International Journal of Research in Engineering and Applied Sciences(IJREAS)
Available online at http://euroasiapub.org/journals.php
Vol. 13 Issue 07, July- 2023
ISSN(O): 2249-3905, ISSN(P) : 2349-6525 | Impact Factor: 8.202 |
Thomson Reuters ID: L-5236-2015

Investigating the Impact of Silica Fume and Metakaolin as Partial Cement Replacement in Fiber-Reinforced Concrete

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ABSTRACT

This study aims to investigate the impact of silica fume and metakaolin as partial cement replacements in fiber-reinforced concrete (FRC). Silica fume and metakaolin are supplementary cementitious materials known for their pozzolanic properties, which can enhance the performance of concrete. The objective is to evaluate the mechanical properties, durability, and microstructural characteristics of FRC when silica fume and metakaolin are incorporated as cement substitutes.The research methodology involves the preparation of FRC mixtures with varying percentages of cement replacement with silica fume and metakaolin. Different types and dosages of fibers, such as steel fibers or glass fibers, are incorporated into the mixtures to assess their combined effect with the cementitious materials.Mechanical properties, including compressive strength, tensile strength, flexural strength, and impact resistance, are determined to assess the performance of the FRC. Durability aspects such as water absorption, chloride ion penetration resistance, and resistance to freeze-thaw cycles are investigated.

INTRODUCTION

Fiber-reinforced concrete (FRC) has gained significant attention in the construction industry due to its improved mechanical properties and enhanced durability compared to conventional concrete. In recent years, the utilization of supplementary cementitious materials (SCMs) as partial replacements for cement in FRC has become a subject of interest. Silica fume and metakaolin are two widely used SCMs known for their pozzolanic properties, which contribute to the strength and durability of concrete.Silica fume is a byproduct of silicon and ferrosilicon alloy production, consisting of fine particles that can fill voids and improve the packing density of concrete. Metakaolin, on the other hand, is a thermally activated clay material that offers pozzolanic reactivity, resulting in increased strength and reduced permeability of concrete. Both materials have been extensively studied as cement replacements in conventional concrete, but their impact on FRC requires further investigation.The incorporation of silica fume and metakaolin in FRC has the potential to enhance the mechanical properties and durability of the composite. By replacing a portion of cement with these SCMs, the interfacial bonding between the cementitious matrix and fibers may be improved, resulting in enhanced crack resistance and overall strength. Additionally, the use of SCMs can lead to denser microstructures and improved resistance to aggressive environmental conditions.This study aims to explore the impact of silica fume and metakaolin as partial cement replacements in FRC. The research will focus on assessing the mechanical properties, durability, and microstructural characteristics of the resulting composites. The investigation will involve the preparation of FRC mixtures with varying percentages of cement replacement, incorporating different types and dosages of fibers.Through comprehensive experimental testing and analysis, the study aims to provide valuable insights into the feasibility and effectiveness of using silica fume and metakaolin in FRC. The findings will contribute to the understanding of the behavior of fiber-reinforced concrete with these SCMs, paving the way for the development of sustainable and high-performance FRC mixtures.

MATERIAL USED

The materials used in this investigation are…

1. Cement
2. Fine aggregate
3. Coarse aggregate
4. Water
5. Steel fibers
6. Silica fume
7. Chemical Admixture
8. Metakaolin

CEMENT

The experimental work in this study utilizes Ordinary Portland Cement (OPC) of grade 50, and all the cement properties are assessed following the guidelines specified in I.S. 12269: 1987, ensuring compliance with standard testing procedures. Table 1 provides a summary of the cement properties examined in the study.

Fig. 1 Cement

SILICA FUME

Silica fume, also known as microsilica, is a highly reactive pozzolanic material that is obtained as a byproduct of silicon and ferrosilicon alloy production. It consists of very fine particles, predominantly composed of amorphous silicon dioxide (SiO_2). Due to its unique characteristics, silica fume is widely used as a supplementary cementitious material (SCM) in concrete.The key properties of silica fume include its high specific surface area, fine particle size distribution, and high silica content. These properties contribute to its exceptional pozzolanic reactivity, which allows it to react with calcium hydroxide (lime) in the presence of water to form additional calcium silicate hydrate (C-S-H) gel. This reaction enhances the overall strength and durability of concrete. When incorporated as a partial cement replacement, silica fume improves the mechanical properties of concrete, such as compressive strength, tensile strength, and flexural strength. It reduces the porosity of the concrete matrix, resulting in increased density and reduced permeability. Silica fume also enhances the concrete's resistance to chloride ion penetration, sulfate attack, and alkali-silica reaction.

Properties of Silica Fume

Silica fume, also known as microsilica, possesses several notable properties that make it a valuable material in various applications. Some of the key properties of silica fume include:

Particle Size: Silica fume consists of extremely fine particles, with most particles being smaller than 1 micron in size. This fine particle size provides a large surface area, which enhances its reactivity and pozzolanic properties.

Fig. 2: Silica Fume

Pozzolanic Reactivity: Silica fume exhibits high pozzolanic reactivity, meaning it reacts with calcium hydroxide (lime) in the presence of water to form additional calcium silicate hydrate (C-S-H) gel. This reaction contributes to the strength and durability of concrete.

Silica Content: Silica fume has a high silica content, typically around 85% to 95%. The high silica content contributes to the formation of additional C-S-H gel and improves the binding properties of the concrete matrix.

Surface Area: Due to its fine particle size, silica fume has a significantly high surface area. This large surface area allows for increased contact and interaction with the surrounding cementitious matrix, enhancing its overall performance.

High Specific Gravity: Silica fume has a relatively high specific gravity, typically ranging from 2.2 to 2.3. This characteristic contributes to the density and compactness of concrete, leading to improved strength and reduced permeability.

Color: Silica fume is typically dark grey to black in color, which can impact the appearance of the concrete when used as an additive. However, its color does not affect its performance or properties.

Moisture Content: Silica fume is hygroscopic, meaning it has the ability to absorb and retain moisture. Proper storage and handling of silica fume are necessary to prevent moisture absorption and maintain its effectiveness.

Chemical Inertness: Silica fume is chemically inert and does not contribute to the chemical reactions that occur during the hydration process of cement. Its presence in concrete primarily influences the physical properties and microstructure of the material.

The unique properties of silica fume, including its fine particle size, pozzolanic reactivity, high silica content, and specific gravity, contribute to its effectiveness as a supplementary cementitious material. By incorporating silica fume into concrete, the resulting material exhibits improved strength, durability, and overall performance.

FINE AGGREGATE

The fine aggregate utilized in this experimental work was obtained from a local source and was able to pass through a 4.75mm sieve. It exhibited a specific gravity of 2.80. The properties of the fine aggregate are outlined in the table provided below.

Fig. 3: Fine aggregates

Properties of fine aggregate

Fine aggregate, also known as sand, possesses several important properties that influence the performance of concrete. Some of the key properties of fine aggregate include:

Particle Size Distribution: Fine aggregate consists of particles ranging from 0.075mm to 4.75mm in size. The particle size distribution affects the workability of concrete, with a well-graded and uniform distribution promoting better cohesion and reduced segregation.

Fineness Modulus: The fineness modulus is a measure of the fineness of the aggregate particles and is calculated based on the cumulative percentages of the aggregate retained on specific sieves. It helps determine the suitability of the fine aggregate for specific applications.

Shape and Texture: The shape and texture of fine aggregate particles can vary, with options ranging from rounded to angular or a combination of both. Rounded particles generally provide better workability, while angular particles can enhance the bond between particles and the cement paste.

Surface Texture: The surface texture of fine aggregate can be smooth, rough, or a combination of both. A rougher surface texture can improve the bond between the aggregate and cement paste, leading to better overall strength.

Absorption and Moisture Content: Fine aggregate can have varying levels of absorption and moisture content. Higher absorption can lead to increased water demand in concrete mixtures, while excessive moisture content can affect the water-cement ratio and potentially impact the workability and strength of the concrete.

Cleanliness: Fine aggregate should be free from organic matter, clay, silt, and other deleterious substances. Contaminants can affect the setting time, strength development, and durability of the concrete.

The properties of fine aggregate significantly influence the workability, strength, durability, and overall performance of concrete. Careful selection and evaluation of fine aggregate characteristics are essential to ensure that the resulting concrete meets the specific requirements and performance goals of the intended application.

COARSE AGGREGATE

Coarse aggregate is an essential component of concrete and plays a significant role in determining its strength and durability. It refers to the granular material, typically larger than 4.75 mm in size, that is used as a major ingredient in concrete production. The primary function of coarse aggregate is to provide strength to the concrete by acting as a load-bearing material. It helps distribute the applied loads evenly throughout the structure, enhancing its ability to resist compressive forces. Additionally, coarse aggregate improves the overall stability and durability of the concrete, making it suitable for a wide range of applications.

Coarse aggregates are commonly sourced from natural materials such as gravel, crushed stone, or recycled concrete. These materials are carefully selected based on their physical properties, including hardness, strength, and particle shape. The aggregates should be clean, free from impurities, and capable of bonding well with the cement paste. In the concrete mix, coarse aggregate occupies a significant volume, typically comprising 60% to 75% of the total volume. The size and grading of the coarse aggregate have a direct influence on the workability, strength, and density of the concrete. Different types of coarse aggregates can be used depending on the specific requirements of the project, such as lightweight aggregates for reducing the overall weight of the structure or dense aggregates for increased strength.

Fig. 4: Coarse aggregates

Properties of coarse aggregate

Coarse aggregates possess several important properties that influence the performance of concrete. Here are some key properties of coarse aggregates:

Particle Size: Coarse aggregates typically range in size from 4.75 mm (No. 4 sieve) to 20 mm or larger. The particle size distribution affects the workability of concrete and influences the amount of cement paste required to fill the voids between the particles.

Shape and Texture: The shape and texture of coarse aggregate particles can be angular, rounded, or a combination of both. Angular particles provide better interlocking and improve the strength of the concrete. However, rounded particles result in a more workable mix and reduce the risk of segregation.

Strength and Durability: Coarse aggregates should possess sufficient strength to resist the applied loads and the potential forces that may act on the concrete. Strong aggregates contribute to the overall strength and durability of the concrete structure.

Absorption and Moisture Content: The absorption capacity of coarse aggregates determines the amount of water that they can absorb and retain. It is important to consider the moisture content of aggregates to adjust the water-cement ratio accurately.

Specific Gravity: Coarse aggregates have a specific gravity that affects the weight and density of the concrete. It is important to have aggregates with a specific gravity close to that of the cement paste to avoid segregation.

Gradation: The gradation or distribution of particle sizes within the coarse aggregate affects the workability, strength, and density of concrete. Proper gradation ensures a well-compacted mixture with minimal voids.

Cleanliness: Coarse aggregates should be free from organic matter, clay, silt, and other impurities that can affect the bonding between the aggregate and cement paste.

These properties of coarse aggregates significantly impact the performance and quality of concrete. Therefore, careful selection and testing of aggregates are crucial in ensuring the desired characteristics and long-term durability of concrete structures.

STEEL FIBRE

Steel fiber is a reinforcing material commonly used in concrete to enhance its mechanical properties and improve its performance in various applications. Steel fibers are small, discontinuous strands or filaments made from high-strength steel, typically in the form of short, straight wires or thin, crimped fibers. The addition of steel fibers to concrete offers several benefits. Firstly, it enhances the tensile strength and ductility of the concrete, making it more resistant to cracking and improving its overall structural integrity. This is particularly important in applications where the concrete is subjected to significant tensile forces, such as in industrial floors, pavements, and precast elements. Moreover, steel fibers help to control crack propagation and minimize crack widths. The fibers act as micro-reinforcements, bridging the cracks that occur in the concrete and redistributing stress, thus reducing the likelihood of catastrophic failure. This improves the durability and serviceability of the concrete, especially in harsh environments or under dynamic loading conditions. Steel fibers also contribute to the impact resistance and fatigue performance of concrete. They absorb and dissipate energy during dynamic loading, reducing the risk of brittle failure and extending the service life of the structure. Additionally, the presence of steel fibers can enhance the fire resistance of concrete by providing a thermal barrier and reducing spalling. The effectiveness of steel fibers in concrete depends on factors such as fiber type, aspect ratio, volume fraction, and distribution. Proper mix design and fiber selection are crucial to ensure optimal performance and compatibility with the specific application requirements.

Fig. 5: Crimpled steel fiber

WATER

Ordinary clean potable water is used for both mixing & curing.

CHEMICAL ADMIXTURE

Chemical admixtures are substances that are added to concrete during the mixing process to modify and enhance its properties. These admixtures can be in the form of liquids or powders, and they are specifically designed to improve various aspects of concrete performance.There are different types of chemical admixtures available, each serving a specific purpose. Water reducers are used to reduce the water content in concrete mixes, increasing their strength and durability. Air entrainers introduce small air bubbles into the concrete, improving its resistance to freeze-thaw cycles. Accelerators speed up the setting and hardening process of concrete, while retarders slow down the setting time, allowing for more workable and manageable mixes. Superplasticizers are used to increase the flowability and workability of concrete, without sacrificing its strength.

Metakaolin

Metakaolin is a highly reactive pozzolanic material derived from the calcination of kaolin clay at high temperatures (600-800°C). It is known for its excellent pozzolanic properties, which make it a valuable additive in cement and concrete production. Metakaolin reacts with calcium hydroxide produced during cement hydration, forming additional calcium silicate hydrate (C-S-H) gel, which improves the strength, durability, and workability of concrete. It also reduces the porosity of concrete, enhancing its resistance to chemical attack and improving its long-term performance. Metakaolin is commonly used in high-performance concrete, fiber-reinforced concrete, and self-compacting concrete to achieve superior mechanical and durability properties.

RESULTS

FLEXURAL STRENGTH TEST

Flexural strength testing is a technique used to assess the ability of materials, such as concrete, to resist bending or deformation when subjected to applied loads. This test involves the use of a beam-shaped specimen, which is loaded from multiple points to induce a bending moment. Gradually, a load is applied until the specimen fractures, and the maximum load at failure is recorded. The flexural strength test provides valuable information about the material's capacity to withstand bending stresses and is a crucial parameter for evaluating its structural performance. It is commonly employed to evaluate the quality and suitability of concrete for various structural elements like beams, slabs, and other load-bearing components. By analyzingthe flexural strength, engineers and researchers can assess the material's ability to resist bending forces and ensure it meets the required design standards. This test plays a vital role in determining the structural integrity and reliability of concrete, aiding in the selection and design of concrete elements to withstand the anticipated loads and prevent potential failures.

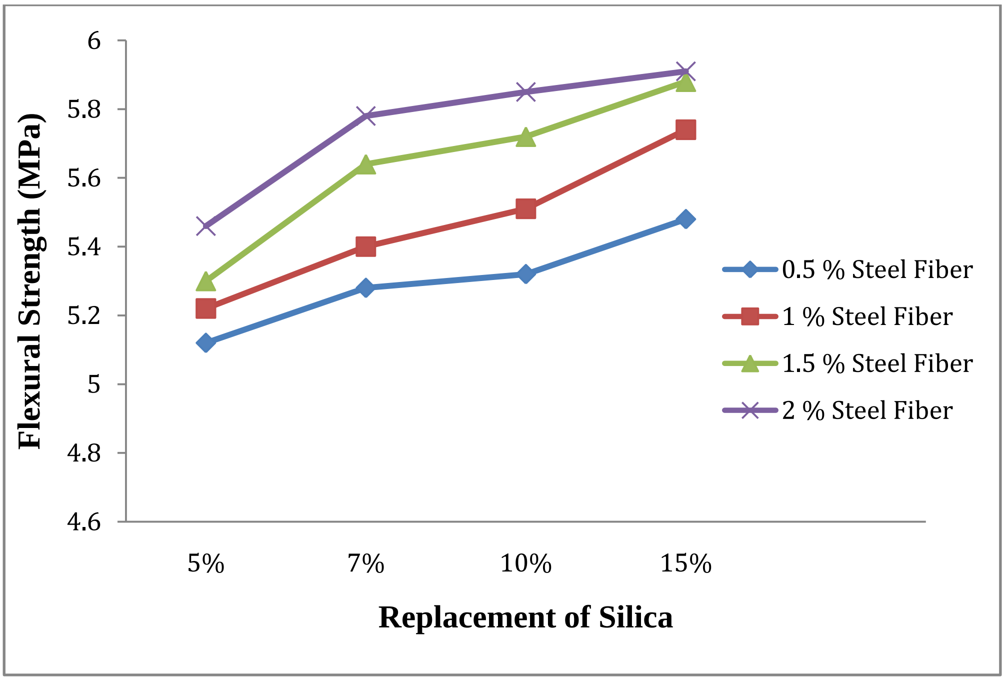
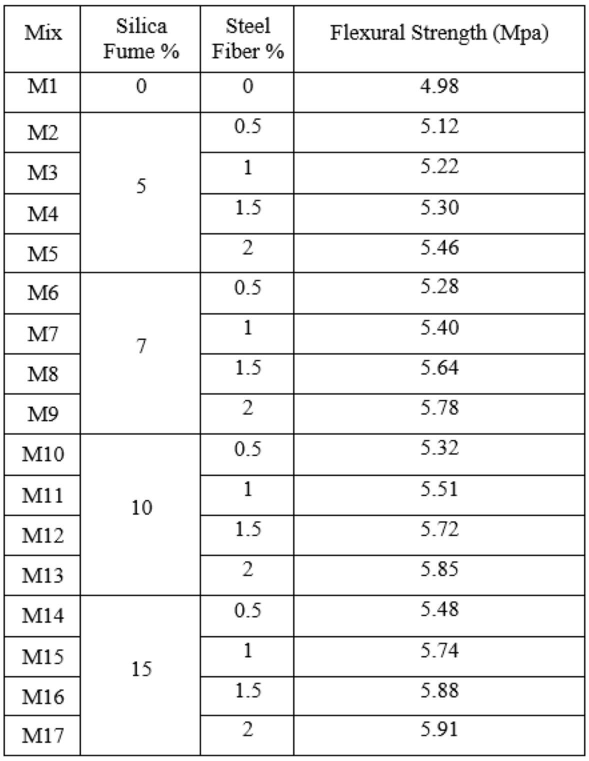


Fig. 6: Flexural Strength of M50 grade concrete at 28 days curing

Table 1 Flexural Strength of M50 grade at 28 days curing



Mix	Silica Fume %	Steel Fiber %	Flexural Strength (Mpa)
M1	0	0	4.98
M2	5	0.5	5.12
M3		1	5.22
M4		1.5	5.30
M5		2	5.46
M6	7	0.5	5.28
M7		1	5.40
M8		1.5	5.64
M9		2	5.78
M10	10	0.5	5.32
M11		1	5.51
M12		1.5	5.72
M13		2	5.85
M14	15	0.5	5.48
M15		1	5.74
M16		1.5	5.88
M17		2	5.91

CONCLUSION

The investigation into the impact of silica fume and metakaolin as partial cement replacements in fiber-reinforced concrete (FRC) has provided valuable insights into the potential benefits and effects of these supplementary cementitious materials (SCMs). The findings of this study indicate that the incorporation of silica fume and metakaolin as cement substitutes in FRC has a positive impact on its mechanical properties and durability. The use of these SCMs enhances the interfacial bonding between the cementitious matrix and fibers, resulting in improved crack resistance and overall strength. The addition of silica fume and metakaolin contributes to the densification of the microstructure, leading to increased density and reduced permeability of the concrete. Mechanical testing revealed that FRC with silica fume and metakaolin replacements exhibited enhanced compressive strength, tensile strength, and flexural strength compared to conventional FRC. The improvements in these properties can be attributed to the pozzolanic reactivity of the SCMs, which contribute to the formation of additional calcium silicate hydrate (C-S-H) gel and reduce the porosity of the concrete matrix. Moreover, the durability characteristics of the FRC were significantly improved with the incorporation of silica fume and metakaolin. The use of these SCMs resulted in reduced water absorption, improved resistance to chloride ion penetration, and enhanced resistance to freeze-thaw cycles. The denser microstructure and reduced permeability of the concrete contributed to its enhanced durability performance.

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