Experimental Study on Mechanical and Durability Properties Incorporating Recycled Aggregate and Steel Fiber

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Abstract - The growing need for sustainable construction materials has led to increased interest in recycled aggregate concrete (RAC) reinforced with steel fibres. This study aims to evaluate the feasibility and performance enhancement of recycled total concrete incorporating black steel fibres, specifically low-strength fibres with an aspect ratio of 50. The investigation uses natural coarse and fine aggregates, recycled coarse aggregates, black steel fibres, and a superplasticizer. Natural coarse aggregate is progressively replaced with recycled coarse aggregate at five levels: 0%, 25%, 50%, 75%, and 100%. Additionally, steel fibres are incorporated at fibre volume fractions of 0%, 1%, 1.5%, and 2% to assess their effectiveness in improving mechanical and durability characteristics.

The experimental program examines how the combined effects of recycled aggregates and black steel fibres influence the strength, deformation behaviour, and overall structural performance of concrete. Particular emphasis is placed on understanding the contribution of low-strength steel fibres to crack control, toughness, and post-cracking behaviour in RAC. Through comprehensive analysis of various mix combinations, the study aims to identify the optimal fibre content and recycled aggregate replacement level that enhance the performance of concrete while maintaining workability and structural integrity.

The findings of this research provide valuable insights into the potential of integrating recycled aggregates with low-strength black steel fibres in sustainable concrete production. The study supports the development of environmentally responsible construction practices by demonstrating the viability of using waste-derived materials and fibre reinforcement to improve the mechanical behaviour of recycled aggregate concrete.

Keywords: Recycled aggregate concrete; steel fibres; Fibre-reinforced concrete; Sustainable construction materials; Mechanical performance;

1.INTRODUCTION

The rapid expansion of the construction sector has led to an increasing demand for aggregates, prompting a shift in the perception of concrete manufacturers and engineers. Instead of relying on the elusive concept of a “perfect” aggregate, the industry now recognizes the importance of utilizing readily available materials, including recycled aggregates, to produce sustainable and cost-effective concrete. This shift aligns with the global rise in concrete recycling, which has generated substantial quantities of recycled concrete aggregate (RCA). Although much of this material is currently used in unbound pavement layers, its potential for structural and non-structural concrete applications remains significant.

Recycled aggregate concrete (RAC) is primarily produced from construction and demolition (C&D) waste, comprising materials generated during building, renovation, and demolition activities. C&D waste is one of the major contributors to the total solid waste stream across many nations. Historically, landfill disposal was the predominant method of managing this waste. However, increasing pressure on landfill capacity, combined with recognition of the inherent value of discarded materials, has led to the adoption of recycling as a critical component of sustainable waste management. In India, discussions on stringent policies and effective recycling strategies for C&D waste have intensified in recent years.

C&D waste consists of a diverse range of materials, including excavated soil, concrete rubble, tiles, ceramics, asphalt, wood, metals, plastics, and glass. Effective management of these materials requires an integrated strategy involving technological innovation, policy formulation, and strengthened administrative and legal frameworks. A major challenge, especially in India, lies in the lack of reliable data on C&D waste generation, variations in the definition of C&D waste across regions, and the absence of a dedicated regulatory framework distinguishing it from municipal solid waste (MSW). These inconsistencies hinder the development of efficient recycling mechanisms and the establishment of robust waste management systems.

Given the growing emphasis on sustainable construction, there is a strong need to explore the structural suitability of recycled coarse aggregate concrete (RCAC). While developed countries such as the United States, Japan, and European nations have conducted extensive research on RCAC, its application in India remains limited. Expanding research on RCAC using locally available C&D waste, along with advanced reinforcement techniques such as steel fibres, will help unlock its full potential. Such efforts are crucial for advancing sustainable materials, reducing environmental impacts, and promoting circular economy practices in the construction industry.

1.2 RESEARCH SIGNIFICANCE

The increasing demand for sustainable construction materials has intensified the need to utilize recycled aggregates and waste-derived fibres in concrete production. Recycled Concrete Aggregate (RCA),

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 11 | Nov - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

originating from construction and demolition waste, offers

Test	Experimentalvalues	Suggested values as per I.S Specification
Fineness	5.0%	<10.0%
Specific gravity	3.15	--
Normal consistency	32%	--
Setting time Initial setting timeFinal setting time	30min 590 minutes	Min 30 minutes Max 600 minutes

a promising alternative to natural aggregates, helping reduce environmental degradation, landfill burden, and dependence on virgin materials. However, the inferior quality of RCA often leads to reduced mechanical strength and durability, limiting its structural application.

Steel Fibre Reinforced Concrete (SFRC), particularly using black steel fibres with a moderate aspect ratio, has the potential to counteract these limitations by enhancing crack resistance, ductility, tensile strength, and post-cracking behaviour. Integrating low-strength black steel fibres with varying proportions of RCA can potentially produce a sustainable composite material with improved structural performance.

This study is significant because it systematically evaluates the combined influence of RCA and black steel fibres on both mechanical and durability properties of concrete. The findings will help identify optimal mix proportions that balance strength, durability, workability, and sustainability. The outcomes contribute to the broader goal of advancing greener construction practices, supporting circular economy principles, and facilitating the large-scale adoption of recycled aggregates in structural concrete.

1.3 Objectives of the Present Study

The present investigation is carried out with the following objectives:

1. To examine the mechanical properties (compressive strength, split tensile strength, and flexural strength) of Steel Fibre Reinforced Recycled Aggregate Concrete (SFR-RAC) with varying RCA replacement levels at 7, 14, and 28 days.
2. To evaluate the influence of black steel fibre content (0%, 1%, 1.5%, and 2% by volume; aspect ratio 50) on the mechanical performance of concrete incorporating different RCA proportions.
3. To assess durability characteristics, including water absorption and chloride penetration resistance, of SFR-RAC mixes with different RCA and fibre combinations.
4. To analyse the combined effect of RCA incorporation and steel fibre addition on improving or modifying the long-term performance of recycled aggregate concrete.
5. To determine the optimal mix proportions of RCA and black steel fibres that maximize mechanical strength and durability while supporting sustainable and environmentally responsible construction practices.

2.MATERIAL AND METHODOLOGY

Material selection and study of material properties of recycled aggregate

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Tests on materials (mechanical properties of recycled aggregate and natural aggregate and fine aggregate and fiber

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Figure 1Flow chart for methodology

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To investigate the mechanical properties (compressive strength, flexural strength, and split tensile strength) of Steel Fiber Reinforced Concrete (SFRC) with different proportions of Recycled Concrete Aggregate (RCA) at curing ages of 7, 14, and 28 days

To assess the durability properties for optimum proportion (water absorption, Rcpt, porosity.etc)

↓

Conclusion

2.1 Materials

2.1.2 Cement

In this research work, we utilized ULTRATECH Ordinary Portland Cement of 53 grade, adhering to the IS (Indian Standards) IS269 - 2018 guidelines. To ensure the quality and suitability of the cement, a series of tests were conducted in accordance with the IS standards. The results of these tests are compiled and presented in Table 1, providing an overview of the cement's properties.

Table 2 Fine Aggregate

S. No.	Property	Value
1	Specific Gravity	2.65
2	Fineness Modulus	2.74
3	Bulk Density i) Loose ii) Compacted	 14.67 kN/m^3 16.04 kN/m^3
4	Grading	Zone - II

The slump

Table1 Physical properties of cement

Table 3 physical properties of Coarse aggregate

Property	NCA	RCA
Specific Gravity	2.80	2.54
Bulk Density		
Loose	1368 kg/m^3	1230 kg/m^3
Compacted	1520 kg/m^3	1380 kg/m^3
Water absorption	0.53%	3.08%

Table 4 Mix proportions of concrete (kg/m3)

Nomenclature	RCA Replacement percentage	w/c	Cement (kg)	Fine aggregate (kg)	NCA (kg)	RCA (kg)	Mixing water (Lit)
NAC-0	0	0.45	338	697	1264	-	152
RAC-25	25	0.45	338	697	948	316	152
RAC-50	50	0.45	338	697	632	632	152
RAC-75	75	0.45	338	697	316	948	152
RAC-100	100	0.45	338	697	-	843	152

3.RESULT AND DISCUSSION

3.1 Slump

test results indicate a gradual reduction in workability as recycled aggregate content and fiber dosage increase. The control mix MRAC-0 shows the highest slump of 75 mm, while MRAC-100 records 62 mm, confirming that higher recycled aggregate replacement reduces flowability due to its angular shape and higher water absorption. For MRAC-50 mixes, the addition of fibers further decreases slump from 61 mm (0% fiber) to 53 mm at 1.5% fiber. This reduction occurs because fibers restrict the free movement of particles and increase internal friction. Overall, both higher RA content and fiber addition significantly reduce workability.

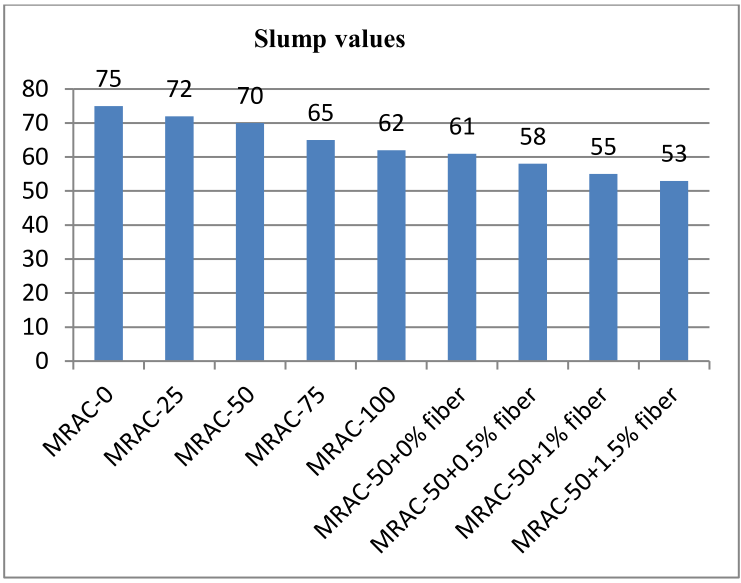

Figure 2 slump varitons for different mixes

3.2 Test on hardened concrete

3.2.1 Compressive strength

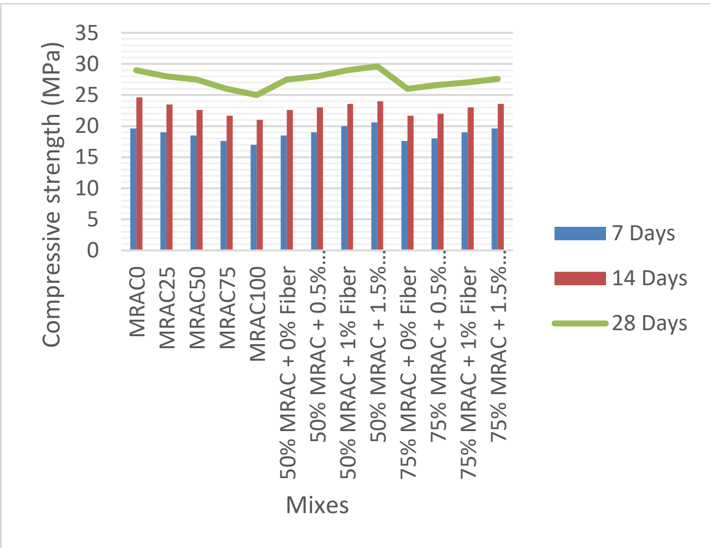

Figure 3 variation of compressive strength with different mixes

The compressive strength results show a decreasing trend as recycled aggregate content increases. At 28 days, MRAC25, MRAC50, MRAC75, and MRAC100 recorded reductions of 3.4%, 5.2%, 10.3%, and 13.8%, respectively, compared with the control mix MRAC0 (29 MPa). This reduction is primarily due to the higher porosity, angularity, and weaker adhered mortar associated with recycled aggregates, which negatively affect the interfacial transition zone (ITZ).

For the fiber-reinforced MRAC50 mixes, strength improved with increasing fiber dosage. At 28 days, the inclusion of 0.5%, 1%, and 1.5% fibers enhanced strength by 1.8%, 6.8%, and 7.6%, respectively, over the MRAC50 mix. Similarly, for MRAC75 mixes, fibers improved strength by 2.3%, 3.8%, and 6.1% compared to MRAC75. The improvement is attributed to better crack-bridging, enhanced post-cracking resistance, and improved stress redistribution due to fibres.

Overall, 50% MRAC with 1.5% fiber achieved the highest strength (29.6 MPa), demonstrating an optimal balance between sustainability and performance. The trend as shown in figure3

3.2.2 Split tensile strength

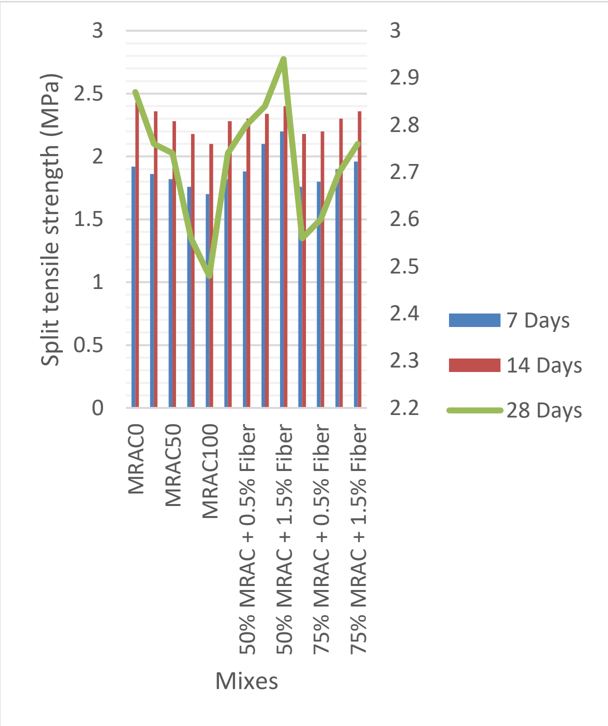

Figure 3 variation of Split Tensile strength with different mixes

The split tensile strength results show a consistent declining trend with increasing recycled aggregate content. At 28 days, MRAC25, MRAC50, MRAC75, and MRAC100 exhibited 3.83%, 4.53%, 10.80%, and 13.59% lower tensile strength compared to MRAC0 (2.87 MPa). This reduction is attributed to the weaker adhered mortar, higher porosity, and less dense interfacial transition zone (ITZ) present in RCA, which collectively reduce tensile load-carrying capacity and increase microcrack formation.

Fiber incorporation substantially improved tensile performance in both 50% and 75% MRAC mixes. For 50% MRAC, fibers enhanced the 28-day tensile strength by 2.17% (0.5% fiber), 3.65% (1% fiber), and 7.30% (1.5% fiber) relative to non-fiber MRAC50. Similarly, for 75% MRAC, the improvements were 1.56%, 5.47%, and 7.81%, respectively. The highest tensile strength recorded was 2.94 MPa for *50%* MRAC + 1.5% fiber, which is only 1.04% lower than the control mix, demonstrating excellent recovery of mechanical performance.

These improvements are due to fiber bridging, which controls microcrack propagation, delays crack initiation, and enhances stress distribution across the concrete matrix. Overall, the results confirm that although RCA reduces tensile strength, optimal fiber dosages successfully restore and even enhance tensile performance, ensuring better resistance under tensile loading conditions.

3.2.3 Flexural strength

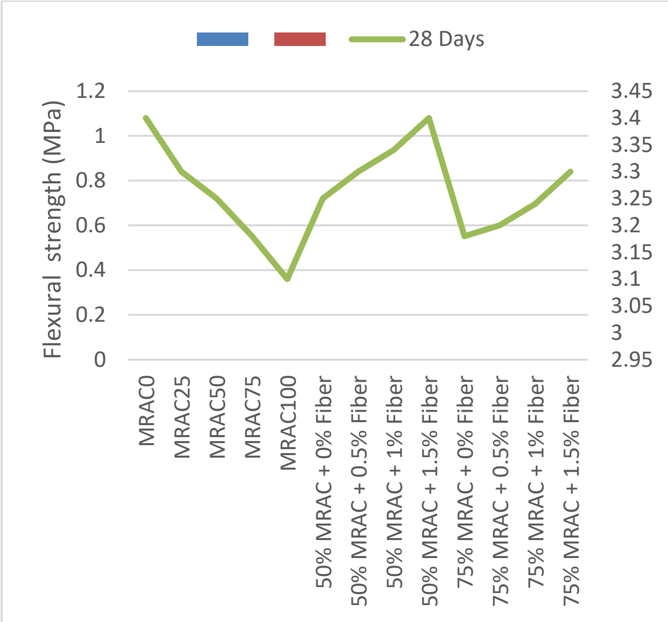

Figure 4 variation of Flexural strength with different mixes

Flexural strength showed a gradual reduction with increasing recycled aggregate content. At 28 days, MRAC25, MRAC50, MRAC75, and MRAC100 exhibited 2.94%, 4.41%, 6.47%, and 8.82% lower flexural strength compared to MRAC0 (3.40 MPa). This decline is attributed to the weaker adhered mortar, higher microcracking potential, and reduced ductility associated with RCA, which collectively reduce bending resistance and lead to increased brittleness in the flexural zone.

Fiber incorporation significantly compensated for these reductions. In 50% MRAC mixes, flexural strength improved by 1.54% (0.5% fiber), 2.77% (1% fiber), and 4.62% (1.5% fiber) relative to the non-fiber MRAC50. For 75% MRAC mixes, improvements of 0.63%, 1.89%, and 3.77% were observed for the same fiber levels. The highest flexural strength was achieved by 50% MRAC + 1.5% fiber (3.40 MPa), matching the MRAC0 value and outperforming all other RCA-based mixes.

The improvement is attributed to fibre bridging action, which enhances post-crack load-carrying capacity, delays crack propagation, and increases energy absorption. This allows the matrix to sustain greater bending stresses without catastrophic failure. Overall, the synergy between moderate RCA replacement and optimal fibre dosage effectively restores flexural strength, ensuring both sustainability and mechanical reliability. The trend shows in figure 4

4.Durability properties

4.1 Water absorption

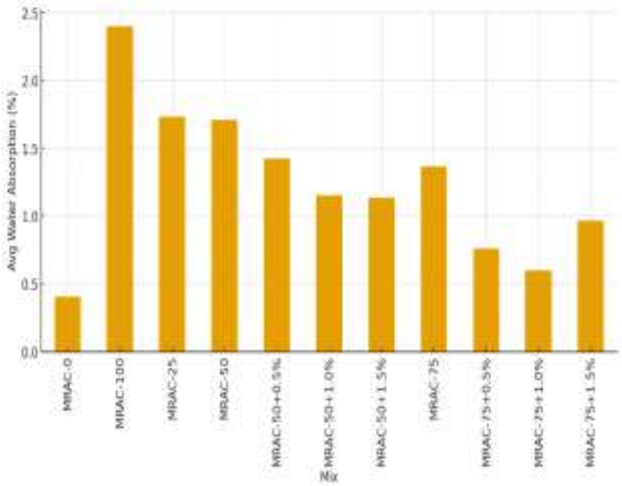

Figure 4 variation of Water absorption with different mixes

The saturated water absorption (SWA) values showed a clear increasing trend with higher replacement of natural aggregates by recycled aggregates (RA). The control mix MRAC-0 exhibited the lowest average absorption (0.40%), confirming its dense and less permeable microstructure. With increasing RA content, the absorption increased significantly: MRAC-25 (1.73%), MRAC-50 (1.71%), MRAC-75 (1.37%), and MRAC-100 recorded the highest value (2.40%). This rise is attributed to the porous adhered mortar, higher microcrack density, and weaker interfacial transition zone (ITZ) present in RA particles.

Fiber incorporation reduced absorption in both MRAC-50 and MRAC-75 mixes. For MRAC-50, the addition of 0.5%, 1.0%, and 1.5% fibers reduced absorption to 1.42%, 1.15%, and 1.13%, respectively. A similar reduction was observed for MRAC-75, where absorption decreased to 0.76%, 0.59%, and 0.43%. Fibers effectively minimized water uptake by refining pore structure, improving matrix integrity, and enhancing crack-bridging, leading to reduced permeability.

4.2 Porosity

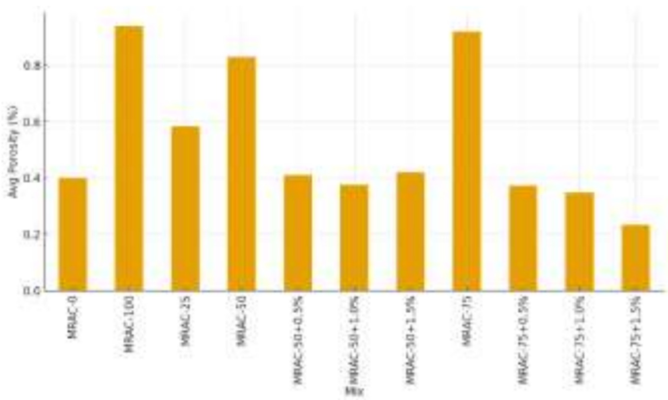

Figure 4 variation of Water porosity with different mixes

The porosity results show a clear increasing trend with higher recycled aggregate (RA) content. The control mix MRAC-0 exhibited the lowest porosity values (0.30–0.50%), reflecting its dense microstructure and well-formed interfacial transition zone (ITZ). With the introduction of RA, porosity increased notably due to the adhered mortar, higher pore connectivity, and microcracking associated with RA particles. Average porosity increased for MRAC-25 (0.58%), MRAC-50 (0.83%), MRAC-75 (0.92%), and MRAC-100 (0.94%), demonstrating a progressive reduction in matrix compactness.

Fiber incorporation significantly reduced porosity in both MRAC-50 and MRAC-75 mixes. For MRAC-50, porosity dropped to 0.51%, 0.38%, and 0.42% for 0.5%, 1.0%, and 1.5% fiber levels, respectively. A similar improvement was seen in MRAC-75 with reductions to 0.37%, 0.35%, and 0.23%. Fibers enhanced the microstructure by bridging microcracks, reducing pore continuity, and improving internal densification. Overall, fiber addition effectively mitigated RA-induced porosity, improving durability-related performance.

4.3 RCPT

The Rapid Chloride Penetration Test (RCPT) results qualitatively indicated that chloride ion permeability increased with higher recycled aggregate (RA) content due to the porous adhered mortar and weaker ITZ. Control mix MRAC-0 exhibited “Low” chloride ion penetrability as per ASTM C1202, reflecting its dense microstructure. With increasing RA levels, penetrability shifted toward “Moderate” and “High,” indicating faster ion migration and greater risk of reinforcement corrosion.

Fiber-reinforced mixes demonstrated clear improvement. For both MRAC-50 and MRAC-75 blends, the incorporation of fibers significantly reduced total charge passed by enhancing crack resistance, reducing pore connectivity, and improving the tortuous path for chloride mobility. Higher fiber dosages consistently resulted in lower chloride permeability, shifting RCPT classification from “High” to “Moderate” or “Low,” depending on fiber content.

Overall, RCPT results confirm that while RA increases chloride susceptibility, fiber reinforcement effectively restores durability by limiting ion diffusion pathways and improving matrix integrity.

4.Conclusion

Compressive strength: The optimum compressive strength obtained was 27.5 N/mm² at 50% MRAC replacement of the binding material, and 26 N/mm² at 75% MRAC for 28 days strength. It was observed that the addition of 1.5% fiber to MRAC led to a maximum compressive strength of 29.6 N/mm², while MRAC with 1.5% fiber achieved a maximum compressive strength of 27.6 N/mm².

Split tensile strength: The optimum split tensile strength obtained was 27.5 N/mm² at 50% MRAC replacement of the binding material, and 26 N/mm² at 75% MRAC for 28 days strength. It was observed that the addition of 1.5% fiber to MRAC led to a maximum split tensile strength of 29.6 N/mm², while MRAC with 1.5% fiber achieved a maximum split tensile strength of 27.6 N/mm².,

flexural strength: The optimum flexural strength obtained was 27.5 N/mm² at 50% MRAC replacement of the binding material, and 26 N/mm² at 75% MRAC for 28 days strength. It was observed that the addition of 1.5% fiber to MRAC led to a maximum flexural strength of 29.6 N/mm², while MRAC with 1.5% fiber achieved a maximum split flexural strength of 27.6 N/mm².

The Ultra-pulse Velocity (UPV): Test results showed that the range of UPV values for all mixtures varied from 4.7 km/s to 5.10 km/s. As the recycled aggregate replacement increased, the UPV values decreased due to poor bonding structures in the recycled aggregate. Consequently, the concrete exhibited uniform homogeneity with fewer cracks, voids, and imperfections.

the Water absorption test, conventional concrete typically has a water absorption percentage of 0.5% However, in the case of recycled aggregate concrete admixed with MRAC-100 and 1.5% fiber, it exhibited higher water absorption due to porous structures and adhered mortar in the recycled aggregate. Nonetheless, the addition of 1.5% fiber significantly reduced the water absorption to a range of 1.1-1.6%, which is much lower than that of conventional concrete.

The final absorption results indicated that geopolymer concretes, including MRAC, have lower absorption rates compared to normal concretes. Additionally, the absorption rate decreased with the increase in strength.

The porosity of concrete increases with the replacement of recycled aggregates. This is primarily because recycled aggregates often contain adhered mortar and have a more porous structure compared to natural aggregates. As a result, when these recycled aggregates are used in concrete, they create a higher volume of voids and spaces within the concrete matrix, leading to increased overall porosity. This higher porosity can affect the concrete's properties, such as its strength, durability, and water absorption capacity. Proper mix design and optimization techniques are essential to mitigate the negative effects of increased porosity when using recycled aggregates in concrete.

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