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Effect of Incorporating Crimped Steel Fibers on the Durability of High-Strength Metakaolin Blended Concrete

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Abstract:

Cement concrete is the most often utilized material in many structures. Concrete that has been properly built and prepared has high strength and durability. Even well-designed and constructed cement concrete mixes under regulated conditions have limitations, which lead the above-mentioned concrete qualities to be unsuitable for certain situations and buildings. The primary constituent in typical concrete is Portland cement. The amount of cement produced releases roughly the same amount of carbon dioxide into the environment. Cement manufacture consumes a substantial quantity of natural resources. To combat the aforementioned negative consequences, the development of newer materials and building processes, as well as the incorporation of other items with varied uses, has become necessary. The availability of mineral admixtures signaled the beginning of a new age in concrete mix design, with increasing and higher strengths. Metakaolin is a novel mineral admixture whose potential has not been completely realized. Furthermore, just a few research have been conducted in India on the usage of Metakaolin for the construction of high strength concrete. This study examines how crimped steel fibers affect the mechanical and long-term characteristics of metakaolin-blended high-strength concrete (HSC) of M50 grade. Concrete that contains "metakaolin, a highly reactive pozzolanic" substance, has been shown to have increased resistance to chemical assaults, decreased permeability, and greater compressive strength. By incorporating crimped steel fibres of aspect ratio 80(36mm long and 0.45mm diameter) into the metakaolin- blended concrete matrix, this study investigates the resulting improvements in tensile strength, impact resistance, and long-term durability. The experiments involve meticulous mix design optimization, comprehensive tests to evaluate mechanical properties, and thorough exposure conditions to assess durability. The results indicate that, "compared to plain high-strength concrete", the addition of crimped steel fibres significantly enhances structural performance and resilience to aggressive environments. This work underscores the potential of fibre-reinforced metakaolin-blended concrete in critical infrastructural applications where reliability and longevity are paramount.

Keywords: Crimped steel fibres, Metakaolin, High-strength concrete (HSC), Durability, Mechanical properties, Pozzolanic materials.

1. Introduction

1.1 Background:

Concrete is the most widely used building material in the world, and it may be used for anything from large- scale civil infrastructure to residential buildings. Despite its versatility, conventional concrete often exhibits limited ductility, susceptibility to crack formation, and culminating in relatively lower tensile strength (Neville, 2011). These restrictions have been somewhat overcome by the creation of "high- strength concrete (HSC)," which increases the concrete mix's total density and compressive strength. However, combining HSC with various supplementary cementitious materials (SCMs) can further improve the durability and mechanical performance of the resulting composite (Mehta & Monteiro, 2014). The capacity of "metakaolin, a high-reactive aluminosilicate pozzolanic" substance obtained by thermally treating kaolin clay, to improve compressive strength, decrease porosity, and polish the microstructure of cementitious matrices has made it a popular SCM (Sabir et al., 2001). Several experimental studies have been conducted to investigate the workability, mechanical, and durability properties.

1.2 Crimped Steel Fibres:

Steel fibers are manufactured in accordance with ASTM-A 820 requirements. Steel fibre reinforced concrete incorporating crimped steel fibres provides exceptional performance, contributing to significantly increased durability, load-bearing capacity, and impact resistance for a longer lifespan (ASTM A 820, 1996).

Parking lots, play areas, taxiways, maintenance hangars, airport runways, access roads, and workshops are all examples of SFRC flooring applications. It is also utilized in shotcreting, precast concrete manufacturing, tunnel and underwater concrete reinforcing overlays, manhole coverings, piles, and pillars.

Steel fibers have been investigated as a potential additive to metakaolin-blended concrete to increase its structural stability and durability. Fibre reinforcement in concrete helps control crack propagation, improve tensile and flexural strengths, and enhance energy absorption capacity (ACI Committee 544,1996).

1.3 Durability:

The capacity of cement concrete to withstand weathering action, chemical assault, abrasion, or any other deteriorating process is referred to as its durability. When exposed to the environment, durable concrete retains its original shape, quality, and serviceability.

When developing a concrete mix or a concrete building, the exposure condition that the concrete is expected to withstand should be considered from the outset using sound judgement. Soil qualities are critical for solid foundations and should be properly examined. Environmental contamination is rising by the day, particularly in urban and industrial regions. According to reports, even industrialized countries spend 40% of their resources on repair and maintenance. We perform repairs in a casual manner, utilizing merely regular cement mortar used decades ago. Today, specialized repair materials and processes are available. These materials considerably enhance repair operations by increasing its effectiveness and durability (Shetty, M.S., 2004).

The primary aim of this research is to evaluate the impact of adding crimped steel fibers on the mechanical behavior and longevity of high-strength concrete mixed with metakaolin under different exposure scenarios. This research aims to supply relevant design insights for critical infrastructural applications, including bridges, tunnels, high-rise buildings, and marine structures that require both high mechanical performance and superior durability.

1.4 Significance of the Study

1. Improved Concrete Performance: The investigation provides data on the synergy between metakaolin as a pozzolanic additive and steel fibre reinforcement.

2. Sustainability: Utilizing metakaolin, which is often derived from kaolinitic clays, supports sustainable material practices by reducing reliance on portland cement and enhancing the longevity of concrete structures.

3. Long-Term Cost Efficiency: Robust durability performance implies decreased maintenance costs, presenting significant economic benefits across large infrastructures and extended service life.

1.5 Objectives

- To measure how much the volumetric percentage of steel fiber affects the metakaolin-blended HSC's compressive, tensile, and flexural strengths.

- To assess how steel fibers affect important durability metrics such exposure to sulfate attack, water absorption, and chloride ion penetration.

- To recommend an optimal mixture design and fibre content for improved performance of metakaolin-blended concrete.

2. **Literature Review**

2.1 "High-Strength Concrete and Metakaolin"

"High-strength concrete" typically exhibits a compressive strength greater than 60 MPa (ACI Committee 363, 2010). Factors that contribute to HSC’s superior mechanical properties include reduced water-binder ratio, efficient particle packing, and the use of various "chemical and mineral admixtures." Among these, metakaolin has demonstrated pronounced benefits:

- Enhanced Particle Packing: Metakaolin particles are finer than ordinary cement, filling voids and reducing porosity (Justice & Kurtis, 2007).

- Pozzolanic Action: Metakaolin actively reacts with calcium hydroxide (CH) produced during hydration to form additional calcium silicate hydrates (C-S-H), thereby refining the microstructure (Ambroise, Murat, &Pera, 1994).

2.2 Fibre-Reinforced Concrete

"Fibre-reinforced concrete (FRC)" incorporates short discrete fibres within the concrete matrix. These fibres vary in material type (steel, synthetic, glass, etc.), geometry, and dimensional characteristics. Steel fibre-reinforced concrete (SFRC) stands out for its superior tensile strength, impact resistance, and crack bridging capabilities (ACI Committee 544,1996). Crimped steel fibres, in particular, provide enhanced bonding with the cement matrix due to their deformed surface.

2.3 Synergistic Effects of Metakaolin and Steel Fibres

Recent studies have shown that the coupling of SCMs with steel fibres yields improved mechanical and durability properties (Vairagade & Kene, 2012). For instance, metakaolin reduces pore sizes and overall porosity, providing better bond interface for steel fibres and reducing microcracking (Uysal SYilmaz, 2011). This synergy translates into improved flexural strength, reduced water permeability, and enhanced resistance to detrimental agents such as chlorides and sulfates.

2.4 Durability Indices and Test Methods

Several standard and well-accepted test methods are employed to assess the durability of concrete:

- Rapid Chloride Permeability Test (RCPT): Evaluates resistance to chloride ion penetration (ASTM C1202, 2012).

- Water Absorption: Measures the capacity of concrete to absorb water under vacuum or partial submersion.

- Sulfate Resistance Test: Detects expansion and weight loss of specimens exposed to sodium or magnesium sulfate solutions (ASTM C1012, 2018).

The following are the findings drawn from the aforesaid literature review:
(a) Using Metakaolin as a cement replacement improves concrete properties by increasing $Ca(OH)_2$ consumption, improving pore refinement, micro filling action, resistance to permeability, higher pozzolanic reaction, early strength gain, and reducing cement consumption. Which inturn saves natural resources and reduces the emissions of greenhouse gases such as CO_2.

There was also no detailed investigation on the strength and durability attributes of Metakaolin concrete made with crimped steel fibers. Given the gap in the available literature, an attempt was undertaken to explore the strength and durability attributes of crimped steel fibres at various volume fractions.

This study’s experimental program aligned with these standardized methodologies to provide a thorough assessment of durability performance.

3. Materials and Methods

The various materials and their mix proportions used in the present study are given below.

3.1 Materials

1. Cement: Ordinary Portland Cement (OPC) (Type I).

2. Metakaolin: Commercial-grade metakaolin with a median particle size of approximately 2 µm.

3. Aggregates:

- Fine aggregate: Natural River sand (Zone II as per IS 383).

- Coarse aggregate: Crushed angular granite with a nominal maximum size of 20mm.

4. Admixtures: High-range water reducer (HRWR) to achieve desired workability.

5. Steel Fibres: Crimped steel fibres, 36

mm in length, diameter 0.45mm with aspect ratio of 80, tensile strength-1100 MPa.

3.2 Mix Proportioning

The control mix (i.e., HSC with no SCM or fibres) was designed to achieve a target compressive strength of 50 MPa at 28 days. Metakaolin replaced 10% of the cement content by weight based on existing literature indicating optimal reactivity at around 8-15% replacement (Alonso & Wesche, 1998). Water-to- binder ratio (W/B) was maintained at 0.30 for all mixes. Crimped steel fibres were introduced at 0%, 1%, 1.5% and 2% by volume of the concrete mix.

Table 1 provides an overview of the mix proportions:

M0 (Control)
M10-MK + 0%SteelF
M10-MK + 1%SteelF
M10-MK + 1.5%SteelF
M10-MK + 2%SteelF

Source: Adapted from Alonso & Wesche (1998); modified proportions used in this study.

3.3 Specimen Preparation and Curing

All concrete batches were mixed using a pan mixer capable of 60-liter capacity. The mixing sequence was as follows:

1. Dry mix coarse and fine aggregates.
2. Add cementitious materials (cement + metakaolin) and blend thoroughly.
3. Gradually introduce ~80% of the required water.
4. Incorporate HRWR diluted in remaining water to fine-tune the slump.
5. Introduce steel fibres uniformly, ensuring homogeneous distribution.

Cube specimens (150mm x 150mm x 150mm) were cast for compressive strength, cylinders of size 150mm diameter and 300mm long were used for splitting tensile strength, prisms of size 100mm x 100mm x 500mm were used for modulus of rupture and durability tests. Samples were demolded after 24 hours and cured in a water tank at 27 ± 2°C until the designated testing age (28 days).

3.4 Test Methods

3.4.1 Fresh Concrete Properties

Slump tests were conducted per ASTM C143 (2015) to ensure a workable concrete consistent with high- strength concrete requirements. For each mix, slump was recorded immediately after mixing.

3.4.2 Mechanical Tests

1. Compressive Strength:

- Conducted at 28 days on cubical specimens as per ASTM C39 (2018).

2. Splitting Tensile Strength:

- Examined as per ASTM C496 (2017) at 28 days using cylindrical specimens.

3. Modulus of Rupture:

- Determined by the two-point bending test on prisms according to ASTM C78 (2018) on prismatic beam specimens after 28 days.

3.4.3 Durability Tests

1. Rapid Chloride Permeability Test (RCPT):

- Following ASTM C1202 (2012), a voltage of 60 V was applied across 50 mm thick slices of the cylindrical specimens. The total charge passed was recorded in coulombs.

2. Water Absorption:

- Measured per ASTM C642 (2013). Specimens were oven-dried and then immersed in water to determine weight differences.

3. Sulfate Attack:

- A set of specimens was immersed in a 5% sodium sulfate (Na_2SO_4) solution per ASTM C1012 (2018). Length changes and mass losses were recorded periodically up to 90 days.

4. Results and Discussion

4.1 Fresh Concrete Properties

All mixes achieved an acceptable slump in the range of 60 to 90 mm. Addition of steel fibres slightly reduced workability due to fibre interlocking, requiring a slightly higher dosage of HRWR. However, the slump was maintained above 60 mm to ensure adequate placement and consolidation.

4.2 Mechanical Properties

4.2.1 Compressive Strength

Table 2 shows compressive strength values of various concrete mixes considered in the study.

Table 2: Compressive Strength of Concrete Mixes

Mix ID	**Compressive Strength (MPa)**
M0 (Control)	61.8
M10-MK + 0%SteelF	68.7
M10-MK + 1%SteelF	72.68
M10-MK + 1.5%SteelF	73.32
M10-MK + 2.0%SteelF	75.20

Source: Experimental data from this study.

Table 2 presents the compressive strength results obtained at 28 days. Incorporating metakaolin (10% by weight) increased early-age and 28-day compressive strength compared to the control mix without SCM. The presence of steel fibres showed only marginal improvements in compressive strength but was more apparent with higher fibre volume (2%).

4.2.2 Splitting Tensile Strength

Table 3 shows split tensile strength values of various concrete mixes considered in the study.

Table 3: Split Tensile Strength of Concrete Mixes

Mix ID	**Split Tensile Strength (MPa)**
M0 (Control)	4.28
M10-MK + 0%SteelF	4.50
M10-MK + 1%SteelF	4.90
M10-MK + 1.5%SteelF	5.05
M10-MK + 2.0%SteelF	5.38

Splitting tensile tests confirmed the beneficial effect of steel fibres in arresting cracks and improving tensile capacity. M10-MK + 2%SteelF achieved a splitting tensile strength of around 5.38 MPa, a 25% increase compared to M10-MK + 0%SteelF.

4.2.3 Modulus of Rupture

The addition of steel fibers increased the Modulus of Rupture in a manner similar to that of splitting tensile strength. The crack width was noticeably smaller in fibre-reinforced specimens, suggesting enhanced ductility and crack-bridging capacity. The synergy between metakaolin's refined concrete matrix and steel fibres' mechanical reinforcement showed an improvement of up to 68% in Modulus of Rupture at 2% fibre content. Table 4 shows the values of Modulus of Rupture of various concrete mixes used in this study.

Table 4: Modulus of Rupture of Concrete Mixes

Mix ID	**Modulus of Rupture (MPa)**
M0 (Control)	5.44
M10-MK + 0%SteelF	5.80
M10-MK + 1%SteelF	7.31
M10-MK + 1.5%SteelF	8.22
M10-MK + 2.0%SteelF	9.42

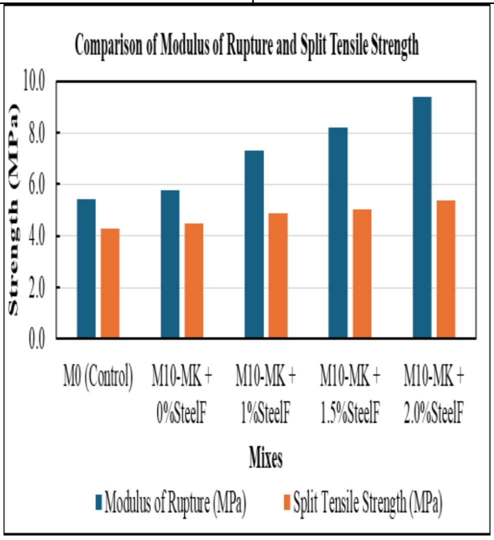

Figure -1: Comparison of Modulus of Rupture and Split Tensile Strength

4.3 Durability Performance

4.3.1 Rapid Chloride Permeability Test (RCPT)

Figure 2 depicts the total charge passed (coulombs) in the RCPT for all mixes tested at 28 days. Lower coulomb readings indicate higher resistance to chloride ion penetration.

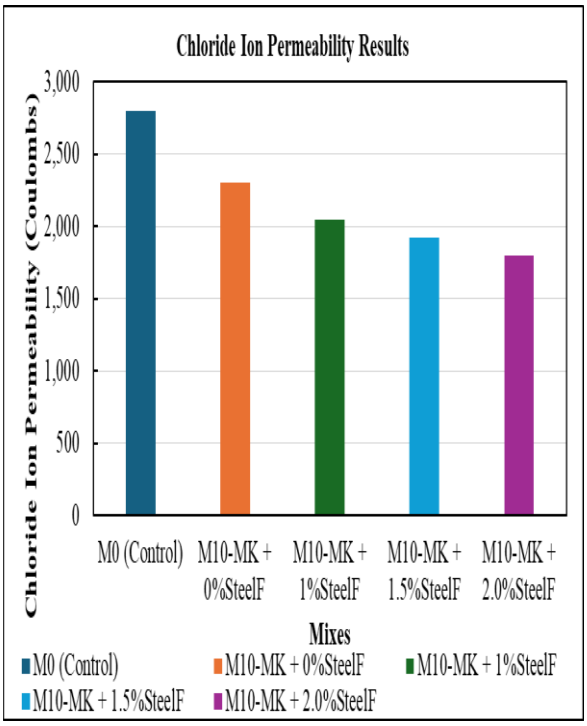

Figure-2: The Rapid Chloride Permeability Test (RCPT) Results

Figure 2. Chloride Ion Permeability Results (Adapted from Original ASTM Testing Procedure)

- MO (Control) exhibited around 2800 coulombs.

- Metakaolin-containing concretes showed substantially lower values (~2000-2200 coulombs).

- When steel fibres were included, the values further dropped to ~1900 coulombs at 2% fibre content, reflecting the refined pore structure and crack-bridging action that minimize ionic transport pathways.

4.3.2 Water Absorption

Water absorption findings generally paralleled the RCPT trends. Metakaolin’s pore-refining property contributed to a decline in water absorption from 3.2% (control) to about 2.6% in metakaolin-blended samples. With 2% steel fibres, a further modest reduction to ~2.4% was observed. This improvement in moisture ingress resistance is crucial for preventing corrosion of embedded steel elements (Bentur & Mindess, 2007).

4.3.3 Sulfate Attack

Specimens exposed to 5% Na_2SO_4 solution for up to 90 days exhibited minimal expansion in metakaolin- blended mixes. The presence of metakaolin reduced the formation of expansive products such as ettringite, while steel fibres displayed negligible signs of corrosion due to the enhanced concrete matrix. Maximum expansion measured in MO (Control) over 90 days was 0.14%, whereas M10-MK + 2%SteelF recorded only 0.07%, indicating the positive role of both metakaolin and steel fibres in mitigating sulfate-induced deterioration.

5. Discussions

5.1 Synergistic Effects of Metakaolin and Steel Fibres

The results obtained from this experimental investigation corroborate findings from earlier studies emphasizing the effectiveness of metakaolin as an SCM and steel fibres as an external reinforcement. Metakaolin’s pozzolanic reactivity lent the concrete matrix a dense microstructure with lower permeability. In parallel, the presence of steel fibres significantly improved the tensile and flexural characteristics, enabling better crack absorption and propagation control.

A crucial observation is that the inclusion of steel fibres marginally enhances compressive strength, but it markedly augments tensile and flexural properties. This behavior indicates that steel fibres are extremely beneficial in applications subjected to significant flexural loads, dynamic loading, or where cracking has to be minimized (Mirza & Soroushian, 2002).

5.2 Practical Implications

In addition to the mechanical improvements, metakaolin and steel fibre synergy provides enhanced durability, which is paramount for structures exposed to aggressive environments. The reduced chloride permeability diminishes chloride-induced corrosion, extending service life in maritime or de-icing salt conditions. Meanwhile, the improved resistance to sulfate attack signals the potential to use this composite in applications with high sulfate concentrations, such as coastal foundations or wastewater treatment plants.

Given the enhanced ductility, crack resistance, and durability, metakaolin-blended FRO shows considerable promise for high-rise building columns, bridge decks, industrial floors, and other hardened surfaces subject to heavy traffic or repeated loading. "The relatively small increase in material costs due to steel fibres may be offset by a significantly longer service life and reduced maintenance requirements." (Bentur & Mindess, 2007).

6. Conclusion

The impact of crimped steel fibers in reinforcing high-strength concrete that uses metakaolin as a partial cement substitute is clarified by this research. The key findings can be summarized as follows:

1. Enhanced Mechanical Properties:

- Metakaolin replacement (10%) increases compressive strength.
- Steel fibres, particularly at 2% volume, significantly boost splitting tensile and modulus of rupture.

2. Improved Durability:

- Reduced chloride permeability and water absorption were consistently observed with the incorporation of metakaolin and steel fibres.
- Specimens displayed superior resistance to sulfate attack, with substantially lower expansion rates compared to control specimens.

3. Synergistic Effect:

- The combination of metakaolin’s refined matrix and steel fibres’ crack-bridging function leads to improved structural integrity and extended service life potential for high-strength concrete applications.

In future work, varying percentages of metakaolin (e.g., 5-15%) and steel fibres (0.5-2.5%) could be further investigated in conjunction with other advanced admixtures or nanomaterials for optimizing performance. Moreover, long-term field validations under real-life loading and environmental conditions would strengthen confidence in adopting metakaolin-blended steel fibre-reinforced high-strength concrete for critical infrastructure projects.

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