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Evaluation of uniaxial compressive strength, moisture content, and soundness in recycled-content ceramics for sustainable building materials

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Recycling waste materials into ceramics offers a promising pathway for developing sustainable building materials, addressing both environmental challenges and resource depletion. This study investigates the effects of incorporating industrial and post-consumer waste—such as glass, and fly ash- into ceramic formulations designed for building applications. Key parameters, including uniaxial compressive strength, moisture content, and soundness tests, are evaluated to determine the performance characteristics of the recycled-content ceramics. The research optimizes the composition and processing methods to enhance mechanical strength and durability, ensuring that the ceramics meet industry standards for structural applications. Results indicate that ceramics produced from recycled materials exhibit uniaxial compressive strengths comparable to traditional ceramics while maintaining acceptable moisture levels and soundness. This research underscores the viability of recycled-content ceramics as effective building materials, contributing to waste reduction, cost efficiency, and a circular economy within the construction industry.

Keywords: Ceramics, Building materials.

Introduction

The rapid growth of industrial activities and urbanization has led to an unprecedented generation of waste materials, posing significant environmental challenges and exacerbating resource depletion. Addressing these concerns requires innovative approaches to resource recovery and sustainability. One promising avenue is the recycling of industrial and post-consumer waste into ceramics, which offers a dual advantage of waste mitigation and the creation of high-value materials for construction applications. Ceramic materials are widely recognized for their mechanical strength, durability, and resistance to environmental factors, making them ideal candidates for building applications. However, traditional ceramic production relies heavily on virgin raw materials, contributing to environmental degradation and resource scarcity.

In this context, the incorporation of waste materials, such as glass and fly ash, into ceramic formulations presents a sustainable alternative for the development of building materials. Glass, a common post-consumer waste, is abundant and possesses desirable properties such as chemical stability and high silica content, making it suitable for ceramic production. Similarly, fly ash, a byproduct of coal combustion, is a pozzolanic material with a fine particle size that can enhance the mechanical properties of ceramics when appropriately utilized. The recycling of these materials not only diverts waste from landfills but also reduces the carbon footprint associated with raw material extraction and processing.

This study explores the integration of glass and fly ash into ceramic formulations designed for structural applications, with a focus on optimizing material composition and processing methods. Key performance parameters, including uniaxial compressive strength, moisture content, and soundness, are systematically evaluated to assess the suitability of recycled-content ceramics for building applications. By tailoring the proportions of waste materials, the research aims to enhance the mechanical strength and durability of the ceramics, ensuring they meet or exceed industry standards for structural use. Preliminary results indicate that ceramics incorporating recycled materials achieve uniaxial compressive strengths comparable to or exceeding those of conventional ceramics while maintaining acceptable moisture levels and soundness. These findings demonstrate the potential of recycled-content ceramics as a viable and sustainable alternative in the construction industry. Furthermore, the adoption of such materials aligns with the principles of a circular economy, promoting waste reduction, cost efficiency, and environmental stewardship.

This paper highlights the feasibility and advantages of utilizing waste materials in ceramic production and aims to contribute to the growing body of knowledge on sustainable building materials. By addressing the dual

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challenges of waste management and resource depletion, this research underscores the potential for a paradigm shift in construction practices, fostering innovation and sustainability in the built environment.

Experimental

The experimental procedure aimed at recycling waste materials into ceramics for sustainable building applications begins with the collection and preparation of raw materials. The primary materials used in this study are glass waste and fly ash, which are sourced from industrial and post-consumer waste streams. The glass waste is first cleaned, then crushed into small particles using a mechanical grinder or ball mill, with a typical particle size range of 100-200 μm. Fly ash, obtained from coal combustion in power plants, is sieved through a 150 μm mesh to ensure a fine powder free of large aggregates. Commercially available clay is also used, which is sieved to remove large particles before being mixed with a small amount of water to create a homogeneous paste. The raw materials are then blended to form ceramic mixtures with varying amounts of glass and fly ash. The weight percentage of glass waste is varied from 5% to 20%, and fly ash content is adjusted between 5% and 20%, while the remaining portion is filled with clay. Water is gradually added to achieve the desired consistency, typically in the range of 15-20% by weight. The mixture is thoroughly mixed for 30 minutes to ensure uniform distribution of the components. The ceramic mixtures are then molded into samples using pre-made molds. These samples are compacted using a hydraulic press to achieve a consistent density and are left to dry at room temperature for 24 to 48 hours before being placed in a furnace for sintering. The samples are pre-heated gradually to 1000°C at a rate of 2°C per minute, and then sintered at 1000°C for two hours, allowing the materials to bond and form a solid ceramic structure. The furnace is then allowed to cool naturally at room temperature. Once the sintering process is complete, the samples are characterized for their mechanical and physical properties. The uniaxial compressive strength of each sample is measured using a universal testing machine, and the moisture content is determined by drying the samples in an oven at 105°C until a constant weight is achieved. The soundness of the ceramics is assessed by immersing the samples in boiling water and measuring the expansion after a specified time.

The data collected from these tests are analyzed to determine the optimal proportions of glass waste and fly ash for creating durable, high-performance ceramics. The results are compared with traditional ceramic formulations to evaluate the effectiveness of using recycled materials. Additionally, the study examines the environmental benefits of using waste materials in ceramics, focusing on waste reduction, energy savings, and the potential for developing sustainable building materials. This experimental procedure highlights the feasibility of incorporating industrial and post-consumer waste into ceramic formulations for building applications, offering a promising pathway toward more sustainable and environmentally friendly construction practices.

Results and Discussion

The heat map matrix data provides a correlation analysis between glass content, fly ash content, and uniaxial compressive strength (Fig. 1). The values in the matrix represent the strength of the relationships between these variables, where a positive value indicates a direct correlation and a negative value suggests an inverse relationship. The correlation between glass content and uniaxial compressive strength is strongly positive (0.8292), indicating that as the glass content increases, the compressive strength also tends to increase. This is consistent with the assumption that glass helps in forming a denser, stronger matrix due to its vitrification properties during sintering, which improves the overall strength of the ceramic materials. The correlation between fly ash content and uniaxial compressive strength is negative (-0.65978). This suggests that as the fly ash content increases, the uniaxial compressive strength tends to decrease. This could be due to the higher porosity and lower bonding strength resulting from excessive fly ash in the matrix, which reduces the overall structural integrity.

The interaction between glass content and fly ash content shows a moderate negative correlation (-0.4779), meaning that when one component increases, the other generally decreases. This indicates that an increase in fly ash content might reduce the beneficial effects of glass in enhancing compressive strength. A high proportion of fly ash could potentially disrupt the optimal composition

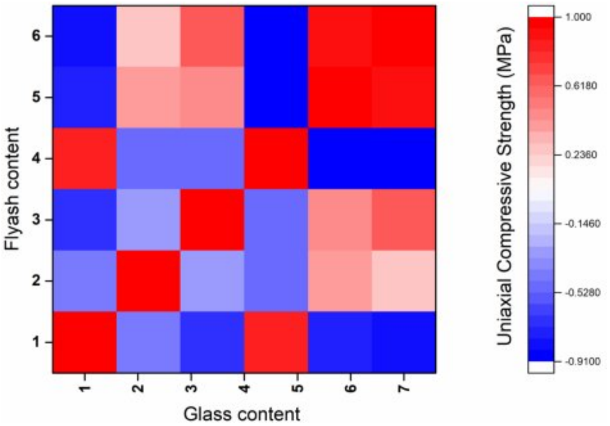

Fig. 1. Heat map matrix showing the correlation analysis between glass content, fly ash content, and uniaxial compressive strength. Positive correlation values (e.g., 0.8292 between glass content and compressive strength) indicate a direct relationship, where higher glass content contributes to increased strength, likely due to vitrification enhancing the material's density and bonding.

needed for maximum densification and strength, leading to a less effective ceramic structure. There is an inverse relationship between glass content and fly ash content when both are present in high amounts, as seen with the correlation of -0.90736 between glass content and compressive strength at high fly ash levels. This suggests that when both glass and fly ash are used in large quantities, the benefits of glass content in improving compressive strength are overshadowed by the negative effects of excess fly ash, which could lead to weakening of the ceramic structure.

The interaction between fly ash and strength at higher glass levels is positive (0.44066), but it is much weaker compared to the glass-strength relationship. This indicates that while fly ash can still contribute to the overall strength at higher glass contents, its impact is less significant than that of glass itself. The negative correlations between fly ash content and compressive strength underscore the importance of optimizing fly ash content in the formulation. Excessive fly ash content could counteract the positive effects of glass, and careful attention is needed to balance both components to achieve an optimal performance in terms of strength. The heat map matrix analysis shows the need for an optimal balance between glass and fly ash content in the ceramic formulations. While glass positively influences compressive strength, excessive fly ash content can reduce the structural integrity of the material. Therefore, careful consideration of the proportion of glass and fly ash in the mixture will be crucial in developing high-performance, sustainable ceramics for building applications.

The plot reveals the complex interplay between glass content, fly ash content, and moisture content. As the glass content increases from lower to higher percentages, there is a noticeable variation in moisture content. Similarly, fly ash content also demonstrates its impact on moisture levels, with higher fly ash content typically correlating with lower moisture content in the ceramics. Sample S1 (Glass: 9.2%, Fly Ash: 12.3%, Moisture: 4.1%) and Sample S2 (Glass: 14.6%, Fly Ash: 7.8%, Moisture: 4.0%) have relatively higher moisture content (around 4%), indicating that a balanced combination of glass and fly ash content tends to maintain moisture content within this range. Sample S7 (Glass: 19.2%, Fly Ash: 9.1%, Moisture: 3.8%) shows a slight decrease in moisture content despite a higher glass content. This suggests that increasing the glass content without significantly increasing the fly ash content results in a marginal decrease in moisture. Sample S3 (Glass: 18.7%, Fly Ash: 6.4%, Moisture: 3.9%) and Sample S10 (Glass: 18.6%, Fly Ash: 2.7%, Moisture: 3.9%) demonstrate similar moisture content values (around 3.9%) despite variations in fly ash content, which implies that beyond a certain level of glass content (close to 18%), the moisture content stabilizes within this range. Sample S13 (Glass: 19.7%, Fly Ash: 14.3%, Moisture: 3.8%) represents the highest combination of both glass and fly ash content, yet the moisture content remains relatively low at 3.8%. This suggests that higher fly ash content helps in reducing the moisture content, especially when coupled with high glass content. The lowest moisture content value is observed in Sample S14 (Glass: 10.2%, Fly Ash: 7.6%, Moisture: 4.0%), showing that lower fly ash content does not significantly reduce the moisture content compared to other samples, indicating a possible optimum moisture content range for this composition.

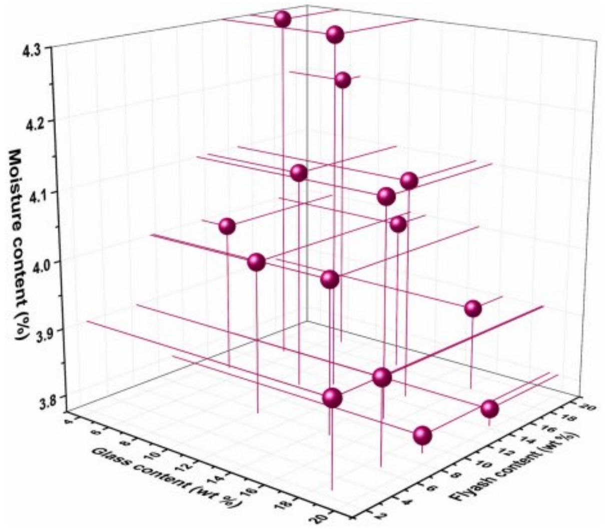

Fig. 2. Scatter plot showing the relationship between moisture content and the combination of glass and fly ash content. The moisture content decreases slightly with increasing glass content, potentially due to the hydrophobic nature of glass particles compared to the hygroscopic properties of fly ash.

From the scatter plot (Fig. 2), it is observed that moisture content tends to decrease slightly with higher glass content in combination with higher fly ash content. This trend may be attributed to the hydrophobic nature of glass particles, which likely absorb less moisture compared to the fly ash, which is more hygroscopic. Fly ash, with its high surface area and ability to absorb water, seems to influence moisture levels more significantly. The combination of both materials impacts the ceramic matrix, potentially creating a more compact and stable structure that holds less moisture.

The scatter plot shows clusters of data points where moisture content remains consistent despite changes in glass or fly ash content. This suggests that there is an equilibrium point for moisture retention, likely dependent on the interactions between the two materials. Sample S6 (Glass: 4.8%, Fly Ash: 11.7%, Moisture: 4.0%) and Sample S12 (Glass: 5.3%, Fly Ash: 15.9%, Moisture: 4.3%) represent potential outliers as they have relatively high moisture content at lower glass and higher fly ash contents. This could be due to the high fly ash content in these samples, which might lead to the absorption of more moisture.

The data suggests that controlling the glass content and fly ash content in ceramic formulations can be a key factor in optimizing moisture content. Higher glass content seems to stabilize moisture content, while the presence of fly ash contributes to variations. This observation is important when considering moisture content in the final product, as excessive moisture could affect the structural integrity and durability of the ceramics, especially in applications requiring low moisture retention. The results indicate that a balance between glass and fly ash content may lead to a more desirable moisture content for ceramic applications. For instance, the compositions with glass content between 9.2% and 18.7%, and fly ash content between 7.6% and 14.3%, tend to maintain moisture levels in the range of 3.8-4.1%. The 3D scatter plot analysis of Glass Content, Fly Ash Content, and Moisture Content reveals a complex but insightful relationship between the ceramic components. It suggests that adjusting the content of glass and fly ash can help control moisture content within a specific range, which is crucial for optimizing the mechanical properties and overall quality of the ceramic materials. Future studies could further explore the role of other additives and processing conditions to fine-tune these properties for industrial and construction applications.

Conclusion

The investigation of recycled-content ceramics incorporating glass and fly ash has provided valuable insights into their performance and properties, as revealed through heat map matrix correlations and 3D scatter plot analyses. The findings highlight the complex interplay between glass content, fly ash content, uniaxial compressive strength, and moisture content, underscoring the need for an optimized balance of these components. The heat map matrix data demonstrates that glass content has a strong positive correlation with uniaxial compressive strength, suggesting that its inclusion significantly enhances the ceramic matrix's mechanical properties through improved densification and strength. Conversely, fly ash content exhibits a negative correlation with compressive strength, emphasizing the necessity to limit its proportion to avoid increased porosity and reduced structural integrity. The moderate negative correlation between glass and fly ash content further indicates their competing effects on ceramic properties, with excessive fly ash content diminishing the benefits provided by glass. The 3D scatter plot analysis reveals that moisture content stabilizes at higher glass content levels, likely due to the hydrophobic nature of glass reducing moisture absorption. Fly ash, on the other hand, plays a more variable role, with its high surface area and hygroscopic nature influencing moisture retention. The optimal range of compositions identified - glass content between 9.2% and 18.7% and fly ash content between 7.6% and 14.3% maintains moisture levels in the range of 3.8 - 4.1%, indicating the potential for tailoring ceramic formulations to achieve desired moisture characteristics. These results emphasize that careful optimization of glass and fly ash content is essential for producing high-performance ceramics suitable for structural applications. Achieving the right balance can enhance compressive strength while maintaining acceptable moisture levels, making these recycled-content ceramics a viable and sustainable alternative to traditional materials. Future research should focus on the impact of additional waste materials, advanced processing techniques, and varying sintering conditions to further enhance the mechanical and durability properties of these materials. The findings contribute to a broader understanding of sustainable ceramic production and its potential role in addressing environmental and resource challenges within the construction industry.

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