

Strength Prediction and Optimization of Portland Limestone Cement Blended with Metakaolin and Rice Husk Ash

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Abstract

This study explores the effects of Rice Husk Ash (RHA) and Metakaolin (MK) on the compressive strength of Portland Limestone Cement (PLC) mortar, aiming to promote sustainable construction materials. RHA and MK, derived from agricultural and industrial byproducts, serve as supplementary cementitious materials (SCMs) that offer environmental benefits and improve cement properties. Using response surface methodology (RSM) and central composite design (CCD), the research optimized the ternary blend of PLC, RHA, and MK to develop a predictive model for compressive strength, considering factors like blending ratio, replacement level, and curing age. The blending ratio denotes the proportion of RHA and MK to PLC, the replacement level is the percentage of PLC substituted by these SCMs, and curing age is the time allowed for mortar strength development. Various mortar samples with different RHA, MK, and PLC combinations were prepared, cured, and tested for compressive strength. The results showed that higher blending ratios, increased replacement levels, and longer curing ages enhanced mortar compressive strength. The optimal conditions identified were a blending ratio of 0.53, a replacement level of 3.40 wt.%, and a curing age of 56.30 days, yielding a compressive strength of 40.30 N/mm². This demonstrates that incorporating RHA and MK in PLC blends significantly enhances mortar strength, supporting sustainable construction practices. The study emphasizes how RHA and MK can be used as SCMs to improve mechanical qualities and promote environmental sustainability. Future studies should look into these optimized blends' long-term durability and usefulness in diverse construction settings.

Keywords: Portland limestone cement, rice husk ash, metakaolin, compressive strength, response surface methodology, optimization

INTRODUCTION

The construction industry is a major contributor to global greenhouse gas emissions, with cement production being a significant source. The energy-intensive process of cement manufacturing and the subsequent release of carbon dioxide pose serious environmental concerns [1]. Specific data on CO₂ emissions from cement production and their impact on climate change, e.g., annual global CO₂ emissions from cement, the percentage of total anthropogenic CO₂ emissions and specific climate change impacts such as global warming and ocean acidification [2]. To mitigate these environmental impacts, researchers have explored alternative materials and production techniques. One promising approach is the use of cement-pozzolanic material mixes. Pozzolans, such as fly ash and silica fume, can partially replace Portland cement clinker, reducing energy consumption and CO₂ emissions [3].

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This study investigates the potential of cement-pozzolanic material mixes to reduce the environmental footprint of cement production [2]. By analyzing the properties and performance of these mixes, we aim to identify optimal formulations that balance strength, durability, and sustainability. These problems are made worse by the industry's reliance on conventional Portland cement, which uses a lot of energy and raw materials and results in unsustainable practices [4]. As a result, there is an urgent need for creative ways to lessen the negative environmental effects of cement production.

In response to these challenges, researchers have increasingly turned to the use of supplementary cementitious materials (SCMs) such as Metakaolin (MK). These materials, derived from industrial and agricultural waste, offer a promising solution by reducing the carbon footprint of cement production while simultaneously enhancing the properties of mortar and concrete [5, 6]. MK, which is obtained from the thermal treatment of kaolin clay, and RHA, a byproduct of rice milling, are both rich in silica and alumina, making them highly suitable for use in cementitious applications [7, 8]. Their incorporation into cement blends has been shown to improve various properties, including compressive strength, durability, and resistance to chemical attack [9, 10].

This study aims to optimize the compressive strength of a ternary cement blend incorporating RHA and MK with Portland Limestone Cement (PLC). The mechanical and durability qualities of cementitious materials can be greatly enhanced by integrating RHA and MK as partial substitutes for conventional cement components [11, 12]. By employing response surface methodology (RSM) and central composite design (CCD), we can systematically explore the effects of varying proportions of RHA and MK on the compressive strength of PLC mortar. This approach allows us to develop a predictive model and identify the optimal blend that maximizes strength while minimizing environmental impact [13, 14].

The research methodology involves preparing and testing various mix designs to evaluate their performance in terms of compressive strength. Through rigorous statistical analysis, the study seeks to establish a comprehensive understanding of how different levels of RHA and MK, when combined with PLC, influence the overall strength of the mortar [15, 16]. The RSM and CCD provide a structured framework for conducting experiments and analyzing data, ensuring that the findings are both reliable and replicable [17]. By systematically varying the proportions of RHA and MK, we can identify the combinations that offer the best performance, providing valuable insights for the development of more sustainable cementitious materials.

The ultimate goal is to formulate an optimal mix that not only meets structural requirements but also contributes to sustainable construction practices. Achieving this balance requires a thorough understanding of the interactions between the various components of the cement blend and their effects on the properties of the resulting mortar [18, 19]. By leveraging the benefits of RHA and MK, we aim to reduce the environmental impact of cement production without compromising on performance. This approach aligns with broader efforts to promote sustainability in the construction industry, supporting the transition to greener building materials and practices [20, 21].

By utilizing industrial and agricultural waste products as SCMs, this research supports the development of eco-friendly building materials, paving the way for a more sustainable future in the construction industry. The use of RHA and MK not only helps in managing waste but also contributes to resource conservation by reducing the demand for traditional cement materials [22, 23]. This dual benefit underscores the potential of SCMs to drive significant environmental improvements in the construction sector, highlighting their importance in the pursuit of sustainable development goals [24].

Furthermore, the successful optimization of RHA and MK in PLC blends can have broader implications for the construction industry. As the demand for sustainable building materials continues to grow, the adoption of these alternative cementitious materials can help reduce the industry's overall carbon footprint [25]. The findings of this study can serve as a valuable reference for construction

professionals, policymakers, and researchers, providing a foundation for the wider application of SCMs in various construction projects [26].

In conclusion, this study represents a significant step towards addressing the environmental challenges associated with cement production. By optimizing the use of RHA and MK in ternary cement blends, we can enhance the performance of cementitious materials while promoting sustainability. The integration of RSM and CCD in the research methodology ensures that the findings are robust and applicable to real-world scenarios, paving the way for the development of more eco-friendly construction practices. Through this work, we aim to contribute to the ongoing efforts to make the construction industry more sustainable and environmentally responsible.

POZZOLANIC MATERIALS AND THEIR BENEFITS

Pozzolanic materials, such as Rice Husk Ash (RHA) and Metakaolin (MK), play a crucial role in enhancing the properties of cementitious composites. Silica and alumina, the main constituents of these materials, combine with calcium hydroxide, a byproduct of the cement hydration process, to generate more calcium silicate hydrate (C-S-H) [27]. Since C-S-H is the main compound that gives cement-based products their strength and durability, its creation is advantageous [28]. In addition to strengthening the composite, this reaction, known as the pozzolanic reaction, improves its resistance against a variety of environmental elements, including chemical attacks and freeze-thaw cycles [29].

One of the significant advantages of using pozzolanic materials like RHA and MK is their ability to improve the mechanical properties of cementitious composites. When RHA and MK are incorporated into cement, they fill the micro-pores within the matrix, leading to a denser and more compact structure. By decreasing the concrete's permeability, this densification increases the material's durability and compressive strength [30]. According to studies, the mechanical qualities of the finished product can be significantly enhanced by partially substituting pozzolanic materials for cement [8]. Abdullahi, for example, pointed shown that adding pozzolanic elements to cement blends significantly increases their compressive strength and general endurance [27].

In addition to the mechanical benefits, pozzolanic materials contribute significantly to the environmental sustainability of cement production. The use of RHA and MK, both derived from industrial and agricultural waste, helps in reducing the demand for traditional cement materials, which are associated with high energy consumption and CO₂ emissions [32]. The carbon footprint of cement manufacturing can be greatly decreased by using these waste products in place of some of the cement. This strategy supports international initiatives to encourage environmentally friendly building methods and lessen the influence of the construction sector on the environment. Abdullahi emphasized the environmental benefits of using pozzolanic materials, noting that their inclusion in cement not only enhances performance but also supports waste management and resource conservation [27].

Moreover, the use of pozzolanic materials can improve the long-term durability of cementitious composites. The additional C-S-H formed through the pozzolanic reaction contributes to the development of a more stable and resilient matrix, capable of withstanding various forms of degradation over time [33, 34]. This increased durability is particularly beneficial in harsh environmental conditions where conventional cement might fail. For example, in marine environments or areas subjected to heavy industrial pollution, the enhanced durability provided by pozzolanic materials can lead to longer-lasting structures, thereby reducing maintenance costs and extending the service life of infrastructure [29].

Finally, the incorporation of pozzolanic materials like RHA and MK into cementitious composites promotes innovation and diversity in construction materials. By exploring the potential of different waste materials as supplementary cementitious materials, the construction industry can develop new formulations that meet specific performance criteria while addressing environmental concerns [28]. This innovative approach encourages the use of locally available resources, reduces dependency on

traditional cement, and opens up new avenues for research and development. Abdullahi concluded that the partial replacement of cement with pozzolanic materials offers a promising path towards more sustainable and resilient construction practices, highlighting the need for continued research and application in this area [27].

Rice Husk Ash (RHA)

Rice Husk Ash (RHA) is a byproduct obtained from the controlled combustion of rice husks, which are an agricultural waste product. The process of producing RHA involves burning rice husks at a controlled temperature to yield ash rich in amorphous silica. This silica content is highly reactive and plays a significant role in the pozzolanic reaction when used in cementitious composites [31]. The high silica content of RHA, typically over 80%, makes it an excellent supplementary cementitious material (SCM) that can enhance the properties of concrete and mortar.

The many advantages of adding RHA to cementitious materials have been shown in studies. RHA dramatically increases the compressive strength of mortar and concrete, according to Amarnath [28]. The amorphous silica in RHA and the calcium hydroxide generated during cement hydration undergo a pozzolanic reaction, producing more calcium silicate hydrate (C-S-H), which is responsible for this enhancement.

The presence of more C-S-H leads to a denser and more robust microstructure, thereby increasing the compressive strength of the material [33].

Moreover, the inclusion of RHA in concrete and mortar mixes can substantially reduce their permeability. Rayaprolu *et al.* emphasized that the fine particles of RHA fill the micro-pores and voids within the cement matrix, leading to a more compact and impermeable structure [29]. Because it restricts the entry of dangerous chemicals like water, chlorides, and sulfates that might eventually cause degradation, this decreased permeability is essential for improving the longevity of concrete. As a result, RHA-modified concrete and mortar exhibit improved resistance to chemical attacks and environmental deterioration [32].

The durability of concrete and mortar is further enhanced by the use of RHA. The additional C-S-H formed through the pozzolanic reaction not only strengthens the matrix but also improves its resistance to various forms of physical and chemical damage. For instance, concrete containing RHA has shown better performance in freeze-thaw cycles, alkali-silica reaction (ASR) mitigation, and resistance to sulfate attack [30]. These durability improvements contribute to the longevity and sustainability of structures, reducing the need for frequent repairs and maintenance [31].

In conclusion, Rice Husk Ash (RHA) is a valuable supplementary cementitious material that offers significant benefits when used in concrete and mortar. The high amorphous silica content of RHA enables it to participate effectively in the pozzolanic reaction, enhancing the compressive strength, reducing permeability, and increasing the durability of cementitious composites. The findings of studies by Amarnath and Rayaprolu *et al.* underscore the potential of RHA to improve the performance of concrete and mortar while promoting environmental sustainability by utilizing agricultural waste [28, 29]. As the construction industry continues to seek sustainable and high-performance materials, RHA stands out as a promising option that aligns with the goals of reducing environmental impact and enhancing structural longevity.

Metakaolin (MK)

Metakaolin (MK) is a highly effective supplementary cementitious material produced by calcining kaolinite clay at temperatures typically ranging between 650 and 800°C. This thermal treatment results in the dehydroxylation of kaolinite, transforming it into an amorphous, highly reactive pozzolanic material [30]. MK is renowned for its high pozzolanic activity, which significantly contributes to the

improvement of cementitious composites. The high surface area and the presence of reactive alumina and silica in MK make it an excellent additive for enhancing the mechanical and durability properties of concrete and mortar [32].

Research conducted by Rahman *et al.* has demonstrated the remarkable ability of MK to enhance the early strength development of cementitious materials. Because it restricts the entry of dangerous chemicals like water, chlorides, and sulfates that might eventually cause degradation, this decreased permeability is essential for improving the longevity of concrete [30].

These hydrates contribute to a denser and stronger microstructure, leading to significant improvements in early-age compressive strength [31]. This characteristic is especially helpful in construction situations where quick strength increase is essential, such as fast-track construction projects and precast concrete applications [33].

In addition to enhancing early strength, MK also improves the resistance of cementitious materials to chemical attacks. Kumar *et al.* highlighted that the dense microstructure formed due to the pozzolanic reaction with MK reduces the permeability of concrete and mortar, thereby limiting the ingress of aggressive substances such as chlorides, sulfates, and acids [32]. This enhanced resistance to chemical attack extends the service life of structures exposed to harsh environments, such as marine and industrial settings, where chemical durability is paramount. By reducing the permeability and enhancing chemical resistance, MK contributes to the longevity and sustainability of concrete structures [29].

Another significant benefit of incorporating MK into cementitious materials is the reduction of shrinkage. Shrinkage, both plastic and drying, can lead to the development of cracks in concrete, compromising its structural integrity and durability. The addition of MK helps mitigate this issue by refining the pore structure and reducing the overall water demand of the mix [28]. The pozzolanic reaction of MK consumes calcium hydroxide, which otherwise contributes to the shrinkage of concrete. Consequently, the use of MK results in reduced shrinkage, minimizing the risk of crack formation and enhancing the long-term durability of concrete and mortar [32].

In summary, Metakaolin (MK) is a highly effective supplementary cementitious material that offers multiple benefits when used in concrete and mortar. The high pozzolanic activity of MK contributes to the early strength development, improves resistance to chemical attack, and reduces shrinkage. According to studies by Rahman *et al.* and Kumar *et al.*, MK has the ability to improve cementitious materials' performance and durability, which makes it a useful addition to contemporary building techniques. The incorporation of MK into cement-based composites not only improves their mechanical properties but also supports sustainable construction by reducing the reliance on traditional Portland cement and enhancing the durability of structures [32, 30].

Metakaolin Rice Husk Ash Mix

The combined use of Rice Husk Ash (RHA) and Metakaolin (MK) with Portland Limestone Cement (PLC) has garnered considerable attention due to the synergistic effects that enhance both mechanical properties and durability of cementitious composites. By incorporating these supplementary cementitious materials (SCMs), researchers aim to optimize the performance of concrete and mortar while promoting sustainable construction practices. The interaction between RHA and MK, when used together, provides a complementary set of benefits that address various challenges in the construction industry.

De Weerd *et al.* conducted extensive studies on ternary blends of SCMs, demonstrating that the combined use of RHA and MK with PLC significantly enhances the compressive strength of mortar [35, 31]. Additional calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) are formed as a result of pozzolanic reactions involving the reactive alumina and silica in MK and the high

silica content in RHA. These hydrates help create a denser microstructure, which increases the mortar's overall strength and resilience. The study shows that these ternary blends have the potential to perform better than conventional cement mixes, particularly when it comes to the development of strength over the long term.

Sathanatam further investigated the durability aspects of ternary blends incorporating RHA and MK with PLC. The study found that the combination of these SCMs results in a significant reduction in permeability, which is crucial for enhancing the durability of concrete structures [33]. The dense microstructure formed by the pozzolanic reactions limits the ingress of harmful substances such as chlorides, sulfates, and acids. This enhanced durability is particularly beneficial in environments exposed to harsh chemical conditions, such as marine and industrial settings. The research underscores the potential of ternary blends to extend the service life of concrete structures, thereby contributing to more sustainable construction practices.

In addition to mechanical strength and durability, the combined use of RHA and MK also addresses issues related to shrinkage and thermal properties. The incorporation of these SCMs refines the pore structure of the mortar, reducing the overall water demand and mitigating shrinkage. This reduction in shrinkage minimizes the risk of crack formation, which is a common problem in traditional cementitious materials. Furthermore, the thermal properties of the ternary blends are improved, as the reduced permeability and enhanced microstructure help in better resistance to thermal stresses. This makes the blends suitable for applications in regions with extreme temperature variations.

The environmental benefits of using RHA and MK with PLC cannot be overstated. Both RHA and MK are derived from industrial and agricultural waste, promoting the recycling of these materials and reducing the carbon footprint of cement production. The use of these SCMs decreases the reliance on Portland cement, which is associated with high energy consumption and CO₂ emissions. By integrating RHA and MK into cementitious composites, the construction industry can move towards more eco-friendly practices, aligning with global efforts to combat climate change and promote sustainability.

In summary, the combined use of RHA and MK with PLC presents a promising approach to enhancing the mechanical properties, durability, and sustainability of concrete and mortar. Research by De Weerd *et al.* and Sathanatam highlights the synergistic effects of these SCMs, leading to optimized performance in terms of strength, durability, shrinkage, and thermal properties [31, 33]. The environmental advantages further underscore the importance of adopting ternary blends in the construction industry. As the demand for sustainable building materials grows, the integration of RHA and MK into cementitious composites offers a viable solution for developing high-performance, eco-friendly construction practices.

CHALLENGES AND CONSIDERATIONS IN USING POZZOLANIC MATERIALS

While the benefits of using pozzolanic materials like Rice Husk Ash (RHA) and Metakaolin (MK) are well-documented, there are challenges and considerations that must be addressed to optimize their use in cementitious composites. One of the primary challenges is the variability in the quality of pozzolanic materials. The chemical composition, fineness, and reactivity of RHA and MK can vary significantly depending on the source and production process. This variability can affect the consistency and performance of the final product, making it essential to conduct thorough quality control and testing before use [33].

Another consideration is the potential for increased water demand when using pozzolanic materials. Both RHA and MK have high surface areas and can absorb more water compared to traditional Portland cement. This increased water demand can lead to challenges in workability, requiring the use of additional water or chemical admixtures to achieve the desired consistency [32]. However, careful mix design and the use of superplasticizers can help mitigate this issue, ensuring that the benefits of pozzolanic materials are fully realized without compromising workability [30].

Moreover, the availability and cost of pozzolanic materials can be a limiting factor, particularly in regions where these materials are not produced locally. The transportation and processing of RHA and MK can add to the overall cost, making them less attractive in comparison to conventional cement. However, as the demand for sustainable construction practices grows, the production and availability of pozzolanic materials are expected to increase, potentially reducing costs over time [29].

Finally, the environmental impact of producing pozzolanic materials must be considered. While the use of RHA and MK can reduce the carbon footprint of cementitious composites, the production processes themselves can be energy-intensive and generate emissions. It is essential to evaluate the environmental impact of the entire lifecycle of pozzolanic materials, from production to disposal, to ensure that their use aligns with sustainability goals [31].

In conclusion, while pozzolanic materials like RHA and MK offer significant benefits in enhancing the performance and sustainability of cementitious composites, their use presents challenges that must be carefully managed. The variability in quality, increased water demand, availability and cost, and environmental impact are key considerations that must be addressed to optimize the use of pozzolanic materials in construction. Strength prediction is essential in determining the load structures can withstand which is a unique property in assessing the quality of material employed [36]. By addressing these challenges, the construction industry can fully harness the potential of pozzolanic materials to improve the performance, durability, and sustainability of cement-based composites.

METHODOLOGY

In this study, three primary materials were utilized: Portland Limestone Cement (PLC), Metakaolin (MK), and Rice Husk Ash (RHA). Each of these materials was carefully selected for their unique properties and contributions to the overall performance of the cementitious blends. The combination of these materials aimed to enhance the mechanical strength and durability of the mortar, while also promoting sustainability in construction practices (Figure 1).

MATERIALS

Portland Limestone Cement (PLC)

Portland Limestone Cement (PLC) served as the primary binder in this study. PLC is known for its moderate strength development and environmental benefits compared to traditional Portland cement. The inclusion of limestone in PLC reduces the clinker content, thereby decreasing the overall CO₂ emissions associated with cement production. This makes PLC a more sustainable choice without compromising the essential binding properties required for strong and durable concrete and mortar.

Metakaolin (MK)

Metakaolin (MK), a high-reactivity pozzolan, was obtained from the calcination of kaolinite clay. MK is widely recognized for its ability to significantly enhance the early strength development of cementitious materials.

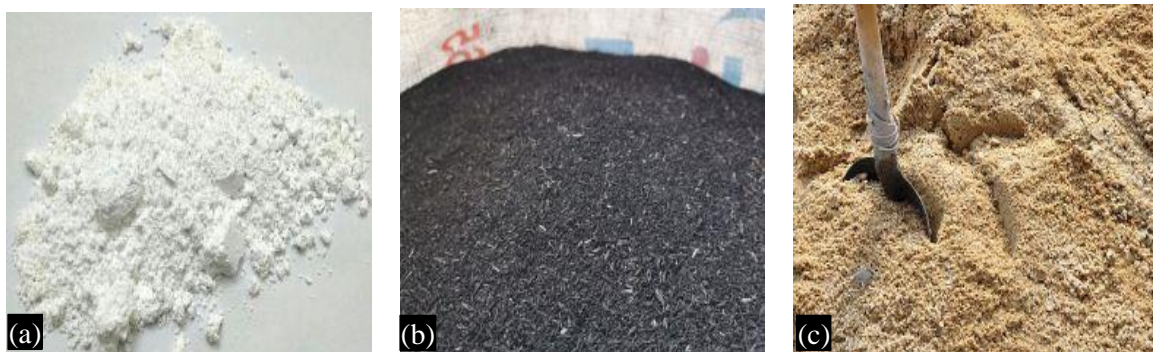


Figure 1. (a) Metakaolin, (b) Rice Husk Ash, (c) Standard Sand.

Because of the thermal activation process, which creates a reactive aluminosilicate substance that can react with calcium hydroxide to make more calcium silicate hydrate (C-S-H), it has a high pozzolanic activity. This reaction enhances the mortar's overall durability and chemical resistance in addition to its compressive strength. MK was selected because it has the ability to improve the PLC blend's performance, especially during the initial curing phases.

Rice Husk Ash (RHA)

Rice Husk Ash (RHA) was another critical component of the study. RHA is an agricultural byproduct rich in amorphous silica, produced from the controlled burning of rice husks. The high silica content of RHA makes it an effective pozzolanic material, capable of reacting with calcium hydroxide to form additional C-S-H, similar to MK. The use of RHA in cementitious materials not only improves the compressive strength and durability but also promotes the recycling of agricultural waste, contributing to more sustainable construction practices. The controlled burning process ensures that the RHA produced is rich in reactive silica, which is essential for its pozzolanic activity.

The integration of these materials: PLC, MK, and RHA, was carefully designed to optimize the performance of the cementitious blends. By combining the moderate strength development and environmental benefits of PLC with the high pozzolanic activity of MK and RHA, the study aimed to create a mortar that excels in both mechanical properties and sustainability. Each material was characterized and prepared according to standardized procedures to ensure consistency and reliability in the experimental results.

EXPERIMENTAL PROCEDURE

A central composite design (CCD) was employed in this study to systematically investigate the effects of three independent variables: blending ratio, replacement level, and curing age, on the compressive strength of the cementitious mortar. This experimental design method is particularly effective for optimizing processes, as it allows for the evaluation of interactions between multiple factors and the identification of optimal conditions. By using CCD, the study aimed to develop a comprehensive predictive model that could accurately forecast the compressive strength of the ternary cement blend under various conditions with the design of experiment as shown in Table 1.

Blending Ratio

The first independent variable, blending ratio, refers to the proportion of Rice Husk Ash (RHA) and Metakaolin (MK) relative to Portland Limestone Cement (PLC). This ratio was varied between 0.25 and 0.75. The rationale behind selecting this range was to explore both lower and higher proportions of SCMs to PLC, thus assessing the impact of different blending levels on the overall performance of the mortar. This variable is crucial as it determines the extent to which the pozzolanic materials influence the hydration process and the resultant mechanical properties of the mortar.

Table 1. Design of Experiment for lower and upper limits of PLC, MK and RHA.

S. No.	Cement blends	RHA/MK ratio	PLC wt.% L-U	RHA wt.% L-U	MK wt.% L-U
1	1.5MK0.5RHA	0.25	98	0.5	1.5
2	1MK1RHA	0.5	98	1	1
3	0.5MK1.5RHA	0.75	98	1.5	0.5
4	3MK1RHA	0.25	96	1	3
5	2MK2RHA	0.5	96	2	2
6	1MK3RHA	0.75	96	3	1
7	4.5MK1.5RHA	0.25	94	1.5	4.5
8	3MK3RHA	0.5	94	3	3
9	1.5MK4.5RHA	0.75	94	4.5	1.5

Replacement Level

The second independent variable, replacement level, denotes the percentage of PLC that is replaced by RHA and MK, with the range set between 2 to 6 wt.%. This range was chosen based on preliminary studies and literature, which suggest that small to moderate replacement levels can significantly enhance the properties of cementitious composites without adversely affecting the workability or setting times. By varying the replacement level, the study aimed to determine the optimal amount of SCMs that can be incorporated to achieve maximum compressive strength while maintaining sustainability.

Curing age Importance

The third independent variable, curing age, represents the duration for which the mortar samples were allowed to cure, ranging from 3 to 60 days. Curing age is a critical factor in the development of compressive strength, as it influences the degree of hydration and the formation of calcium silicate hydrate (C-S-H) gel. By examining a wide range of curing periods, the study sought to capture the strength development profile of the ternary blends over time. This variable helps in understanding the early and long-term performance of the cementitious materials, providing insights into their potential applications in various construction scenarios.

The mortar's compressive strength, expressed in N/mm^2 , served as the study's response variable. One essential characteristic that shows how much weight cementitious materials can support is their compressive strength. To evaluate the strength development throughout time, it was evaluated at various curing ages. The use of CCD enabled the researchers to generate a set of experimental runs that systematically varied the blending ratio, replacement level, and curing age, allowing for a detailed analysis of their combined effects on compressive strength. Statistical tools were then used to analyze the data and develop a predictive model that could guide the formulation of optimal ternary blends.

Sample Preparation

Mortar samples were meticulously prepared by mixing Portland Limestone Cement (PLC) with predetermined proportions of Rice Husk Ash (RHA) and Metakaolin (MK). The blending ratios and replacement levels were carefully calculated based on the central composite design framework. To ensure homogeneity, the dry components were first thoroughly mixed before water was gradually added to achieve the desired consistency. This mixing process was crucial to ensure that the RHA and MK were evenly distributed throughout the mortar, thereby ensuring consistent performance across all samples.

Once the mortar mixtures were prepared, they were cast into standardized molds to form test specimens. The molds were designed to produce samples of uniform size and shape, which is essential for accurate compressive strength testing. The casting process was carried out with precision to avoid air entrapment and segregation of materials, which could affect the integrity and performance of the samples. After casting, the molds were gently vibrated to eliminate any air bubbles and to compact the mortar mixture, ensuring a dense and uniform structure.

The cast samples were then placed in a humidity-controlled curing environment to simulate optimal curing conditions. Maintaining consistent humidity and temperature is vital during the curing process, as it influences the hydration reactions and strength development of the mortar. The samples were cured for the specified periods, ranging from 3 to 60 days, to capture the early and long-term strength development. After the designated curing periods, the samples were carefully demolded and subjected to compressive strength testing using a universal testing machine. This testing machine applied a steadily increasing load until the samples failed, providing a precise measurement of their compressive strength. The data collected from these tests were then analyzed to determine the effects of the different proportions of RHA and MK on the mortar's compressive strength, contributing valuable insights into the optimization of sustainable cementitious materials.

Statistical Analysis

Statistical analysis was conducted using Response Surface Methodology (RSM), a powerful tool for modeling and analyzing complex interactions among multiple variables. RSM was employed to examine the relationships between the blending ratio, replacement level, and curing age on the compressive strength of the mortar. This method facilitated the development of a comprehensive predictive model that could accurately forecast compressive strength based on the specified parameters. The experimental design incorporated a central composite design (CCD) to systematically explore the effects of varying proportions of RHA and MK, ensuring a robust and reliable dataset for analysis.

Analysis of Variance (ANOVA) was used to thoroughly validate the predictive model's accuracy and dependability. In order to determine which elements had the greatest influence on compressive strength, the statistical significance of the model and its constituent parts was evaluated using ANOVA. The main effects, interaction effects, and quadratic effects of the independent variables were all clarified by this study. By evaluating the F-values and p-values, the study determined the contribution and relevance of each factor in the model. The validation process ensured that the model was not only statistically significant but also capable of accurately predicting the compressive strength of the mortar under various conditions.

RESULTS

Compressive Strength Analysis

The study revealed a significant improvement in the compressive strength of mortar when higher blending ratios and replacement levels of RHA and MK were used, particularly with extended curing periods. Enhanced mechanical performance was observed with increased proportions of RHA and MK due to their pozzolanic activity and filler effects, which contribute to additional calcium silicate hydrate (C-S-H) gel formation, strengthening the mortar matrix. Optimal compressive strength was achieved with a blend ratio of 0.53, a replacement level of 3.40 wt.%, and a curing age of 56.30 days, resulting in a compressive strength of 40.30 N/mm². These findings emphasize the importance of selecting appropriate blend proportions and curing conditions to optimize the performance of cementitious materials (Table 2).

Table 2. Experimental design and results for compressive strength (CS).

Run	Factor 1 A Curing age (days)	Factor 2 B Cement replacement (wt.%)	Factor 3 C Blending ratio	PLC wt.%	Response Compressive Strength (CS) (N/mm ²)
1	60	6	0.75	94	21.08
2	28	6	0.5	94	13.49
3	28	2	0.5	98	30
4	60	2	0.75	98	37.56
5	28	4	0.75	96	31.13
6	3	2	0.75	98	23.7
7	60	4	0.5	96	40.18
8	28	4	0.5	96	33.88
9	60	2	0.25	98	34.34
10	3	4	0.5	96	23.88
11	28	4	0.5	96	33.88
12	3	6	0.25	94	9.56
13	60	6	0.25	94	18.28
14	28	4	0.25	96	23.2
15	3	2	0.25	98	24.55
16	3	6	0.75	94	7.58

Response Surface Methodology

The investigation of the effect of the various factors on the responses were determined using Design Expert 13. The resultant equations were obtained from the ANOVA for strength prediction for RHA-MK cement blend using CCD model (Table 3).

$$\text{Strength} = -4.45 + 0.075A + 13.18B + 50.12C - 0.003AB + 0.143AC - 0.388BC + 0.00134A^2 - 2.11B^2 - 48.51C^2 \quad (1)$$

Response Surface Methodology (RSM) was used to model and analyze the effects of blending ratio, replacement level, and curing age on compressive strength, resulting in a robust predictive model with a high coefficient of determination ($R^2=0.7646$). This high R^2 value indicates a strong fit between the model predictions and the experimental data, demonstrating the effectiveness of RSM in capturing complex interactions between variables. The model's accuracy was validated through Analysis of Variance (ANOVA), which confirmed the statistical significance of the model's components and highlighted the critical role of curing age in achieving optimal performance. RSM facilitated a comprehensive exploration of the relationships between variables, offering valuable insights for optimizing cementitious blends in sustainable construction materials.

Optimization

The optimization process identified ideal conditions for achieving maximum compressive strength in the ternary cement blend using RSM and the desirability function approach. The study determined that a blending ratio of 0.53, a replacement level of 3.40 wt.%, and a curing age of 56.30 days provided the most favorable outcomes, yielding a compressive strength of 40.30 N/mm². The desirability function confirmed a perfect score of 1.000, indicating that these optimal conditions met the desired criteria for compressive strength and sustainability. This successful optimization highlights the potential for improving cementitious materials through careful adjustment of blend ratios and curing conditions, supporting the development of high-performance, sustainable construction materials with enhanced structural properties and reduced environmental impact as shown in the Figure 2.

Table 3. ANOVA for Response surface quadratic model analysis of variance for mortar strength prediction of RHA-MK cement blend.

Source	Sum of Squares	DF	Mean Square	F Value	Prob>F	
Model	1381.19	9	153.47	17.28	0.0012	Significant
A-Curing age	386.51	1	386.51	43.52	0.0006	Significant
B-Replacement	642.75	1	642.75	72.37	0.0001	Significant
C-Blending ratio	12.92	1	12.92	1.45	0.2732	
AB	0.2344	1	0.2344	0.0264	0.8763	
AC	8.28	1	8.28	0.9319	0.3717	
BC	0.3003	1	0.3003	0.0338	0.8602	
A ²	3.01	1	3.01	0.3384	0.5820	
B ²	188.32	1	188.32	21.20	0.0037	Significant
C ²	24.23	1	24.23	2.73	0.1497	
Residual	53.29	6	8.88			
Lack of Fit	53.29	5	10.66			
Pure Error	0.0000	1	0.0000			
Cor Total	1434.38	15				

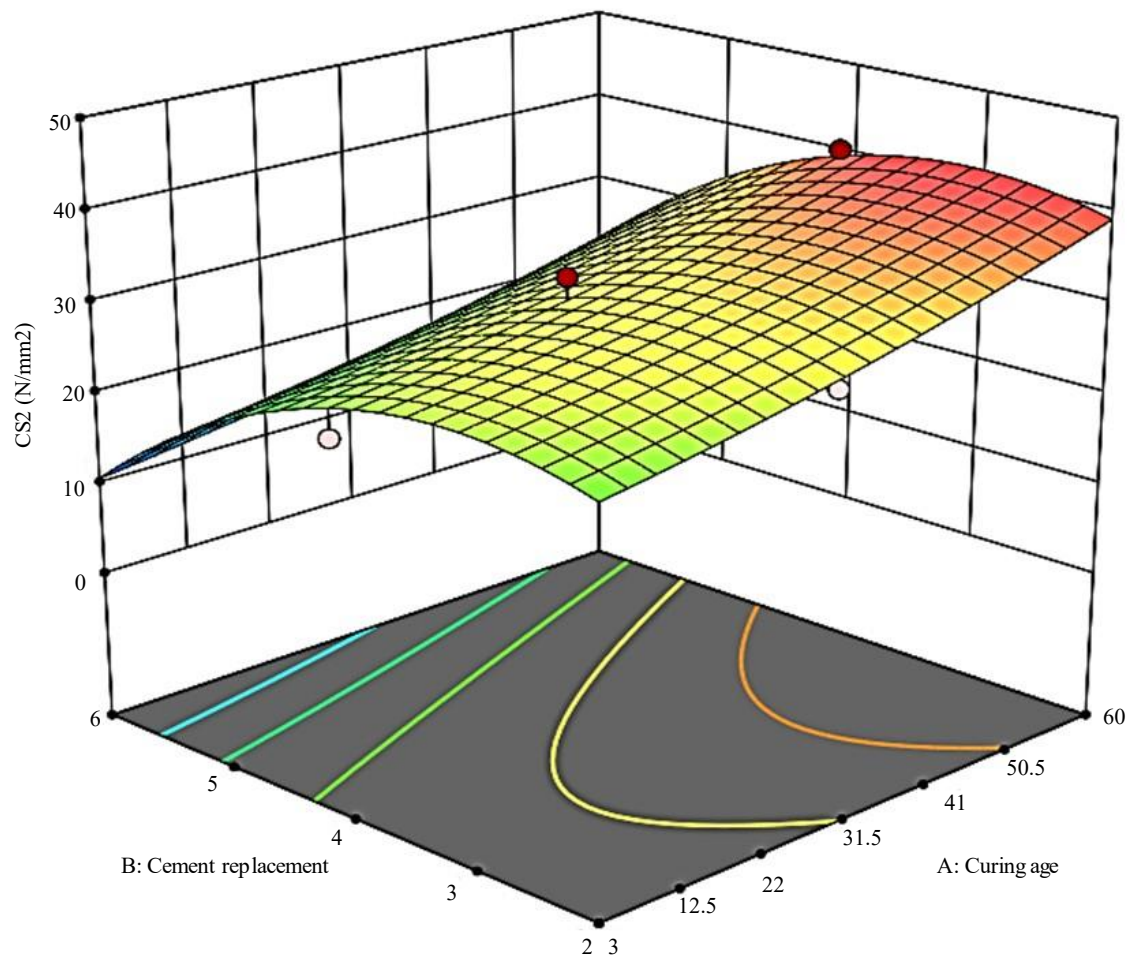


Figure 2. Response surface indicating the optimal conditions for interaction on mortar strength of RHA-MK-cement blends between curing age and Replacement level.

CONCLUSION

The study underscores the effectiveness of RHA and MK as supplementary cementitious materials (SCMs) in enhancing mortar properties while promoting environmental sustainability. Both RHA and MK are valuable byproducts that help reduce the environmental footprint of cement production. Their use lessens dependency on conventional cement, which uses a lot of energy and contributes significantly to CO₂ emissions. The improved compressive strength with these SCMs indicates their potential to maintain and enhance cement blend performance, aligning with sustainable development principles and supporting greener construction practices.

Future studies should concentrate on examining these mixed cements' practical uses in actual construction projects as well as their long-term durability. Assessing their performance over extended periods, including factors such as weathering, chemical exposure, and mechanical wear, is crucial for evaluating their suitability for various environmental conditions. Additionally, exploring the feasibility and economic viability of these blended cements in actual construction projects will provide valuable insights into their broader adoption. By addressing these aspects, future research can further solidify the role of RHA and MK in advancing sustainable construction technologies, contributing to the development of more eco-friendly and efficient building materials.

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