Mechanical Behavior of Binary Blend Concrete Incorporating Micro Silica and Recycled Ceramic Aggregates

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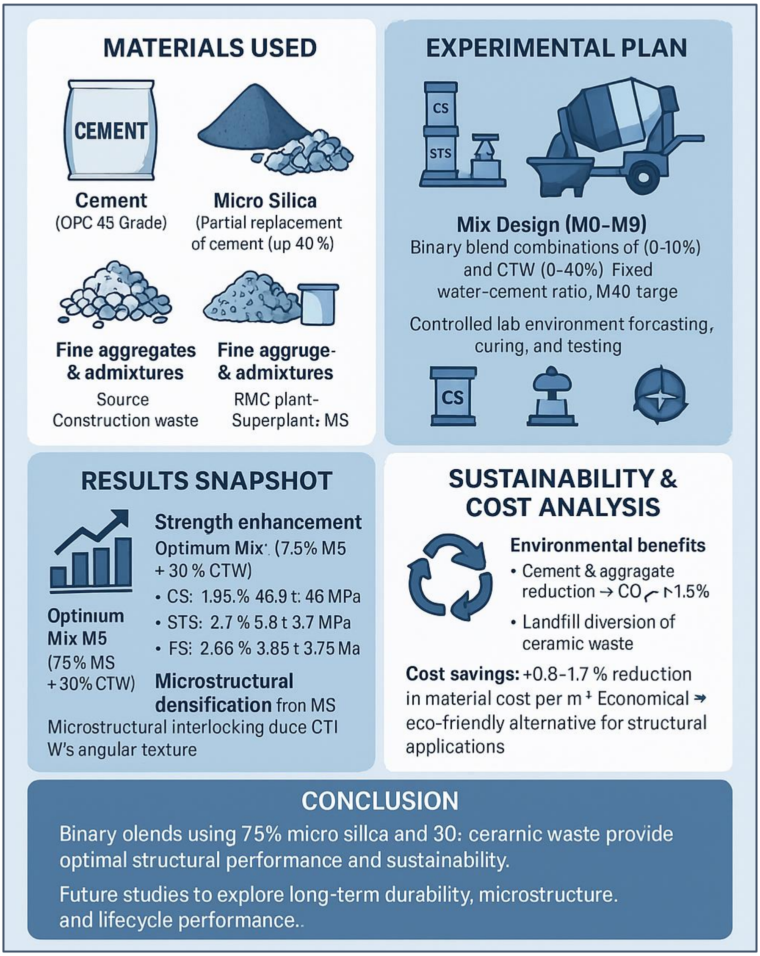
Abstract. The demand for sustainable and high-performance concrete has intensified the exploration of industrial by-products and waste materials as partial replacements in conventional mix designs. In response to these concerns, this study assesses the feasibility of incorporating ceramic tile waste (CTW) as a replacement for coarse aggregates and micro silica (MS) as a partial binder substitute in the production of sustainable concrete. The binary mixes (M4) demonstrated the synergistic potential of combining micro silica and ceramic tile waste. Optimum values of 7.5% micro silica and 30% ceramic waste taken from the individual study in both cases for combined designated binary mix for M40 grade of concrete as strength enhanced compared to the reference mix. Additionally, microstructural densification due to reduced porosity enhanced the durability characteristics of the composite material. By utilizing industrial waste products, thereby addressing environmental challenges by lowering CO2 emissions and promoting circular economy by lowering the cost of concrete construction.

Keywords: Binar blend, ceramic waste, micro silica, aggregates, cement, sustainability.

S. Kumar et al. (eds.), *Proceedings of the 2nd International Conference on Advanced Materials & Devices for Futuristic Applications-2024 (IC-AMDFA 2024)*, Atlantis Highlights in Materials Science and Technology 5,
https://doi.org/10.2991/978-94-6239-695-1_14

Graphical Abstract



MATERIALS USED

Cement (OPC 45 Grade)

Micro Silica (Partial replacement of cement (up 40 %)

Fine aggregates & admixtures Source Construction waste

Fine aggruge- & admixtures RMC plant- Superplant: MS

EXPERIMENTAL PLAN

Mix Design (M0-M9) Binary blend combinations of (0-10%) and CTW (0-40%) Fixed water-cement ratio, M40 targe

Controlled lab environment forcasting, curing, and testing

RESULTS SNAPSHOT

Strength enhancement
Optimum Mix: (7.5% M5 + 30 % CTW)
- CS: 1.95.% 46.9 t: 46 MPa
- STS: 2.7 % 5.8 t 3.7 MPa
- FS: 2.66 % 3.85 t 3.75 Ma

Optinium Mix M5 (75% MS +30% CTW)

Microstructural densification fron MS
Microstructural interlocking duce CTI W's angular texture

SUSTAINABILITY & COST ANALYSIS

Environmental benefits
- Cement & aggregate reduction → CO ↑1.5%
- Landfill diversion of ceramic waste

Cost savings: +0.8-1.7 % reduction in material cost per m³ Economical → eco-friendly alternative for structural applications

CONCLUSION

Binary olends using 75% micro sillca and 30: cerarnic waste provide optimal structural performance and sustainability.

Future studies to explore long-term durability, microstructure. and lifecycle performance..

1. Introduction

The present research seeks to fill these gaps by providing an in-depth experimental analysis by varying combinations of micro silica and ceramic tile waste. By maintaining constant parameters and standardized testing environments, the study aims to establish reliable relationships between the substitution levels and strength outcomes [1-2]. In doing so, it contributes valuable insights into the practical feasibility of deploying these materials in structural applications, aligning with global efforts toward environmentally responsible construction practices. The reuse of ceramic tile waste (CTW) in concrete has gained substantial attention due to the volume of such waste generated in urban areas. Crushed ceramic tiles possess angular, rough-textured surfaces that enhance mechanical interlocking when used as aggregate [3-6]. Several investigations have demonstrated the potential of ceramic waste in improving or at least sustaining the mechanical performance of concrete [7]. This improvement is primarily credited to the mechanical bonding facilitated by the rough surface of ceramic particles and their rigidity under load. However, at higher substitution rates, a decline in strength has been reported, which researchers often relate to increased void content and poor inter-particle packing. In addition to strength parameters, ceramic aggregates have also been evaluated for their durability [8]. Some researchers reported that the addition of ceramic particles reduced water absorption and enhanced resistance to sulphate attacks, due to the low porosity and chemically inert nature of the ceramic fragments. This property makes CTW a particularly valuable material in aggressive environmental conditions [9-10]. The introduction of micro silica facilitates pozzolanic reactions forming (C-S-H) gel [11]. This process contributes significantly to enhancing the strength and permeability of the matrix. Research has consistently demonstrated the benefits of incorporating micro silica at replacement levels ranging from 5% to 15% by weight of cement. Optimal improvements in compressive and flexural strength have been observed around 8% to 10% substitution levels. Excessive replacement, however, may reduce workability due to the high surface area of micro silica, which demands additional water or admixtures to maintain flowability [12]. The durability benefits of micro silica inclusion are well-documented. Studies have shown increased resistance to chloride penetration, reduced permeability, and superior resistance to chemical attacks [13-14]. Studies shown that material like fly ash incorporation in concrete enhances the mechanical properties due to its fine's particle size. [15-19]. These enhancements are particularly significant for structures exposed to marine environments or chemical industrial atmospheres. Despite the abundant individual studies on CTW and MS, their combined use in concrete is still underrepresented in academic literature. A few pioneering investigations suggest that the simultaneous incorporation of micro silica and ceramic waste may yield synergistic effects. The densification of the cementitious matrix through pozzolanic reaction, combined with the mechanical stability of ceramic aggregates, can lead to a more robust composite material [20-22]. Some researchers have reported that concrete mixes containing 20% ceramic waste as aggregate and 5–10% micro silica as binder substitution achieved superior strength properties compared to control mixes. These studies emphasized that micro silica's micro-filling action compensates for the internal voids introduced by ceramic aggregates, leading to a refined pore structure [23-24].

2. Materials & Methodology

2.1 Material

Cement – The OPC of 43-grade, complying with the requirements of IS: 269-2015. This grade of cement was chosen due to its widespread application in structural concrete works. The cement was free from lumps and showed consistent fineness, ensuring effective hydration and early strength development.
Micro Silica – Micro silica collected from the RMC plant located in the Mohali, Punjab.
Aggregate - Conforming to Zone II grading fine aggregates used in the study, as per IS: 383-2016, was employed as the fine aggregate. Coarse aggregate with maximum size of 20mm take for the study conforming to the IS:2386.

Ceramic Waste (CW) – Collected from the demolished waste of the construction site and converted into the broken pieces as of coarse aggregates
Chemical Admixture – Sika Plast Superplasticizer by 1% mixed with water to increase the workability of concrete.

2.2 Methodology

Table 1 shows the nomenclature and the M40 grade of concrete taken from the experimental study.

Table 1: Nomenclature and proportions

Mixes	Cement (%)	Micro Silica (%)	Coarse Aggregates (%)	Ceramic waste (%)	Fine Aggregates (%)
M0	100	0	100	0	100
M1	95	5	80	20	100
M2	92.5	7.5	80	20	100
M3	90	10	80	20	100
M4	92.5	7.5	70	30	100
M5	90	5	70	30	100
M6	90	10	70	30	100
M7	95	5	60	40	100
M8	92.5	7.5	60	40	100
M9	90	10	60	40	100

Raw material, mixing of concrete, compaction by vibration and casting shown in Figure 1, Figure 2, Figure 3 and Figure 4 respectively.

Fig. 1: Collection of material

Fig. 2: Mixing of samples

Fig. 3: Compaction by vibration

Fig. 4: Casting of specimen

3. Results and Discussion

3.1 Compressive Strength Test (CS) - The CS test performed on cube specimens at 7D and 28D. The rate of loading was maintained at 140 kg/cm²/min and figure 5 shows the image of machine. The mix M6 attained optimum strength compared with the reference mix. The optimum strength of 46.9 N/mm^2 and the reference concrete having strength of 46 N/mm^2 and overall CS enhanced by 1.95% as compared with the reference mix. The results shown in table 2 and figure 6 represents the graphical presentation.

Fig. 5: Compressive strength test

Table 2: Compressive strength results (CS)

Mixes	CS (7 Days)	CS (28 Days)
M0	27	46
M1	28.2	46.1
M2	28	46.3
M3	26	43
M4	28	44.7

M5	28.8	46.9
M6	27	44
M7	24.4	36.5
M8	25	38
M9	24.1	36

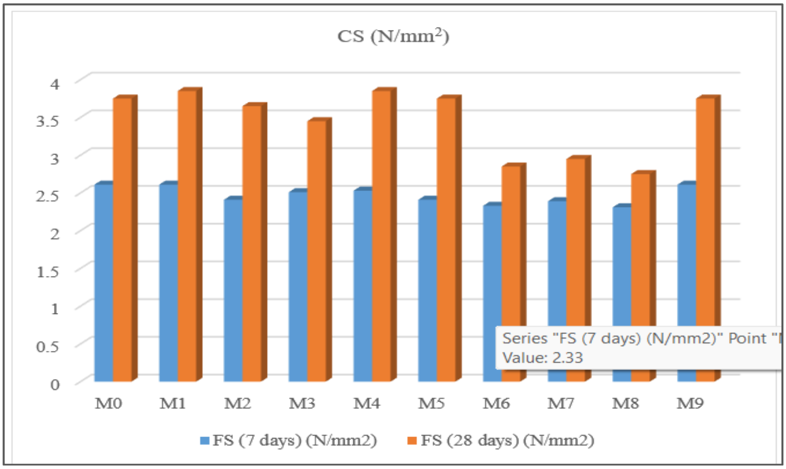


Fig. 6: Graphical presentation of compressive strength

3.2 Split Tensile Strength (SPT) - It was evaluated on cylindrical specimens as per ASTM C496. The specimens were placed horizontally, and a uniform diametrical load was applied until failure and figure 7 shows the machine image. The split tensile strength was calculated till load sustained. Mix 4 having optimum strength with 3.8 N/mm^2 and the reference concrete having strength of 3.7 N/mm^2 as results shown in Table 3 and Figure 8 shows its graphical presentation and hence the results show very little enhancement in strength.

Fig.7: Split Tensile strength apparatus.

Table 3: Split tensile strength results (SPT)

Mixes	SPT (7 Days)	SPT (28 Days)
M0	2.6	3.7
M1	2.6	3.8
M2	2.4	3.6
M3	2.5	3.4
M4	2.52	3.8
M5	2.4	3.7
M6	2.32	2.8
M7	2.38	2.9
M8	2.3	2.7
M9	2.6	3.7

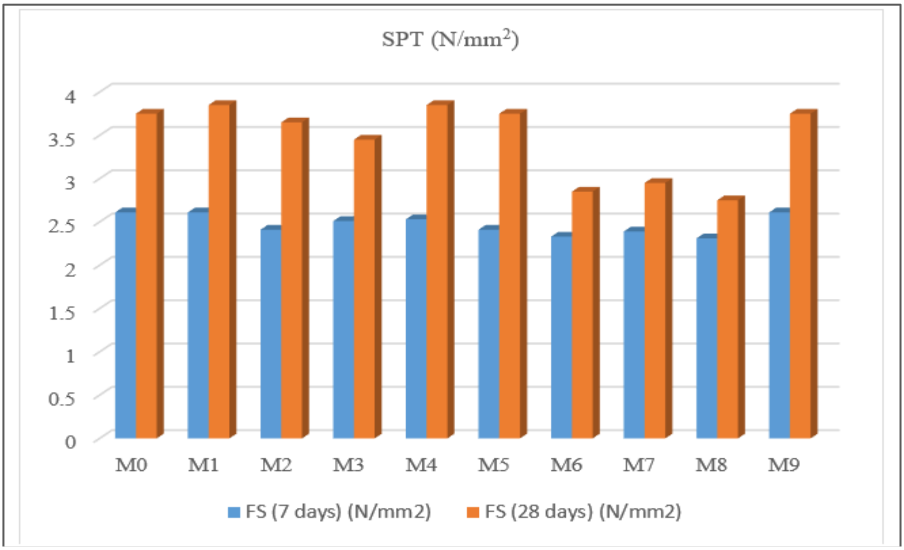


Fig. 8: Graphical presentation of SPT

3.3 Flexural Strength (FS): Figure 9 shows the FS machine to test the beam of concrete. Mix M4 shows the optimum value of 3.85 N/mm^2 and the reference concrete having strength of 3.75 N/mm^2. Results show overall enhancement of strength by 2.66% compared with the reference mix in Table 4 and its graphical presentation in Figure 10.

Fig. 9: Flexural strength test

Table 4: Flexural Strength results (FS)

Mixes	FS (7 Days)	FS (28 Days)
M0	2.61	3.75
M1	2.61	3.85
M2	2.41	3.65
M3	2.51	3.45
M4	2.53	3.85
M5	2.41	3.75
M6	2.33	2.85
M7	2.39	2.95
M8	2.31	2.75
M9	2.61	3.75

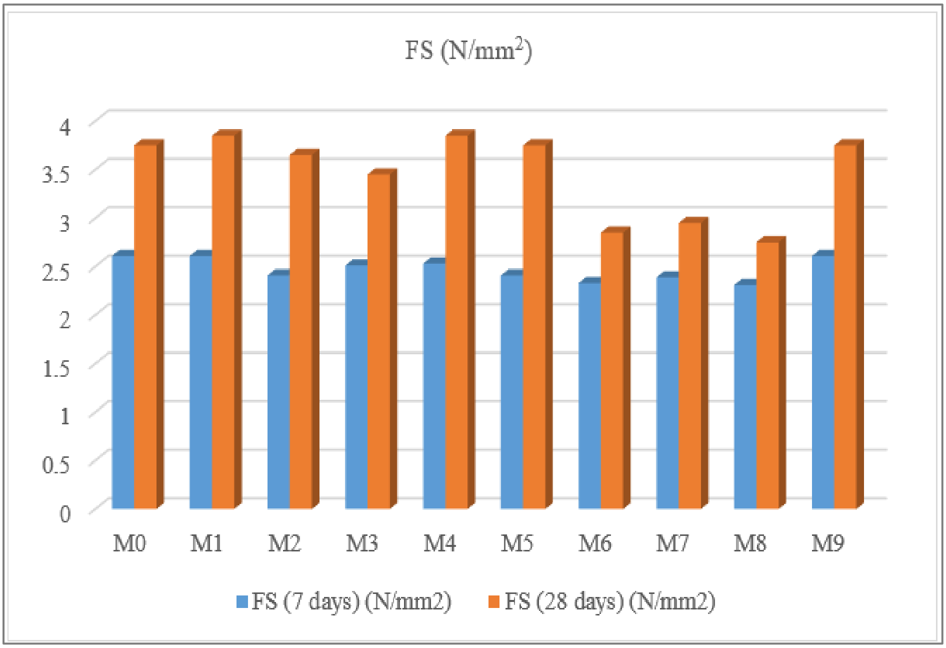


Fig. 10: Graphical presentation of FS test

4. Cost Analysis and Environmental impact analysis

In engineering solutions, a cost-effective approach must be considered [25]. It must be accompanied in the direction of reducing environmental impact through sustainable practices [26-27]. The optimum strength achieved at 7.5% micro silica replaced with cement and 30% ceramic waste replaced with coarse aggregates. This reduction of 7.5 by percentage of per cubic meter of cement can affect the cost of concrete as cement known as most expensive material as compared with the remaining ingredients of concrete. Also, the maximum volume of concrete is covered by coarse aggregates and the second most expensive material in concrete. So, overall reduction of this natural material by replacing material that is less expensive than cement and coarse aggregates can contribute to economical construction. The cost analysis gives approximately 0.8 to 1.2 % approximate reduction in the overall cost of the concrete as per pilot study conducted which makes it economical. Figure 11 shows the cost analysis and carbon emissions analysis.

Carbon emissions are one of the biggest problems and to achieve the goal of sustainability this emission to be reduced [28-29]. The manufacturing process of cement contributes to the maximum amount of carbon emissions and waste like ceramic leads to the dumping like problem. The environmental impact analysis revealed approximately 1-1.5 % reduction in the overall carbon emission as per pilot study.

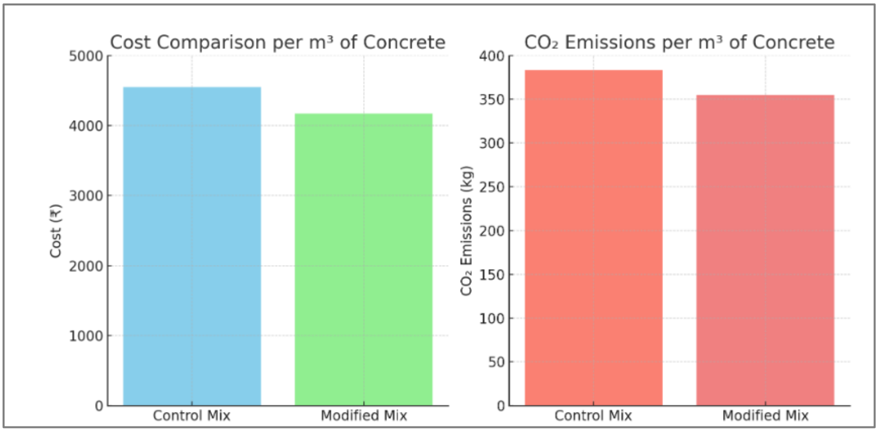


Fig. 11: Cost and CO_2 analysis in concrete

5. Conclusion

- This research undertook a systematic experimental investigation into the mechanical behavior of sustainable concrete produced by incorporating micro silica as a cement substitute and CWT as a coarse aggregate replacement. The primary objective was to evaluate the feasibility of these materials, individually and in combination, in producing concrete that meets structural performance requirements while contributing to environmental sustainability.
- The mix M6 attained the optimum strength compared with the reference concrete. The optimum strength of 46.9 N/mm2 and the reference concrete having strength of 46 N/mm2 and overall CS enhanced by 1.95% as compared with the reference mix.
- Mix 4 having optimum strength with 3.8 N/mm2 and the reference concrete having strength of 3.7 N/mm2 and hence the results show very little enhancement in strength.

- Mix M4 shows the optimum value of 3.85 N/mm^2 and the reference concrete having strength of 3.75 N/mm^2. Results show overall enhancement of strength by 2.66%.
- Replacement levels of both constituents beyond the optimum threshold showed marginal or negative effects on strength parameters. While 10% micro silica still contributed positively to durability, the accompanying reduction in cementitious content may have caused a reduction in the rate of primary hydration. Similarly, higher ceramic waste content (40%) introduced brittleness and micro voids, slightly compromising structural integrity.
- The practical implications of this study suggest that a judicious combination of industrial by-products can yield concrete with improved performance and reduced environmental impact. Furthermore, the valorization of waste materials such as ceramic tiles not only minimizes landfill disposal but also reduces the exploitation of non-renewable natural resources. These findings align with global efforts to promote low-carbon, circular construction practices and provide a viable pathway toward greener infrastructure development.
- In conclusion, the use of micro silica and ceramic tile waste in concrete should be further encouraged through standardization, policy incentives, and pilot-scale implementations in real-world structures. Future studies should also explore long-term durability, life cycle assessments, and microstructural evaluations to support the large-scale adoption of such sustainable composites.

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