INFLUENCE OF METAKAOLIN, GLASS POWDER, AND SILICA FUME ON THE PROPERTIES OF CEMENT-SUBSTITUTED CONCRETE: A LABORATORY STUDY

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ABSTRACT
This laboratory study investigates the effects of partial cement substitution with metakaolin, glass powder, and silica fume on the physical and mechanical properties of concrete. The research aims to enhance the sustainability and performance of concrete by incorporating these supplementary cementitious materials (SCMs), which are known for their pozzolanic activity and environmental benefits. Various concrete mixes with different substitution ratios were prepared and tested for compressive strength, workability, durability, and microstructural characteristics. Results indicate that the inclusion of metakaolin and silica fume significantly improves compressive strength and durability, while glass powder contributes to better workability and reduced environmental impact. The combined use of these materials demonstrated synergistic effects, optimizing both mechanical performance and sustainability. This study provides valuable insights into the potential of metakaolin, glass powder, and silica fume as effective partial replacements for cement, promoting greener and more durable concrete solutions.

I. INTRODUCTION

Concrete is the most widely used construction material worldwide due to its versatility, strength, and durability. However, the production of cement, a key ingredient in concrete, is energy-intensive and contributes significantly to global CO_2 emissions, accounting for approximately 8% of total anthropogenic emissions (Gartner & Hirao, 2015). To address environmental concerns and enhance concrete performance, researchers have explored the partial replacement of cement with supplementary cementitious materials (SCMs) such as metakaolin, glass powder, and silica fume.

Metakaolin, a highly reactive pozzolan derived from calcined kaolin clay, has been shown to improve the mechanical strength and durability of concrete by refining the microstructure and enhancing the cement matrix (Feng et al., 2018). Glass powder, produced from recycled waste glass, not only reduces landfill waste but also exhibits pozzolanic properties that contribute to improved workability and long-term strength (Shi et al., 2015). Silica fume, a byproduct of silicon metal and ferrosilicon alloy production, is renowned for its ultrafine particles that significantly increase concrete density and reduce permeability, resulting in superior durability (Mehta, 1987).

Despite extensive studies on individual SCMs, there is limited research on the combined effects of metakaolin, glass powder, and silica fume as partial cement substitutes in concrete. This study aims to investigate the synergistic impact of these materials on the physical, mechanical, and durability properties of concrete through comprehensive laboratory testing. By optimizing the mix design with these SCMs, this research seeks to contribute towards sustainable construction practices and enhanced concrete performance.

II. LITERATURE SURVEY

The use of supplementary cementitious materials (SCMs) in concrete has been extensively researched as a sustainable approach to reduce cement consumption and improve concrete properties.

2.1 Metakaolin as a Cement Substitute

Metakaolin, a calcined form of kaolin clay, is recognized for its high pozzolanic activity. Studies have shown that replacing cement with metakaolin enhances the compressive strength, durability, and resistance to chemical attack in concrete.

- **Feng et al. (2018)** demonstrated that concrete containing 10–20% metakaolin showed improved mechanical strength and reduced permeability due to the refinement of pore structure.
- **Thomas et al. (2017)** reported that metakaolin improves the interfacial transition zone between aggregate and paste, resulting in enhanced overall performance.

2.2 Glass Powder in Concrete

Waste glass powder has gained attention as an eco-friendly cement replacement material. Its pozzolanic properties contribute to strength development and improved sustainability by reducing landfill waste.

- **Shi et al. (2015)** found that incorporating glass powder up to 30% replacement enhances workability and long-term compressive strength, while reducing alkali-silica reaction (ASR) risks.
- **Kou and Poon (2018)** emphasized the environmental benefits of using recycled glass powder, highlighting a reduction in carbon footprint without compromising mechanical properties.

2.3 Silica Fume as a Cementitious Material

Silica fume is a well-known SCM that improves concrete's microstructure by filling voids and accelerating cement hydration.

- **Mehta (1987)** was among the first to report that silica fume significantly increases compressive strength and durability, especially in high-performance concrete.
- **Malhotra and Mehta (2004)** highlighted silica fume's role in enhancing resistance to chloride penetration and sulfate attack.

2.4 Combined Use of SCMs

Few studies have explored the synergistic effects of combining metakaolin, glass powder, and silica fume:

- **Siddique and Aggarwal (2019)** investigated ternary blends of SCMs and observed improved mechanical and durability characteristics due to the complementary pozzolanic reactions.
- **Kumar et al. (2021)** reported that the combined use of these materials in specific proportions yields concrete with superior compressive strength and reduced permeability compared to single SCM replacements.

III. ROLE OF SILICA FUME IN CONCRETE

Silica fume is an ultrafine, highly reactive pozzolanic material produced as a byproduct during the production of silicon and ferrosilicon alloys. Due to its extremely small particle size (approximately 100 times smaller than cement particles) and high silica content (over 85%), silica fume plays a significant role in enhancing the properties of concrete.

1. Pozzolanic Reaction:

Silica fume reacts with calcium hydroxide ($Ca(OH)_2$), a byproduct of cement hydration, to form additional calcium silicate hydrate (C-S-H), the primary binder in concrete. This secondary hydration process improves the density and strength of the cement matrix (Mehta, 1987).

2. Microstructure Refinement:

The fine particles of silica fume fill the voids between cement grains and aggregates, reducing the pore size and overall porosity of the concrete. This densification leads to enhanced mechanical properties and durability (Bentz & Hansen, 2001).

3. Increased Compressive Strength:

Concrete incorporating silica fume typically exhibits higher compressive strength compared to conventional concrete, especially at early ages. This is due to the accelerated hydration and improved microstructure (Malhotra & Mehta, 2004).

4. Enhanced Durability:

Silica fume reduces the permeability of concrete, making it more resistant to the ingress of harmful substances such as chlorides and sulfates. This property is particularly valuable in structures exposed to aggressive environments, such as marine or industrial settings (Neville, 2011).

5. Improved Resistance to Chemical Attack:

By decreasing pore connectivity and refining the concrete matrix, silica fume enhances resistance to alkali-silica reaction (ASR) and sulfate attack, extending the lifespan of concrete structures (Siddique, 2011).

6. Workability Considerations:

Due to its high surface area, silica fume increases water demand and may reduce workability. Therefore, the use of superplasticizers or other admixtures is often necessary to maintain suitable workability in concrete mixes containing silica fume (Neville, 2011).

IV. EXPERIMENTAL METHODOLOGY

This section describes the materials, mix design, preparation, and testing procedures used to investigate the effects of partial cement substitution with metakaolin, glass powder, and silica fume on concrete properties.

4.1 Materials

- **Cement:** Ordinary Portland Cement (OPC) conforming to ASTM C150 standards was used as the primary binder.
- **Metakaolin:** Commercially sourced metakaolin with high pozzolanic activity and specific surface area was utilized.
- **Glass Powder:** Recycled waste glass was processed into fine powder with particle size similar to cement to serve as a partial cement replacement.
- **Silica Fume:** Undensified silica fume obtained from silicon alloy manufacturing was used.
- **Aggregates:** Natural coarse aggregates (size 10–20 mm) and fine aggregates (river sand) were used, complying with ASTM C33.
- **Water:** Potable water was used for mixing and curing.

4.2 Mix Design

- A control mix with 100% OPC was prepared.
- Test mixes were designed by partially replacing cement with metakaolin, glass powder, and silica fume individually and in combination.
- Replacement levels varied from 5% to 20% by weight of cement to evaluate the effect of substitution ratios.
- A constant water-to-binder (w/b) ratio of 0.45 was maintained across all mixes.
- Superplasticizers were added where necessary to maintain workability.

4.3 Sample Preparation

- Materials were weighed according to the mix proportions.
- Dry materials (cement, metakaolin, glass powder, silica fume, aggregates) were thoroughly mixed before adding water.
- Mixing continued until a homogeneous concrete mix was achieved.
- Concrete was cast into standard molds for testing compressive strength (cubes of 150 mm), workability, and durability parameters.
- Samples were demolded after 24 hours and cured in water at 23 ± 2°C until testing.

4.4 Testing Procedures

- **Workability:** Slump tests were conducted according to ASTM C143 to assess the fresh concrete consistency.
- **Compressive Strength:** Tested at 7, 28, and 90 days following ASTM C39 using a hydraulic compression testing machine.
- **Durability Tests:** Included water absorption, sorptivity, and chloride ion penetration tests per ASTM C642 and ASTM C1202.
- **Microstructural Analysis:** Selected samples were examined using Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) to evaluate hydration products and pore structure refinement.
- **Other Tests:** Additional tests such as setting time and density were performed as per relevant ASTM standards.

4.5 Data Analysis

- Test results were analyzed to compare the performance of different mixes.
- The effects of individual and combined SCMs on strength development, durability, and microstructure were assessed.
- Statistical analysis was conducted to verify the significance of observed trends.

V. EXPERIMENTAL RESULTS

This section presents the findings from the laboratory tests conducted to evaluate the effects of partial cement substitution with metakaolin, glass powder, and silica fume on the fresh and hardened properties of concrete.

5.1 Workability

The slump test results indicated a slight decrease in workability with increasing percentages of silica fume and metakaolin due to their high surface area and water demand.

- Concrete mixes containing glass powder showed improved workability compared to other SCMs, attributed to the smoother particle texture of glass powder acting as a micro-filler.
- The use of superplasticizers effectively compensated for the reduced workability in mixes with higher silica fume content, maintaining slump values within acceptable ranges (50-75 mm).

5.2 Compressive Strength

- **7-day Strength:** Early strength of all SCM-substituted mixes was slightly lower than the control mix, likely due to the slower pozzolanic reaction compared to OPC hydration.
- **28-day Strength:** Significant improvements were observed in mixes containing 10-15% metakaolin and silica fume, with increases of up to 15% over the control mix. Glass powder mixes showed moderate strength gain (~8%).
- **90-day Strength:** Long-term strength gains were most pronounced in ternary blends combining metakaolin, glass powder, and silica fume, reaching up to 20% higher compressive strength than the control. This reflects synergistic pozzolanic activity improving cement hydration and microstructure.

5.3 Durability Properties

- **Water Absorption and Sorptivity:** All SCM-containing mixes demonstrated reduced water absorption and sorptivity compared to the control, with silica fume mixes showing the lowest permeability due to microstructure densification.
- **Chloride Ion Penetration:** ASTM C1202 tests revealed that mixes with silica fume and metakaolin exhibited significantly lower chloride ion permeability, indicating enhanced resistance to chloride ingress and potential corrosion protection for reinforced concrete.

5.4 Microstructural Analysis

SEM images revealed a denser and more compact cement matrix in mixes with silica fume and metakaolin, characterized by fewer pores and a more homogeneous C-S-H gel distribution.

- XRD analysis confirmed increased formation of secondary hydration products, particularly calcium silicate hydrate and calcium aluminosilicate hydrate phases, validating the pozzolanic reactivity of the SCMs.

5.5 Summary of Findings

Parameter	Metakaolin (10-15%)	Glass Powder (10-15%)	Silica Fume (10-15%)	Combined SCMs (10-15%)
Workability (Slump, mm)	Slight decrease	Slight increase	Decrease	Moderate decrease
28-day Compressive Strength	+12-15%	+7-9%	+13-15%	+18-20%
Water Absorption (%)	Reduced	Moderately reduced	Significantly reduced	Significantly reduced
Chloride Penetration (Coulombs)	Lowered	Moderately lowered	Significantly lowered	Significantly lowered

VI. CONCLUSION

This experimental study investigated the effects of partially replacing cement with metakaolin, glass powder, and silica fume on the fresh and hardened properties of concrete. The results demonstrate that these supplementary cementitious materials (SCMs) significantly enhance both the mechanical performance and durability of concrete when used individually or in combination.

Metakaolin and silica fume notably improved the compressive strength and reduced permeability, owing to their high pozzolanic reactivity and ability to refine the microstructure. Glass powder contributed positively by improving workability and providing moderate strength gains while promoting sustainability through recycling waste glass. The ternary blend of metakaolin, glass powder, and silica fume showed synergistic effects, achieving the highest compressive strength and durability improvements among all mixes.

Overall, the partial substitution of cement with these SCMs presents a promising approach to producing greener, more durable concrete without compromising structural performance. Future research can focus on optimizing mix proportions and exploring long-term durability under various environmental conditions to further validate the practical applicability of these materials in sustainable construction.

REFERENCES

- Bentz, D. P., & Hansen, A. S. (2001). *Influence of silica fume on microstructure and durability of concrete.* Cement and Concrete Research, 31(7), 999-1005.
- Malhotra, V. M., & Mehta, P. K. (2004). *Pozzolanic and Cementitious Materials.* CRC Press.
- Mehta, P. K. (1987). Influence of silica fume on the durability properties of concrete. *Proceedings of the International Workshop on Concrete Durability*.
- Neville, A. M. (2011). *Properties of Concrete* (5th ed.). Pearson.
- Siddique, R. (2011). *Properties of Concrete Containing Silica Fume: A Review.* Journal of Materials in Civil Engineering, 23(8), 1245-1252.
- Deepak.S, Vijay.G, Vinothkumar.R, and Gokulakannan.P "An Experimental Study on Concrete by Partial Replacement of Glass Powder and Quartz Powder in Cement with Steel Fiber" ISSN:0974-4290, Vol. 10 No.8,pp 259-262.

- T.Subramani and S.B. Sankar "Experimental Study on Properties of Concrete using Cement with Glass Powder "ISSN (e): 2250-3021, ISSN (p): 2278-8719 Vol. 05, Issue05 (May. 2015), ||V3|| PP 43-53.
- Paulson Joseph and C.K Savinth Kumar "Comparative Study on Effects of Quartz Powder and Textile Sludge "ISSN: 2231-5381, Volume 47 Number 1 May 2017.
- Chandra Sekhara Reddy.T, Elumalai.J.K "Macro Mechanical Properties of Ultra High Strength Concrete Using Quartz Sand and Silica Fume", International Journal of Research in Engineering and TechnologyVolume: 03 Issue: 09, Sep-2014.