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Experimental Study on M40 Concrete with Partial Cement Replacement Using Silicon Carbide and Carboxymethyl Cellulose Hybrid Matrix

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ABSTRACT - The growing demand for high-performance and sustainable construction materials has accelerated the development of advanced cementitious composites with enhanced mechanical and microstructural properties. This study presents an experimental investigation on M40 grade concrete incorporating a hybrid matrix composed of Silicon Carbide (SiC) and Carboxymethyl Cellulose (CMC) as a partial replacement of cement. The hybrid system was introduced at replacement levels of 2%, 4%, 6%, and 8% by weight of cement to evaluate its influence on fresh and hardened properties.

The experimental program included workability assessment using the slump cone test and compressive strength evaluation at curing ages of 7, 14, and 28 days, in accordance with relevant Indian Standard codes. The results indicate a consistent reduction in workability with increasing hybrid content, attributed to the high surface area of SiC particles and the viscosity-modifying behavior of CMC. However, a significant improvement in compressive strength was observed up to an optimum replacement level of 6%, beyond which strength declined due to possible particle agglomeration and disruption in hydration mechanisms.

At 6% replacement, the concrete achieved a maximum compressive strength of 47.8 MPa, representing an increase of approximately 14.9% compared to conventional M40 concrete. The enhancement in mechanical performance is primarily attributed to the synergistic interaction between SiC and CMC, where SiC acts as a micro-filler improving particle packing density, while CMC enhances dispersion, hydration control, and interfacial bonding within the cement matrix. This combined effect leads to a denser microstructure and improved load transfer efficiency.

The study concludes that the SiC–CMC hybrid matrix offers a viable approach for optimizing strength and material performance while reducing cement consumption. Although the inclusion of hybrid additives increases the overall cost, the improved structural efficiency makes it suitable for high-performance and specialized construction applications. This research contributes to the advancement of hybrid composite technology in concrete and provides a foundation for future studies on durability and large-scale implementation.

Key Words: M40 Concrete, Silicon Carbide (SiC), Carboxymethyl Cellulose (CMC), Hybrid Matrix Composite, Compressive Strength, Workability, Sustainable Concrete.

1.INTRODUCTION

The increasing demand for high-performance and sustainable construction materials has led to the development of advanced cementitious composites with improved mechanical properties and reduced environmental impact. Conventional concrete, although widely used, suffers from inherent drawbacks such as brittleness, micro-crack formation, and high cement consumption, which contributes significantly to carbon emissions. These limitations necessitate the exploration of innovative material systems capable of enhancing strength and durability.

Hybrid matrix composites (HMCs) have emerged as a promising solution by combining different materials to achieve superior performance through synergistic interaction. In this context, Silicon Carbide (SiC), a high-strength ceramic material, acts as a micro-filler that improves particle packing and reduces internal porosity, thereby enhancing compressive strength. On the other hand, Carboxymethyl Cellulose (CMC), a polymer-based additive, functions as a viscosity-modifying and dispersing agent that improves workability, hydration control, and interfacial bonding within the concrete matrix.

The combined use of SiC and CMC forms a hybrid system that enhances both the microstructure and mechanical performance of concrete. However, limited research exists on their combined application as partial cement replacement in high-strength concrete, particularly in M40 grade. Additionally, the optimization of replacement levels remains a critical concern, as excessive addition may negatively affect workability and strength.

Furthermore, the interaction between ceramic particles and polymer modifiers plays a crucial role in improving the interfacial transition zone (ITZ), which governs the overall strength and durability of concrete. The micro-filling ability of SiC reduces voids, while CMC ensures uniform dispersion, resulting in a denser and more cohesive matrix. This improved internal structure enhances load transfer efficiency and resistance to crack propagation. Such hybrid systems also contribute to material efficiency by reducing cement usage without compromising structural performance.

Therefore, this study investigates the effect of a SiC–CMC hybrid matrix as a partial replacement of cement at varying levels (2% to 8%) in M40 grade concrete. The research focuses on evaluating workability and compressive strength to determine the optimum replacement level that achieves enhanced performance while maintaining practical applicability.

2. LITERATURE SURVEY

The development of high-performance concrete has witnessed a significant transformation with the incorporation of hybrid materials that combine multiple reinforcing mechanisms within a single matrix. Traditional concrete, though widely used, suffers from limitations such as brittleness, low tensile capacity, and susceptibility to micro-cracking. To address these issues, recent research has focused on hybrid composite systems that integrate ceramic, polymeric, and fibrous materials to enhance both mechanical and durability characteristics.

Hybrid fiber-reinforced concrete has been extensively studied as a foundational concept in composite material design. Vairagade [1] conducted a comprehensive review on hybrid fiber systems and reported that the combination of different fibers significantly improves ductility, crack resistance, and load-bearing capacity. The study highlighted that hybridization enables multi-scale crack control, where different materials act at different stages of crack propagation. This concept of synergy forms the basis for extending hybridization beyond fibers to ceramic-polymer systems such as SiC–CMC matrices.

Similarly, Seydibeyoğlu et al. [2] investigated hybrid polymer matrix composites reinforced with nanocellulose and nanomaterials. Their findings demonstrated that the combination of organic and inorganic constituents enhances interfacial bonding and mechanical strength through improved dispersion and structural compatibility. The study emphasized the importance of controlled filler distribution, which is directly relevant to the use of CMC as a dispersing agent in hybrid cementitious systems.

Optimization techniques have also played a crucial role in hybrid composite research. Kumar et al. [3] applied the Six Sigma DMAIC methodology to hybrid composites and reported a significant improvement in stiffness and reduction in defects. Their work highlights the importance of systematic optimization in determining the ideal proportion of hybrid constituents, which is critical when evaluating different replacement levels in concrete systems.

In the context of concrete materials, Murugesan [4] experimentally investigated hybrid fiber-reinforced concrete and observed improvements in both workability and mechanical properties when appropriate proportions were used. The study demonstrated that hybrid systems can balance fresh and hardened properties, though excessive addition may lead to reduced workability. This observation aligns with the expected behavior of SiC–CMC hybrid systems, where increased dosage affects rheological properties.

Further studies by Suman et al. [5] utilized response surface methodology to optimize hybrid fiber content in concrete. The results indicated that compressive and flexural strengths increase up to an optimal dosage, beyond which performance declines. This trend of peak performance followed by reduction is a critical characteristic of hybrid systems and provides a theoretical basis for evaluating optimum replacement levels in ceramic-polymer composites.

The role of individual materials such as Silicon Carbide has also been explored in cementitious composites. Al-Salim et al. [6] investigated the effect of SiC in concrete and reported a significant increase in compressive and flexural strength due to microstructural densification. The study attributed this improvement to the micro-filling effect of SiC, which reduces porosity and enhances particle packing density. These findings strongly support the use of SiC as a high-performance additive in hybrid concrete systems.

In addition to static mechanical properties, dynamic behavior has also been studied. Li et al. [7] analyzed the dynamic mechanical performance of SiC-reinforced concrete and found that SiC improves energy absorption and resistance to crack propagation under high strain rates. This highlights the potential of SiC in enhancing the durability and resilience of concrete structures subjected to dynamic loading conditions.

On the polymer side, Pourchez et al. [8] examined the influence of Carboxymethyl Cellulose (CMC) on cement properties and reported improvements in cohesion, hydration control, and microstructural refinement. The study revealed that CMC enhances the internal bonding of the cement matrix by forming a thin polymer film, which improves the interfacial transition zone (ITZ). However, excessive dosage was found to delay hydration and reduce early strength, indicating the need for controlled usage.

The combined effect of ceramic and polymer materials has been investigated in hybrid systems. Gupta et al. [9] studied polymer-ceramic hybrid composites and observed that the interaction between the two components leads to significant improvements in strength and durability. The polymer component enhances dispersion and bonding, while the ceramic component contributes to stiffness and strength. This synergistic mechanism is directly applicable to SiC–CMC hybrid concrete systems.

Microstructural studies further support the effectiveness of hybrid materials. Khan et al. [10] reported that cellulose-based nanomaterials combined with carbon reinforcements significantly reduce porosity and improve the mechanical performance of cement composites. The study emphasized that uniform dispersion of particles is essential for achieving optimal results, reinforcing the role of CMC as a dispersing agent in hybrid systems.

Research on nanomaterials has also demonstrated similar trends. Zhang et al. [11] investigated nano-SiC in cementitious composites and observed substantial improvements in compressive strength and durability due to accelerated hydration and refined pore structure. Although the study focused on nano-scale materials, the underlying mechanism of pore refinement is applicable to micro-scale SiC used in this research.

Additionally, Liu et al. [12] studied SiC whiskers in cement paste and found that they effectively bridge micro-cracks and improve fracture toughness. This crack-bridging mechanism enhances the load-carrying capacity of concrete and delays failure, contributing to improved structural performance.

Despite the extensive research on individual materials and hybrid systems, a critical gap remains in the combined application of ceramic and polymer additives as partial cement replacement in high-strength concrete. Most studies focus on either fiber-based hybrids, nanomaterials, or single additives, with limited attention given to ceramic-polymer hybrid matrices in conventional grades such as M40 concrete. Furthermore, the optimization of replacement levels and the balance between workability and strength are not sufficiently addressed in existing literature.

Therefore, there is a clear need for systematic experimental investigation into hybrid systems that combine the micro-filling capability of ceramic materials like Silicon Carbide with the dispersion and bonding enhancement of polymers like Carboxymethyl Cellulose. Such studies can provide valuable insights into the development of high-performance, sustainable concrete with improved mechanical properties and reduced cement consumption.

3.RESEARCH GAP & PROBLEM STATEMENT

The advancement of concrete technology has been significantly influenced by the incorporation of supplementary materials such as fibers, nanomaterials, and mineral admixtures. Numerous studies have demonstrated that hybrid systems, particularly fiber-based and nano-reinforced composites, can enhance the mechanical and durability properties of concrete through synergistic interactions between different constituents. However, the majority of existing research is primarily focused on fiber hybridization or nano-scale additives, with limited attention given to ceramic–polymer hybrid systems in conventional structural concrete.

Previous investigations have established that Silicon Carbide (SiC) acts as an effective micro-filler, improving compressive strength through pore refinement and enhanced particle packing. Similarly, Carboxymethyl Cellulose (CMC) has been shown to improve dispersion, hydration control, and interfacial bonding within the cement matrix. While these materials have been studied individually, there is a lack of comprehensive experimental research on their combined application as a hybrid matrix in concrete.

Furthermore, existing literature does not adequately address the behavior of such hybrid systems in M40 grade concrete, which is widely used in structural applications. Most studies are limited to either high-performance or nano-modified systems, leaving a gap in understanding how ceramic–polymer hybrids perform in practical, field-relevant concrete grades. Additionally, the interaction between SiC and CMC within the Interfacial Transition Zone (ITZ) and its influence on strength development has not been sufficiently explored.

Another critical gap lies in the optimization of replacement **levels**. While hybrid materials are known to improve strength, excessive addition may lead to reduced workability, particle agglomeration, and disruption of hydration processes. However, there is limited research that systematically evaluates the optimal percentage of hybrid replacement that balances both fresh and hardened properties of concrete.

Moreover, the trade-off between workability and strength in hybrid-modified concrete remains underexplored. The inclusion of fine ceramic particles and polymer modifiers significantly alters the rheological behavior of concrete, yet few studies provide a clear correlation between these changes and the resulting mechanical performance.

In addition to technical aspects, the economic feasibility of using such hybrid materials has received minimal attention. Although advanced materials improve performance, their higher cost may limit practical application unless justified through performance gains.

Problem Statement

M40 grade concrete, widely used in structural construction, exhibits limitations such as brittleness, micro-cracking, and high cement dependency, contributing to environmental concerns and reduced durability. While individual additives like Silicon Carbide (SiC) and Carboxymethyl Cellulose (CMC) have shown potential in improving concrete performance, their combined effect as a hybrid cement replacement material is not well understood.

There is a need to investigate whether the integration of a SiC–CMC hybrid matrix can enhance the mechanical properties of concrete through microstructural densification and improved bonding, while maintaining acceptable workability. Additionally, the optimal replacement level must be identified to maximize strength without causing adverse effects such as reduced consistency or inefficient hydration.

Therefore, this study aims to experimentally evaluate the performance of M40 concrete with partial cement replacement using a SiC–CMC hybrid matrix at varying percentages, in order to establish an optimal balance between strength, workability, and practical applicability.

4.METHODOLOGY

4.1 Research Design

The present study adopts a controlled experimental methodology to investigate the influence of a hybrid matrix composite comprising Silicon Carbide (SiC) and Carboxymethyl Cellulose (CMC) on the performance of M40 grade concrete. The investigation focuses on evaluating both fresh properties (workability) and hardened properties (compressive strength) under standardized laboratory conditions.

A comparative analysis was performed between a conventional control mix and hybrid-modified concrete mixes with varying levels of cement replacement. The experimental program was designed to ensure consistency, repeatability, and compliance with relevant Indian Standard (IS) codes.

4.2 Mix Design Procedure

The mix design for M40 grade concrete was carried out in accordance with IS 10262:2019, considering moderate exposure conditions as per IS 456:2000.

The target mean compressive strength was calculated using:

$$f'_{ck} = f_{ck} + 1.65S$$

Where:
$f_{ck} = 40\,MPa, S = 5\,MPa$

$$f'_{ck} = 48.25\,MPa$$

A water–cement ratio of 0.40 was adopted to achieve the required strength and durability. The cementitious content was determined as:

$$C = \frac{W}{(w/c)} = \frac{158}{0.40} = 395\,kg/m^3$$

The mix proportions were maintained constant for all batches except for the variation in hybrid replacement.

4.3 Materials Characterization

All materials used in this study were tested and verified to comply with standard specifications.

Cement: Ordinary Portland Cement (OPC) 53 grade conforming to IS 269:2015, with specific gravity of 3.15.

Fine Aggregate: Manufactured sand (M-Sand), Zone II grading as per IS 383:2016, specific gravity 2.62.

Coarse Aggregate: Crushed angular aggregates of 20 mm maximum size, specific gravity 2.70.

Water: Clean potable water suitable for mixing and curing as per IS 456:2000.

Silicon Carbide (SiC): Fine powder (220–600 mesh), specific gravity ≈ 3.22, used as micro-filler.

Carboxymethyl Cellulose (CMC): Water-soluble polymer with specific gravity ≈ 1.60, used as viscosity modifier and dispersant.

Superplasticizer: Polycarboxylate Ether (PCE)-based admixture conforming to IS 9103.

4.4 Hybrid Matrix Proportioning

The hybrid matrix was prepared using a fixed proportion of CMC:SiC = 1:4, ensuring effective dispersion of ceramic particles within the cementitious matrix.

Cement was partially replaced by the hybrid composite at four levels:

H1: 2% replacement

H2: 4% replacement

H3: 6% replacement

H4: 8% replacement

A control mix (CM) with 0% replacement was also prepared.

The replacement was performed on a mass basis, maintaining constant total binder content across all mixes.

4.5 Mixing and Casting Procedure

The mixing process was carried out using a laboratory mixer to ensure uniform distribution of materials. Initially, cement, SiC, and CMC were dry-mixed for 5 minutes to achieve a homogeneous hybrid binder. This step is critical to prevent agglomeration of fine particles.

Subsequently, fine and coarse aggregates were added and mixed thoroughly. Water mixed with superplasticizer was then introduced gradually to achieve the desired consistency.

Fresh concrete was placed into 150 mm cube moulds in three layers. Each layer was compacted using 25 strokes of a tamping rod in accordance with IS standards. The top surface was leveled and finished smoothly.

4.6 Curing Regime

After casting, specimens were kept undisturbed for 24 hours at room temperature. They were then demoulded and transferred to a curing tank containing clean water maintained at standard laboratory temperature.

All specimens were cured for 7, 14, and 28 days to ensure proper hydration and strength development.

4.7 Testing of Fresh Concrete

Workability was assessed using the Slump Cone Test as per IS 1199:2018. The test measures the consistency of fresh concrete and indicates its ease of handling and placement.

The slump value was recorded as:

$$Slump = H_{mould} - H_{concrete}$$

where the difference represents the vertical subsidence of concrete after removal of the mould.

4.8 Testing of Hardened Concrete

The compressive strength test was conducted on cube specimens using a Compression Testing Machine (CTM) with a capacity of 2000 kN, as per IS 516:2021.

The compressive strength was determined using:

$$f_c = \frac{P}{A}$$

Where:
P= failure load (N)
A= cross-sectional area (mm²)

For each mix and curing age, three specimens were tested, and the average value was considered to ensure reliability.

4.9 Experimental Variables

The primary variable in this study is the percentage replacement of cement with hybrid matrix (2%–8%). All other parameters such as:

- Water–cement ratio
- Aggregate proportions
- Curing conditions
- Specimen size

were kept constant to ensure a controlled comparison.

4.10 Evaluation Criteria

The performance of hybrid concrete was evaluated based on:

Workability behavior (slump variation)

Compressive strength development (7, 14, 28 days)

The results were analyzed to identify the optimum replacement level that provides maximum strength with acceptable workability.

5.RESULTS AND DISCUSSION

5.1 General Overview

The experimental investigation was conducted to evaluate the influence of partial cement replacement using a Silicon Carbide (SiC) and Carboxymethyl Cellulose (CMC) hybrid matrix on the performance of M40 grade concrete. The results were analyzed in terms of workability through slump test and compressive strength at 7, 14, and 28 days. A comparative assessment with the control mix was carried out to establish performance trends and determine the effectiveness of the hybrid system.

5.2 Workability Analysis

The results obtained from the slump cone test reveal a gradual decrease in workability with an increase in the percentage of hybrid replacement. The control mix exhibited the highest slump value, indicating better flowability, whereas mixes with higher hybrid content showed reduced consistency. This behavior is primarily attributed to the presence of Silicon Carbide particles, which possess a high surface area and increase the internal friction within the mix. Additionally, the incorporation of Carboxymethyl Cellulose contributes to increased viscosity due to its water-retaining and thickening properties.

As the replacement level increases from 2% to 8%, the combined effect of these materials results in a denser and more cohesive mix, thereby reducing the ease of flow. However, the reduction in workability remains within acceptable limits for structural applications, particularly with the use of superplasticizer. This indicates that although the hybrid matrix influences rheological behavior, it does not render the concrete unworkable. The observed trend highlights the inherent trade-off between workability and internal structural enhancement in modified concrete systems.

5.3 Compressive Strength Analysis

Table 5.1: Compressive Strength Test Results

ID	Replacement (%)	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)	% Gain (vs CM)
CM	0% (Control)	27.8	37.6	41.6	Baseline
H1	2%	30.1	39.6	43.5	+4.6%
H2	4%	31.5	41.2	45.4	+9.1%
H3	6% (Peak)	34.2	44.8	47.8	+14.9%
H4	8%	30.8	40.5	44.7	+7.4%

The compressive strength results demonstrate a clear trend of strength enhancement with increasing hybrid replacement up to a certain limit, followed by a reduction beyond that point. At early curing stages, particularly at 7 days, hybrid mixes showed higher strength compared to the control mix, indicating that the presence of Silicon Carbide contributes to early matrix densification. This improvement continues at 14 and 28 days, confirming the sustained influence of the hybrid system on strength development.

The maximum compressive strength was achieved at 6% replacement, where the concrete reached a value of 47.8 MPa compared to 41.6 MPa for the control mix . This significant increase in strength can be attributed to the synergistic interaction between SiC and CMC within the concrete matrix. The fine SiC particles act as micro-fillers, occupying voids and improving particle packing density, while CMC ensures uniform dispersion and enhances bonding between the constituents.

At 8% replacement, a reduction in compressive strength is observed. This decline may be due to excessive addition of hybrid materials leading to particle agglomeration, increased viscosity, and interference with proper hydration. The results suggest that there exists an optimum threshold beyond which the beneficial effects of the hybrid system are diminished.

5.4 Strength Development Behavior

The strength development pattern across different curing periods indicates that all mixes follow a consistent hydration trend, with strength increasing over time. However, hybrid mixes exhibit a comparatively higher rate of strength gain, particularly between 7 and 28 days. This behavior suggests that the hybrid matrix enhances the efficiency of hydration and contributes to a more refined microstructure.

The improved strength development can be associated with reduced porosity and better moisture retention within the matrix. The presence of CMC helps maintain internal moisture, allowing continued hydration, while SiC contributes to structural densification. As a result, the hybrid concrete exhibits improved load-bearing capacity and structural integrity over time.

5.5 Combined Performance Evaluation

A combined analysis of workability and compressive strength clearly indicates that 6% replacement represents the optimum condition for the hybrid system. At this level, the concrete achieves maximum compressive strength while maintaining workable consistency suitable for practical applications. As the replacement percentage increases, compressive strength initially improves due to enhanced microstructure, whereas workability decreases due to increased internal resistance.

The intersection of these opposing trends defines the performance threshold of the hybrid concrete. This balance is crucial in determining the practical applicability of the material, as both strength and workability are essential parameters in construction.

5.6 Microstructural Interpretation

The improved performance of hybrid concrete can be explained through microstructural modifications within the cementitious matrix. The inclusion of Silicon Carbide leads to a reduction in pore size and overall porosity, resulting in a denser structure. At the same time, Carboxymethyl Cellulose enhances particle dispersion and forms a thin polymer film that improves bonding at the interfacial transition zone.

This combined effect strengthens the weakest region of concrete, namely the interfacial transition zone, thereby improving stress distribution and reducing the likelihood of crack initiation. The enhanced bonding and reduced void content contribute significantly to the observed increase in compressive strength.

5.7 Practical Implications

From a practical perspective, the results indicate that the incorporation of a SiC–CMC hybrid matrix can significantly

improve the performance of M40 grade concrete, making it suitable for high-strength structural applications. However, the reduction in workability at higher replacement levels necessitates the use of suitable admixtures to maintain consistency. Additionally, the increased cost associated with hybrid materials must be justified by the improvement in mechanical performance, particularly in specialized construction scenarios.

6.CONCLUSION

The present study investigated the effect of partial cement replacement using a hybrid matrix composed of Silicon Carbide (SiC) and Carboxymethyl Cellulose (CMC) on the performance of M40 grade concrete. Based on the experimental results and analysis, it is evident that the incorporation of the hybrid matrix significantly influences both fresh and hardened properties of concrete.

The workability of concrete was found to decrease progressively with an increase in hybrid replacement due to the high surface area of SiC particles and the viscosity-modifying nature of CMC. However, the mixes remained within acceptable limits for practical application, particularly with the use of superplasticizer. In contrast, compressive strength exhibited a notable improvement with increasing replacement levels up to an optimum value, beyond which a decline was observed.

The maximum compressive strength was achieved at 6% replacement, reaching 47.8 MPa compared to 41.6 MPa for conventional concrete . This enhancement is attributed to the synergistic interaction between SiC and CMC, where SiC contributes to microstructural densification through its micro-filling effect, and CMC improves dispersion, hydration control, and interfacial bonding within the cement matrix. The combined effect results in a denser and more cohesive structure with improved load-bearing capacity.

Beyond the optimum level, a reduction in strength was observed, indicating that excessive hybrid content may lead to particle agglomeration and disruption of hydration processes. This highlights the importance of optimizing the dosage of hybrid materials to achieve maximum performance benefits.

Overall, the study demonstrates that the SiC–CMC hybrid matrix is an effective approach for enhancing the mechanical performance of M40 concrete while reducing cement consumption. Although the incorporation of hybrid materials increases the cost of concrete, the improvement in strength and structural efficiency justifies its application in high-performance and specialized construction. The findings of this research contribute to the development of advanced hybrid concrete systems and provide a foundation for future studies focusing on durability, long-term performance, and large-scale implementation.

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