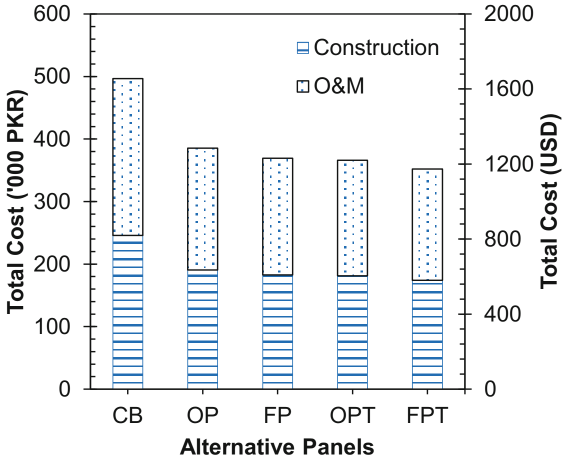


Fig. 5. Total costs as sum of construction and present value O&M for five alternatives.

3.3 Net Present Value and Benefit-To-Cost Ratio

The NPV of all five types of construction is shown in Fig. 6. Only the FPT case depicted a positive NPV value. It is because this case had the lowest costs while the benefit was the same as others. Hence constructing the wall with FA-based panels having thermopore layer inside will provide best financial benefits along with sufficient strength of masonry.

In terms of B/C ratio, again the FPT came out to be the best alternative with only one that had a ratio value greater than 1.0 (Fig. 7). The reason being lower costs of construction and O&M and same amount of revenue generated compared to any other construction case. The inclusion of FA and the reduced volume of concrete due to thermopore layer posed the greater benefits in FPT.

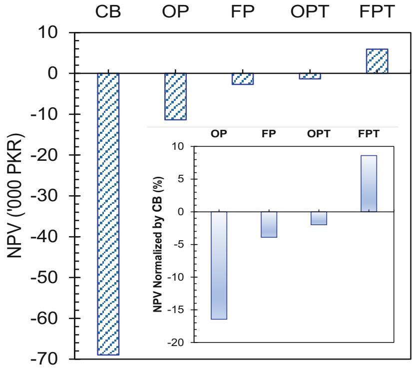


Fig. 6. NPV of all alternatives

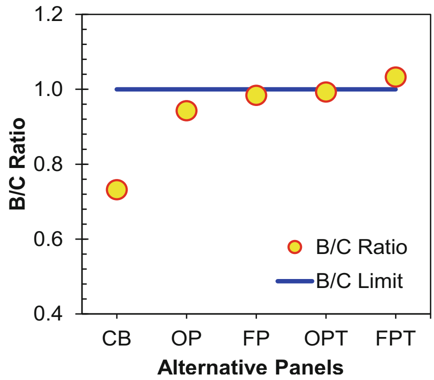


Fig. 7. Benefit-to-cost ratio of all panels

4 Conclusion

The study developed masonry alternatives to conventional clay bricks (CB) using OPC and FA. Four wall panels were tested—two solid and two with a thermopore layer—compared to CB for strength and cost-effectiveness. The findings of the study concluded that:

1. All concrete panels provide compressive strength greater than the CB and are recommended to be used in wall masonry
2. In terms of construction cost, the concrete panels overall are cheaper than CB, however, FPT was cheapest for construction among all alternatives.
3. Construction by FA panels with thermopore is the most financially feasible option with a positive net present value and a B/C greater than 1.0, among all alternatives.

Alternative to burnt clay brick indirectly solves the smog produced by manufacturing bricks. However, a detailed analysis related to smog is being reviewed and will be reported soon.

References

1. Siddqiue, M.U., Jamil, M., Arshad, A.: Digital solutions and technological innovations driving public awareness and community initiatives for smog reduction in Lahore: a descriptive overview. Pakistan Soc. Sci. Rev. **7**(4), 425–438 (2023)
2. Nazir, U., Ather, M.A., Taj, M.: Detection of illegal kiln activity during SMOG period. In: 2023 International Conference on Robotics and Automation in Industry (ICRAI), pp. 1–6 (2023)
3. Ahmad, M., Rashid, K.: Novel approach to synthesize clay-based geopolymer brick: optimizing molding pressure and precursors' proportioning. Constr. Build. Mater. **322**, 126472 (2022)
4. Mawra, K., Rashid, K., Alqahtani, F.K., Zafar, I., Ju, M.: Load bearing geopolymer from agro-waste and its energy-environmental - economic (E3) performance: application through building information modeling. Constr. Build. Mater. **440**, 137425 (2024)
5. Ganiyu, B.O., Fapohunda, J.A., Haldenwang, R.: Construction approaches to enhance sustainability in affordable housing in developing countries. In: 2015 World Congress on Sustainable Technologies (WCST), pp. 101–107. IEEE (2015)
6. Khalid, S., Rashid, K., Mawra, K., Tariq, Z., Kim, H., Ju, M.: Multimodal optimization of concrete mix design for sustainable load bearing wall panels: mean-mix − artificial Intelligence − experimentation fusion. Case Stud. Construct. Mater. **21**, e03868 (2024)

Healing of Cracked Cementitious Composite Through Microorganism-Based Agent Encapsulated with Varying Techniques

Sadaqat Ullah Khan[1], Tehmina Ayub[2](✉), and Bilal Ahmed[3]

[1] Department of Civil Engineering, Sciences and Technology, Thar Institute of Engineering, NED University of Engineering and Technology, Karachi, Pakistan
[2] Department of Civil Engineering, NED University of Engineering and Technology, Karachi, Pakistan
tehmina@neduet.edu.pk
[3] Department of Urban and Infrastructure Engineering, NED University of Engineering and Technology, Karachi, Pakistan

Abstract. Incorporation of bacteria into the Cementitious composite using different carrier has been reported to be an efficient approach for Microorganism-based self-healing. However, the literature does not mention the utilisation of hard gelatin capsules. Thus, the feasibility of hard gelatin capsules as a novel microorganism carrier via immobilization of Bacillus subtilis was demonstrated in this study. Gelatin capsules coated with two types of coating were employed that is (a) epoxy coating and (b) Epoxy + Tape coating on the capsules filled with microorganisms and were examined in cementitious composite. 3 discs of the size of 85 mm diameter and 50 mm depth were cast and cured for 7 days for each mix. After 7 days of curing, discs were bifurcated using a split tensile test and encased in the PVC pipe. The specimens were then immersed in water to assess the healing effect at 3, 7, and 14 days with the help of a crack-width sensing camera. Based on the observation, it was deduced that the healing effect was significantly efficient in healing containing epoxy-coated capsules filled with microorganisms.

Keywords: Gelatin Capsule · Bacillus Subtilis · Cementitious Composite

1 Introduction

Concrete's brittleness and low tensile strength make it prone to cracking from shrinkage, settlement, and freeze-thaw cycles, allowing corrosive agents to damage steel reinforcement and reduce structural durability. While repair methods exist, ongoing maintenance and monitoring incur significant long-term costs.

Concrete has a harsh, alkaline environment [1], so Jonkers and Schlangen chose bacteria that could withstand these conditions and tested their self-healing potential [2]. Their research showed promising results using non-ureolytic bacteria to self-heal cracks. Several studies [3–5] have since explored different bacteria to evaluate their self-healing ability, impact on concrete strength, and resistance to acid. Jonkers et.al also

T. Ayub et al. (Eds.): GCGC 2025, LNCE 774, pp. 79–86, 2026.
https://doi.org/10.1007/978-981-95-6592-4_10

tested *Bacillus psuedofirmus* and *Bacillus cohnii* at a concentration of 100–1000 million spores/cm3, finding that these bacteria produced larger crack-filling minerals in young concrete [6].

The choice of bacterial carrier is crucial for self-healing. Wasim et al. found that Bacillus subtilis in Graphite Nano Platelets (GNP) and Lightweight Aggregates (LWA) improved strength recovery by 7% with direct addition, 9.8% with GNP, and 12% with LWA. GNP was more effective for early cracks, while LWA worked better for later ones [7]. Various encapsulation methods, including expanded clay, perlite, hydrogels, and microcapsules, have been explored for bacterial carriers [8, 9], [10, 11], but hard gelatin capsules are less studied.

This study used hard gelatin capsules filled with Bacillus subtilis, a calcite-producing bacterium and calcium lactate as a precursor. To improve durability, the capsules were modified to be hydrophobic and brittle, then incorporated into concrete samples to assess their effectiveness in healing surface cracks using a crack width tester.

2 Experimental Program

2.1 Bacteria and Calcium Lactate

Bacillus subtilis is a non-ureolytic, alkaliphilic, spore-forming bacterium available in the light yellow powdered form shown in Fig. 1(a) with a concentration of 20 billion CFU/g. Calcium lactate, also in powdered form displayed in Fig. 1(b), served as the organic precursor. By combining dormant bacteria with calcium lactate, a two-component healing agent was created, enhancing concrete self-healing capabilities.

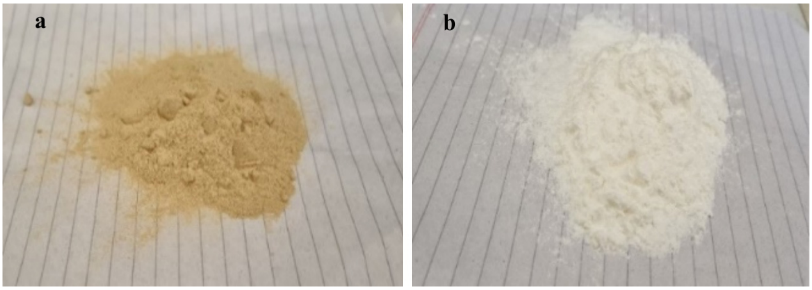


Fig. 1. Two-Component healing agents (a) Bacillus subtilis (b) Calcium Lactate

2.2 Gelatin Capsules

In this study, locally available size No. 4 hard gelatin capsules were used for encapsulation. These capsules measure 14.2 mm in length, have a 4.3 mm cap diameters as shown in Fig. 2 and an empty mass of 36 mg. They can hold 120–240 mg of powder, depending on its density. The smaller size was selected to allow more capsules to be included, increasing the chance of rupture and release of healing agents.

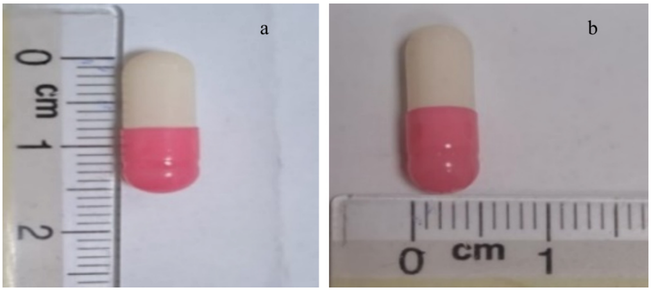


Fig. 2. Capsule dimensions (a) Length of capsule (b) Diameter of capsule

2.3 Encapsulation Process

A low-cost, practical encapsulation method was chosen for the two-component healing agent, with hard gelatin capsules selected for the first time due to their availability and ease of filling. Made from collagen, these capsules dissolve in water, fully dissolving within 60 min, as shown in Fig. 3. This highlighted the need to protect the capsules from moisture, leading to efforts to improve their durability and brittleness.

Fig. 3. Distortion of capsules immersed in water

Details of Techniques. Ten gelatin capsules were tested under three conditions: room temperature, 55 °C for one hour, and 80 °C. Capsules heated to 80 °C became brittle and harder to compress, while room-temperature capsules showed no change. To further test brittleness, capsules were heated to 100 °C for an hour; one set was stored in airtight bags for 24 h, and another was left at room temperature. Both methods produced brittle, stiffer capsules with distorted but functional locking areas. However, this treatment exceeded Bacillus Subtilis's tolerance limit of 80 °C.

To protect gelatin capsules from moisture and increase stiffness, various coatings were tested: spray paint, acrylic paint, and play-dough. Spray-painted capsules lost their shape upon water immersion, similar to uncoated capsules. Acrylic paint and play-dough coatings made capsules too soft, breaking easily. Additionally, play-dough-coated capsules released a gel-like substance upon breaking, as shown in Fig. 4(c), due to moisture in the play-dough reacting with the gelatin. These coatings were found ineffective for capsule protection.

Fig. 4. Coatings of capsules through different materials (a) Spray-painted capsules (b) Acrylic-painted capsules (c) Breakage of play-dough coated capsules

Lastly, capsule caps were coated with hot glue and an epoxy solution (1:2 resin-to-hardener ratio) for moisture protection. After air-drying for 24 h, the hot glue produced a rubbery finish, while the epoxy created a brittle, shiny coating. In water, the epoxy-coated capsules remained intact for over an hour, showing strong moisture resistance (see Fig. 5).

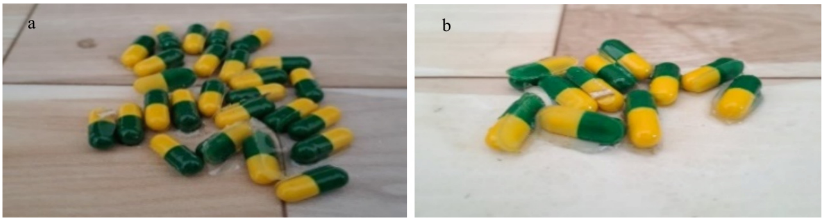


Fig. 5. Trial 4 (a) Capsules coated with epoxy (b) Effect of water on epoxy-coated capsules

Epoxy-coated capsules showed promising results, transforming dissolvable gelatin into a brittle, water-resistant material. To further assess performance, two groups were tested: one with only epoxy-coated capsules and another with capsules wrapped in paper tape before applying epoxy.

2.4 Mixing Casting and Curing

Two cementitious composites, "Mix 1" and "Mix 2," were prepared with Type-I Ordinary Portland Cement, local sand, and a 0.5 water-to-cement ratio, yielding a compressive strength of 21 MPa. Mix 1 included epoxy-coated gelatin capsules, while Mix 2 used double-coated (tape and epoxy) capsules, each filled with a 1:1 mix of *Bacillus subtilis* and calcium lactate as healing agents. Three samples per mix (see Table 1) were cast for self-healing evaluation. After dry-mixing cement and sand, a superplasticizer-water solution was added, and the capsules were gently incorporated. The paste was placed in oiled molds in tamped layers, cast into six disk molds, and cured in water for seven days after a 24-h de-molding period (Fig. 6).

Fig. 6. Casting of specimens (a) Capsules sprinkled on mix (b) Oiling of molds (c) Filled molds with mix

Table 1. Proportions of the cementitious composite mix

Materials	Mix 1	Mix 2
Cement (Kg/m^3)	544	544
Fine (Kg/m^3)	1342	1342
Admixture (%)	0.5	0.5
Bacteria (cells/caps)	1 x 10^9	1 x 10^9
Calcium Lactate (kg/caps)	5 x 10^{-5}	5 x 10^{-5}
No. of capsules (/Sample)	26	26

2.5 Testing

After 7 days of curing, specimens were air-dried for several hours before testing. Each dried sample was then placed in a compression testing machine (CTM) and tested according to ASTM C496/C496M-17 [8], with incremental loading until it split in half. The split pieces were reassembled using a PVC pipe and bound with wire, exposing the cracked surfaces on the top and bottom. Figure 7 illustrates the pre-cracking process step-by-step. The average crack width was measured with a TP-102 crack width tester at five points across the diameter, and the final value was the average of these measurements. After recording crack widths at 0 days of curing, specimens were immersed in water to allow crack healing, with measurements repeated at 3, 7, and 14 days.

Fig. 7. Step-by-step procedure for pre-cracking

3 Results and Discussion

3.1 Healing of Cracks

Bacterial crack healing was assessed in bifurcated specimens over 3, 7, and 14 days, with initial crack widths of 0.52 mm, 0.43 mm, and 0.3 mm for Samples 1, 2, and 3, respectively. After 3 days, cracks reduced in all samples, with Sample 3 healing the most and Sample 2 the least. By day 7, Sample 2 showed notable healing (0.356 mm), Sample 3 reduced to 0.19 mm, and Sample 1 showed minimal progress. By day 14, Sample 3 exhibited the greatest healing (0.102 mm), while Samples 2 and 1 had final widths of 0.306 mm and 0.438 mm, respectively. For simultaneous healing with epoxy + tape-coated capsules, initial crack widths were 0.72 mm, 0.6 mm, and 1.068 mm for Samples 1, 2, and 3. After 3 days, crack widths reduced to 0.538 mm, 0.403 mm, and 0.8 mm. By day 14, final widths were 0.445 mm, 0.383 mm, and 0.716 mm, with Sample 1 showing the most healing. Detailed data is in Table 2.

Table 2. Summary of crack widths at different days of curing

Days	Mix-1			Mix-2		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
	Crack Widths (mm)			Crack Widths (mm)		
0	0.5	0.43	0.3	0.72	0.6	1.068
3	0.472	0.421	0.206	0.538	0.403	0.8
7	0.47	0.356	0.19	0.527	0.4	0.718
14	0.438	0.306	0.102	0.445	0.383	0.716

3.2 Precipitation on Cracked Samples

Figure 8 displays split samples over healing days, showing bacterial conversion of calcium lactate into white $CaCO_3$ precipitates. By day 3, crack widths reduced, though no precipitates were visible. After 14 days, Samples 2 and 3 had slight $CaCO_3$ deposits filling cracks, aligning with previous studies [2, 3, 6]. Sample 1 showed no precipitation, likely due to fewer capsules in crack-prone areas, limiting bacterial conversion and resulting in no visible white deposits.

Fig. 8. Split samples with respect to days of healing (a) 0 day (b) 14 day

3.3 Comparison of Two Methods

Figure 9 compares crack healing in samples with two types of bacteria-filled capsule coatings. Epoxy-coated capsules showed 31.3% healing after 3 days, while epoxy + tape-coated capsules achieved 25.1%, likely due to the smaller initial crack width of 0.3 mm, as seen in Zhang et al. [9], After 7 days, healing increased to 32.77% for epoxy + tape-coated and 36.66% for epoxy-coated samples. By day 14, epoxy-coated samples reached 66% healing, consistent with Ganesh et al. [1] who observed up to 60% healing in bacteria-based samples.

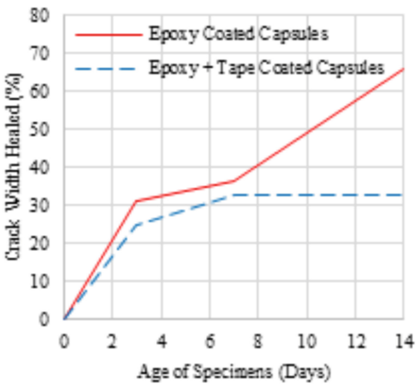


Fig. 9. Comparison of crack healing.

4 Conclusion and Recommendations

Based on this study, the following conclusions are drawn:

- Epoxy coating was the only method that made hard gelatin capsules both hydrophobic and brittle, ensuring effective performance as carriers in the mix.
- Epoxy-coated capsules showed the highest healing, achieving 66% of the initial crack width, compared to 38% for epoxy + tape-coated capsules.
- After 14 days, slight $CaCO_3$ precipitates were observed in Samples 2 and 3, while Sample 1 had no visible precipitation due to fewer capsules in crack-prone areas.

For maximum effectiveness, capsules should target expected crack sites, with future studies exploring larger sizes and their mechanical impact.

References

1. Chithambar Ganesh, A., et al.: An experimental study on effects of bacterial strain combination in fibre concrete and self-healing efficiency. KSCE J. Civ. Eng. **23**(10), 4368–4377 (2019)
2. Jonkers, H.M., Schlangen, E.: Development of a bacteria-based self healing concrete. Tailor Made Concr. Struct. **1**, 425–430 (2008)
3. Wiktor, V., Jonkers, H.M.: Quantification of crack-healing in novel bacteria-based self-healing concrete. Cement Concr. Compos. **33**(7), 763–770 (2011)
4. Mohanasundharam, C., Jeevakkumar, R., Shankar, K.: An experimental study on performance of bacteria in concrete. Int. J. Innov. Res. Comput. Sci. Technol. (IJIRCST) **2**, 1–5 (2014)
5. Keerthana, K.: Comparative study on durability properties of bacterial concrete. Int. Res. J. Eng. Technol. **3**(12), 29–132 (2016)
6. Jonkers, H.M., et al.: Application of bacteria as self-healing agent for the development of sustainable concrete. Ecol. Eng. **36**(2), 230–235 (2010)
7. Khaliq, W., Ehsan, M.B.: Crack healing in concrete using various bio influenced self-healing techniques. Constr. Build. Mater. **102**, 349–357 (2016)
8. ASTM, C469, Standard test method for splitting tensile strength of cylindrical concrete specimens. Annual Book of ASTM Standards, American Society for Testing and Materials: West Conshohocken, PA (2022)
9. Zhang, J., et al.: Immobilizing bacteria in expanded perlite for the crack self-healing in concrete. Constr. Build. Mater. **148**, 610–617 (2017)

Utilization of Thar Fly Ash as a Green Material for Reducing Carbon Footprint in Concrete Production

Muhammad Aslam Bhutto[1(✉)], Monsin Ali[1], Aqsa Murad[1], Sagar Ali[2], Sharjeel Ahmed[2], Abdul Raqeeb[2], and Sher Afzal[2]

[1] Department of Civil Engineering, Thar Institute of Engineering, Sciences and Technology (TIEST), Mithi-Tharparkar, Pakistan
mabhutto@cloud.neduet.edu.pk, {mohsinjani, aqsa.murad}@neduet.edu.pk

[2] Undergraduate Student of Civil Engineering, Thar Institute of Engineering, Sciences and Technology (TIEST), Mithi-Tharparkar, Pakistan

Abstract. Construction industry is a significant contributor to worldwide economic growth. It is also contributing greatly to global greenhouse gas emissions up to nearly 40%. Only the commonly used construction materials like cement, concrete, steel and asphalt are a major source of global carbon dioxide (CO_2) emissions up to approximately 15%. This global problem has introduced the concept of green materials that are also known as sustainable materials and minimize environmental impacts throughout their life cycle by lowering embodied energy, greenhouse emissions and waste generation. Thar fly and bottom ashes (TFA and TBA) are produced as by-products due to coal combustion in the Thar coal-fired power plants (CFPPs) accounting for annual production of over 2 million tons. Among them, the TFA offers a promising solution for low-carbon and sustainable construction practices. This study explores the potential of the TFA as a green material in construction and also evaluates the environmental impact and economic benefits of the utilization of the TFA as partial replacements with different construction materials. The results show that the 10–30% TFA-replacements with cement in the concrete reduced CO_2 emissions and embodied energies by up to 28% as well as decreased cost of the cement by up to 30%. Thus, the Thar fly ash can be utilized as a green and sustainable material in construction applications.

Keywords: Green materials · Thar fly ash · greenhouse emissions

1 Introduction

The coal-fired power plant (CFPP) produces a by-product called as coal fly ash (FA). Large FA quantities are generated in the CFPPs throughout the world where both their storage at power plants and disposal in open landfills are serious ecological problems. The coal reserves in 13 coalfields in Pakistan are 184,645 million tons with the largest (95.95%) share of Thar coalfield that produces the FA at nearly 2 million tons annually [1]. At present, all the produced Thar FA is being dumped in open landfills since July 2019 when the first CFPP was started by the Engro PowerGreen Thar Limited (EPTL).

T. Ayub et al. (Eds.): GCGC 2025, LNCE 774, pp. 87–95, 2026.
https://doi.org/10.1007/978-981-95-6592-4_11

Construction industry plays a vital role in economic growth worldwide, contributing significantly to global GDP, employment opportunities, foreign and domestic investments, etc. The construction industry uses concrete and cement as major construction materials that generate greenhouse gas emissions and whose consumption worldwide in 2020 reached 14 billion cubic meters and 4.2 billion tons, respectively. Thus, this industry is a significant contributor to greenhouse gas emissions, accounting for nearly 40% of global carbon footprint [2]. One of the possible utilizations can be the FA-use as an additive or partially replaced material in construction applications. In this context, the Thar Fly Ash (TFA) has gained attention as a potential green material for reducing carbon footprint in construction practices. This study is intended to explore the potential TFA-utilization as a green and sustainable material in concrete production together with evaluating the associated environmental and economic benefits.

2 Review of Existing Literature

2.1 Coal Reserves in Pakistan

Pakistan is renowned for its fossil coal deposits, which are estimated to contain nearly 186.6 billion tons of coal reserves. This accounts for almost 73% of the country's total known fossil fuel assets. Table 1 presents a detailed chemical analysis of some major coal deposits in million tons (MT); compared with the ASTM D3172 'Standard Practice for Proximate Analysis of Coal and Coke'. In addition to this, nearly 249.5 billion tons of unrecoverable coal deposits exist worldwide that are distributed around different regions, with almost 50% of the total coal reserves being low-rank lignite to low-rank sub-bituminous and the rest of the reserves as the bituminous and anthracite in nature [3, 4].

Table 1. Pakistani Coal Reserves and Average Proximate Analyses [6]

Region-wise Coal Fields	Coal Reserves (MT)	Average Proximate Analyses (%)				
		Total Moisture (M)	Volatile Matter (VM)	Fixed Carbon (FC)	Ash (A)	Total Sulfur (TS)
Baluchistan: Duki Sharig	50	3.5–11.5	32–50	28–42	5–38	4–6
Sor Range Degari	50	3.9–18.5	20.7–37.5	41–50.8	4.9–17.2	0.6–5.5
Chamalang	06	1.1–12.9	24.9–43.5	19.4–47.1	9.1–36.5	3–8.5
Punjab: Makarwal	22	2.8–6	31.5–48.1	34.9–44.9	4.3–49	1.2–14.8
Salt Range	213	3.2–10.8	21.5–38.8	25.7–44.8	12.3–44.2	2.6–10.7
Sindh: Lakhra	1328	9.7–38.1	18.3–38.6	9.8–38.2	4.3–49	1.2–14.8

(*continued*)

Table 1. (*continued*)

Region-wise Coal Fields	Coal Reserves (MT)	Average Proximate Analyses (%)				
		Total Moisture (M)	Volatile Matter (VM)	Fixed Carbon (FC)	Ash (A)	Total Sulfur (TS)
Sonda –Thatta	3700	22.6–48	16.1–36.9	8.9–31.6	2.7–52	0.2–15
Sonda -Jherruk	1823	9–39.5	20–44.2	15–58.8	5–39	0.4–7.7
Thar Coal	**175,505**	**29.6–55.5**	**23.1–36.6**	**14.2–34**	**2.9–11.5**	**0.4–2.9**
KPK: Hangu	82	0.2–2.5	16.2–33.4	21.8–49.8	5.3–43.3	1.5–9.5
Cherat	9	0.1–7.1	14–31.2	37–76.9	6.1–39	2.3–5.4
Dara Adam Khail	3.75	2–6	5–7	75–84	16–22	1.5–3
ASTM D3172 Ranges	**---**	**0.5–25**	**15–55**	**30–90**	**2–40**	**0.2–6.0**

2.2 Coal Fly Ash and Use in Construction

The Coal fired fly ash (FA), generated from thermal power plants, is one of the solid residues amongst various industrial wastes. Bhatt et al. [5] reported that there is substantial potential for utilization of coal fly ash (CFA) as it is seen that 45% of fly ash utilization rates for China, 38% utilization rates for India and 65% for the United States in 2015. Figure 1 illustrates global yearly data of fly ash production and utilization in various nations. Thar coal is characterized by higher CaO and MgO with lower SiO_2 and Al_2O_3 compared to bituminous and anthracite coals [6]. Table 2 depicts the chemical composition of main FA classes, namely Class C and F, compared to that of the Thar fly ash (TFA).

Atis et al. [7] conducted lab testing to access the carbonation of fly ash in concrete. The ordinary Portland cement (OPC) was replaced with 0%, 50% and 70% of fly ash to study their carbonation effects. Concrete mixtures with 70% FA contents showed higher carbonation than that of 50% and 0% FA contents. It was also reported that the FA-replacement also reduces the water requirement for concrete. Chandio et al. [8] used six 1:2:4 concrete mixes using water-cement ratio as 0.5 where demolishing waste was used in equal proportion with conventional aggregates and fly ash was used from 0%-10% with an increment of 2.5%. Reddy [9] investigated M20 grade concrete with partial replacements of cement by 0%, 5%, 10%, 15% and by 20% FA contents. The compressive strength of concrete also increased with the FA contents and increment was 28% for the 20%FA content.

Kumar et al. [10] studied the quality, properties and possible usage of Thar coal fly ash. They concluded that the Thar coal type is lignite and fly ash produced is Type C; the chemical composition is given in Table 2. Munesh et al. [11] studied the use of Thar fly ash (TFA) (TCFA) as partial replacement of ordinary Portland cement (OPC) in concrete. They prepared concrete specimens with varying proportions of TFA (0%, 10%, 20%, and 30% by mass) as cement substitutes. The findings demonstrate that a higher TFA component enhances the workability of the concrete. At all curing ages of 7, 14, and 28 days, the compressive strength 20% TFA-replaced concrete was greater than that of standard concrete and was slightly decreased at 30% TFA-replacement. The split tensile strengths surpassed conventional concrete for all TFA-replacement levels.

Table 2. Chemical Composition of Class C & F Fly Ashes and Thar Fly Ash [19]

Item/Property	Thar Coal Fly Ash	ASTM Class F	ASTM Class C
Chemical Composition:			
$SiO2 + Al2O2 + Fe2O3$	**85–90%**	**>50%**	>50%
CaO	**30.02%**	**≤18%**	**>18%**
SO3	**13.05%**	**<5%**	**<5%**
Loss of ignition (LoI)	**2.18%**	**<6%**	**<6%**
Physical Properties:			
Moisture content	**2.43%**	**<3%**	<3%
Fineness (retained on 45 μm #325 sieve)	**20–30%**	**<34%**	<34%
Strength Activity Index (SAI) 7, 28 and 56 days (% of control)	**70–80%**	**>75%**	>75%
Water requirement (%)	**55–60%**	**<105%**	<105%
Soundness autoclave expansion	**0.5–1.0%**	**<0.8%**	<0.8%
Remarks	**Class C**		

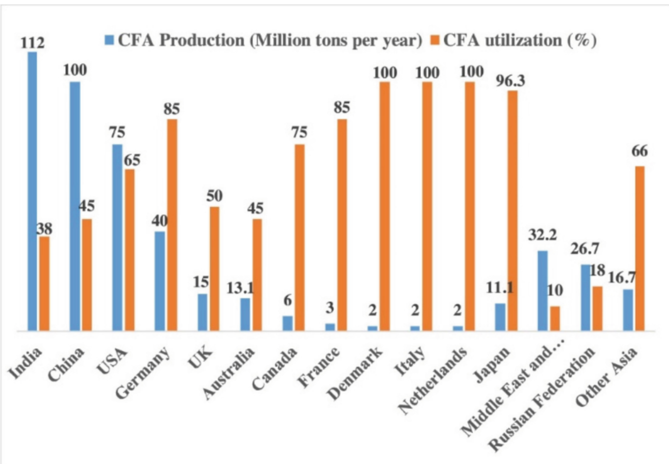


Fig. 1. Yearly Production & Use of Coal Ash in various nations [5]

2.3 Environmental Impacts of Fly Ash

Although harmful emissions from coal-fired power plants (CFPPs) cause several environmental and health hazards globally, coal has still been considered a component of global energy for decades. In India, over 86.35% of the total installed capacity of thermal power stations is produced from coal [1]. Vig et al. [12] envisaged to understand the rising environmental and multiple health issues from CFPPs and particularly studied their adverse impacts on soil, surface water, groundwater and air quality.

3 Results of Environmental and Economical Assessments with Discussions

3.1 Chemical Composition of Thar Coal Fly Ash

The XRF test of Thar coal fly ash was carried to classify the class of Fly ash. According to the ASTM C618–2021, it can be concluded that Thar coal fly ash belongs to Class C because CaO content exceeds 18%. Furthermore, the results of the test are mentioned in Table 2 [13].

3.2 Environmental Assessment of the TFA-Replaced Concrete

In view of the successful use of the Thar fly ash (TFA) as partial replacement of the OPC in concrete [11], the environmental and economical assessment of TFA-replaced concrete have been carried out in this study. The environmental assessments are based upon the embodied energies and embodied carbon dioxide emissions (CO_2) from different ingredients of cement concrete as given by Kumar et al., [14] and shown in Table 3. Accordingly, the embodied energies and embodied carbon dioxide emissions have been calculated for the Control as well as for the 10%, 20% and 30% TFA-replaced concrete mixes used by Munesh et al. [11]. The embodied energies and embodied carbon dioxide were calculated using the methodology of Kumar et al. [14] i.e. with the help of constants mentioned in Table 3.

The results are presented in Table 4; also shown by Figs. 2 and 3 respectively. Fly ash is a supplementary cementitious material (SCM) that reacts with lime to form additional cementitious compounds, reducing the need for Portland cement. It can therefore be observed that the carbon dioxide (CO_2) emissions in the one cubic metre volume of the concrete can be reduced by approximately 6.3%, 17%, 28% by replacing 10%, 20% and 30% cement with the Thar fly ash (TFA), respectively. Also, the embodied energies can also be reduced was also reduced by 8%, 16.4% and 27% by these replacements.

Table 3. Embodied Energies and Embodied Carbon Emissions of different Ingredients of Cement Concrete [14]

S. No.	Construction Material	Embodied Energy (Mega Joule per Kilogram -MJ/Kg)	Embodied Carbon (Kilogram of CO2 per Kilogram -KgCO2/Kg)
1	Cement	5.50	0.93
2	Coal Fly Ash	0.10	0.027
3	Fine Aggregate	0.08	0.0139
4	Coarse Aggregate	0.08	0.0139
5	Water	0.01	0.000196

Table 4. Embodied Energies and CO2 Emissions for Control and TFA-replaced Concrete Mixes

S. No.	Details of Concrete Mix	Embodied Energy		CO_2 Emissions	
		Per m3 Concrete (MJ/m^3)	Reduction By (%)	Per m3 Concrete ($Kg\text{-}CO^2/m^3$)	Reduction By (%)
1	Control Concrete 0% TFA, 100% OPC	3677.50	---	634.85	---
2	TFA-replaced Concrete 10% TFA, 90% OPC	3389.23	7.84%	594.73	6.32%
3	TFA-replaced Concrete 20% TFA, 80% OPC	3037.84	17.39%	525.60	17.21%
4	TFA-replaced Concrete 30% TFA, 70% OPC	2686.36	26.95%	456.87	28.03%

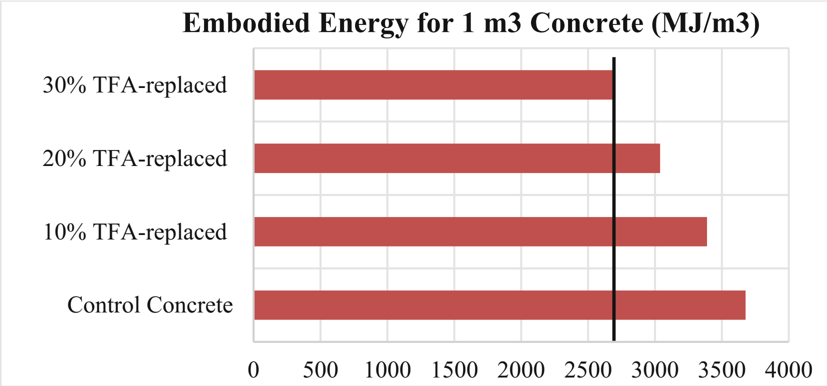


Fig. 2. Embodied Energies for Control and TFA-replaced Concrete Mixes used

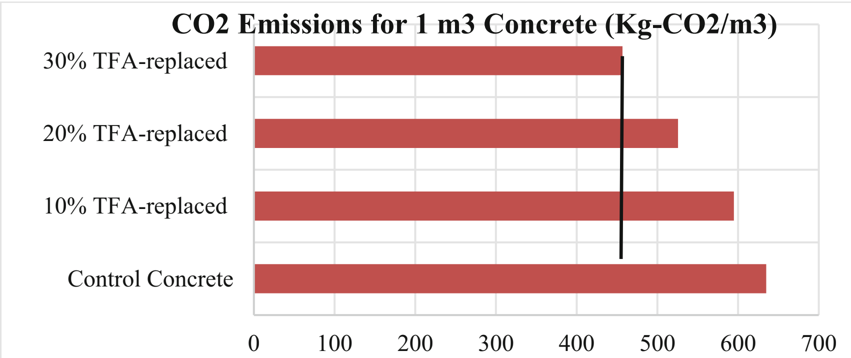


Fig. 3. CO_2 Emissions for Control and TFA-replaced Concrete Mixes

3.3 Economical Assessment of the TFA-Replaced Concrete

The Thar fly ash (TFA) is a waste product and consumes financial resources on account of costs incurred in its transportation and dumping to landfills. The commonly used cement content in concrete is around 14% by volume [15]. Presently the price of 50-kg (1.25 cft) bag of ordinary Portland cement (OPC) is around Rs 1400–1500 or Rs 28–30 per Kg or Rs 1120–1200 per cft. For one cubic metre of the concrete, the cement requirement at 14% would be 0.14 cum or 5 cft, say 4 bags or 200 kg. If 10% cement is replaced by the TFA, it would save 20 kg of cement or Rs 560–600; detailed analyses for the concrete mixes and TFA-replacements used by Munesh et al. [11] are given in Table 5 and also shown by Fig. 4. The results highlight the economic benefits of utilizing Thar Fly Ash (TFA) as a supplementary cementitious material (SCM) in concrete. The partial replacement of cement in concrete by the TFA would save approximately Rs 590, 1190 and 1780 per cubic meter of concrete by replacing 10%, 20% and 30% cement with the Thar fly ash (TFA), respectively.

Table 5. Economical Assessment for Control and TFA-replaced Concrete Mixes.

S. No.	Details of Concrete Mix	Volume of Cement Per m^3 Concrete		Cost of Cement at Rs 28–30 per Kg (Rs)	Cost Saving (Rs)
		(Cum)	(Cft)		
1	Control Concrete 0% TFA, 100% OPC	0.14	4.94	5932.87	0
2	TFA-replaced Concrete 10% TFA, 90% OPC	0.126	4.45	5339.58	593.29
3	TFA-replaced Concrete 20% TFA, 80% OPC	0.112	3.96	4746.30	1186.57
4	TFA-replaced Concrete 30% TFA, 70% OPC	0.098	3.46	4153.01	1779.86

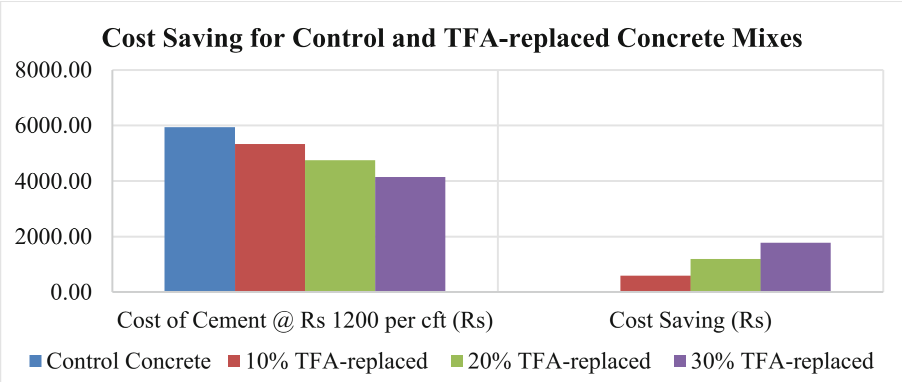


Fig. 4. Cost Saving (in Pak Rs) for Control and TFA-replaced Concrete Mixes

4 Conclusions

This study has investigated the potential of the Thar fly ash (TFA) as a supplementary cementitious material (SCM) in construction applications such as concrete production. The TFA possesses properties of a green material and can be used as partial replacement of the ordinary Portland cement (OPC) up to 30% in concrete. Such replacement not only improves the concrete workability but also has positive effects on the compressive and split tensile strengths. The TFA-replacements appear to be an effective for reducing CO2 emissions and embodied energies in concrete by up to 28%. Also, the 10–30% cement replacement with TFA can make an average saving up to Rs 1200 per cubic meter of the concrete. Conclusively, there are challenges like standardization, quality control, scalability, public perception and regulatory hurdles but the Thar fly ash (TFA) is still technically feasible as well as environmentally and economically viable to be utilized as a green and sustainable material in the concrete production.

References

1. Malkani, M.S., et al.: Coal resources of Pakistan: new coalfields. Lasbela Univ. J. Sci. Technol. **5**, 7–22 (2016)
2. Bhogayata, A.C.: Sustainable Construction: Development of Eco-efficient Concrete with Plastic and Industrial Wastes. CRC Press (2023)
3. Statista. Proved coal reserves worldwide from 2010 to 2020, 21 May 2024. https://www.statista.com/statistics/237096/proven-coal-reserves-of-the-top-ten-countries/
4. Malkani, M.S.: Coal and petroleum resources of Khyber Pakhtunkhwa and FATA (Pakistan)—an overview. J. Himalayan Earth Sci. Special **2013**, 27–29 (2013)
5. Bhatt, A., et al.: Physical, chemical, and geotechnical properties of coal fly ash: a global review. Case Stud. Construc. Mater. **11**, e00263 (2019)
6. Adjei, S., Elkatatny, S.: A highlight on the application of industrial and agro wastes in cement-based materials. J. Petrol. Sci. Eng. **195**, 107911 (2020)
7. Atiş, C.D.: Accelerated carbonation and testing of concrete made with fly ash. Constr. Build. Mater. **17**(3), 147–152 (2003)
8. Chandio, S.A., et al.: Effect of fly ash on the compressive strength of green concrete. Eng. Technol. Appl. Sci. Res. **10**(3), 5728–5731 (2020)
9. Reddy, S.A.K., Reddy, K.C.: Effect of fly ash on strength and durability parameters of concrete. Int. J. Sci. Res. **4**(5), 1368–1370 (2013)
10. Kumar, D., et al.: Quality analysis of ash from lignite coal and its utilization at Thar power plant. Int. J. Eng. Manuf **11**(3), 18–27 (2021)
11. Meghwar, M., et al.: Effect of Thar Coal Fly Ash on Compressive and Tensile Strength of Concrete
12. Vig, N., Ravindra, K., Mor, S.: Environmental impacts of Indian coal thermal power plants and associated human health risk to the nearby residential communities: a potential review. Chemosphere **341**, 140103 (2023)
13. International, A.: ASTM C618-19 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete (2016)
14. Kumar, A., et al.: Effect of silica fume and fly ash as cementitious material on hardened properties and embodied carbon of roller compacted concrete. Environ. Sci. Pollut. Res. **29**, 1210–1222 (2022)
15. ACI, Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91) (2002)

Utilization of Plastic Waste in Developing Sustainable Construction Pavers

Muhammad Khizar Hassan[1](✉), Anas Ahmed[2], Rana Rabnawaz Ahmed[1], and Aiman Siddiqui[1]

[1] Department of Civil Engineering, NED University of Engineering & Technology, Karachi, Pakistan
m.khizar.hassan@hotmail.com
[2] Institute of Civil Engineering, Peter the Great St. Petersburg Polytechnic University, St Petersburg, Russia

Abstract. The construction industry significantly contributes to environmental degradation through carbon-intensive cement production and unsustainable resource use, while plastic waste continues to pollute ecosystems globally. This study explores a dual-solution approach to these challenges by utilizing Acrylonitrile-butadiene-styrene (ABS) plastic waste as a raw material to manufacture sustainable plastic-sand pavers. Locally sourced ABS plastic was shredded, mixed with manufactured sand in a 1:1 ratio, and processed to create durable pavers. The study conducted comparative tests on plastic-sand and traditional concrete pavers, including compressive strength and water absorption evaluations. Results demonstrated that plastic-sand pavers exhibit superior compressive strength (19.8 MPa), significantly lower water absorption rates (as low as 4.81%), enhanced thermal resistance, improved soundness with minimal structural degradation, and higher hardness levels compared to concrete pavers. These findings underscore the potential of plastic-sand pavers as a sustainable alternative, addressing both plastic waste management and carbon emissions in the construction industry. By repurposing waste into high-performance building materials, this study contributes to the discourse on sustainable construction and circular economy practices. The proposed methodology offers scalability, adaptability to various waste streams, and the potential for widespread adoption, particularly in resource-constrained regions like Pakistan. Further research on long-term performance and economic feasibility is recommended to bridge the gap between innovation and industrial application.

Keywords: Plastic Waste · Plastic Pavers · Waste Management · Sustainable Construction Material · Circular Economy

1 Introduction

The construction industry stands as one of the most resource-intensive sectors globally, contributing significantly to environmental degradation and greenhouse gas emissions [1]. As urbanization and infrastructure development accelerate, the demand for construction materials, particularly cement and concrete, continues to rise. Concrete pavers

T. Ayub et al. (Eds.): GCGC 2025, LNCE 774, pp. 96–104, 2026.
https://doi.org/10.1007/978-981-95-6592-4_12

are widely used in construction for pathways, driveways, and outdoor flooring, owing to their durability and versatility [2]. However, their production contributes significantly to environmental degradation. Cement, a primary ingredient in concrete pavers, accounts for approximately 8% of global carbon dioxide emissions due to its energy-intensive production process [1]. Moreover, the extraction of raw materials and high energy consumption during manufacturing exacerbate resource depletion and pollution [3]. These challenges necessitate a shift toward more environmentally responsible practices within the sector, urging the adoption of innovative and sustainable solutions to mitigate its ecological footprint [4]. Click or tap here to enter text.

Parallel to this, plastic waste has emerged as a critical environmental challenge worldwide. Plastics, with their non-biodegradable nature, have persisted in the environment for centuries, causing extensive pollution in landfills, waterways, and marine ecosystems. The annual global plastic production has exceeded 300 million tons, a significant proportion of which ends up as unmanaged waste [5]. The dual crises of carbon-intensive concrete production and the proliferation of plastic pollution call for innovative, sustainable solutions that address both issues simultaneously [6].

In Pakistan, the situation is particularly dire. The demand for concrete pavers has grown with urbanization and infrastructure development, leading to increased carbon emissions and resource strain [7]. At the same time, plastic waste management is inadequate, with cities like Karachi generating thousands of tons of plastic waste daily, much of which is improperly disposed of [3]. The plastic waste clogs drainage systems, exacerbate urban flooding, and poses a significant environmental threat [7]. These dual crises involving carbon-intensive concrete production and escalating plastic pollution highlight the urgent need for sustainable solutions [4–6].

2 Literature Review

The utilization of plastic waste in construction materials has been the focus of extensive research due to its potential to address both environmental and structural challenges. Numerous studies have explored various combinations of plastic types and additives to create sustainable alternatives to conventional construction materials [8].

Table 1 summarizes key studies, detailing plastic types, additives, and outcomes, highlighting the versatility of plastic waste in construction and underpinning this study's focus on ABS plastic pavers.

From the data presented in Table 1, it is evident that integrating plastic waste with different binding materials results in significant improvements in compressive strength and durability, often outperforming traditional construction materials. For instance, studies utilizing LDPE with sawdust and sand demonstrated compressive strengths exceeding 60 MPa, a remarkable enhancement that meets and surpasses industry standards [15]. Similarly, the use of HDPE and PET with clay not only improved strength but also reduced the overall weight of the bricks, making them cost-effective and easier to transport.

Observations from previous literature reveal that despite being one of the most widely used plastic types globally, ABS plastic has been underutilized in construction material applications. ABS is a thermoplastic renowned for its thermal stability, mechanical toughness, and high gloss, making it an attractive candidate for construction uses. Notably, ABS accounts for approximately 75% of the plastic plating market [16]. In this research, we explored the potential of utilizing ABS plastic waste as a raw material for

Table 1. Properties of Plastic Waste Composites

S. No	Waste Type	Composition	Compressive Strength (MPa)	Water Absorption (%)	References
1	LDPE	LDPE (25%), Sand (75%)	4.141	0.322	[9]
2	PET	PET (70%), Sand (30%)	2.15	2.4	[10]
3	HDPE	HDPE (60%), Fine Aggregate (40%)	32.6	4.1	[10, 11]
4	Mixed Plastic Waste	Mixed Waste (60%), Sand (40%)	20.7	3.2	[12]
5	PP	PP (50%), Sand (50%)	18.9	5.3	[13]
6	LDPE (Plastic Bags)	LDPE (80%), Sand (20%)	10.2	6.7	[14]

manufacturing pavers. By substituting cement with processed plastic waste, such as ABS (Acrylonitrile Butadiene Styrene), in the production of pavers, we aim to reduce carbon emissions and repurpose plastic waste effectively. While this study focuses on ABS, the approach can be extended to other types of plastic, including HDPE (High-Density Polyethylene) and PP (Polypropylene), demonstrating scalability and adaptability across different waste streams. The proposed method not only diverts plastic waste from landfills but also offers a sustainable alternative to traditional concrete pavers.

3 Experimental Study

3.1 Conceptual Framework

This study investigates the development of a sustainable construction material by converting ABS Plastic waste into plastic-sand pavers, as shown in Fig. 1. The process begins with the manual shredding of ABS plastic waste, followed by mixing the shredded plastic with manufactured sand (M-sand) in a 1:1 ratio, which was found to yield superior strength properties through iterative trials. the mixture undergoes several steps, including weighing, proportioning, heating, molding, and cooling, to form the plastic-sand paver. The engineering properties of these pavers, including dimensions, density, compressive strength, water absorption, thermal conductivity, soundness, and hardness, are rigorously tested. The Results from These tests are compared to those of traditional construction materials to assess the viability of plastic-sand pavers in construction applications. Based on the findings, recommendations are made regarding the optimal mix ratio and the potential use of these pavers in the construction industry.

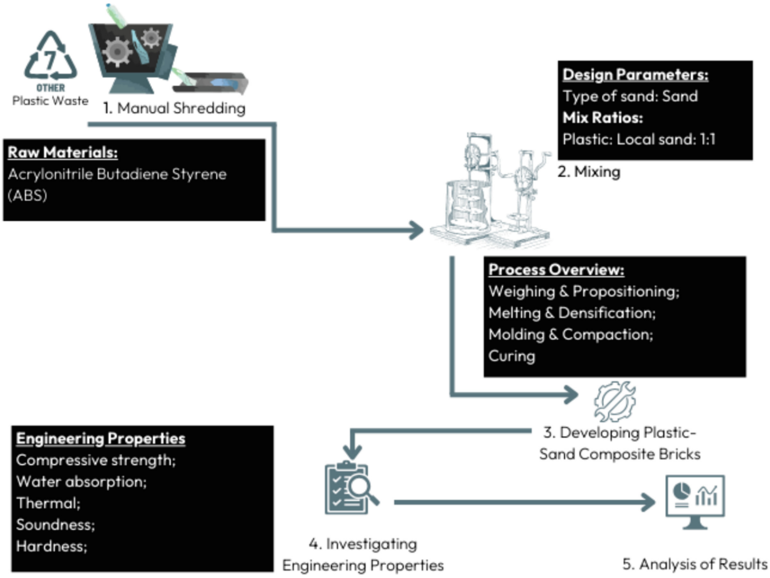


Fig. 1. Conceptual Framework of Plastic Sand Paver

3.2 Methodology

The ABS plastic waste was sourced from a local recycled plastic supplier in Karachi, Pakistan. To prepare the plastic for paver manufacturing, it was necessary to reduce it into smaller fragments (Fig. 2). This was done manually to facilitate subsequent burning. After shredding, the plastic was sun-dried to remove any moisture content.

The plastic waste and sand were mixed in a 1:1 ratio, which had been determined through a process of trial and error to provide the highest strength. The plastic waste was then combined with sand and heated using an electric stove to form a homogeneous mixture. The heating process was carefully controlled to ensure that the plastic melted without releasing harmful emissions. The electric stove provided a controlled environment, allowing the plastic to melt and integrate thoroughly with the sand. Once a dough-like consistency was achieved, the mixture was poured into a steel mold measuring 3.5 x 5.0 x 9.5 in^3. The filled mold was allowed to cool for approximately one hour before being demolished. This step resulted in the solidified paver taking its final shape.

The study conducted several tests on both the plastic-sand paver and conventional concrete pavers. These tests included compression strength, water absorption, thermal resistance, soundness, and hardness. A comparative analysis of the results was performed to evaluate the potential of plastic sand pavers for use in the construction sector.

Fig. 2. Formation of ABS Plastic Sand Pavers

Fig. 3. Final Form of Plastic Sand Pavers

4 Results & Discussion

4.1 Compressive Strength Test

Compressive strength is a critical property for construction materials, determining their ability to withstand loads and ensuring their suitability for use in infrastructure. In this study, the compressive strength of plastic-sand pavers was tested following IS 2185–2005 (Part 1) standards. The test was conducted using a compression testing machine, where the pavers were sequentially placed, and a gradual load was applied until failure. The load at which the pavers crushed was recorded, and the compressive strength was calculated using the following formula:

$$CompressiveStrength = \frac{MaximumLoad\,(kipps)}{AreaofSpecimen\left(in^2\right)} \tag{1}$$

The results of the compressive strength tests for both types of pavers are presented in Table 2. The compressive strength of traditional concrete pavers tested after 28 days of curing ranged between 8.90 MPa and 10.3 MPa. In contrast, plastic-sand pavers demonstrated significantly higher compressive strength, ranging between 14.8 MPa and 19.8 MPa, with a maximum strength of 19.8 MPa. This indicates that plastic-sand pavers exhibit superior load-bearing capacity compared to traditional concrete pavers.

Moreover, the compressive strength of plastic-sand pavers complies with the strength criteria specified in IS 2185–2005 (Part 1), surpassing the minimum requirement of 5 MPa (725 psi) for solid concrete pavers. Figure 3 further illustrates the comparative analysis, highlighting the enhanced performance of plastic-sand pavers over traditional concrete pavers.

The dimensions of the construction pavers used in our research were 7 x 3.5 x 2.5. However, for the compressive strength test, we utilized a testing area of 7 x 3.5. The difference in dimensions is due to the fact that the compressive strength test is typically performed on a flat surface, and the testing machine's loading platens are designed to apply force to a specific area. By using the 7 x 3.5 testing area, we ensured that the load was applied uniformly across the paver's surface, allowing for accurate measurement of its compressive strength. The height of the paver (2.5) was not a factor in this test, as the loading was applied parallel to the paver's surface.

Table 2. Comparison of Compressive Strength

Sample Type	Paver Size (in)	Test Size (in)	Cross Section (in2)	Max Load (Kips)	Compressive Strength (MPa)
Plasic-Sand Paver	7 x 3.5 x 2.5	7 x 3.5	24.5	65.72	18.5
				70.56	19.8
				52.61	14.8
Concrete Paver	7 x 3.5 x 2.5	7 x 3.5	24.5	36.59	10.3
				31.61	8.90
				34.55	9.73

4.2 Water Absorption Test

A water absorption test is an indirect measure of the percentage of pores in the construction pavers and therefore can be considered as an assessment criterion for monitoring durability properties, indicating their quality and behavior in different weathering and harsh climatic conditions. The research confirmed that the water absorption test results complied with the standard range stated in IS 2185(2005).

The test specimens were initially immersed in water for 24 h at room temperature, followed by weighing of the samples. The oven-dried samples were weighed again after undergoing a 24-h drying process in a ventilation oven at 100 °C. The procedure was repeated for three full-size units after which the average results were calculated.

Table 3. Comparison of Water Absorption

Sample Type	Paver Size (in)	Dry Weight, W1 (Kgs)	Wet Weight, W2 (Kgs)	% Water Absorbed
Plastic-Sand Paver	7 x 3.5 x 2.5	7.67	8.2	6.46
		7.89	8.34	5.39
		7.26	7.49	4.81
Concrete Paver	7 x 3.5 x 2.5	4.75	5.63	15.73

(*continued*)

Table 3. (*continued*)

Sample Type	Paver Size (in)	Dry Weight, W1 (Kgs)	Wet Weight, W2 (Kgs)	% Water Absorbed
		4.75	5.42	12.5
		4.75	5.46	13

$$WaterAbsorption = \frac{WA - WB}{WB} \times 100 \quad (2)$$

where;

A = wet mass of units, in kg; and
B = dry mass of units, in kg.

The pavers exhibit percentages of 6.46%, 5.39%, and 4.81% of water absorption as shown in Table 3, all of which are well below the code limit of 10%. This result underscores the robustness of the plastic-sand paver in meeting and even surpassing the stipulated criteria set by the code. Figure 4 illustrates a comparison of percentage water absorption between a plastic-sand pavers and a traditionally used concrete paver, indicating that plastic-sand pavers demonstrate significantly higher water resistance compared to the traditional concrete block. Water absorption serves as an indirect indicator of the presence of pores within the pavers. Therefore, these findings suggest that the blocks possess a minimal number of pores, contributing to their higher level of compactness. Equation 2 is used to determine the water absorption in plastic-sand pavers.

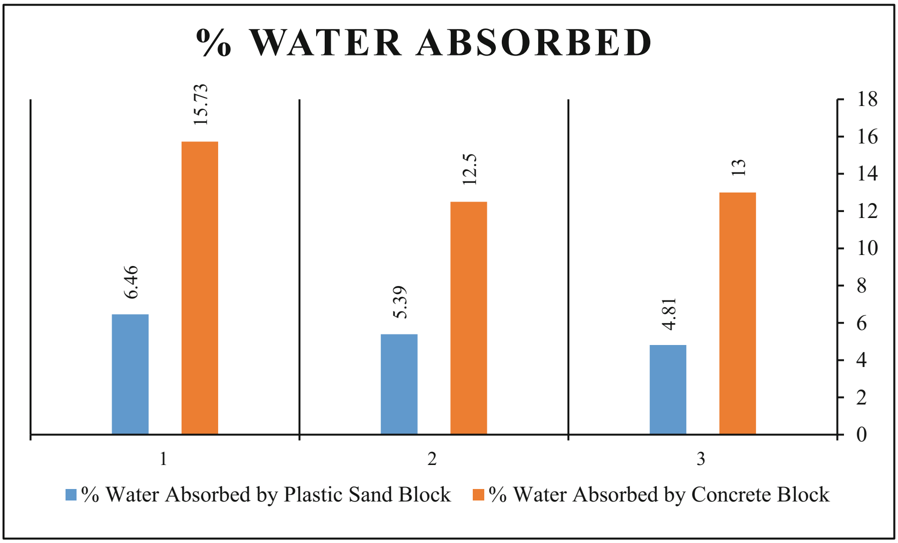


Fig. 4. Comparative Analysis of Water Absorption Test

4.3 Thermal Test

A thermal test is performed to get to know more about how structures behave when exposed to high temperatures. Construction pavers that have higher density exhibit better heat resistance Plastic, as a material, is susceptible to fire. However, the plastic-sand paver contains a significant proportion of sand with high thermal resistance. Therefore, the paver as a whole is less susceptible to high temperatures and can withstand them. The paver was placed inside the muffle furnace and heated at high temperatures, with the temperature being increased every 30 min. Tests showed that plastic pavers retain their structure up to 290 °C, beyond which fissures appear, and their strength diminishes.

4.4 Soundness Test

The plastic-sand pavers are air-dried for 48 h after manufacturing. They are then tapped together, producing a ringing sound that signifies good quality. A clear ringing sound is an indication of high-quality paver.

4.5 Hardness Test

A hardness test was performed on the plastic-sand paver to assess its hardness by using a sharp nail by running it over the surface of the paver while carefully observing the process. There were no scratches observed after the test; therefore, it can be inferred that the paver has a high level of hardness [17].

5 Conclusion & Recommendations

This study successfully demonstrates the viability of using ABS plastic waste as a raw material for manufacturing sustainable plastic-sand pavers. The experimental results revealed that these pavers outperform traditional concrete pavers in compressive strength and water absorption characteristics. With a compressive strength of 19.8 MPa and water absorption rates as low as 4.81%, offering enhanced durability and resilience. This solution addresses two global challenges: excessive plastic waste and the environmental impact of cement production, contributing to sustainable waste management and the circular economy.

While the study highlights the potential of plastic-sand pavers, further research is needed to evaluate long-term performance, environmental impacts, and economic feasibility, including exploring different plastics, optimizing processes, and conducting life-cycle assessments. With continued innovation and policy support, this technology can reduce pollution and promote greener construction practices.

References

1. Barbhuiya, S., Das, B.B., Adak, D.: Roadmap to a net-zero carbon cement sector: strategies, innovations and policy imperatives. J. Environ. Manage. **359**, 121052 (2024)

2. Siddique, R., Khatib, J., Kaur, I.: Use of recycled plastic in concrete: a review. Waste Manage. **28**(10), 1835–1852 (2008)
3. Ahmad, I., Aslam, S., Hussain, U.: Assessment of plastic pollution in coastal areas of Karachi: case study of West Warf, Kemari Jetty, and Manora. Mar. Pollut. Bull. **195**, 115501 (2023)
4. Real, L.E.P.: Plastics statistics: production, recycling, and market data. In: Recycled materials for construction applications: plastic products and composites, pp. 103–113. Springer (2022)
5. Geyer, R., Jambeck, J.R., Law, K.L.: Production, use, and fate of all plastics ever made. Sci. Adv. **3**(7), e1700782 (2017)
6. Saikia, N., De Brito, J.: Use of plastic waste as aggregate in cement mortar and concrete preparation: a review. Constr. Build. Mater. **34**, 385–401 (2012)
7. Sanjrani, M.A., et al.: Impact of Plastic waste on the environment and humans health in Pakistan: effective waste management strategies and sustainable solutions. Journal of Recycling Economy & Sustainability Policy **2**(1), 34–41 (2023)
8. Zulkernain, N.H., et al.: Utilisation of plastic waste as aggregate in construction materials: a review. Constr. Build. Mater. **296**, 123669 (2021)
9. Tempa, K., et al.: An experimental study and sustainability assessment of plastic waste as a binding material for producing economical cement-less paver blocks. Engineering Science and Technology, an International Journal **26**, 101008 (2022)
10. Limami, H., et al.: Thermal performance of unfired lightweight clay bricks with HDPE & PET waste plastics additives. Journal of Building Engineering **30**, 101251 (2020)
11. Sarwar, S., et al.: Preparation of environmental friendly plastic brick from high-density polyethylene waste. Case studies in chemical and Environmental Engineering **7**, 100291 (2023)
12. Aneke, F.I., Shabangu, C.: Green-efficient masonry bricks produced from scrap plastic waste and foundry sand. Case Studies in Construction Materials **14**, e00515 (2021)
13. Kulkarni, P., et al.: Recycling of waste HDPE and PP plastic in preparation of plastic brick and its mechanical properties. Cleaner materials **5**, 100113 (2022)
14. Solomon, A.A., Shelton, J.J., Daniel, C.: Turning low-density polyethylene plastic waste into plastics bricks for sustainable development. Materials Today: Proceedings (2023)
15. Hamzah, A.F., Alkhafaj, R.M.: An investigation of manufacturing technique and characterization of low-density polyethylene waste base bricks. Materials Today: Proceedings **61**, 724–733 (2022)
16. Hiremath, N., et al.: Polyacrylonitrile nanocomposite fibers from acrylonitrile-grafted carbon nanofibers. Compos. B Eng. **130**, 64–69 (2017)
17. Kavinkumar, V., et al.: Development of plastbrick using plastic wastes & PET bottles. Materials Today: Proceedings **68**, 2601–2604 (2022)

Conference Track III: Case Studies and Best Practices of Green Construction

Examining the Market Feasibility of Residential Green Buildings in Tier-II Cities Within the Indian Context: Bhopal Case Study

Anshul Jain(✉) and K. Ananda Babu

Shri Vaishnav Vidyapeeth Vishwavidyalaya, Indore, M.P. 453111, India
jainanshul17@gmail.com

Abstract. The contemporary trend observed among corporate and residential apartments is the adoption of environmentally friendly practices. In line with the global movement towards environmental conservation, the green rated projects in India uplifted from a few hundred in 2009 to a few thousands by the end of 2024. This study expands the understanding of residential green projects in Tier II Indian cities among local authorities, developers, and consumers. The study's specific focus is Bhopal, a rapidly growing residential area in central India. To determine the level of awareness among all Bhopal stakeholders regarding the advantages of green projects, a thorough survey including developers, government agencies, and potential buyers was carried out. The survey also aimed to determine the public's willingness to invest in energy efficiency, analyze perspectives on green buildings from customers, developers, and government entities, assess the market potential of residential green buildings, identify challenges faced by developers in green construction, and provide information about current situation of residential green rated projects. The findings suggest that effective collaboration among stakeholders involved in the development of residential green buildings can make them viable for developing cities of India.

Keywords: Green city · sustainable development · energy efficiency · green residential projects · environmental protection

1 Introduction

Around the globe, the momentum of green construction is increasing as it is being recognized as a lucrative long-term business prospect. Green methods are spreading throughout the global building sector and are not limited to any one area or economic situation. By 2025, the market for green-rated buildings is expected to reach a value of over $8 billion yearly, according to the Indian Green Building Council (IGBC). Embracing green practices has emerged as a prevailing trend among both corporate entities and residential complexes. Green construction, characterized by its emphasis on environmental preservation, conservation of water, saving energy needs, promoting recycling of materials, and replenishable energy sources, has witnessed a significant surge in India, with the number of green projects escalating from 164 in 2009 to over 4000 by 2024 [1].

T. Ayub et al. (Eds.): GCGC 2025, LNCE 774, pp. 107–112, 2026.
https://doi.org/10.1007/978-981-95-6592-4_13

The primary challenge is insufficient awareness regarding Residential Green projects design in India. This issue is widespread, with a general lack of awareness among the public and developers leading to widespread skepticism [2]. Various experts echo the same sentiment about the necessity to address customer perceptions. While incorporating the concept of green building design in project brochures and pamphlets may be a modest beginning, the impact on a broad spectrum of customers is noteworthy. Tackling such issues categorized as myths poses a significant challenge that requires innovative solutions [3]. The Indian real estate sector is largely unorganized, with a wide array of developers ranging from large groups to local entities affecting project quality and customer trust. Insufficient knowledge and reliance on traditional methods are key factors contributing to the misconception surrounding projects like green buildings. Developers must enhance their knowledge base as simply adding greenery near a multi-story residential building cannot classify the building as green. This challenge extends beyond developers, as local development authorities also demonstrate a lack of awareness regarding innovation and new techniques [4].

The Concept of Green building: Numerous definitions of sustainable or green buildings exist, with the USGBC (United States Green Building Council) being a prominent advocate of green buildings worldwide. The ‘green building’ resembles with ‘high performance building,’ ‘sustainable design and construction,’ emphasizing a comprehensive approach to design and construction. Green building design harmonizes environmental stewardship, efficient utilization of available resources, well-being of stakeholders, by integrating community [5]. According to the Indian Green Building Council (IGBC), a green building is characterized by its ability to operate with optimal energy usage, minimal water consumption, and preservation of natural resources, reduced waste generation, and provision of spaces conducive to healthy and comfortable living, in comparison to traditional buildings [6]. The Energy and Resources Institute (TERI), dedicated to sustainable development, states that green building is meticulously planned, built, and maintained to minimize adverse impacts on environment by simultaneously enhancing comfort of stakeholders along with productivity [7]. Sustainable buildings encompass the integration of sustainability considerations in every phase of building design and planning, as well as during the construction and manufacturing of building materials. Sustainable buildings inculcates better health and environmental-friendly materials and products, along with efficient systems that are easy to maintain and service [8]. These buildings prioritize high functionality, flexibility, adaptability, user health, and comfort, while focusing on appearance and design quality having acceptance by all the stakeholders. Furthermore, they are strategically located near public transportation services. [2]. Conventional construction methods typically involve substantial quantities of non-renewable and toxic materials, with little regard for the environmental impact of the building [2]. In contrast, green buildings mitigate these impacts, offer improved health benefits, and consume less energy, resulting in long-term cost savings [9]. The design of green buildings is a pragmatic and environmentally conscious approach, considering factors such as appropriate location, utilization of local materials having minimized embodied energy, and design considerations based on building usage [9]. Sustainable buildings overall consume optimized energy and water, emit fewer harmful gases, use materials eminently, and generate fewer waste as compared to traditional buildings throughout lifespan [10].

Objectives of research.

1. Adopting green buildings technology for minimizing harm to the environment throughout their lifecycle [11].
2. Forming green zones by clustering together, green buildings that promote a healthier environment, reduce the heat-island effect.
3. Contributing towards significant energy savings and a lower global carbon footprint at the city and national levels.

The scope of the present research is to help in developing a green city leading to the sustainable development of nation. The study area is broad enough to cover all the Tier-II and Tier-III cities which are undergoing rapid urbanization in India.

2 Methodology

In recent times, Bhopal has emerged as a promising real estate destination after Indore in the state of Madhya Pradesh. Specifically, questionnaires were formulated targeting Potential Buyers, Developers. The specific aims were:

1. To assess the level of knowledge/awareness about green building systems among residents of Tier-II cities.
2. To identify whether the advantages of green building projects are known to people or not.
3. To determine the reasons of not implementing the green construction practices and opting the traditional methods only.
4. To understand the ways of achieving client satisfaction for green buildings.

Survey questionnaires: A systematic questionnaire was prepared and this survey aimed to gain respondents':

- Academic information and corresponding experience.
- Basic knowledge about the benefits of green buildings.
- Perspectives being the most or the least appropriate for green buildings.
- Ways of achieving client satisfaction for green projects.

From the perspective of potential buyers, it was observed that 20% exhibit a comprehensive understanding of the green building concept, whereas nearly 50% possess a moderate awareness of the same. Most potential buyers fall within the age brackets of 18–35 years and 35–49 years, with the most informed individuals belonging to the former group. Furthermore, a large portion of potential buyers hail from the middle and upper middle class, with 47% falling within the income range of Rs. 2–5-6 LPA and 42% falling within Rs. 6–12 LPA. Print media emerges as the primary source of awareness regarding green buildings, accounting for 42%, while social media contributes 10% to the awareness pool. Notably, burgeoning areas in Bhopal such as Hoshangabad Road, Ayodhya Bypass, and Arera Colony Extension attract considerable customer interest.

From the perspective of the developers, it is noted that 80%, have acquired knowledge regarding the concept of green building, yet have not implemented it practically.

Furthermore, a vast majority, around 90%, are currently employing various sustainable practices such as conserving rainwater, using renewable energy sources, natural lighting, and recycling the collected water by various techniques in the projects. However, there exists a reluctance among 90% of developers to embrace green building technology due to regulatory concerns, refrain from opting for it because of market-related issues. Additionally, developers express hesitance towards green building technology due to complex guidelines necessary for obtaining green certifications. Another 40% abstain from green development owing to the substantial initial investment linked with green construction.

The construction industry encountered challenges, prompting the gradual emergence of the concept of sustainable construction. To disseminate this concept globally, various rating systems have been established worldwide. The progress of sustainable development hinges on external factors such as policy development, certification schemes, and economic incentives, as well as internal factors including technological advancements. In India Green Rated Integrated Habitat Assessment (GRIHA) is the major rating system developed by TERI. Effective implementation of green building technologies necessitates enhancements in governmental policies and incentive frameworks. Several State governments in India are providing incentives for constructing green projects. Professional assessments, technical skills of workers and staff, and engagement of relevant consultants are essential. These collective efforts will contribute to national development (Fig. 1).

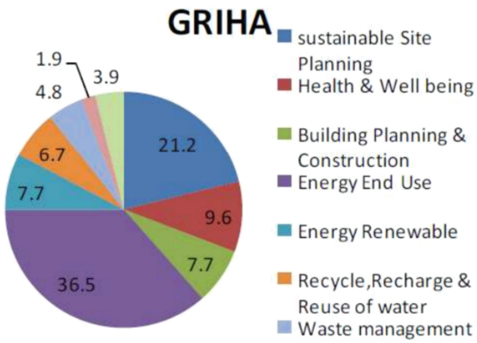


Fig. 1. Weightage of major sections as per GRIHA guidelines [12]

Along with the development of city and real estate growth, the requirements of residential green building development become equally important. Coordination among all stakeholders involved in the process can lead the way for feasible residential green buildings in Bhopal. By implementing the above points, the vision of establishing green rated projects in Tier-II cities like Bhopal can be realized.

3 Results

Based on the discussions, the subsequent recommendations are highlighted to enhance the development of residential green rated projects in the Tier-II city Bhopal.

1. To enhance knowledge among the stakeholders regarding development of green rated projects, it is imperative to devise an efficacious promotional strategy and campaign targeting the predominant demographic of potential buyers, specifically individuals within the middle to upper-middle class aged between 18–49 years.
2. The promotional strategy must encompass all facets of green building construction and development to ensure comprehensive customer awareness and prevent developers from exploiting customers unlawfully.
3. The primary source of awareness is print media, closely trailed by the internet and social media. Considering that a substantial portion of potential buyers fall within the 18–49 age bracket, who are the primary users of social media, hence social media platform shall be the potential promotional tool for the green building concept.
4. The State and Central Government shall actively conduct training programs for developers and engineers to enhance the technical knowledge associated with green building construction.

4 Conclusions

1. The Government shall provide subsidies for purchasing green rated buildings and incentives to facilitate developers in establishing green residential projects which will enhance confidence among the stakeholders due to involvement of government.
2. The Green Building guidelines by government and Rating Systems developed for Green rated construction shall be structured favorably for developers to encourage investments in green residential development projects.
3. Collaboration among various governmental entities such as the Bhopal Municipal Corporation (BMC), Environmental Planning & Conservation Organization (EPCO), Bhopal Development Authority (BDA), local developers, and Non-Governmental Organizations (NGOs) is essential to ensure seamless coordination in facilitating the feasibility and success of residential green rated project development in the recent years.

References

1. Li, Y.Y., Chen, P.H., Chew, D.A.S., Teo, C.C., Ding, R.G.: Critical project management factors of AEC firms for delivering green building projects in Singapore. J. Constr. Eng. Manag. **137**(12), 1153–1163 (2011)
2. Castleton, H.F., Stovin, V., Beck, S.B.M., Davison, J.B.: Green roofs; building energy savings and the potential for retrofit. Energy and Buildings **42**(10), 1582–1591 (2010)
3. Potbhare, V., Syal, M., Korkmaz, S.: Adoption of Green Building guidelines in developing countries based on US and India experiences. Journal of Green Building **4**(2), 58 (2009)
4. Rajat, G., Matt, G., Sanyogita, M., Prasad, V.: Customized performance evaluation approach for Indian green buildings. Building Research and Information **47**(01), 56–74 (2019)
5. Gogoi, D.B.J., Giri, D.T.K.: Green building requirement in India and factors driving green building purchase. International Journal of Civil Engineering and Technology **8**(10), 153–165 (2017)
6. Satya, S.S., Sridharan, U.: Environment sustainability guidelines for Green Buildings in India. International Journal of Scientific Research and Technology **4**(1) (2016)

7. Gehlot, M., Shrivastava, S.: Sustainable construction Practices: A perspective view of Indian construction industry professionals. Materials Today, Elsevier **61**(Part 2), 315–319 (2022)
8. Zhang, Y., et al.: A survey of the status and challenges of green building development in various countries. Sustainability **11**(19), 5385 (2019)
9. Trivedi, P., Sharma, M.: Impact of green production and green technology on sustainability: cases on companies in India. International J. Mechanical and Production Engineering Research and Development **7**(6), 591–606 (2017)
10. Srinivasan, B., Ganeswaran: Optimization of day lighting towards in green building concepts. International Journal of Civil Engineering and Technology **7**(4), 521–532 (2016)
11. Srinivasan, B., Ganeswaran, D.P., Meenambal, D.T.: Optimization with sun light source in old constructed building and converting to green building. International Journal of Civil Engineering and Technology **7**(5), 428–434 (2016)
12. Jain, A., Ananda Babu, K.: Incentivization of the green rated projects by government for promoting sustainable development: case study of indian states and union territories. International Journal on Emerging Technologies **15**(2), 33–38 (2024)
13. Sheth, K.: Sustainable building materials used in green buildings. In: 9th International Conference on Engineering and Business Education (ICEBE) & 6th International Conference on Innovation and Entrepreneurship (ICIE) (2016)
14. Satya, S.S., et al.: Environmental sustainability guidelines for green buildings in India: a review. Indian Journal of Scientific Research and Technology **4**(1), 11–18 (2016)

Zero-Energy Building-Energy Efficient and Effective Design Strategies

Aamir Khan(✉), Isra Shaikh, and Shakeel Ahmed

Department of Civil Engineering, Quaid-E-Awam University, Nawabshah, Pakistan
aamirkhansarki190502@gmail.com

Abstract. Net-Zero Energy Buildings (NZEBs) are an emerging solution to the rising costs of energy and the environmental impacts of fossil fuel-based electricity, including climate change. NZEBs are designed to produce the same amount. According to the IEA, building operations contribute to 27% of global energy sector emissions, with 8% directly from buildings and 19% from heat and electricity production. Many buildings in our area consume excessive energy due to poor design, leading to high operational costs and significant environmental impacts, such as global warming. This study explores strategies to transition traditional buildings to NZEBs by implementing energy-efficient design elements such as optimized orientation for natural lighting and ventilation, energy-efficient lighting, solar panels, shading to reduce heat absorption, and green surfaces. Autodesk insights and Revit software were used to evaluate the efficacy of these tactics. After applying NZEB principles, the proposed building achieved a 57.3% reduction in energy consumption, through the simulation of Autodesk Insights. The paper concludes by discussing the future of NZEBs as a critical step toward sustainable building practices, reducing both costs and CO2 emissions.

Keywords: Net-Zero energy buildings (NZEBs) · Building Integrated photovoltics · energy use intensity · Revit Software · Autodesk Insights · Energy analysis · enhancing energy efficiency · NZEB design aspects

1 Introduction

Net Zero Energy Buildings (ZEBs) are cutting-edge structures built to generate an amount of renewable energy equal to their energy consumption over a defined time period, typically measured annually [1]. In the context of a rapidly developing world, the building sector has emerged as the largest consumer of energy, accounting for 40% of global energy use, much of which is obtained from non-renewable sources like coal and oil [2]. According to the International Energy Agency (IEA, 2022), buildings alone are responsible for 30% of total primary energy consumption worldwide [3]. This substantial energy demand has far-reaching environmental consequences, including the production of greenhouse gases, atmospheric pollutants, and the depletion of finite resources. These changes have prompted the global community to adopt the concept of sustainable development, aiming to mitigate environmental harm while addressing societal and economic

T. Ayub et al. (Eds.): GCGC 2025, LNCE 774, pp. 113–119, 2026.
https://doi.org/10.1007/978-981-95-6592-4_14

needs [4]. Studies have shown that urban areas contribute 70% of global greenhouse gas emissions, with housing construction and real estate development responsible for 40% of these emissions. Furthermore, buildings significantly impact the environment, contributing approximately 50% of the world's air pollution, 42% of greenhouse gas emissions, 50% of water pollution, and 48% of solid waste [5].

A net zero energy building is defined as a structure that produces as much renewable energy as it consumes over a given period. A ZEB is a structure that generates as much energy as it consumes over the course of a year. This is typically achieved through a combination of energy-efficient design and construction. The use of renewable energy can create a more sustainable and self-sufficient building environment [1] (Figs. 1, 2 and 4).

Fig. 1. Infrastructure Development Authority of the Punjab, Lahore

Fig. 2. Indria Paryavaran Bhavan, India

Fig. 3. The Bullitt Center, Washington, USA

Fig. 4. Design and Environment Department in National University of Singapore

The construction industry contributes significantly to both global energy consumption and greenhouse gas emissions, with operations responsible for 27% of the total emissions in the energy sector. Poor building designs exacerbate these issues by increasing energy consumption, operational costs, and environmental challenges like global warming. This research focuses on transitioning traditional buildings into Zero Energy Buildings (ZEBs) through energy-efficient and sustainable strategies. By incorporating renewable energy, optimizing ventilation, utilizing direct sunlight, and employing sustainable materials [6]. ZEBs aim to reduce reliance on fossil fuels, minimize emissions, and lower operational costs. As a key solution to the climate crisis, these buildings offer a sustainable approach to reducing carbon footprints and mitigating environmental impacts. To achieve this aim, the research sets forth. To design an energy-efficient and effective building that diverges from traditional practices (Table 1).

2 Research Methodology

2.1 Collection of Required Data (Proposed Building Properties)

Table 1. Building Specifications

Specific	Properties of Building
Building Type	Educational Building
Build-up Area	16980 sq. ft
Plot Area	16800 sq. ft
No.of Floors	G + 1
Orientation of Building	South-East Facing

2.2 2D and 3D Modeling

In second step, we have to design our proposed building as 2D and 3D model, by using AutoCAD and 3D max respectively. Here are our obtained 2D Models by use of AutoCAD as shown in Figs. 5 and 6 and 3D Models by use of 3D Max Software as shown in Figs. 7 and 8.

2.3 Passive Design Strategy

In the Passive Design Strategy, we have to decide the orientation of the building for maximizing natural daylight, which can help lower a building's energy comsumption [7].

2.4 Active Design Strategy

These tactics, which include effective lighting systems, concentrate on the production, distribution, and control of energy inside the structure.

2.5 Renewable Energy Design Strategy

This method determines the size of a solar photovoltaic power plant based on the amount of power needed and the amount of roof space that is not shaded. The building's solar panels absorb solar radiation and transform it into electrical power.

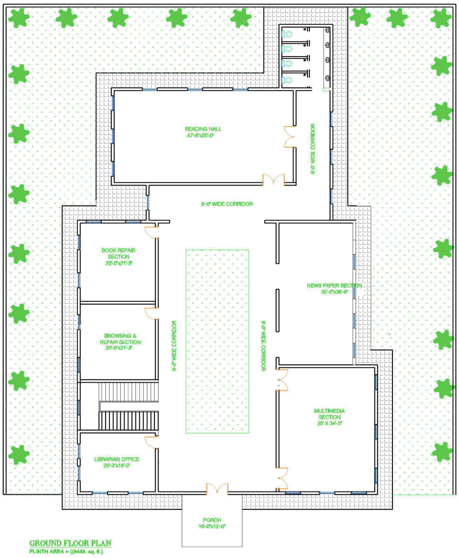


Fig. 5. Ground Floor Plan

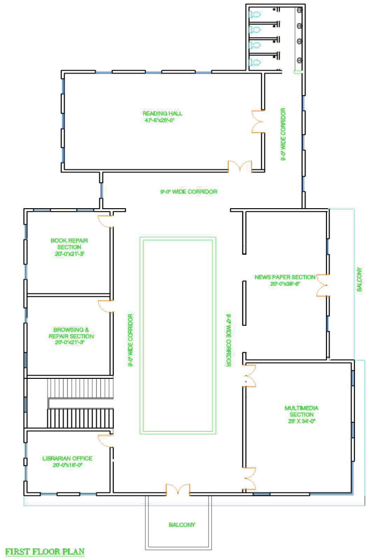


Fig. 6. First Floor Plan

Fig. 7. Top 3D view of Proposed Building

Fig. 8. Side 3D view of Proposed Building

2.6 Final Analysis of Building and Simulations

The use of Autodesk Insights facilitated the analysis of the building's overall energy consumption and comparing of before and after implementing different strategies and technology.

3 Results and Discussions

3.1 Building Orientation

Passive design strategies were implemented to lower energy demand by optimizing the building's orientation, using shading devices to manage solar gain, and maximizing the use of natural daylight [8]. The building's orientation was found to be key in enhancing solar gains and reducing energy consumption. The analysis showed that positioning the building towards the **South-East** would result the highest solar energy production of 147.12 MWh/year (Fig. 9).

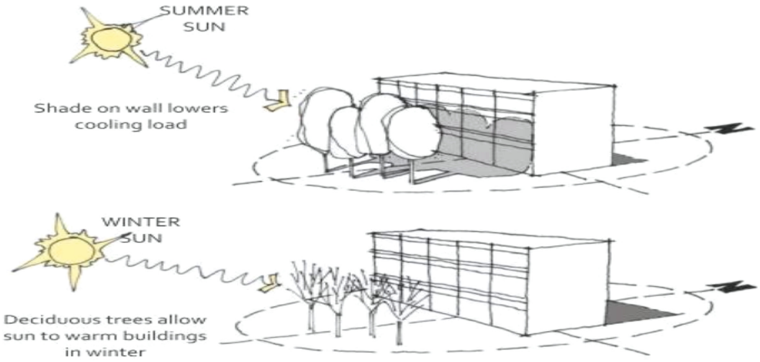


Fig. 9. Solar Gain control through Shading Devices

3.2 Natural Lighting, Ventilation and Solar Panel Coverage

In our proposed building we have allocated a spacious area (Fig. 10) at the top for a skylight. We use monochromatic technology in the skylight glass panels to reduce excessive solar heat gain. The estimated daily energy production of the 500-W solar panel in Pakistan, considering 6 peak sun hours, would be **approximately 2.8 kWh**. So, 24 solar panels (See Fig. 11) will produce approximately 403.2kWh.

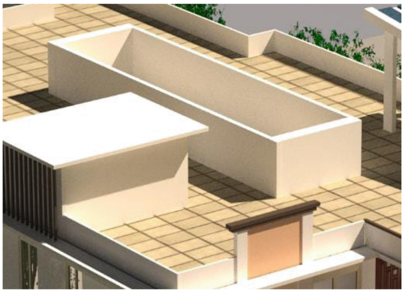


Fig. 10. Opening for Skylight

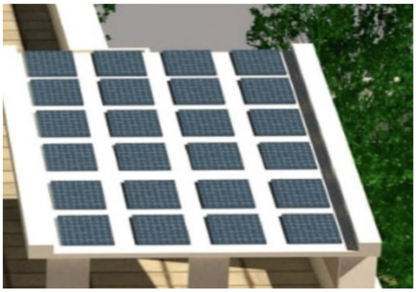


Fig. 11. Installed 24-Solar Panels on Roof Top of Building

3.3 Analyzing Energy Model

To attain maximum energy efficiency, a thorough examination of our projected building's numerous components was carried out and contrasted with cutting-edge technology. Autodesk Insights was utilized to assess the building's energy consumption (Fig. 12), allowing for the exploration of different energy use scenarios and technology alternatives aimed at minimizing energy usage.

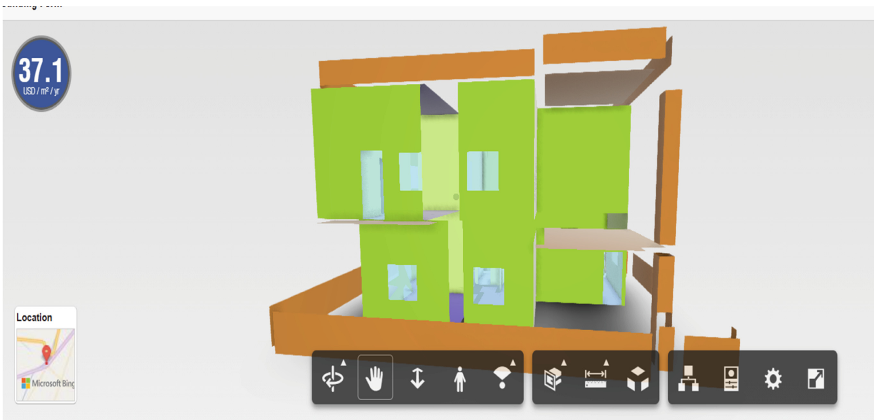


Fig. 12. Analyzing the Buildings energy consumption in Autodesk Insights by evaluating various energy consumption scenarios

3.4 EUI Building Performance Analysis

The mean Energy Use Intensity (EUI) of the building is compared before and after the implementation of energy-efficient and renewable energy solutions in order to evaluate their efficacy. In this study, the building's initial EUI, prior to the adoption of any energy efficient technologies, was recorded at 426 kWh/sq (Figs. 13 and 14).

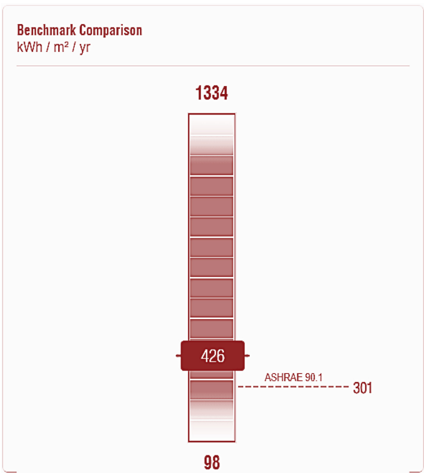


Fig. 13. EUI value before implementing any strategy and energy efficiency technology.

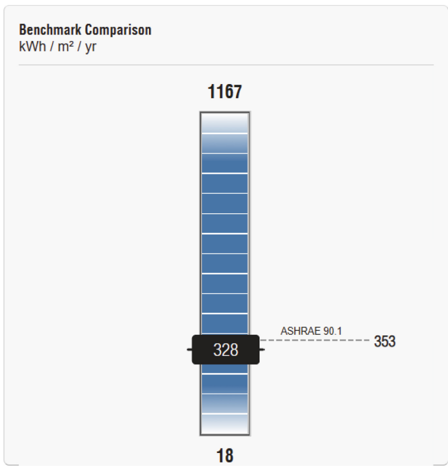


Fig. 14. This represents the EUI value after implementing different strategies and technology.

4 Conclusion

- This study assessed methods for using solar energy and lowering energy usagein order to achieve a Net Zero Energy Building (NZEB).
- Key findings include the effectiveness of both passive and active design strategies, renewable energy sources, and emerging technologies in improving energy efficiency.
- Passive design strategies, such as optimizing building orientation, using skylights, enhancing insulation, and incorporating landscaping, significantly reduced energy consumption.
- Energy-efficient HVAC systems contributed to lower energy use while maintaining indoor air quality.
- It is anticipated that the proposed building will produce 5.98 MWh of solar energy annually, resulting in zero net energy usage.
- The study demonstrates the potential of advanced technologies and smart design strategies to develop sustainable, energy-efficient buildings that positively impact both the environment and society.
- The study shows how cutting-edge technologies and clever design techniques may be used to create environmentally and socially beneficial, energy-efficient buildings.

References

1. Wadalkar, S.S., et al.: Sustainable Approach for Conversion of Building to 'Zero Energy Building'. In: E3S Web of Conferences. EDP Sciences (2023)
2. Torcellini, P., et al.: Zero energy buildings: a critical look at the definition. National Renewable Energy Lab.(NREL), Golden, CO (United States) (2006)
3. IEA. Buildings, IEA, Paris (2022). https://www.iea.org/reports/buildings
4. Bagheri, M., Barfeh, D.G., Hamisi, M.: Building design based on zero energy approach (2023)
5. Manu, S., et al.: Energy Conservation and Commercialization (ECO-III) (2010)
6. Noguchi, M., et al.: Net zero energy homes of the future: A case study of the EcoTerraTM house in Canada. In: Renewable Energy Congress, Glasgow, Scotland (2008)
7. Sami, S., et al.: Design and optimization of a CCHDP system integrated with NZEB from energy, exergy and exergoeconomic perspectives. Energy Convers. Manage. **271**, 116347 (2022)
8. Saitho, T.: Natural energy autonomous house with underground water reservoir. Bulletin of JSME **27**(226), p. 773–778 (1984)

Detailed Study of Traditional Residential Projects of Tier-II Cities in India for Promoting Less Carbon Intensive and Eco-Friendly Construction Practices

Anshul Jain(✉) and K. Ananda Babu

Shri Vaishnav Vidyapeeth Vishwavidyalaya, Indore, Madhya Pradesh 453111, India
jainanshul17@gmail.com

Abstract. The necessity of green construction technologies is currently a fundamental requirement in India. Although not a novel technology, an examination of Indian statistics reveals a limited number of green-rated projects or buildings. A fundamental benefit of any green building is the reduction in electricity usage, reliance on underground water resources, and the need for air conditioning. The occupants of green buildings experience a noticeable disparity in comfort and energy conservation compared to conventional structures. Within this academic study, the analysis of a residential projects in Bhopal named Sagar Green Hills (SGH), Sage Golden Spring (SGS), Sage Milestone Sage Suncity and Prime Square, Indore is presented, assessed against the 34 criteria of Green Rating for Integrated Habitat Assessment (GRIHA) revised in 2021, emphasizing key findings on achieving a minimum 1-star evaluation. This investigation aims to inspire developers in Tier II cities of India like Bhopal and Indore to undertake green residential projects and encourage potential residents, or clients, to choose environmentally- friendly initiatives. The evaluation of the project follows the GRIHA guidelines, outlining essential actions required to fulfil mandatory criteria.

Keywords: Sustainable projects · environmental sustainability · Green Residential project · eco-friendly construction · Low carbon emission

1 Introduction

Sustainable construction practices are the prime requirement and it is possible by adopting green construction practices. Although in Tier-II cities, most of the projects are traditional. Hence it is essential to determine the present status of traditional projects as compared to green rated projects. Hence, five residential projects of Tier-II cities have been evaluated as per 2021 revised GRIHA manual existing in India. This evaluation will determine the extent to which this project falls short of achieving a 1- to 5-star rating stipulated by GRIHA. Additionally, it will identify which criteria are overlooked by conventional residential projects [1, 2]. The major aim is to find out the status of

T. Ayub et al. (Eds.): GCGC 2025, LNCE 774, pp. 120–126, 2026.
https://doi.org/10.1007/978-981-95-6592-4_15

present residential projects of Tier-II cities and to improve their performance along with the shortcomings [3, 4]. The case study focuses on the selection of the first project Sagar Green Hills (SGH), situated on Kolar Road in Bhopal, featuring luxurious 3, 4, and 5 BHK flats equipped with modern amenities including rainwater harvesting, swimming pools, jogging tracks, a club house, Jain temple, and landscaped gardens. The second project is Golden Spring (GS) which is located on Ayodhya Bypass Road, Bhopal and comprises of 3, 4 and 5 BHK Bungalows, 2 and 3 BHK luxurious flats. The third project is Milestone which is located in Hoshangabad comprising of 3, 4 and 5 BHK Bungalows 2 and 3 BHK luxurious flats. The fourth project is Suncity which is located in Katara Hills Bhopal comprising of 3 and 4 BHK Duplexes. The fifth project Prime Square located in Balyakhedi Indore is residential project having luxurious flats.

Green building entails the process of constructing structures that prioritize environmental sustainability and resource efficiency from site selection to deconstruction throughout the building's life cycle [5]. The construction industry stands as the largest polluting and resource-consuming sector globally. Consequently, infrastructure development significantly contributes to greenhouse gas emissions [6]. The primary cause of global warming is intricately linked to climate change concerns, necessitating urgent actions for the benefit of future generations [7]. According to the United Nations Environmental Program, adherence to standard building norms can effectively reduce environmental pollution, conserve energy, minimize waste generation, and preserve the natural environment [7]. The conceptualization of green building initiatives involves not only architects but also designers, consultants, and engineers collaborating to achieve common objectives in planning, designing, constructing, and operating buildings [8]. This collective team focuses on mitigating negative impacts while promoting positive project approaches.

Key aspects of green building design include site selection, infrastructure design, HVAC systems, lighting, electrical systems, water heating, and utilization of renewable energy sources for on-site energy generation, water management, waste management strategies, and selection of sustainable materials that are easily recyclable [9]. Indians have made significant advancements in embracing green initiatives within the infrastructure sector; however, there is a lack of mandatory regulations compelling the adoption of these practices, resulting in widespread disregard for this construction technique [10]. Despite the higher cost associated with green buildings compared to conventional ones, there is a sluggish demand for them [11]. Nevertheless, the environmental damages caused by construction activities cannot be overlooked. Therefore, it is imperative for the government and relevant authorities to raise awareness among citizens regarding the significance of green infrastructures [12].

1.1 Objectives of Research

This research eliminates the dependency on non-renewable resources and ultimately reutilize renewable resources in the construction industry to protect the environment from losses [13, 14] and optimizes the use of advanced construction materials and advanced techniques by utilizing minimum energy in the project and using equipment that can satisfy the lighting, air conditioning, and other needs [6].

2 Methodology

The evaluation of site is a continuous process leading to collection of data which helps in promoting green residential projects soon by preventing the environmental losses and promoting the use of renewable energy sources. This reduces the carbon emission by the construction sector and leading to sustainable development. The comparative analysis of marks gained by all the residential projects has been shown in form of table (Table 1).

Table 1. Marked gained by projects as per GRIHA criteria [12].

Sub heads of Criterion	Lacuna/Recommendations	Max Marks	P1	P2	P3	P4	P4
1. Suitable site Planning	The project site selected is appropriate and as per the City's Master plan. Excavated soil was reutilized on the project site. The net paved area is under limits but the shaded area shall be enhanced. Arrangements for the shading of pedestrian roads are required	17	10	8	12	10	7
2.Water management during construction/compensatory depository forestation	Landscape water use was reduced by 30%, with potential savings of 25–50% through low-flow fixtures. Lawn areas can be minimized. While government water reports are available, wastewater treatment is lacking. Rainwater collection and wastewater treatment via a WTP could enable 75% annual water reuse	13	6	8	5	4	4
3.Energy Optimization	Solar-powered street and parking lights will be installed, along with adequate daylighting on all floors. Renewable energy systems will be placed on every building, covering at least 20% of annual hot water needs. ECBC guidelines will be followed	35	8	10	8	8	4

(*continued*)

Table 1. (*continued*)

Sub heads of Criterion	Lacuna/Recommendations	Max Marks	P1	P2	P3	P4	P4
4.Sustainble building materials	The utilization of low-energy materials and lightweight concrete is to be enhanced. Industrial waste or recycled products shall be used in interiors (false ceiling, doors, windows, flooring, etc.) to minimize wood	14	7	8	9	7	8
5.Waste management	Construction waste was minimized by reusing mortar and concrete. However, on-site waste segregation and resource recovery for biodegradable waste were not implemented	5	2	2	2	2	3
6. Health and wellbeing	Worker sanitation needs improvement, air pollution minimized, and VOC adhesives avoided. Water quality details need compilation. Smoking was prohibited, and accessibility met NBC standards	14	6	6	7	7	9
Sub heads of Criterion	Lacuna/Recommendations	Max Marks	P1	P2	P3	P4	P4
7. Building operation & maintenance	An energy audit report shall also be prepared. Installation of digital smart water meters shall be done at all main supply points to measure the total water consumption of the building	2	0	0	0	0	0
8. Innovation	No innovative idea on the project site was implemented. Four innovation points are available alternative transportation, environmental education, company policy on green supply chain, life cycle cost analysis or any other criteria proposed by applicant	4	0	0	0	0	0

Now the marks obtained by all the projects as per the major GRIHA guidelines is shown in the form of a figure below. It can be noticed that none of the traditional projects have scored 50 marks or more. Hence none of the project is green rated.

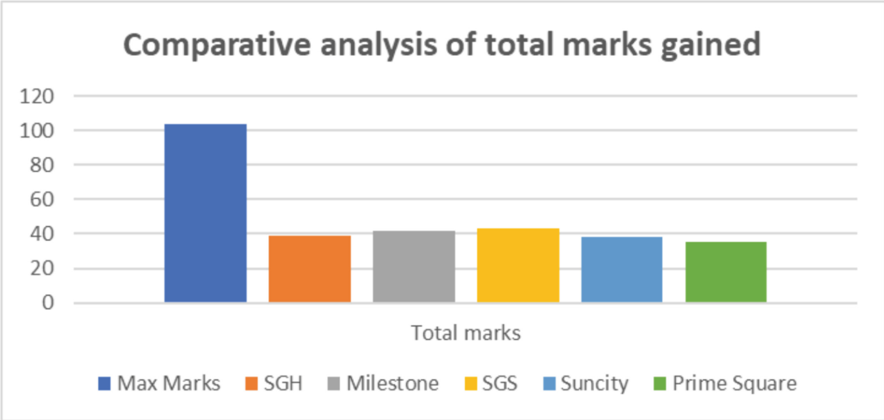


Fig. 1. Marked gained by projects as per GRIHA guidelines [12]

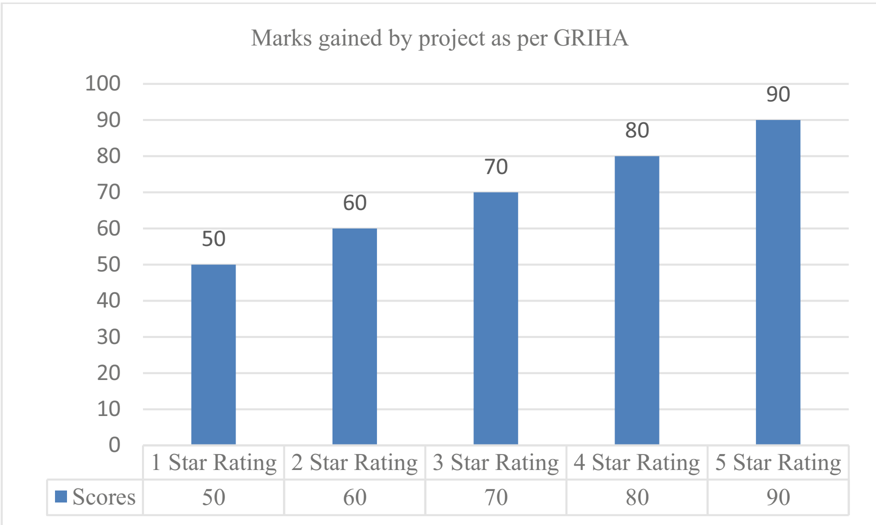


Fig. 2. Rating awarded as per GRIHA guidelines [12]

3 Result

In this study we have tried to identify the initiatives taken by the conventional residential projects of Bhopal and evaluated their scores as per the guidelines of GRIHA. As per the Figs. 1 and 2, it is clear that the traditional projects are unable to cross 50 marks as per GRIHA. Hence none of the traditional project can be considered as green rated.

In order to be green rated certain tasks need to be completed. Following are the results obtained from the intensive evaluation of 5 residential projects. The shortcomings of the sub heads of criterion have been discussed along with suitable suggestions to overcome them.

1) No measures were implemented to decrease air pollution and enhance air quality at the site during the process of vehicles entering or exiting. Therefore, it is imperative to ensure thorough cleaning of the wheels of such vehicles to minimize air pollution. During the loading of demolished waste or unloading of construction materials at the site, it is essential to sprinkle fresh water to mitigate air pollution and meet the requirements of criterion 9.
2) To diminish the reliance on traditional energy sources, areas of the infrastructure exposed to excessive sunlight can be shaded or covered using external structures like green facades or mechanisms.
3) Precast concrete components like precast stone blocks, pre-cast concrete blocks, pre-cast finished concrete blocks, lightweight concrete blocks over dense concrete blocks shall be used.
4) Improved fire safety provisions should be introduced in multi-story buildings, such as an automatic sprinkler system activated by heat generation. Additionally, efforts should be made to reduce the usage of CFC-emitting equipment like air conditioning and refrigeration systems.
5) Water quality testing reports should be procured from local municipal authorities to verify adherence to water quality standards outlined in the Indian Standard code 10500.
6) Raising awareness among stakeholders about the hazards of tobacco consumption and smoking is crucial for achieving points under criterion 30. Workshops for workers and the installation of signboards across the premises indicating “Ban on Tobacco & No Smoking Zone” can aid in this effort.
7) Energy Audits, water quality Audits, and Solid waste audits on the site shall be conducted with the assistance of experts within two years of occupancy.
8) Installation of smart water meters along the supply mains is necessary to curb water wastage and fulfill the requirements.

Implementation of these recommendations and adjustments will facilitate compliance with mandatory criteria of GRIHA, ultimately leading to the attainment of a minimum 1-star rating. Similar investigations can be conducted on conventional projects, with a comprehensive report subsequently submitted to governmental bodies to enforce green construction practices in Tier-II cities of India, thereby safeguarding against environmental degradation.

References

1. Li, Y., et al.: Green building in China: needs great promotion. Sustain. Cities Soc. **11**, 1–6 (2014)
2. Kasthurba, A., Reddy, K., Reddy, D.V.: Sustainable approaches for utilizing waste in building construction: two case studies in India. Int. J. Earth Sci. Eng. **7**(3), 838–844 (2014)

3. Gehlot, M., Shrivastava, S.: Sustainable construction practices: a perspective view of Indian construction industry professionals. Mater. Today Proc. **61**, 315–319 (2022)
4. Gupta, A., Amin, S., Malik, F.A.: An investigation of Green Buildings in India. NeuroQuantology **20**(15), 3384–3393 (2022)
5. Gogoi, D.B.J., Giri, D.T.K.: Green Building Requirement in India and Factors driving green building purchase. Int. J. Civ. Eng. Technol. **8**(10), 153–165 (2017)
6. Trivedi, P., Sharma, M.: Impact of green production and green technology on sustainability: Cases on companies in India. Int. J. Mech. Prod. Eng. Res. Dev. **7**(6), 591–606 (2017)
7. Srinivasan, B., Ganeswaran, D.P., Meenambal, D.T.: Optimization with sun light source in old constructed building and converting to green building. Int. J. Civ. Eng. Technol. **7**(5), 428–434 (2016)
8. Satya, S.S., Sridharan, U.: Environment sustainability guidelines for Green Buildings in India. Int. J. Sci. Res. Technol. **4** (2016)
9. Ardente, F., et al.: Energy and environmental benefits in public buildings as a result of retrofit actions. Renew. Sustain. Energy Rev. **15**(1), 460–470 (2011)
10. Li, Y.Y., et al.: Critical project management factors of AEC firms for delivering green building projects in Singapore. J. Constr. Eng. Manag. **137**(12), 1153–1163 (2011)
11. Castleton, H.F., et al.: Green roofs; building energy savings and the potential for retrofit. Energ. Build. **42**(10), 1582–1591 (2010)
12. Jain, A., Babu, A.K.: Rating of a conventional residential project as per GRIHA to promote sustainable infrastructure. Fostering Multi. Res. Sustain., 11 (2024)
13. Gupta, R., et al.: Customized performance evaluation approach for Indian green buildings. Build. Res. Inf. **47**(1), 56–74 (2019)
14. Steinemann, A., Wargocki, P., Rismanchi, B.: Ten questions concerning green buildings and indoor air quality. Build. Environ. **112**, 351–358 (2017)

Pakistan's First Structural Application of Limestone Calcined Clay Cement (LC3)

Tariq Jamil[1](✉), Muhammad Danyal Sheikh[1], Tehmina Ayub[1], Asad-ur-Rehman Khan[1], and Chuanlin Hu[2]

[1] NED University of Engineering and Technology, Karachi, Pakistan
{tariqjamil,tariqjamil,danydalsheikh,tehmina,asadkhan}@neduet.edu.pk

[2] School of Materials Science and Engineering, Wuhan University of Technology, Wuhan 430070, China

Abstract. The world is facing a growing climate crisis, with catastrophic events becoming increasingly frequent. While high-polluting industries are transitioning towards greener alternatives, the construction sector remains stagnant. The construction industry contributes approximately 8–10% of global CO_2 emissions, with limited viable alternatives due to supply chain constraints and market demand. Recently, a ternary cementitious blend, Limestone Calcined Clay Cement (LC3), has been developed, demonstrating the potential to reduce CO_2 emissions by up to 40%. This blend offers a cost-effective solution as it can be produced using existing cement manufacturing facilities with minor modifications. Extensive research globally has validated its superior mechanical properties and durability; however, no cement plant has yet adopted full-scale LC3 production in Pakistan. Following a successful full-scale laboratory trial at NED University, a model civil structure was constructed to demonstrate LC3's structural integrity and to build confidence among policymakers, industry stakeholders, and regulatory bodies for its large-scale adoption. Standard construction practices were implemented to ensure comparable performance under real-world conditions, reinforcing the feasibility of LC3 as a sustainable alternative for reducing the carbon footprint of the cement industry.

Keywords: Limestone Calcined Clay Cement · Civil Structure · Low-Carbon Concrete

1 Introduction

The cement industry has recently celebrated the 200th anniversary of Ordinary Portland Cement (OPC). There is no other construction material that provides the same strength and durability to structures at such a low cost [1]. However, the world is seeking alternatives to OPC due to its high carbon emissions [2]. Multiple Supplementary Cementitious Materials (SCMs) have been introduced into cement to reduce the clinker content in OPC, but none have proven feasible in meeting consumer demand [3]. Recently, a new type

T. Ayub et al. (Eds.): GCGC 2025, LNCE 774, pp. 127–133, 2026.
https://doi.org/10.1007/978-981-95-6592-4_16

of ternary blend has been introduced, capable of reducing clinker content by up to 45% while meeting consumer demand and being derived from natural resources instead of products with insufficient supply. This ternary blend includes calcined clay and limestone in a 2:1 ratio, with the rest of the composition consisting of clinker and gypsum. It is commonly known as Limestone Calcined Clay Cement (LC3) [4].

A country like Pakistan has been severely affected by climate change in recent years, facing challenges such as floods, glacier melting, and more [5]. Pakistan is also grappling with an economic crisis. The country's exports are increasingly relying on cement, which helps earn foreign exchange to stabilize the economy. However, the cement industry is likely to face significant challenges in the future. After 2023, various carbon border taxes and other levies are expected to be imposed on carbon-intensive products, with cement likely to be at the top of the list [6]. This could hinder Pakistan's cement exports. Pakistan is a country rich in mineral resources, with diverse terrains ranging from mountains to seas and plains to deserts. Therefore, transitioning from OPC to LC3 cement should not be difficult, as Pakistan has abundant clay resources that could facilitate LC3 production [7, 8]. Shifting to LC3 cement production would not only help Pakistan reduce carbon emissions but also support its struggling economy through the export of green cement. International investors could also show interest in Pakistan's cement sector due to its abundant clay reserves, fostering opportunities for green cement production. Currently, Pakistan produces averaging 112,000 tons of cement per day, relying solely on limestone [9]. This rapid consumption of limestone not only risks depleting this natural resource but also threatens the extinction of various wild species. Such relentless limestone mining poses risks to the country's ecosystem and biodiversity, which could be mitigated by shifting to alternative resources like LC3.

Another challenge is shifting the typical market in Pakistan and convincing stakeholders to move from traditional cement to a greener product. Extensive research is being conducted in Pakistan on LC3 cement. The results of these studies are remarkable, highlighting the availability of abundant clay reserves and demonstrating that LC3 outperforms OPC in terms of mechanical properties and durability [8, 10]. LC3 cement has significant potential in Pakistan. The Government of Pakistan could play a pivotal role by providing incentives to companies for producing this cement. The objective of this study is to persuade industry professionals, consultants, contractors, builders, and others to adopt LC3 and to gain the confidence of the market, the public, and government bodies. As part of this effort, a model structure made with LC3 cement has been built at NED University of Engineering and Technology, Karachi, Pakistan.

2 Raw Materials and Proportions

The raw materials for the LC3 cement were provided by Bestway Cement Limited (BCL), including cement, clay, limestone, and gypsum. To determine the kaolinitic content, three clay samples were tested using the furnace protocol method, revealing up to 70% kaolin content. This clay was sourced from Mianwali, Punjab, and a region near the BCL quarry. The chemical composition of the clay is presented in Table 1. The clay, limestone, and gypsum were ground separately, passing through a #200 sieve (75 microns), with their chemical compositions also detailed in Table 1. Calcination of the clay was performed in a Protherm furnace of the HLF series, which has a capacity of 1000 L, with each cycle calcining a 50 kg batch of clay. After calcination, the clay adopted a distinctive red colour. For LC3 production, clinker was not used directly; instead, a composition of 52% OPC, 30% calcined clay, 15% limestone, and 3% gypsum was adopted to balance the sulphate content. The water-to-cement ratio was maintained at 0.5, consistent with typical construction practices, eliminating the need for additives such as superplasticizers to enhance workability. The concrete produced with LC3 cement achieved a slump of approximately 100–125 mm. The complete LC3 cement composition, along with OPC for comparison, is shown in Table 1. The particle size distribution of OPC, limestone, calcined clay, and gypsum is illustrated in Fig. 1. Typical construction styles and techniques were followed to validate the routine use of LC3 without requiring additional labour training. A lean mix ratio of 1:4:8 was used, while a 1:1.5:3 ratio was employed for general works such as casting bricks, foundations, plinths, columns, and beams. This approach demonstrates the feasibility of LC3 in standard construction practices.

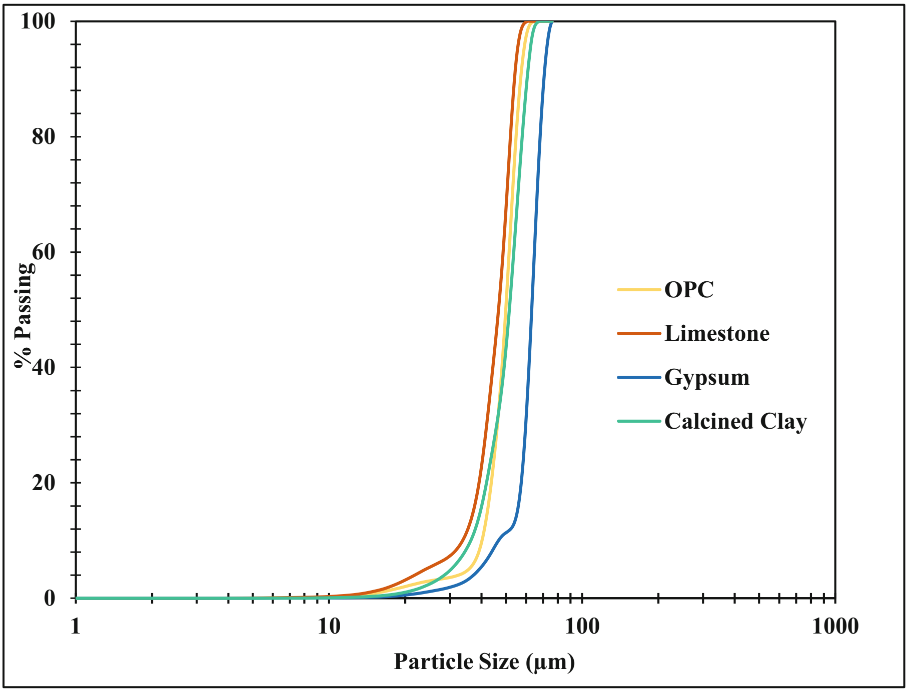


Fig. 1. The particle size distribution of all cementitious material utilized for building the model structure.

Table 1. Chemical Composition of all cementitious materials used in constructing the model structure.

Chemical Analysis (%)	Ordinary Portland Cement	Calcined Clay	Limestone
CaO	59.16	2.31	74.58
SiO2	16.27	49.69	8.2
Al2O3	2.28	33.83	2.32
Fe2O3	4.47	0.48	1.37
MgO	1.51	0.35	1.14
SO3	2.5	0.01	0.03
K2O	0.54	0.06	0
Na2O	0.29	0.1	0.19
Others	12.98	13.17	12.17
Loss on Ignition (LOI)	2.69	5.2	8.05
Specific gravity	3.21	2.6	2.68

3 Full-Scale Testing of Cement and Concrete

Full-scale physical and chemical testing was conducted on LC3 cement to evaluate its performance comprehensively. During each pouring of structural elements, mechanical properties were assessed, with compressive strength determined according to ASTM C39 through cylindrical testing [11]. The compressive strength of concrete was measured for every pouring, as shown in Fig. 3, with an average value of 3100 psi. For the same mix design with OPC. Although a slight compromise in workability was observed when using LC3 cement without superplasticizers, the concrete remained sufficiently workable and was easily transported, placed, and adjusted within the formwork. The compressive strength tests were carried out with strict adherence to the guidelines of EN 196-1:2016 [12]. Additionally, tests for consistency, setting times, and soundness were performed on five samples following EN 196-3:2016 [13], ensuring a comprehensive evaluation of LC3 cement's performance.

4 Building of Model Structure

The mixing of materials for all cementitious components was performed on-site while preparing the concrete, with each ingredient weighed separately to ensure accuracy. Various types of concrete, including in-situ and lean concrete, were used during the construction of the structure, though the composition of cement remained constant across all types. The total plot area was 165 ft2, and standard sizes for the foundation, columns, plinth beams, beams, and slabs were utilized, the plan of the structure can be seen in Fig. 2. The construction process began with the excavation of pits for four foundations, which, after the erection of columns, were filled with compacted sand. Plinth beams were laid out along all boundaries and beneath partition walls. Block masonry was then extended from the Natural Ground Level (NGL) to the Roof Level (RL), concurrently with the erection of columns. Finally, roof beams, slabs, and lintels were cast using a machine mixture and the construction process is comprehensively, as illustrated in Fig. 3. Post-construction, plastering was carried out on both the interior and exterior surfaces using LC3 cement, and flooring work inside the structure and in the passage was also completed with LC3. Workers did not require special training to use LC3 cement; careful weighing of materials ensured proper mixing of LC3 proportions, and labourers mixed, poured, and set the concrete similarly to how they would with OPC cement. No significant differences were observed in the handling or application of LC3, demonstrating that its use in construction can seamlessly replace OPC without requiring specialized training for workers.

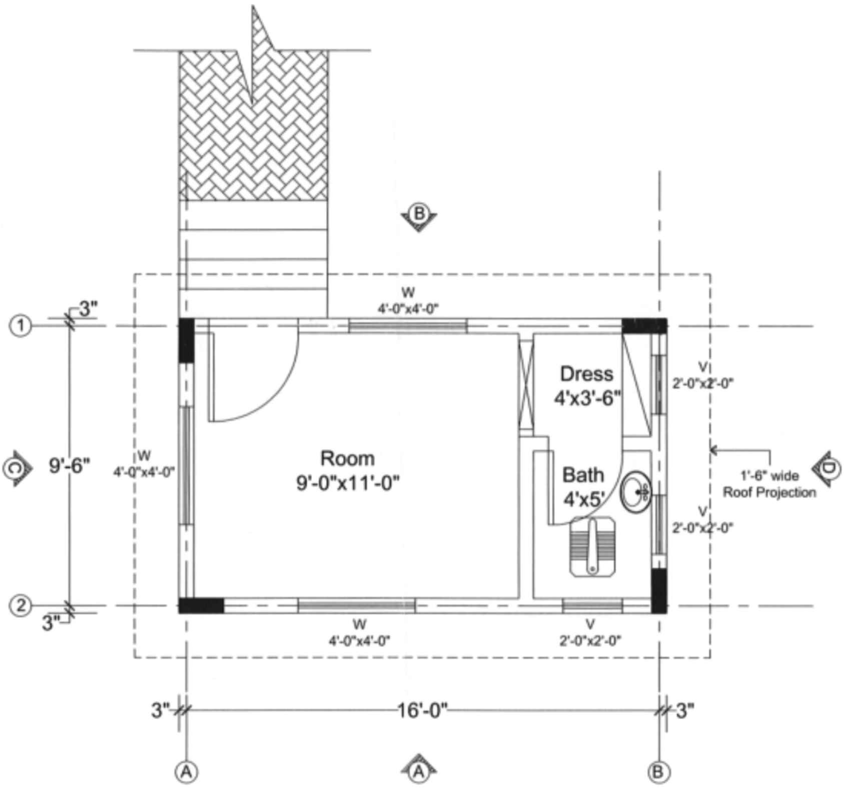


Fig. 2. Plan of model civil structure

Fig. 3. The entire construction process is depicted sequentially

5 Summary and Conclusion

This model structure was constructed using LC3 cement produced on a laboratory scale. The clay was pre-calcined and ground to ensure consistent homogeneity across all mixes throughout the construction process. Workers were not given any special training or protocols for handling this cement; instead, pre-measured quantities of cement, calcined clay, limestone, and gypsum were prepared before mixing. No superplasticizers or admixtures were added during the construction, despite LC3's higher water demand. The water-to-cement ratio was maintained at 0.5, which, while slightly affecting workability, ensured the required strength was achieved after 28 days of curing. Despite its increased water demand, LC3 remains a highly viable alternative for reducing clinker content in cement, offering significant replacement potential while maintaining performance. Additionally, LC3 technology can be implemented in existing cement plants with minimal modifications, making it a practical and cost-effective solution. The challenges encountered during small-scale production are anticipated to decrease with large-scale manufacturing. This lab-scale demonstration highlights the feasibility and benefits of LC3 cement, presenting a strong case for industry stakeholders and government bodies to adopt this sustainable and environmentally friendly alternative in future construction projects.

References

1. Schneider, M., et al.: Sustainable cement production—present and future. Cem. Concr. Res. **41**(7), 642–650 (2011)
2. Afrin, H., Huda, N., Abbasi, R.: An overview of eco-friendly alternatives as the replacement of cement in concrete. IOP Conf. Ser. Mater. Sci. Eng. (2021). IOP Publishing
3. Skibsted, J., Snellings, R.: Reactivity of supplementary cementitious materials (SCMs) in cement blends. Cem. Concr. Res. **124**, 105799 (2019)
4. Sharma, M., et al.: Limestone calcined clay cement and concrete: a state-of-the-art review. Cem. Concr. Res. **149**, 106564 (2021)
5. Hussain, M., et al.: A comprehensive review of climate change impacts, adaptation, and mitigation on environmental and natural calamities in Pakistan. Environ. Monit. Assess. **192**, 1–20 (2020)
6. Quirion, P., Demailly, D.: Leakage from climate policies and border tax adjustment: lessons from a geographic model of the cement industry (2006)
7. Hussain, S.M.F., et al.: Initial search for low grade clay in Pakistan for producing LC3 ecofriendly cement. Low-carbon Mater. Green Constr. **1**(1), 15 (2023)
8. Sheikh, M.D., et al.: Comparative study on LC3-50 with OPC concrete using raw materials from Pakistan. Adv. Mater. Sci. Eng. **2023**(1), 5503670 (2023)
9. CEIC: Pakistan Production: Cement (2020). https://www.ceicdata.com/en/pakistan/production-of-manufacturing-items/production-cement?utm_source=chatgpt.com
10. Ayub, T., et al.: Effect of glass powder on the compressive strength and drying shrinkage behavior of OPC-and LC3-50-based cementitious composites of various strengths. Adv. Mater. Sci. Eng. **2024**(1), 8860083 (2024)
11. ASTM: C39/C39M-21 standard test method for compressive strength of cylindrical concrete specimens, West Conshohocken, PA 19428-2959, United States (2021)
12. EN, BS196-1:2016 - TC Methods of testing cement - determination of strength (2016)
13. EN, BS 196-3:2016 - TC Methods of testing cement - determination of setting times and soundness (2016)

Author Index

T. Ayub et al. (Eds.): GCGC 2025, LNCE 774, p. 135, 2026.
https://doi.org/10.1007/978-981-95-6592-4