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Technical Notes

SUSTAINABLE PAVEMENT SOLUTIONS: INVESTIGATING RECLAIMED ASPHALT PAVEMENT (RAP)-BASED REINFORCED CONCRETE WITH STEEL FIBER

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Abstract: This study investigates the feasibility of incorporating coarse reclaimed asphalt pavement (RAP) into steel fiber-reinforced concrete (SFRC) for pavement applications. RAP aggregates obtained from 20-year-old pavements were utilized as a full replacement for natural aggregates in the steel fiber layer. A series of laboratory experiments were conducted to evaluate the mechanical and durability properties of RAP-based SFRC, focusing on flexural strength, compressive strength, splitting tensile strength, water absorption, and sorptivity. The results indicate that while the inclusion of RAP reduces the tensile strength of concrete due to weakened interfacial bonds and increased porosity, the addition of 0.75% by mass steel fibers effectively mitigates these drawbacks by enhancing crack resistance, energy absorption, and stress redistribution. The steel fiber reinforcement significantly improves the flexural and impact resistance of the concrete, making it more suitable for high-traffic pavements and airfield applications where durability and crack resistance are critical. Moreover, despite an increase in water absorption with higher RAP content, sorptivity is reduced due to the asphalt binder coating on RAP aggregates, which limits capillary absorption. This study highlights the potential of optimizing RAP content and fiber reinforcement to develop sustainable and high-performance concrete for road infrastructure.

Author keywords: Reclaimed asphalt Pavement (RAP), Atmospheric Temperature, Wheel Stress, Concrete, Mechanical Strength, Steel Fibre.

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1. INTRODUCTION

The escalating depletion of natural aggregate resources has resulted in a substantial increase in their market prices, necessitating the investigation of alternative sustainable materials for construction. An option that has garnered significant attention in recent years is the utilisation of recycled aggregates, which provide a feasible solution for diminishing reliance on virgin materials. Among these, reclaimed asphalt pavement (RAP) has emerged as a promising material. RAP is produced from the removal of aged flexible pavements, typically through milling or full-depth reclamation processes, and consists of natural aggregate particles coated with partially or fully aged bitumen. Due to its widespread availability and potential for reuse, RAP has been the subject of extensive research focused on its application in various construction sectors, including pavement engineering, concrete technology, and geotechnical applications. Compared to natural aggregates, RAP exhibits lower density, higher water absorption, and reduced mechanical strength due to the aged binder film and potential degradation of the original aggregate material. The irregular shape and rough texture of RAP particles enhance interlocking within the concrete matrix, potentially improving mechanical interconnectivity but simultaneously reducing workability. Furthermore, the residual asphalt binder in RAP affects the bonding mechanism between the aggregate and the cement paste, which can impact the concrete's overall strength, durability, and stiffness. To effectively incorporate RAP into concrete mixtures, careful mix design adjustments are required. These may include optimizing the water-to-cement ratio and incorporating supplementary cementitious materials to enhance performance. Despite these technical challenges, the use of RAP aggregates supports sustainable construction by reducing the dependence on virgin materials, minimizing landfill waste, and lowering the carbon footprint. This makes RAP a viable and eco-friendly choice for modern infrastructure applications.

Globally, RAP production exceeds 100 million tons annually, with significant contributions from developed regions such as Europe and the USA. However, despite this large-scale generation, only a fraction of the produced RAP is effectively recycled or reused in new construction, with the remainder often being discarded or stockpiled, leading to environmental and logistical concerns

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(Hossiney et al., 2010; Adresi et al., 2019; Nandi and Ransichung, 2021; Adresi et al., 2023). In India, industrial activities and road maintenance operations result in the annual accumulation of vast quantities of RAP, much of which is simply discarded along roadsides following pavement milling (Magar et al., 2022; Kamal and Bas, 2021; Rout et al., 2023). The limited utilization of RAP in cement concrete mixtures is primarily due to concerns regarding its mechanical properties and bonding characteristics, which may affect the overall performance of the concrete mix (Kumari et al., 2018; Yu et al., 2017).

Research has shown that the incorporation of RAP in Portland Cement Concrete (PCC) mixes can lead to significant reductions in mechanical strength. This is attributed to weaker aggregate-mortar bonding caused by the presence of aged bituminous coatings on the aggregate surface. Studies have reported up to a 75% reduction in compressive strength when RAP is directly incorporated into PCC mixes without modification. The weak interfacial transition zone (ITZ) between RAP aggregates and cement mortar, along with the friable nature of aged asphalt, results in inferior strength characteristics (Delwar et al., 1997; Huang et al., 2005; Huang et al., 2006; Shi et al., 2018; Shi et al., 2019). Nevertheless, some researchers argue that RAP's coarse fraction can still be effectively utilized in concrete mixes, particularly in harsh environmental conditions, such as those involving acidic exposure (Singh et al., 2018a). It has also been observed that while compressive strength experiences a sharp decline with RAP inclusion, the flexural strength of concrete mixes remains less adversely affected (Shi et al., 2017). Tiwari & Singh, (2025) analysed the polypropylene fibre on self-compacted recycled aggregate concrete, which enhanced the mechanical properties of concrete.

Several studies advocate for the partial replacement of coarse aggregates with RAP to achieve a balance between sustainability and structural performance. For instance, previous findings indicate that up to 50% replacement of natural coarse aggregates with RAP can yield acceptable mechanical performance for structural applications in highway construction (Ibrahim et al., 2014; Rout et al., 2024; Modarres and Hosseini, 2014; Brand and Roesler, 2016). Additionally, aged RAP aggregates, obtained from extensively oxidized pavements, may offer improved bonding characteristics due to increased stiffness of the residual asphalt binder, making them more suitable for reuse in rigid pavement applications (Singh et al., 2018b; Brand and Roesler, 2017 a,b). Research also suggests that fine RAP fractions can be effectively utilized up to 50% in high-

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performance highway applications and 100% in lower pavement layers, thus broadening the potential applications of RAP (Katsakou and Kolias, 2007).

While RAP has been successfully incorporated into weaker pavement layers, such as cement-treated subbases, roller-compacted base courses, and dry lean concrete subbases, its direct application in cement concrete wearing courses remains limited (Kolias, 1996 a,b; Ferrebee et al., 2014; Singh et al., 2019; Berry et al., 2015). Field studies investigating RAP-modified concrete pavement slabs remain scarce. Notable examples include a 10% RAP inclusion in Austrian highway pavement layers and experimental RAP-based concrete slabs installed in Lewistown, Montana, as part of a performance evaluation study (Armaghani et al., 1987). However, comprehensive investigations assessing RAP's suitability in cement concrete pavement applications under Indian climatic and traffic conditions remain largely unexplored.

One critical factor affecting the long-term performance of cement concrete pavements is the development of thermal differential stresses across the slab thickness (Alam et al., 2024). Temperature and moisture fluctuations during the day create tensile and compressive stresses between the top and bottom fibers of the concrete slab, leading to slab curling and warping (Masad et al., 1996). This phenomenon, exacerbated by environmental exposure and cyclic thermal loading, significantly contributes to pavement deterioration over time (Liang and Niu, 1998; Tia et al., 2012; Ahmadi et al., 2020). Recent numerical studies employing finite element (FE) modelling suggest that RAP-modified concrete slabs may exhibit lower curling stresses due to their reduced elastic modulus, potentially offering improved resistance against thermal cracking (Kim et al., 2017; Kumari et al., 2018). The implications of this characteristic on long-term pavement performance warrant further experimental and analytical investigation.

In this study, extensive efforts have been made to improve RAP aggregate performance by removing dust particles, minimizing the agglomeration of asphalt-coated aggregates, and enhancing interfacial bonding with cement mortar through appropriate mix design modifications. While existing literature suggests that RAP incorporation inevitably reduces the strength of concrete, its sustainability benefits, cost-effectiveness, and potential for partial replacement of natural aggregates make it an attractive option for rigid pavement applications. Furthermore, this study aims to explore the feasibility of utilizing locally available RAP materials, thereby promoting a more sustainable approach to cement concrete pavement construction. Through the

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experimental investigations, the study seeks to provide insights into the mechanical and durability characteristics of RAP-modified concrete, ultimately contributing to the broader goal of sustainable infrastructure development.

2. SIGNIFICANCE OF RESEARCH

Most studies on reclaimed asphalt pavement (RAP) as recycled aggregates in cement concrete mixes have primarily focused on determining optimal RAP proportions based on strength requirements or characterizing RAP through its physical and chemical properties. However, limited research is available on the mechanical behavior of concrete incorporating RAP and the ideal RAP-to-aggregate ratio for achieving enhanced performance. This knowledge gap highlights the need for a comprehensive investigation into the physical characteristics of RAP-derived recycled aggregates and their potential to improve the mechanical properties of concrete when combined with varying proportions of steel fibers. One of the major challenges hindering the widespread adoption of cement concrete pavements in India is the shortage of natural aggregates due to restrictions on quarrying activities. Simultaneously, the disposal of RAP presents a logistical and environmental challenge for paving authorities. The integration of RAP with natural aggregates in concrete pavements offers a sustainable solution by alleviating the burden on disposal facilities while promoting resource efficiency. Although limited field studies have endorsed the use of coarse RAP aggregates in cement concrete mixes under specific capping limits, numerous laboratory experiments have yielded conflicting results. Despite this, no prior research has explored the feasibility of utilizing 100% RAP in the lower layers of pavement and beyond 50% RAP in pavement quality concrete (wearing course) under Indian conditions.

This study addresses these critical gaps by evaluating the suitability of RAP in both the upper and lower layers of rigid pavements. The findings demonstrate that RAP can be effectively incorporated without significantly compromising the structural integrity and durability of the pavement. This research not only provides valuable insights into the optimization of RAP-based concrete mixes but also supports the development of more sustainable and cost-effective pavement solutions in regions facing aggregate shortages.

3. MATERIALS

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3.1 Physical Properties of RAP

RAP aggregate serves as a sustainable and cost-effective alternative to natural aggregates in concrete, offering significant environmental and economic advantages. In this study, RAP aggregate was sourced from a pavement construction site in Bihar and subjected to laboratory testing to assess its physical properties, as presented in Table 1. A visual representation of the collected RAP sample is shown in Fig. 1.

Fig. 1 Bits of RAP accumulated

RAP aggregates are composed of aged asphalt binder, aggregates, and minor impurities. The presence of asphalt binder coats the aggregate particles, influencing their surface texture, porosity, and adhesion characteristics. Compared to natural aggregates, RAP exhibits lower density, higher water absorption, and reduced mechanical strength due to the aged binder film and potential degradation of the original aggregate material. The irregular shape and rough texture of RAP particles enhance interlocking within the concrete matrix, potentially improving mechanical interconnectivity but simultaneously reducing workability. Furthermore, the residual asphalt binder in RAP affects the bonding mechanism between the aggregate and the cement paste, which can impact the concrete's overall strength, durability, and stiffness.

To effectively incorporate RAP into concrete mixtures, careful mix design adjustments are required. These may include optimizing the water-to-cement ratio and incorporating supplementary cementitious materials to enhance performance. Despite these technical challenges, the use of RAP aggregates supports sustainable construction by reducing the dependence on virgin

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materials, minimizing landfill waste, and lowering the carbon footprint. This makes RAP a viable and eco-friendly choice for modern infrastructure applications.

Table 1. Physical properties of RAP

Properties	NCA	NFA	DRAP	Standard Recommendations
Specific Gravity	2.9	2.8	2.6	IRC: 44-2007
Water Absorption	0.59%	0.68%	1.81%	IS: 2386-III
Density	1651.2 kg/m^3	1561.1 kg/m^3	1396.1 kg/m^3	IS: 2386-III
Crushing Value	20.35%	17.82%	14%	<30%
Loss Angeles Abrasion	25.71%	21.46%	17.5%	<30%
Impact Value	17.64%	15.81%	13.54%	<30%
Asphalt Content	0%	0%	4.57%	ASTM D2172

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3.2 Ordinary Portland Cement (OPC)

In this study, Ordinary Portland Cement (OPC) is utilized as the primary binding material, sourced from the local market. OPC is a widely used hydraulic cement known for its superior binding properties, strength development, and long-term durability. Upon mixing with water, OPC undergoes hydration, forming calcium silicate hydrates (C-S-H), which are primarily responsible for strength gain. To ensure consistency and reliability, the OPC used in this study was tested in accordance with standard specifications, evaluating key parameters such as fineness, setting time, and compressive strength. Characterized by its fine particle size, OPC enhances workability and promotes efficient bonding with aggregates. Its inclusion in the concrete mix, particularly when combined with RAP aggregate, contributes to the sustainability and structural performance of the produced concrete. The physical properties of the OPC cement used in this study are detailed in Table 2.

Table 2. Properties of OPC Cement

Properties	Value
Specific Gravity	3.12
Consistency	30.5%
Initial Setting Time	55min
Final Setting Time	290min
Fineness by Sieve	1%

3.3 Steel Fibre Reinforced Concrete (SFRC)

Steel fibers are incorporated into steel fiber-reinforced concrete (SFRC) to enhance its mechanical properties, particularly strength, toughness, and durability. Compared to conventional reinforced concrete, SFRC offers several advantages, including improved crack resistance, reduced spalling, and enhanced load-bearing capacity. Additionally, SFRC exhibits superior workability, making it a more adaptable choice for various structural applications. Fig. 2 shows the steel fiber used in this study.

Fig. 2 Steel fiber for SFRC

In this study, steel fibers were sourced from the local market. The physical and mechanical properties of the steel fibers used are detailed in Table 3. SFRC's high compressive strength makes it well-suited for structural applications, while its superior flexural strength helps mitigate crack propagation. Furthermore, SFRC demonstrates excellent abrasion and fire resistance, contributing to its durability in harsh environments. Its ability to be easily cast into complex shapes further

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enhances its versatility in construction. The combined benefits of strength, longevity, and ease of application make SFRC a desirable material for a wide range of engineering and infrastructure projects.

Table 3. Properties of Steel Fiber

Properties	Description
Length	30 mm
Diameter	0.5 mm
Cross-Section	Straight, Circular
Aspect Ratio	60
Carbon Content	0.3%
Manganese Content	0.16%
Silicon Content	0.21%
Nickel Content	9.01%
Chromium Content	20.2%
Young's Modulus	2.1×10^5 N/mm^2
Heat Resistivity	Good
Tensile Strength	2150 N/mm^2
Specific Gravity	7.87
Elongation	30%

4. MIX DESIGN

The concrete mixture in this study is designed to achieve the required strength and durability using RAP aggregate in accordance with M30 grade specifications. A water/cement (W/C) ratio of 0.42 is maintained to ensure optimal workability (Slump value 50-100mm), strength, and durability. The mix proportions are determined following the guidelines of the Indian Road Congress (IRC: 44-2017), balancing cement, water, fine and coarse aggregates, and RAP materials. The calculated ingredient quantities, presented in Table 4, ensure consistency and repeatability in the mixing process. The chosen W/C ratio of 0.42 facilitates the proper hydration of cement particles, leading to enhanced strength development and reduced permeability. The objective of the designed mixture is to produce a workable and cohesive concrete mix while optimizing mechanical properties and enhancing stability through the incorporation of RAP. The tabulated data serves as a reference for precise material measurement, supporting reliable concrete production and quality control throughout the study.

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Table 4. Mix Design (M30 Grade Concrete)

Ingredient	Quantity
Cement	340 kg/m^3
Water	143 kg/m^3
Natural Sand	268.6 kg/m^3
Coarse aggregate	550.8 kg/m^3
Superplasticizer	1.51 kg/m^3
Final Mix Ratio	1:0.79:1.62
W/C	0.42

5. EXPERIMENTAL PROGRAM

The experimental design in this study systematically examines the mechanical and strength properties of concrete incorporating RAP aggregates as a sustainable alternative to natural aggregates. The study aims to evaluate the impact of coarse RAP on concrete's strength and durability by replacing natural aggregates in varying proportions of 10%, 30%, 50%, 70%, and 100%. This progressive replacement allows for a detailed assessment of RAP's influence on key performance parameters. To achieve this, both the mechanical and strength properties of RAP concrete are tested. The mechanical properties include compressive strength, flexural strength, and tensile strength as per Indian standard (IRC:44). Compressive strength testing assesses the concrete's ability to withstand axial loads, providing insight into its overall load-bearing capacity. Flexural strength measures resistance to bending forces, which is critical for structural elements such as beams and slabs. Splitting tensile strength evaluates concrete's resistance to indirect tension, an essential factor in crack prevention and durability. These tests are conducted at different curing periods—7, 14, and 28 days—to analyze strength development over time.

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Additionally, durability tests such as water absorption and sorption are performed to assess permeability and long-term performance. Water absorption measures the amount of water retained by concrete over time, indicating its porosity and potential durability concerns. Sorption evaluates the rate of capillary water absorption, which directly affects moisture penetration resistance and long-term degradation. These tests are crucial in determining the suitability of RAP concrete for exposure to harsh environmental conditions. To enhance the mechanical performance of RAP concrete, steel fibers are incorporated at 30% and 50% RAP replacement levels (refer to Table 5). The inclusion of steel fibers is expected to improve crack resistance, impact toughness, and post-crack behavior, mitigating any potential strength reductions caused by RAP. By bridging microscopic cracks and distributing stress more effectively, the fibers contribute to increased ductility and improved overall performance. Throughout the experimental program, standardized testing procedures and guidelines are meticulously followed to ensure accuracy and consistency. This comprehensive approach provides valuable insights into the feasibility of using RAP in structural concrete while evaluating its durability. The findings contribute to the sustainable use of recycled materials in construction, ensuring structural integrity and long-term performance.

Table 5. Sample ID and its constituents

Sample ID	NA (%)	RAP (%)	SF (%)
RAP00	100	0	0
RAP10	90	10	0
RAP30	70	30	0
RAP50	50	50	0
RAP70	30	70	0
RAP100	0	100	0
RAPSF30	70	30	0.75
RAPSF50	50	50	0.75

6. RESULTS & DISCUSSIONS

6.1 Effect of RAP and Steel Fiber on Compressive Strength

The incorporation of RAP and steel fibers in concrete significantly influences its compressive strength and overall performance. The results indicate a gradual decrease in compressive strength

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as RAP content increases. This reduction is primarily attributed to the presence of the old bitumen binder coating on RAP aggregates, which weakens the bond between the aggregates and the cement paste. Additionally, RAP aggregates exhibit higher porosity and lower stiffness than natural aggregates, further contributing to strength reduction.

The recorded compressive strength values for different RAP replacement levels are as follows: 37 MPa for 0% RAP, 35 MPa for 10% RAP, 32 MPa for 30% RAP, 30 MPa for 50% RAP, 29 MPa for 70% RAP, and 27 MPa for 100% RAP, as shown in Fig. 3. The decline in strength becomes more pronounced at higher replacement levels (70% and 100%), where the concrete mix exhibits a significant reduction in load-bearing capacity. However, a key trend observed in the study is that compressive strength increases with curing time. This improvement is attributed to the continued hydration of cement, leading to the formation of additional calcium silicate hydrate (C-S-H) gel, which enhances the internal bonding of the concrete matrix. While RAP concrete exhibits lower early strength compared to conventional concrete, it continues to gain strength over time, supporting its potential for long-term structural applications.

To counteract the reduction in compressive strength due to RAP inclusion, 0.75% steel fiber was incorporated into the concrete mixture. The addition of steel fibers significantly enhanced compressive strength by improving crack resistance, energy absorption, and stress distribution within the concrete matrix. Notably, with 30% RAP replacement, compressive strength increased from 32 MPa to 39.5 MPa, while at 50% RAP replacement, strength improved from 30 MPa to 36.6 MPa. This enhancement is attributed to the bridging effect of steel fibers, which mitigates crack propagation, improves impact toughness, and enhances the concrete's ability to withstand external loads. Steel fibers act as reinforcement within the matrix, effectively reducing stress concentration and compensating for the weakening effect of RAP aggregates. Overall, while RAP reduces the compressive strength of concrete, the strategic inclusion of steel fibers significantly improves its performance, making it more suitable for construction applications. This study underscores the importance of optimizing RAP content and fiber reinforcement to balance stability and strength in concrete structures. By incorporating RAP, the environmental impact of concrete production can be minimized, while the use of steel fibers ensures structural integrity, making RAP-based concrete a viable solution for sustainable construction.

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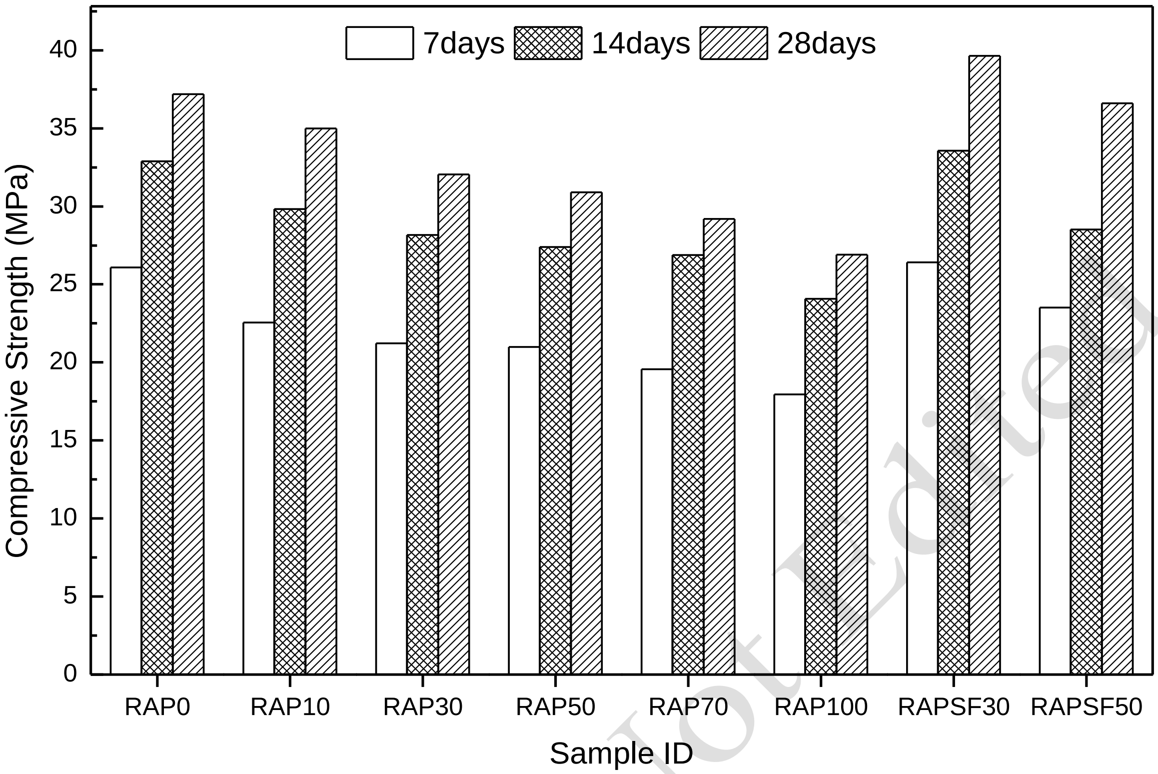

Fig. 3 Compressive strength of concrete with RAP and SF

6.2 Effect of RAP and Steel Fiber on Flexural Strength

The incorporation of RAP and steel fibers in concrete has a notable impact on flexural strength, showing a clear trend of decreasing strength with increasing RAP content. As RAP replaces natural aggregate, flexural strength gradually declines due to the weakened bond between the old asphalt-covered aggregate and the cement matrix. Additionally, RAP aggregates possess lower stiffness and strength compared to natural aggregates, negatively affecting the concrete's ability to withstand bending forces.

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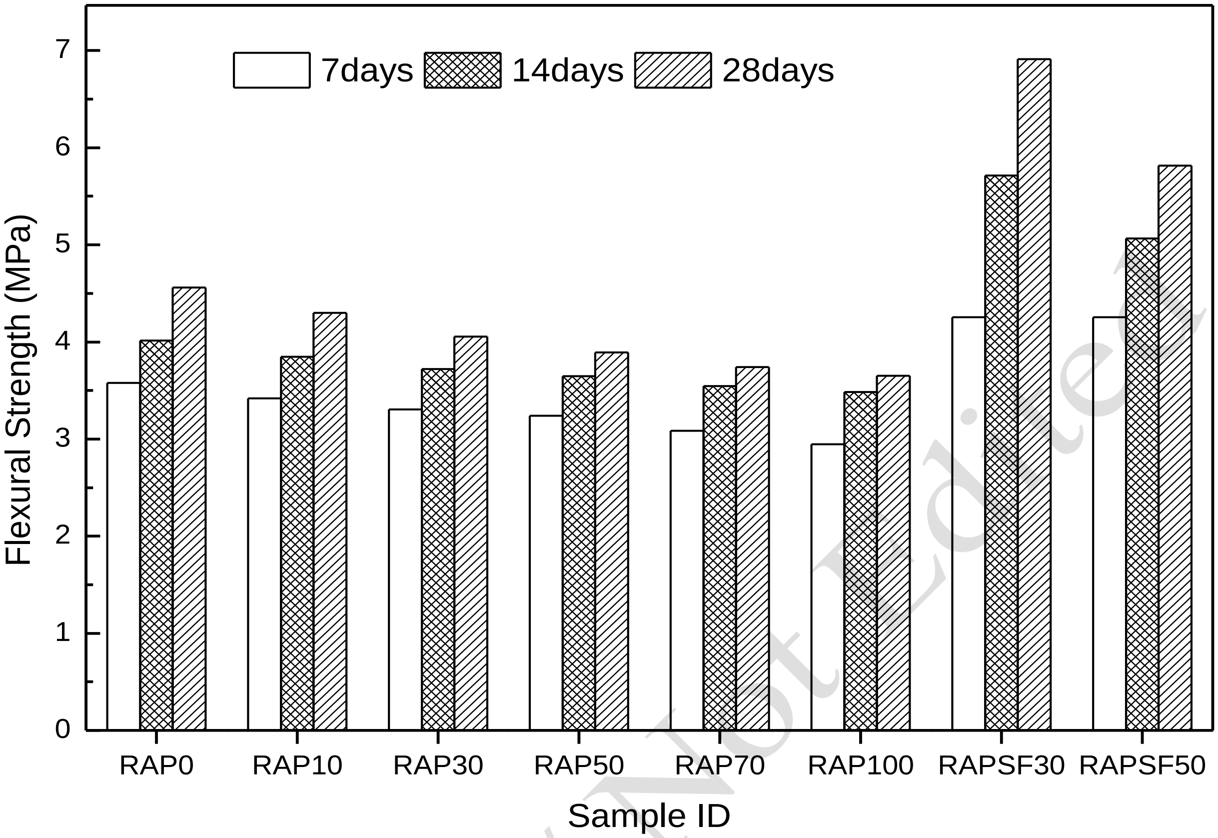

Fig. 4 Flexural strength of concrete with RAP and SF.

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The flexural strength values obtained after 28 days of curing for different RAP replacement levels are as follows: 4.6 MPa for 0% RAP, 4.3 MPa for 10% RAP, 4.05 MPa for 30% RAP, 3.90 MPa for 50% RAP, 3.75 MPa for 70% RAP, and 3.6 MPa for 100% RAP, as shown in Fig. 4. The reduction in flexural strength becomes more pronounced at higher RAP content, as the bitumen binder diminishes aggregate cohesion and weakens the tensile strength of the concrete. However, similar to compressive strength, flexural strength improves with an extended curing period due to the continued hydration of cement, leading to improved bonding within the concrete. Over time, the cement matrix strengthens, enhancing its load-bearing capacity. Despite this improvement, RAP concrete still exhibits lower flexural strength than conventional concrete, emphasizing the necessity for reinforcement strategies. To mitigate the reduction in flexural strength, 0.75% steel fibers were added to the concrete mix, significantly enhancing its performance. The inclusion of steel fibers improved crack resistance, ductility, and stress distribution, resulting in a substantial increase in flexural strength. Notably, for 30% RAP replacement, the flexural strength increased from 4.05 MPa to 6.9 MPa, while at 50% RAP replacement, it improved from 3.90 MPa to 5.8 MPa. This enhancement is attributed to the bridging effect of steel fibers, which controls crack propagation, enhances energy absorption, and improves the concrete’s ability to resist flexural loads. The fibers effectively bind the concrete together, preventing sudden failure and improving its post-cracking behavior. Overall, while RAP reduces the flexural strength of concrete, the strategic addition of steel fibers significantly enhances its structural performance, making RAP-based concrete more suitable for applications where flexural strength is a critical factor. This study highlights the importance of optimizing RAP content and fiber reinforcement to balance stability, strength, and durability in concrete structures.

6.3 Effect of RAP and Steel Fiber on Split Tensile Strength

The splitting tensile strength of concrete is significantly influenced by the incorporation of RAP and steel fibers. The results indicate a gradual decline in tensile strength as the RAP content increases. This reduction is primarily attributed to the presence of old asphalt binder in RAP aggregates, which weakens the bond between aggregates and the cement paste, thereby lowering tensile strength. Additionally, RAP aggregates exhibit lower strength and higher porosity compared to natural aggregates, further contributing to the decline in tensile performance.

The 28-day splitting tensile strength for different RAP replacement levels is as follows: 4.8 MPa for 0% RAP, 4.6 MPa for 10% RAP, 4.05 MPa for 30% RAP, 3.80 MPa for 50% RAP, 3.6 MPa for 70% RAP, and 3.2 MPa for 100% RAP, as shown in Fig. 5. The decrease in tensile strength becomes more pronounced at higher RAP contents due to the weakening of interfacial bonds and the increase in internal voids. However, with an extended curing period, tensile strength improves, indicating a continuous development of strength over time. A longer hydration process promotes the formation of calcium silicate hydrates (C-S-H), which enhance the internal structure of concrete, leading to an increase in tensile strength. Despite this improvement, RAP-based concrete still exhibits lower splitting tensile strength than conventional concrete, emphasizing the need for reinforcement strategies.

To address this limitation, 0.75% steel fibers were introduced into the concrete mix, significantly enhancing tensile strength by improving crack resistance, energy absorption, and stress

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redistribution. Steel fibers act as micro-reinforcement, bridging cracks and preventing early propagation, thereby increasing overall strength and ductility. The results demonstrated a notable improvement in splitting tensile strength, reaching 7.05 MPa for 30% RAP and 5.95 MPa for 50% RAP after the addition of steel fibers. This enhancement underscores the effectiveness of steel fiber reinforcement in mitigating the negative effects of RAP, making the concrete more resistant to tensile stress. Overall, while the inclusion of RAP reduces the splitting tensile strength of concrete, the strategic addition of steel fibers substantially improves its tensile performance. This study highlights the importance of optimizing RAP content and fiber reinforcement to achieve a balance between mechanical resistance and durability, making RAP-based concrete a more viable option for construction applications requiring enhanced crack resistance and long-term performance.

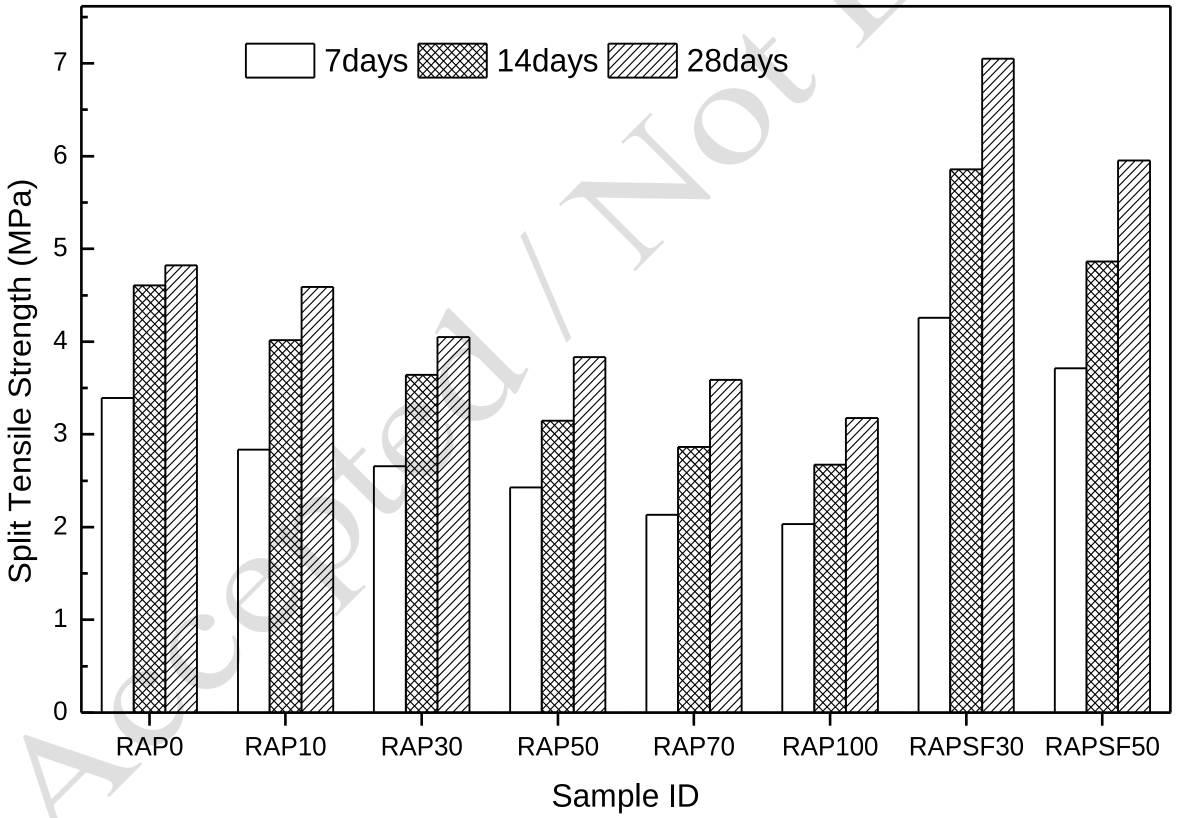

Fig. 5 Split tensile strength of concrete with RAP and SF.

6.4 Effect of RAP and Steel Fiber on Water Absorption of Concrete

The water absorption of concrete is influenced by the incorporation of RAP and steel fibers, showing a gradual increase with higher RAP content. This rise in water absorption is primarily

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attributed to the higher porosity of RAP aggregates and the presence of an aged binder coat, which allows more water to penetrate the concrete matrix. The 28-day water absorption values for different RAP replacement levels are as follows: 4.2% for 0% RAP, 4.95% for 10% RAP, 4.65% for 30% RAP, 4.4% for 50% RAP, 5.0% for 70% RAP, and 5.2% for 100% RAP, as illustrated in Fig. 6. The increase in water absorption is more pronounced at higher RAP contents, reflecting the porous nature of RAP aggregates and their tendency to retain moisture. Despite the increase in water absorption, the addition of steel fibers can enhance concrete's overall durability by improving its resistance to cracking and permeability. This study highlights the need to balance RAP content and fiber reinforcement to optimize concrete performance in terms of strength, durability, and water resistance.

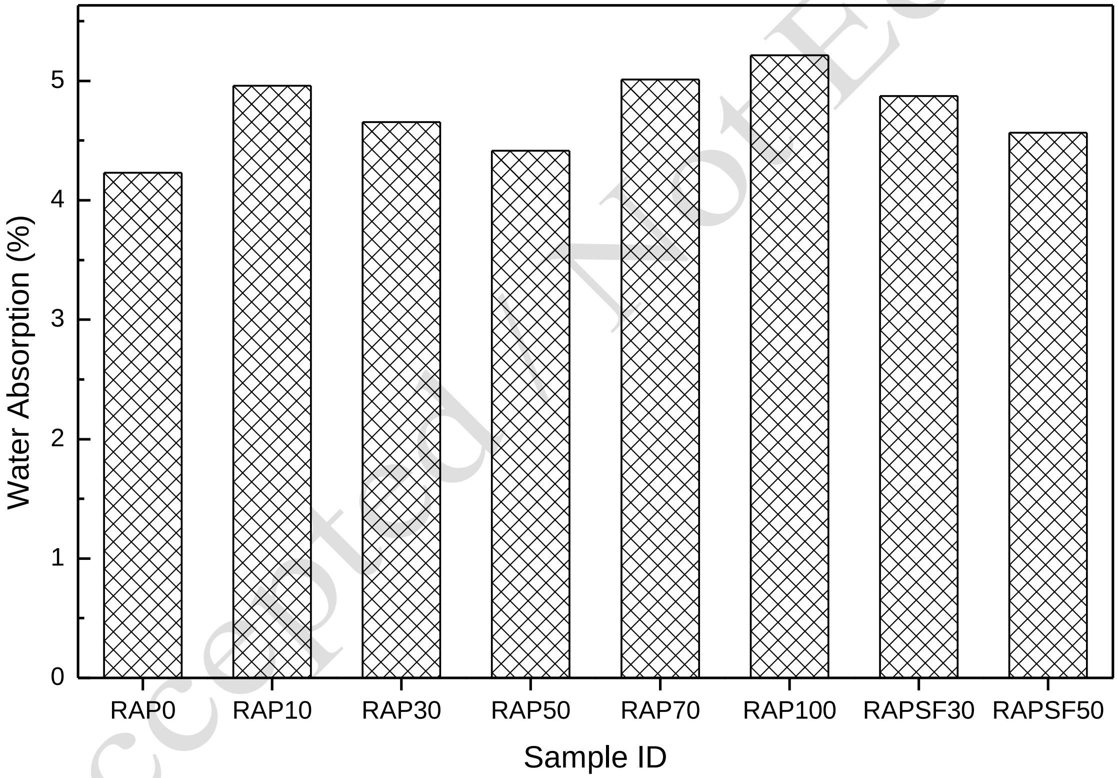

Fig. 6 Variation of water absorption of concrete with RAP and SF

The increase in water absorption is primarily due to the porous nature of RAP aggregates, which contain residual asphalt binder. At higher RAP contents (70% and 100%), this effect becomes more pronounced due to the increased presence of RAP particles, which can absorb more water than natural aggregates. To assess the potential improvement in water absorption, 0.75% steel fibers were incorporated into the concrete mix. The results indicate that after the addition of steel fibers, the water absorption changed only slightly, reaching 4.9% for 30% RAP and 5.5% for 50%

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RAP (refer to Fig. 7). These minimal variations suggest that steel fibers have a limited influence on the absorption characteristics of concrete. This is because steel fibers primarily enhance mechanical properties such as strength and crack resistance but do not significantly alter the permeability or void structure of the concrete matrix.

One possible explanation for the relatively stable water absorption, despite the inclusion of RAP and steel fibers, is the presence of the old bitumen binder on the RAP aggregates. This binder forms a coating that partially limits direct water infiltration into the pores of the aggregate, counteracting the inherently high porosity of RAP and preventing a sharp increase in absorption. Additionally, the cement matrix continues to play a crucial role in regulating water absorption. As long as the paste composition and curing process are properly controlled, the variations remain within a manageable range, ensuring that the concrete maintains a balanced performance in terms of durability and moisture resistance.

6.5 Effect of RAP and Steel Fiber on Sorptivity

The inclusion of RAP and steel fibers significantly influences the sorption capacity of concrete, which gradually decreases as the RAP content increases. Sorption capacity measures the rate of capillary water absorption in concrete, a critical parameter for evaluating permeability and durability. The results indicate that as RAP content increases, sorption values decrease (refer Fig. 7). After 28 days of curing, the recorded values are 5.35×10^{-4} cm/s$^{0.5}$ (0% RAP), 5.1×10^{-4} cm/s$^{0.5}$ (10% RAP), 5.0×10^{-4} cm/s$^{0.5}$ (30% RAP), 4.6×10^{-4} cm/s$^{0.5}$ (50% RAP), 4.6×10^{-4} cm/s$^{0.5}$ (70% RAP), and 3.7×10^{-4} cm/s$^{0.5}$ (100% RAP). The primary reason for this decline in sorption capacity at higher RAP contents is the presence of aged asphalt binder on RAP aggregates, which reduces the number of capillary pores within the concrete matrix. The asphalt-coated surface acts as a barrier, restricting water infiltration and lowering the overall capillary absorption rate.

To assess the impact of steel fibers, 0.75% steel fibers were added to the concrete mix. The results showed a slight reduction in sorption capacity, with values of 4.8×10^{-4} cm/s$^{0.5}$ for 30% RAP and 4.3×10^{-4} cm/s$^{0.5}$ for 50% RAP**.** This minimal change suggests that steel fibers have little direct effect on sorption capacity as they do not significantly alter the capillary pore structure or permeability of the concrete. Instead, steel fibers primarily enhance mechanical properties, such

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as tensile and flexural strength, rather than affecting water absorption rates. The observed reduction in sorption capacity results from the interplay of two opposing factors. While the porous nature of RAP aggregates could potentially increase water absorption, the bitumen binder coating counteracts this effect by limiting water penetration. Additionally, proper hydration and curing contribute to densifying the cement matrix, further reducing capillary absorption and enhancing the durability of the concrete.

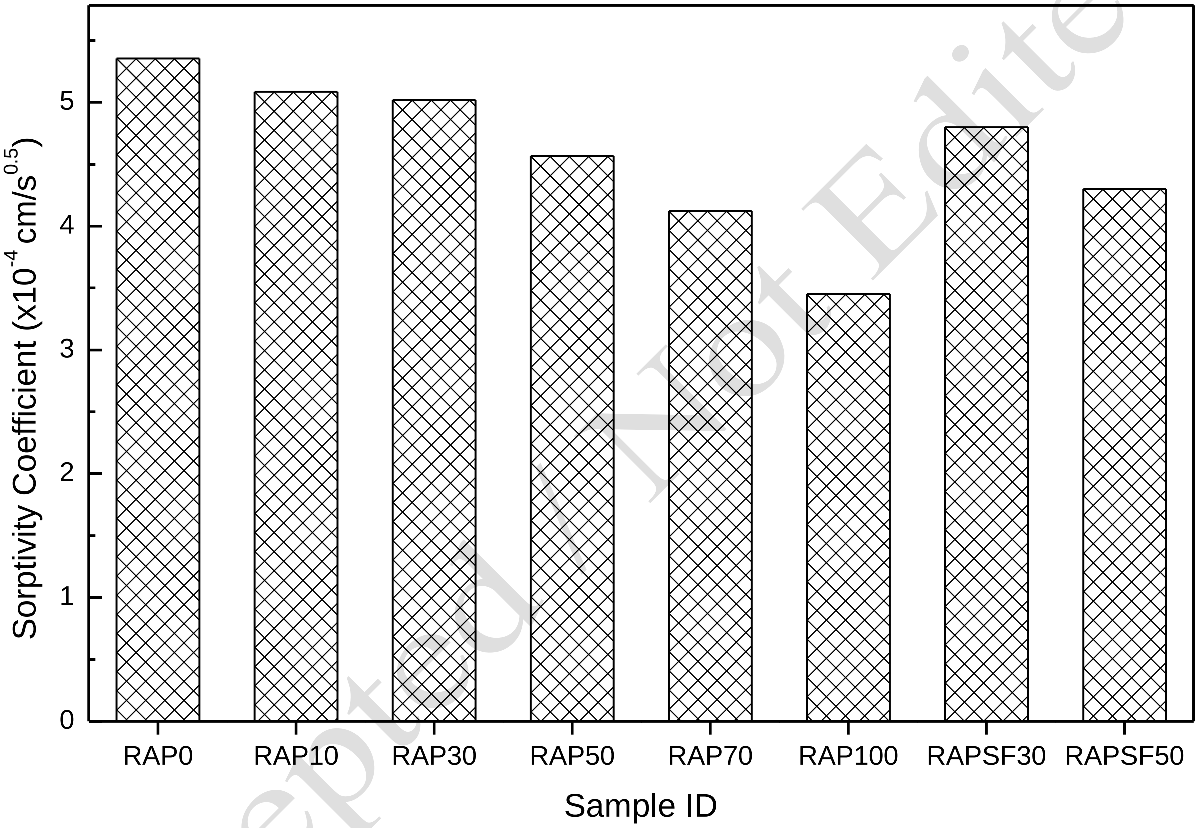

Fig. 7 Variation of sorptivity coefficient of concrete with RAP and SF **.**

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7. CONCLUSIONS

This experimental study assessed the mechanical and strength properties of RAP and steel-fiber-reinforced concrete. The findings indicate that increasing RAP content leads to a reduction in compressive, flexural, and tensile strength, while water absorption and sorption capacity exhibit only slight variations due to the presence of asphalt-coated aggregates. However, the addition of

0.75% steel fibers significantly enhanced the mechanical performance, particularly for mixtures containing 30% and 50% RAP. The key outcomes are:

- Compressive strength decreased with increasing RAP content, but the optimal strength of 40 MPa was achieved at 30% RAP with 0.75% steel fibers, which occurred due to enhancement of mechanical properties by addition of steel fiber.
- Flexural strength declined with RAP content but improved with steel fiber addition. The highest value recorded was 6.9 MPa at 30% RAP with 0.75% steel fibers, which enhanced the crack resistance.
- Split tensile strength showed a similar trend, decreasing with RAP but improving with steel fibers. The peak value was 7 MPa at 30% RAP with fibers.
- Water absorption increased slightly with RAP content but was not significantly influenced by steel fibers.
- Sorptivity coefficient decreased with higher RAP content, while the inclusion of steel fibers had a negligible effect on this parameter.
- The use of RAP in concrete reduces construction waste, minimizes reliance on natural aggregates, and promotes eco-friendly infrastructure.
- Incorporating RAP into concrete mixtures typically results in a reduction of split tensile strength. This is likely due to the inferior cohesion of recycled asphalt pavement (RAP) compared to virgin aggregates, which may result in issues with the bond between the RAP and the cement paste. Conversely, steel fibres inhibit crack propagation and enhance the tensile strength of concrete. They assist in maintaining the integrity of the concrete even when it begins to fracture under stress, so enhancing its total strength.
- Incorporating RAP lowers material costs while maintaining adequate strength and durability, making it a viable option for low-cost housing and road construction.
- The addition of steel fibers compensates for strength loss, making RAP based concrete suitable for sidewalks, pathways, and pavement structures.

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This study confirms that 30% RAP with 0.75% steel fibers offers an optimal balance between strength, durability, and sustainability, reinforcing the potential of RAP-based concrete as an environmentally responsible construction material.

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