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Exploring the Effects of Silica Fume and Metakaolin as Partial Cement Substitutes in Fiber-Reinforced Concrete

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ABSTRACT

This study aims to investigate the effects of incorporating silica fume and metakaolin as partial replacements for cement in fiber-reinforced concrete (FRC). The use of supplementary cementitious materials (SCMs) such as silica fume and metakaolin has gained significant attention in the construction industry due to their potential to improve the mechanical and durability properties of concrete. In this research, different combinations of silica fume and metakaolin were added as partial replacements for cement in FRC mixes.

The experimental program consisted of preparing FRC specimens with varying proportions of silica fume and metakaolin, while keeping the total binder content constant. Mechanical tests, including compressive strength, tensile strength, and flexural strength, were conducted to evaluate the performance of the FRC mixes. Additionally, the durability properties of the concrete, such as chloride ion penetration resistance and carbonation resistance, were also assessed.

The results showed that the addition of silica fume and metakaolin as partial cement replacements in FRC led to significant improvements in the mechanical properties. The compressive strength, tensile strength, and flexural strength of the FRC mixes increased with the increase in the percentage of silica fume and metakaolin. Furthermore, the durability tests revealed enhanced resistance to chloride ion penetration and carbonation for the FRC specimens containing silica fume and metakaolin.

INTRODUCTION

Concrete is one of the most widely used construction materials due to its excellent compressive strength and durability. However, the production of conventional concrete requires a significant amount of cement, which contributes to high carbon emissions and depletion of natural resources. To address these environmental concerns, researchers and engineers have been exploring alternative materials and techniques to enhance the performance and sustainability of concrete.

One promising approach is the incorporation of supplementary cementitious materials (SCMs) as partial replacements for cement. SCMs, such as silica fume and metakaolin, are industrial by-products that can be obtained from various manufacturing processes. These materials possess pozzolanic properties, which means they react with calcium hydroxide in the presence of water to form additional cementitious compounds. By incorporating SCMs in concrete, it is possible to reduce the cement content while maintaining or even improving the mechanical and durability properties of the material.Fiber-reinforced concrete (FRC) is a type of concrete that contains discrete fibers, such as steel, glass, or synthetic fibers, to enhance its tensile and flexural strength. The addition of fibers improves the crack resistance and ductility of the concrete, making it suitable for applications where high tensile strength and resistance to cracking are required. However, the use of SCMs in FRC has received relatively less attention compared to conventional concrete.This study aims to investigate the effects of using silica fume and metakaolin as partial replacements for cement in FRC. The objective is to evaluate the mechanical and durability properties of FRC mixes containing different proportions of silica fume and metakaolin. The research will provide insights into the potential benefits and challenges associated with incorporating these SCMs in FRC and contribute to the knowledge base on sustainable concrete construction.

METHODOLOGY AND EXPERIMENTATION

The current study was undertaken to establish or understand the behavior of Silica fume and when it is reinforced by steel fiber, in light of the growing interest in using these two materials together in concrete. So, the emphasis of the research is on laboratory work.

1. The materials have been collected from a specific location and properties have been studied.
2. Using these properties, mix design is carried out with suitable w/c ratio of M50 grade concrete.
3. Casting concrete cubes and beams allowed researchers to examine the material's compressive and flexural strengths. The compression testing machine was then used on the cubes and beams. Twenty specimens were cast and tested for compressive and flexural strength in the lab.
4. The beam size was 150 mm x 150 mm x 500 mm, and 150 mm cube specimens would be used to calculate the concrete's compressive strength. At 7, 21, and 28 days old, the specimens will be tested in a 200-ton capacity hydraulic type compression-testing equipment, while the beam will be tested at 28 days old.

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 utilizes Ordinary Portland Cement (OPC) with a grade of 50. To ensure compliance with standard testing procedures, all cement properties are examined in accordance with I.S. 12269: 1987. A summary of the cement properties can be found in Table 1.

Table 1: Properties of Cement

Properties	Obtained
Specific gravity	3.15
Initial setting time	65 min
Final setting time	175 min
Consistency	30 %

Fig. 1 Cement

SILICA FUME

Silica fume is a highly reactive pozzolanic material that is obtained as a byproduct during the production of silicon and ferrosilicon alloys in the electric arc furnace process. It is composed of very fine particles, typically with an average diameter of 0.1 micrometers, which gives it a high specific surface area. Silica fume is known for its exceptional properties that contribute to the improvement of concrete performance. When used as a supplementary cementitious material, it can enhance the strength, durability, and other engineering properties of concrete. One of the significant advantages of silica fume is its high pozzolanic reactivity. Due to its small particle size and amorphous nature, silica fume readily reacts with the calcium hydroxide produced during cement hydration, forming additional calcium silicate hydrate (C-S-H) gel. This leads to a denser microstructure with reduced pore size, enhancing the strength and impermeability of the concrete. As a partial replacement for cement, it offers distinct properties, which are detailed in Table 2

Table 2: Properties of Silica Fume

Property	Value
Colour	Dark to Light Gray
Bulk density	450-650 g/cm^3
Specific gravity	2.22
Moisture content	1 %
SiO_2	92%

Fig. 2: Silica Fume

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

Table 3: Properties of fine aggregate

Property	Value
Bulk density	1.49 g/cm3
% of voids ratio	34.23 %
Voids Ratio	0.58
Specific Gravity	2.258
Fineness modulus	2.9

COARSE AGGREGATE

The present study utilizes crushed aggregates with a maximum size of 20mm and a minimum size of 10mm. These aggregates have a specific gravity of 2.85. The properties of the coarse aggregates were tested in accordance with I.S. 383: 1970. The details of the coarse aggregate.

Properties are presented in the table below

Fig. 4: Coarse aggregates

Table 4: Properties of coarse aggregate

S.NO	Property	Test Result
1	Specific Gravity	2.74
2	Bulk density(Kg/m)	1468(loose state) 1611(dry rodded)
3	Fineness Modulus	7.17

STEEL FIBRE

Steel fiber is a reinforcing material commonly used in concrete to improve its mechanical properties and enhance its performance. It is composed of small, uniformly dispersed steel fibers that are incorporated into the concrete mix. These fibers can be either straight or hooked, with varying lengths and aspect ratios.

The addition of steel fibers to concrete offers several benefits. Firstly, it enhances the tensile strength and ductility of the concrete. The fibers act as internal reinforcement, effectively distributing the stress and reducing the formation of cracks. This results in improved structural integrity and resistance to cracking under various loading conditions.

Fig. 5: Crimpled steel fiber

WATER

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

CHEMICAL ADMIXTURE

Chemical admixtures are substances added to concrete during the mixing process to modify its properties and improve its performance. These admixtures can be in liquid or powder form and are designed to enhance various aspects of concrete, such as workability, strength, durability, and setting time. Examples of chemical admixtures include water reducers, air entertainer's, accelerators, retarders, and superplasticizers. Each admixture serves a specific purpose, such as reducing water content, increasing slump, improvingflowability, controlling setting time, or enhancing the resistance to freeze-thaw cycles. Chemical admixtures play a crucial role in optimizing concrete mixes to meet specific project requirements and achieve desired results.

Metakaolin

Metakaolin, or calcined kaolin, is a pozzolanic substance produced through the calcination process of kaolin clay. The chemical composition of metakaolin can vary depending on the initial composition of the kaolin clay and the specific conditions of the calcination process. However, a typical chemical composition of metakaolin is provided below:

Table 4Metakaolin's Chemical Composition

RESULTS

MECHANICAL PROPERTIES

Mechanical properties such as compressive strength and flexural strength tests are evaluated.

COMPRESSIVE STRENGTH TEST

The overall quality of concrete can be gauged from the results of a compressive strength test, as this property is directly correlated to the structure of the hydrated cement paste. The cube specimens were tested for compressive strength at 7, 21, and 28 days of age.

EFFECT OF SILICA FUME WITH STEEL FIBERS

FOR 7 DAYS OF CURING

For 7 days of curing, steel fiber of 0.5%, 1%, 1.5 % and 2% with silica fume of 5 % shows 22%, 26 % and 24% and 27%,silica fume of 7 % shows 25 %, 31 %, 32 % and 33 %,silica fume of 10 % shows 30 %, 34 %, 38 % and 32 %and silica fume of 15 % shows 28 %, 29 %, 31 % and 27 %.

Tableshowed the result of compression strength of concrete with fibers (crimped type) using M50 grade of concrete. Compared to normal concrete, it has been seen that adding more silica fume makes the compression strength go up. Compressive strength of concrete with silica fume is increased up to the 10 % and then decreases. The maximum values of compressive strength at 10 % Silica fume and 1.5 % fiber are 41.34 N/mm^2. So themaximum percentage of the silica fume on the replacementof cement should be 10 % when ppc used.

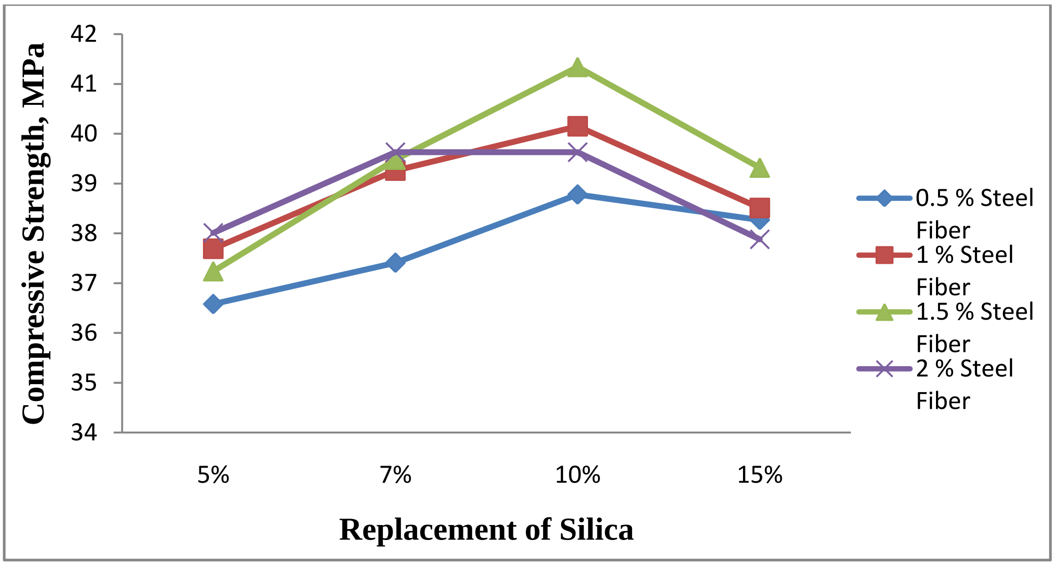

Fig. 6Compressive Strength of M60 grade concrete at 7 days curing

Table 5: Compressive Strength of M50 grade at 7days curing

Mix	Silica Fume %	Steel Fiber %	Compressive Strength (Mpa)
M1	0	0	29.80
M2	5	0.5	36.58
M3		1	37.69
M4		1.5	37.24
M5		2	38.01
M6	7	0.5	37.41
M7		1	39.26
M8		1.5	39.48
M9		2	39.63
M10	10	0.5	38.78
M11		1	40.15
M12		1.5	41.34
M13		2	39.63
M14	15	0.5	38.27
M15		1	38.51
M16		1.5	39.32
M17		2	37.88

FOR 21 DAYS OF CURING

For 21 days of curing, steel fiber of 0.5%, 1%, 1.5 % and 2% with silica fume of 5 % shows 24 %, 31 % and 36 % and 32 %, silica fume of 7 % shows 30 %, 38 %, 39 % and 39 %, silica fume of 10 % shows 34 %, 44 %, 46 % and 34 % and silica fume of 15 % shows 31 %, 38 %, 40 % and 30 %.

Tableshowed the result of compression strength of concrete with fibers (crimped type) using M50 grade of concrete. Compared to normal concrete, it has been seen that adding more silica fume makes the compression strength go up. With silica dust, the compressive strength of concrete goes up up to 10% and then goes down. The maximum values of compressive strength at 10 % Silica fume and 1 % fiber are 46.52 N/mm^2. So themaximum percentage of the silica fume on the replacementof cement should be 10 %.

Table 6: Compressive Strength of M50 grade at 21 days curing

Mix	Silica Fume %	Steel Fiber %	Compressive Strength (Mpa)
M1	0	0	32.20
M2	5	0.5	40.18
M3		1	42.37
M4		1.5	44.10
M5		2	42.55
M6	7	0.5	41.88
M7		1	44.62
M8		1.5	45.06
M9		2	44.77
M10	10	0.5	43.28
M11		1	46.52
M12		1.5	47.18
M13		2	43.21
M14	15	0.5	42.48
M15		1	44.63
M16		1.5	45.10
M17		2	42.18

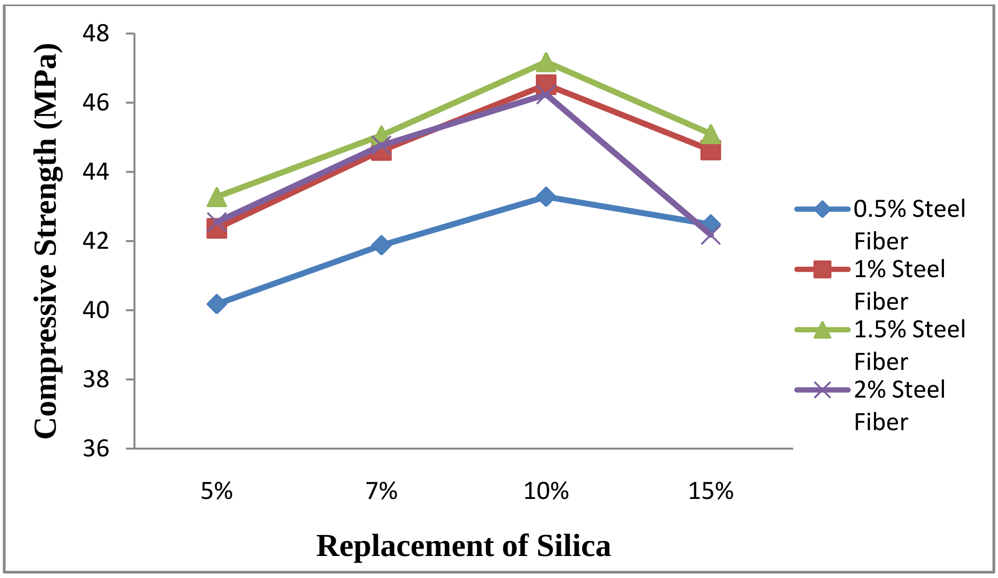

Fig. 7: Compressive Strength of M50 grade concrete at 21 days curing

FOR 28 DAYS OF CURING

Table 7 Compressive Strength of M50 grade at 28 days curing

Mix	Silica Fume %	Steel Fiber %	Compressive Strength (Mpa)
M1	0	0	48.21
M2	5	0.5	53.46
M3		1	53.18
M4		1.5	52.33
M5		2	54.56
M6	7	0.5	53.78
M7		1	54.88
M8		1.5	54.32
M9		2	54.76
M10	10	1	54.55
M11		1.5	56.74
M12		2	55.31
M13		0.5	57.67
M14	15	0.5	51.68
M15		1	54.42
M16		1.5	53.65
M17		2	56.24

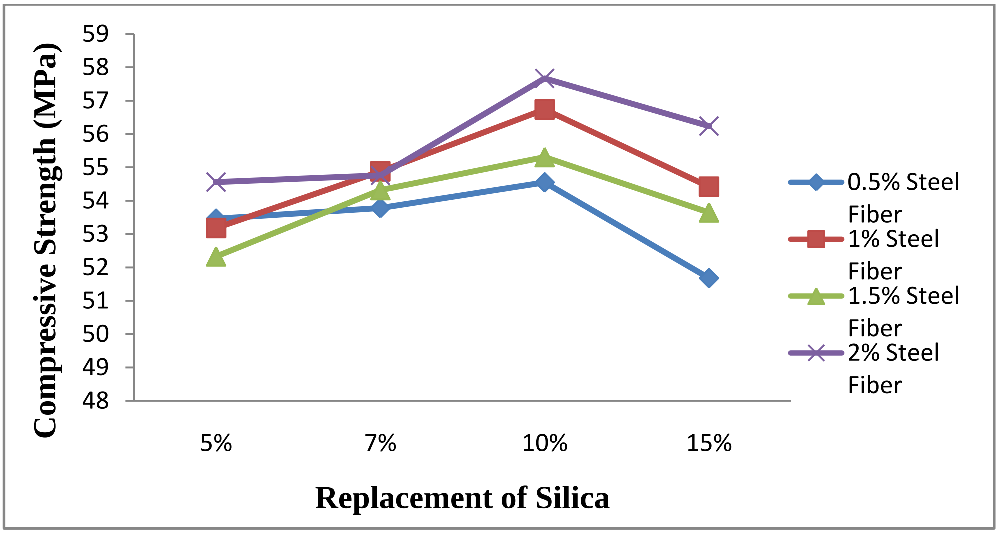

Fig. 8:Compressive Strength of M50 grade concrete at 28 days curing

For 28 days of curing, steel fiber of 0.5%, 1%, 1.5 % and 2% with silica fume of 5 % shows 24 %, 31 % and 36 % and 32 %, silica fume of 7 % shows 30 %, 38 %, 39 % and 39 %, silica fume of 10 % shows 34 %, 44 %, 46 % and 34 % and silica fume of 15 % shows 31 %, 38 %, 40 % and 30 %.

Table shown the M50 grade concrete's effect on the compressive strength of crimpled fiber concrete. Adding silica fume to regular concrete has been shown to improve its compressive strength. The addition of silica fume increases the compressive strength of concrete by up to 10%, but afterwards it begins to diminish. The maximum values of compressive strength at 10 % Silica fume and 1 % fiber are 46.52 N/mm^2. So the maximum percentage of the silica fume on the replacement of cement should be 10 %.

FLEXURAL STRENGTH TEST

The Flexural test of beam specimen is checked after 28days. The effects of silica fume with steel fiber on flexural strength of concrete are shown in Table 4.4 and their graphicaltrends are shown in Figure 6.

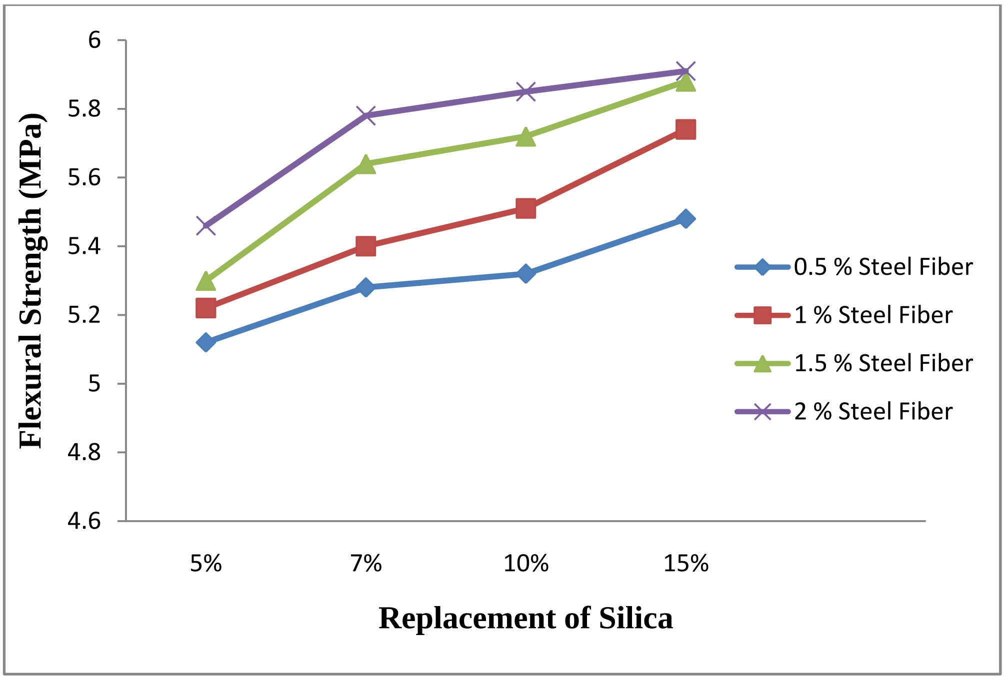

Fig.9:Flexural Strength of M50 grade concrete at 28 days curing

For 28 days of curing, steel fiber of 0.5%, 1%, 1.5 % and 2% with silica fume of 5 % shows 2 %, 4 %, 6 % and 9 %, silica fume of 7 % shows 6 %, 8 %, 13 % and 16 %, silica fume of 10 % shows 6 %, 10 %, 14 % and 17 % and silica fume of 15 % shows 10 %, 15 %, 16 % and 18 %.

Table 8Flexural 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 study conducted on silica fume fiber reinforced concrete with silica fume and metakaolin as partial replacements for cement has yielded several significant conclusions. The findings and observations from the research provide valuable insights into the performance and potential benefits of incorporating these materials into concrete mixtures. The following conclusions can be drawn from the study:the addition of silica fume and metakaolin as partial replacements for cement in fiber reinforced concrete has demonstrated a substantial improvement in both compressive and flexural strength. The pozzolanic reactions of silica fume and metakaolin contribute to the densification of the concrete matrix, resulting in increased strength properties. The study reveals that higher proportions of silica fume and metakaolin tend to enhance the strength characteristics of the concrete, making it suitable for applications requiring high structural performance. study indicates that the inclusion of silica fume and metakaolin can improve the durability of the concrete. By reducing the permeability of the concrete matrix, these supplementary cementations materials enhance its resistance to chemical attacks, such as chloride penetration and sulphate attack. The increased durability is particularly advantageous in environments with aggressive conditions, such as coastal regions or areas with high industrial activity. Moreover, the research demonstrates that the incorporation of silica fume and metakaolin affects the workability of the concrete mixture. The fine particle size of these materials tends to increase the water demand, potentially leading to a decrease in workability. However, through proper mix design and the use of superplasticizers, it is possible to maintain the desired workability while reaping the benefits of silica fume and metakaolin.

Another significant conclusion drawn from the study is the improved crack resistance of the concrete. The increased density and reduced porosity resulting from the addition of silica fume and metakaolin help to mitigate crack propagation and limit crack widths. This characteristic is particularly valuable in structures subjected to heavy loads or exposed to harsh environmental conditions, as it enhances the long-term durability of the concrete. Furthermore, the study emphasizes the sustainability aspect of incorporating silica fume and metakaolin into concrete mixtures. Both materials are industrial by-products, and their utilization reduces waste generation and environmental impact. By incorporating these supplementary cementitious materials, the concrete industry can contribute to sustainable practices without compromising performance. While the initial cost of concrete production may slightly increase due to the addition of silica fume and metakaolin, the long-term benefits outweigh the initial investment. The improved durability and reduced maintenance requirements of the concrete can result in cost savings over the lifespan of the structure. The economic feasibility of using these materials depends on various factors, such as their availability in the local market, transportation costs, and project-specific requirements. the study demonstrates that the incorporation of silica fume and metakaolin as partial replacements for cement in fiber reinforced concrete offers several advantages. These include improved strength and durability, enhanced crack resistance, sustainability, and potential cost savings. However, it is important to consider the specific experimental parameters and limitations of the study when interpreting these conclusions. Further research and field applications are recommended to validate and expand upon these findings.

FUTURE SCOPE

The study of silica fume fiber reinforced concrete with silica fume and metakaolin as partial replacements for cement opens up several future scopes for further research and development. Building upon the findings and conclusions of the current study, the following areas could be explored:

Optimization of Mix Proportions: Further research can focus on optimizing the mix proportions of silica fume, metakaolin, and other cementitious materials to achieve an ideal balance between strength, workability, and durability. By conducting a comprehensive parametric study, researchers can determine the most effective combination of these materials and refine the mix design guidelines for practical applications.

Performance under Dynamic Loading: The study primarily focused on the mechanical properties of silica fume fiber reinforced concrete. Future research can delve into the performance of such concrete under dynamic loading conditions, such as impact or blast loading. Investigating the behavior of this concrete in dynamic scenarios will provide insights into its suitability for high-performance structures subjected to extreme loading conditions.

Long-Term Durability: While the study touched upon the improved durability of silica fume and metakaolin-based concrete, further research can focus on assessing its long-term durability performance. This includes studying the resistance to various deterioration mechanisms over extended periods, such as carbonation, alkali-silica reaction, and freeze-thaw cycles. Evaluating the durability of this concrete will ensure its suitability for long-lasting infrastructure.

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