Enhancing Strength and Durability of Cement Concrete Using Metakaolin, Waste Glass, and Glass Fibres

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Abstract

Enhancing cement concrete's strength and durability is crucial for sustainable infrastructure development. This study investigates the effects of metakaolin (MK) and waste glass (WG) as partial cement and sand replacements, respectively, along with glass fibers (GF) on the mechanical properties of concrete. Five mix designs (S1–S5) were developed with varying metakaolin content (2%, 4%, 6%, 8%, and 10% of cement weight), maintaining a constant 0.50% GF and optimized WG replacement. Compressive strength tests at 7, 28, and 91 days revealed a consistent improvement with increasing MK content, with S5 (10% MK) exhibiting the highest compressive strength (21.27 MPa at 7 days, 28.57 MPa at 28 days, and 29.81 MPa at 91 days). Split tensile strength results followed a similar trend, with S5 achieving the maximum values across all curing periods (4.10 MPa at 7 days, 4.48 MPa at 28 days, and 4.56 MPa at 91 days). Flexural strength tests further confirmed the superior performance of S5, reaching 5.31 MPa at 7 days, 5.64 MPa at 28 days, and 5.91 MPa at 91 days. The results suggest that adding up to 10% of metakaolin significantly enhances concrete's mechanical properties, with improvements in compressive, tensile, and flexural strengths. This study highlights the potential of metakaolin and waste glass as sustainable materials for enhancing concrete performance, contributing to eco-friendly construction practices.

Keywords: Concrete, Durability, Metakaolin, Sustainable Material

Introduction

Cement concrete is the backbone of modern construction, widely utilized due to its versatility, durability, and cost-effectiveness. However, conventional concrete has several limitations, including susceptibility to cracking, shrinkage, and long-term deterioration due to environmental factors. Enhancing the strength and durability of concrete has been a focal point of research in civil engineering to address these issues and improve its long-term performance. Among the various strategies employed, incorporating supplementary cementitious materials (SCMs) and reinforcing agents has gained significant attention. This research examines the use of metakaolin, waste glass, and glass fibers as supplementary materials to enhance the mechanical strength and durability of cement concrete. Metakaolin, a reactive pozzolanic substance obtained from the calcination of kaolin clay, is known for its effectiveness in refining pore structure, boosting early strength, and increasing durability. Waste glass, on the other hand, serves as a promising alternative to traditional aggregates or supplementary material due to its pozzolanic characteristics when ground into fine particles. Glass fibers, known for their high tensile strength and crack-bridging properties, contribute significantly to enhancing concrete’s toughness and resistance to fracture.The integration of these materials into concrete aligns with sustainable development goals by reducing reliance on traditional raw materials, minimizing waste disposal problems, and lowering carbon emissions associated with cement production. The construction industry is under increasing pressure to adopt eco-friendly practices, and utilizing industrial by-products and recycled materials in concrete offers an effective approach to achieving sustainability without compromising structural performance. This research aims to analyze the combined effects of metakaolin, waste glass, and glass fibers on the mechanical properties, durability, and sustainability of cement concrete. The study will examine key parameters such as compressive strength, flexural strength, permeability, and resistance to environmental degradation. Additionally, a comparative analysis will be conducted to assess the benefits and potential challenges associated with using these materials in various proportions. The adoption of such innovative materials in concrete production is expected to revolutionize the construction industry by offering high-performance concrete with extended service life and reduced environmental impact. As infrastructure development continues to expand globally, the need for durable, resilient, and sustainable concrete solutions becomes more critical. The findings of this research will contribute to the advancement of sustainable construction practices, providing insights for engineers, policymakers, and industry professionals seeking to enhance concrete performance through innovative material applications.

Materials and Methodology

Materials

The present study investigates the effects of metakaolin, waste glass, and glass fibers on the strength and durability of cement concrete. The materials used in this research are as follows:

- **Cement:** Ordinary Portland Cement (OPC) conforming to ASTM C150 standards.
- **Fine Aggregates:** River sand with a fineness modulus of 2.6, meeting ASTM C33 specifications.
- **Coarse Aggregates:** Crushed granite aggregates of 20 mm maximum size, meeting ASTM C33 standards.
- **Metakaolin:** A highly reactive pozzolanic material obtained from calcined kaolin clay.
- **Waste Glass Powder:** Finely ground glass waste collected from discarded glass sources, sieved to a particle size of less than 75 µm.
- **Glass Fibers:** Alkali-resistant glass fibers with an aspect ratio of 850 and a diameter of approximately 14 µm.
- **Water:** Potable water conforming to ASTM C1602.

Mix Proportions and Casting

Concrete samples were prepared using standard molds for various strength assessments. For compressive strength tests, cubes measuring 150 mm × 150 mm × 150 mm were used, while cylinders with a diameter of 150 mm and a height of 300 mm were designated for split tensile strength evaluations. Beams of 100 mm × 100 mm × 500 mm were utilized for flexural strength tests. After 24 hours, the specimens were removed from the molds and subjected to water curing for durations of 7, 28, and 91 days. The concrete mixes were designed according to IS 10262-2019 guidelines. Various modified mixes were prepared by incorporating metakaolin as a partial replacement for cement as given below:

S1	Cement: sand + Waste Glass (Best out of 5, 10, 15 & 20%): aggregate: 1: 1.5: 3 + GF (0.50% by weight of cement) + Metakaolin (2% of cement weight replacing Cement)
S2	Cement: sand + Waste Glass (Best out of 5, 10, 15 & 20%): aggregate: 1: 1.5: 3 + GF (0.50% by weight of cement) + Metakaolin (4% of cement weight replacing Cement)
S3	Cement: sand + Waste Glass (Best out of 5, 10, 15 & 20%): aggregate: 1: 1.5: 3 + GF (0.50% by weight of cement) + Metakaolin (6% of cement weight replacing Cement)
S4	Cement: sand + Waste Glass (Best out of 5, 10, 15 & 20%): aggregate: 1: 1.5: 3 + GF (0.50% by weight of cement) + Metakaolin (8% of cement weight replacing Cement)
S5	Cement: sand + Waste Glass (Best out of 5, 10, 15 & 20%): aggregate: 1: 1.5: 3 + GF (0.50% by weight of cement) + Metakaolin (10% of cement weight replacing Cement)

Results:

Compressive Strength Test

S1 vs S2 vs S3 vs S4 vs S5: Samples S1, S2, S3, S4, and S5 consist of M20 grade concrete with 0.5% glass fibers and 15% waste glass as a partial sand replacement (due to its improved compressive strength). These samples also incorporate varying percentages of metakaolin as a replacement for cement (2%, 4%, 6%, 8%, and 10%). Three specimens from each sample were cast and tested for compressive strength. The results demonstrate that the compressive strength of the concrete increases with the rising proportion of metakaolin used as a cement replacement. Metakaolin is used as a partial alternative to cement. It uses lime during hydration, which increases the synthesis of cementitious compounds, resulting in increased strength.

Table 1: Compressive Strength Test Result (S1 vs S2 vs S3 vs S4 vs S5) 7, 28 & 91 Days

Days	Sample No	Sample 1	Sample 2	Sample 3	Average
7 Days	S1	19.58	18.94	19.97	**19.50**
	S2	19.02	19.4	19.99	**19.47**
	S3	19.56	19.47	20.75	**19.93**
	S4	20.82	20.08	20.63	**20.51**
	S5	21.52	20.66	21.64	**21.27**
28 Days	S1	26.84	25.29	27.49	**26.54**
	S2	26.2	26.61	27.63	**26.81**
	S3	27.1	26.97	27.85	**27.31**

	S4	28.12	27.48	28.29	**27.96**
	S5	28.82	27.96	28.94	**28.57**
91 Days	S1	27.64	27.52	28.65	**27.94**
	S2	27.94	27.92	28.91	**28.26**
	S3	28.15	28.12	29.62	**28.63**
	S4	29.79	28.41	29.97	**29.39**
	S5	29.97	28.97	30.49	**29.81**

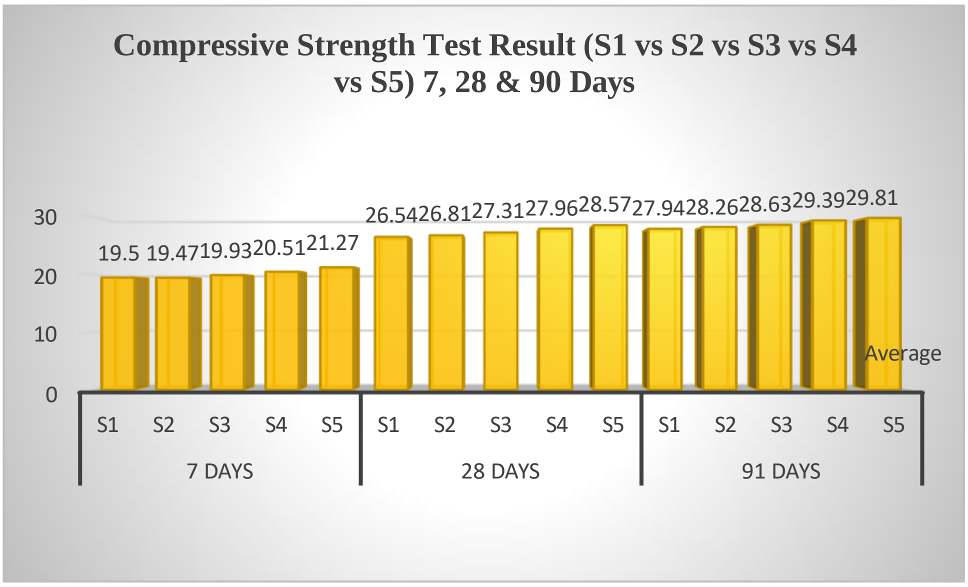

Fig 1: Compressive Strength Test Result (S1 vs S2 vs S3 vs S4 vs S5) 7, 28 & 91 Days

Split Tensile Strength Test

Comparison between: S1 vs S2 vs S3 vs S4 vs S5: Samples S1, S2, S3, S4, and S5 are composed of M20 grade concrete that incorporates 0.5% glass Fibers and 15% recyclable glass as a partial substitute for sand, resulting in enhanced compressive strength. Furthermore, these samples include different proportions of metakaolin as a substitute for cement (2%, 4%, 6%, 8%, and 10%). Three specimens were cast from each sample tested for split tensile strength testing. The results indicate that the split tensile strength of the concrete rises as the percentage of metakaolin employed as a replacement for cement increases.

Table 2: Split Tensile Strength Test Result (S1 vs S2 vs S3 vs S4 vs S5) 7, 28 & 91 Days

Days	Sample No	Sample 1	Sample 2	Sample 3	Average
7 Days	S1	3.19	3.42	3.24	**3.28**
	S2	3.27	3.41	3.57	**3.42**
	S3	3.49	3.68	3.71	**3.63**

	S4	3.54	3.82	3.89	**3.75**
	S5	3.75	4.29	4.26	**4.10**
28 Days	S1	3.46	3.52	3.64	**3.54**
	S2	3.62	3.81	3.87	**3.77**
	S3	3.72	3.91	4.02	**3.88**
	S4	3.93	4.13	4.26	**4.11**
	S5	4.02	4.57	4.86	**4.48**
91 Days	S1	3.25	3.82	3.97	**3.68**
	S2	3.49	4.03	4.19	**3.90**
	S3	3.51	4.29	4.48	**4.09**
	S4	3.73	4.42	4.64	**4.26**
	S5	3.81	4.89	4.99	**4.56**

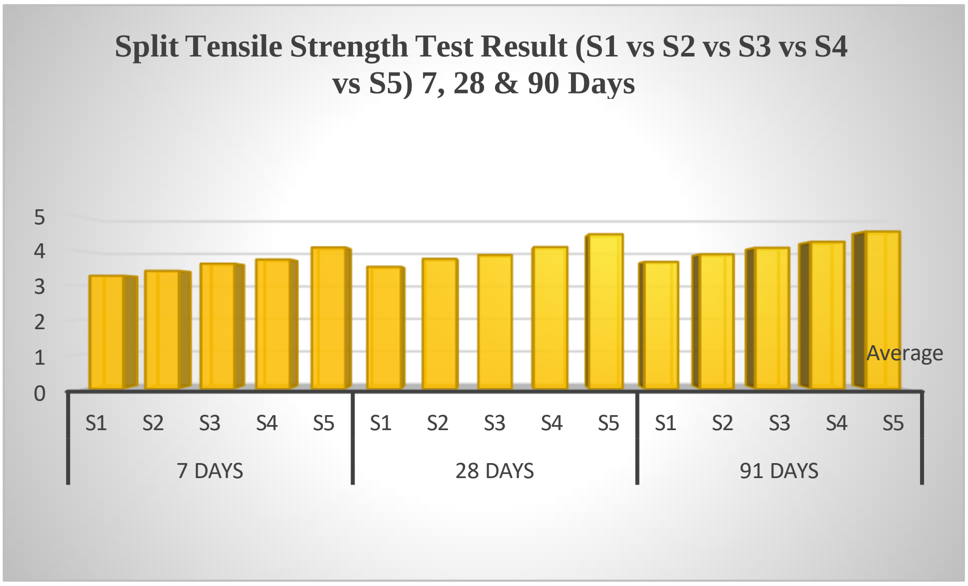

Fig 2: Split Tensile Strength Test Result (S1 vs S2 vs S3 vs S4 vs S5) 7, 28 & 91 Days

Flexural Strength Test

S1 vs S2 vs S3 vs S4 vs S5: Samples S1, S2, S3, S4, and S5 consist of M20 grade concrete that includes 0.5% glass Fibers and 15% recyclable glass as a partial replacement for sand, leading to improved flexural strength. In addition, these samples contain varying ratios of metakaolin utilized as a replacement for cement (2%, 4%, 6%, 8%, and 10%). Three specimens were cast from each sample and then subjected to flexural strength experimental testing. The results indicate the flexural strength of the concrete increases with higher percentages of metakaolin used as a substitution for cement.

Table 3: Flexural Strength Test Result (S1 vs S2 vs S3 vs S4 vs S5) 7, 28 & 91 Days

Days	Sample No	Sample 1	Sample 2	Sample 3	Average
7 Days	S1	3.39	3.76	4.02	3.72

	S2	3.58	4.03	4.19	3.93
	S3	3.95	4.66	4.52	4.38
	S4	4.19	4.67	4.62	4.49
	S5	5.33	5.22	5.37	5.31
28 Days	S1	3.87	4.12	4.47	4.15
	S2	3.98	4.43	4.59	4.33
	S3	4.25	4.96	4.82	4.68
	S4	4.59	5.07	5.02	4.89
	S5	5.73	5.52	5.67	5.64
91 Days	S1	4.1	4.46	4.76	4.44
	S2	4.22	4.68	4.76	4.55
	S3	4.46	5.23	5.06	4.92
	S4	4.76	5.38	5.42	5.19
	S5	5.98	5.79	5.95	5.91

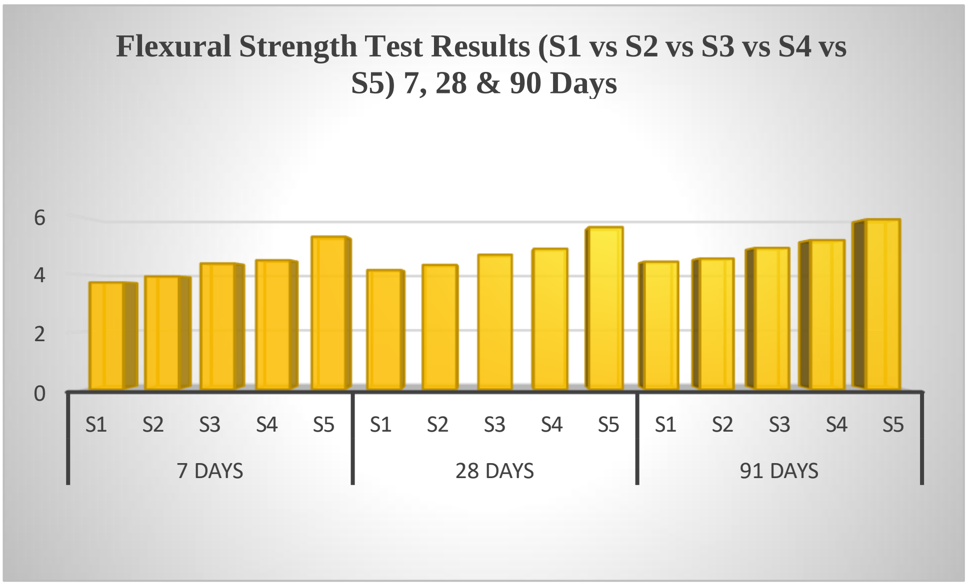

Fig 3: Flexural Strength Test Result (S1 vs S2 vs S3 vs S4 vs S5) 7, 28 & 91 Days

Conclusion

The experimental investigation into strengthening and increasing the durability of cement concrete through the use of metakaolin, waste glass, and glass fibers demonstrated notable enhancements in mechanical properties. Findings from compressive strength, split tensile strength, and flexural strength tests reveal that integrating these supplementary materials improves concrete performance over time.

1. **Compressive Strength**: The inclusion of metakaolin, waste glass, and glass fibers led to a progressive increase in compressive strength over 7, 28, and 91 days. The highest compressive strength was recorded at 91 days, with a peak value of 29.81 MPa, demonstrating that the modified concrete mix continues to gain strength over time.
2. **Split Tensile Strength**: The split tensile strength also showed considerable improvement, with the highest recorded value being 4.56 MPa at 91 days. The increase

in tensile strength suggests that the modified mix enhances the concrete's ability to resist tensile stresses, contributing to overall durability.

3. **Flexural Strength**: The flexural strength results indicate significant improvements, with the highest recorded value being 5.91 MPa at 91 days. This improvement highlights the enhanced toughness and resistance to bending stresses due to the presence of glass fibers and waste glass.

Overall, the study confirms that the combined use of metakaolin, waste glass, and glass fibers significantly enhances the strength and durability of cement concrete. The improvements in compressive, tensile, and flexural strength suggest that this modified concrete mix can be a viable alternative for sustainable and high-performance construction applications. Further studies on long-term durability aspects, environmental impact, and cost-effectiveness would be beneficial to validate the practical implementation of this enhanced concrete mix.

References

[1] Almesfer, N., & Ingham, J. (2014). Effect of waste glass on the properties of concrete. Journal of Materials in Civil Engineering, 26(11), 06014022.

[2] de Castro, S., & de Brito, J. (2013). Evaluation of the durability of concrete made with crushed glass aggregates. Journal of Cleaner Production, 41, 7-14.

[3] Guo, P., Meng, W., Nassif, H., Gou, H., & Bao, Y. (2020). New perspectives on recycling waste glass in manufacturing concrete for sustainable civil infrastructure. Construction and Building Materials, 257, 119579.

[4] Islam, G. S., Rahman, M., & Kazi, N. (2017). Waste glass powder as partial replacement of cement for sustainable concrete practice. International Journal of Sustainable Built Environment, 6(1), 37-44.

[5] Kim, I. S., Choi, S. Y., & Yang, E. I. (2018). Evaluation of durability of concrete substituted heavyweight waste glass as fine aggregate. Construction and Building Materials, 184, 269-277.

[6] Omoding, N., Cunningham, L. S., & Lane-Serff, G. F. (2021). Effect of using recycled waste glass coarse aggregates on the hydrodynamic abrasion resistance of concrete. Construction and Building materials, 268, 121177.

[7] Abdelli, H. E., Mokrani, L., Kennouche, S., & de Aguiar, J. B. (2020). Utilization of waste glass in the improvement of concrete performance: A mini review. Waste Management & Research, 38(11), 1204-1213.

[8] AL-Zubaid, A. B., Shabeeb, K. M., & Ali, A. I. (2017). Study the effect of recycled glass on the mechanical properties of green concrete. Energy procedia, 119, 680-692.

[9] Anisah, N. N., Awang, M., & Kartini, K. (2020, June). Effect of using windscreen glass waste powder (WGWP) as cement replacement on the mechanical properties of mortar. In Journal of Physics: Conference Series (Vol. 1532, No. 1, p. 012011). IOP Publishing.

[10] Atoyebi, O. D., Gana, A. J., & Longe, J. E. (2020). Strength assessment of concrete with waste glass and bankoro (Morinda Citrifolia) as partial replacement for fine and coarse aggregate. Results in Engineering, 6, 100124.

[11] Belouadah, M., Rahmouni, Z. E. A., & Tebbal, N. (2019). Experimental characterization of ordinary concretes obtained by adding construction waste (glass, marble). Procedia Computer Science, 158, 153-162.

[12] Bueno, E. T., Paris, J. M., Clavier, K. A., Spreadbury, C., Ferraro, C. C., & Townsend, T. G. (2020). A review of ground waste glass as a supplementary cementitious material: A focus on alkali-silica reaction. Journal of cleaner production, 257, 120180.

[13] Flores-Ales, V., Alducin-Ochoa, J. M., Martín-del-Río, J. J., Torres-Gonzalez, M., & Jimenez-Bayarri, V. (2020). Physical-mechanical behaviour and transformations at high temperature in a cement mortar with waste glass as aggregate. Journal of Building Engineering, 29, 101158.

[14] Gupta, J., Jethoo, A. S., & Lata, N. (2020, June). Assessment of mechanical properties by using powder waste glass with cement in concrete mix. In IOP conference series: materials science and engineering (Vol. 872, No. 1, p. 012122). IOP Publishing.

[15] Herki, B. M. A. (2020). Engineering properties of concrete incorporating locally produced waste glass aggregate. Int J Emergind Trends Eng Res, 8(9), 1-5.

[16] Islam, G. S., Rahman, M., & Kazi, N. (2017). Waste glass powder as partial replacement of cement for sustainable concrete practice. International Journal of Sustainable Built Environment, 6(1), 37-44.

[17] Jiao, Y., Zhang, Y., Guo, M., Zhang, L., Ning, H., & Liu, S. (2020). Mechanical and fracture properties of ultra-high performance concrete (UHPC) containing waste glass sand as partial replacement material. Journal of Cleaner Production, 277, 123501.

[18] Lu, J. X., Zhan, B. J., Duan, Z. H., & Poon, C. S. (2017). Using glass powder to improve the durability of architectural mortar prepared with glass aggregates. Materials & design, 135, 102-111.

[19] Mostofinejad, D., Hosseini, S. M., Nosouhian, F., Ozbakkaloglu, T., & Tehrani, B. N. (2020). Durability of concrete containing recycled concrete coarse and fine aggregates and milled waste glass in magnesium sulfate environment. Journal of Building Engineering, 29, 101182.

[20] Naeini, M., Mohammadinia, A., Arulrajah, A., Horpibulsuk, S., & Leong, M. (2019). Stiffness and strength characteristics of demolition waste, glass and plastics in railway capping layers. Soils and Foundations, 59(6), 2238-2253.

[21] Moses Ogundipe, O., & Segun Nnochiri, E. (2020). Evaluation of the effects of waste glass in asphalt concrete using the Marshall test. Engineering Review: Međunarodni časopis

namijenjen publiciranju originalnih istraživanja s aspekta analize konstrukcija, materijala i novih tehnologija u području strojarstva, brodogradnje, temeljnih tehničkih znanosti, elektrotehnike, računarstva i građevinarstva, 40(2), 24-33.

[22] Tamanna, N., Tuladhar, R., & Sivakugan, N. (2020). Performance of recycled waste glass sand as partial replacement of sand in concrete. Construction and Building Materials, 239, 117804.

[23] Albidah, A., Abadel, A., Alrshoudi, F., Altheeb, A., Abbas, H., & Al-Salloum, Y. (2020). Bond strength between concrete substrate and metakaolin geopolymer repair mortars at ambient and elevated temperatures. Journal of Materials Research and Technology, 9(5), 10732-10745.

[24] Asadollahfardi, G., MohsenZadeh, P., & Saghravani, S. F. (2019). The effects of using metakaolin and micro-nanobubble water on concrete properties. Journal of Building Engineering, 25, 100781.

[25] Mello, L. C. D. A., dos Anjos, M. A., de Sá, M. V., de Souza, N. S., & de Farias, E. C. (2020). Effect of high temperatures on self-compacting concrete with high levels of sugarcane bagasse ash and metakaolin. Construction and Building Materials, 248, 118715.

[26] Nanda, R. P., Mohapatra, A. K., & Behera, B. (2020). Influence of metakaolin and Recron 3s fiber on mechanical properties of fly ash replaced concrete. Construction and Building Materials, 263, 120949.