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DURABILITY ASSESSMENT OF RECYCLED TIRE STEEL AND NYLON HYBRID FIBER-REINFORCED CONCRETE MODIFIED WITH NANO-ZrO_2 FOR RIGID PAVEMENT APPLICATIONS

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Article Info

Abstract

Excessive mechanical and environmental stresses frequently cause rigid pavements to deteriorate more quickly, resulting in early cracking, moisture intrusion, and a shorter service life. For sustainable rigid pavement applications, this study examines how adding Nano-ZrO_2 to Recycled Hybrid Fiber-Reinforced Concrete (RHFRC) can increase its durability. In order to create seven concrete mixes, 0.2% Nano-ZrO_2 was combined with recycled tire steel fibers (RTSF) and recycled nylon fibers (RNF) in various hybrid ratios. According to the applicable ASTM and ACI standards, durability was assessed using tests for water absorption, freeze-thaw resistance, impact energy absorption, ultrasonic pulse velocity (UPV), and drying shrinkage. The results showed that adding RTSF and Nano-ZrO_2 together greatly improved frost durability and decreased permeability (by more than 20%). After 200 freeze-thaw cycles, the RTSF1.5 + 0RNF mix maintained 94% of its compressive strength. In comparison to the control mix, impact resistance more than seven times increased, and improved internal integrity was indicated by UPV values (3.8–4.35 km/s). At 180 days, hybrid mixes with a moderate amount of nylon (RTSF1 + RNF0.5) successfully reduced drying shrinkage by 20%. In order to create a more resilient and sustainable pavement concrete, recycled fibers and Nano-ZrO_2 worked in concert to refine the microstructure, increase durability, and limit microcracking.

Keywords:

Recycled fibers; Nano-ZrO_2; Durability; Rigid pavement; Hybrid fiber-reinforced concrete (HFRC)

1. INTRODUCTION

Concrete pavements experience rapid deterioration, loss of internal integrity, and a shorter structural service life as a result of aggressive mechanical and environmental stressors such as freeze-thaw cycles, moisture exposure, shrinkage-induced cracking, and impact loads from moving vehicles [1–4]. The increased permeability and microstructural instability of conventional pavement concretes frequently cause them to fail too soon, highlighting the need for advanced materials with better crack resistance and transport-barrier efficiency [5], [6].

A sustainable method of enhancing the durability of concrete is the use of fibers derived from waste. Recycled tire steel fibers (RTSF) effectively mitigate crack propagation and improve impact energy absorption under abrupt dynamic loads because of their high tensile strength and mechanical anchorage [7–9]. On the other hand, RNF, which is recovered from textile and paintbrush waste, reduces early-age shrinkage and minimizes internal defects that serve as channels for fluid ingress by providing ductility and efficient crack bridging at microscales [10], [11]. A combined performance benefit is produced by the hybridization of steel and polymer fibers, whereby nylon fibers enhance toughness and structural continuity and steel fibers stop cracks from widening, improving durability under impact and cyclic loading [12–14]. For rigid pavements, which undergo mechanical and environmental stresses while in use, these performance benefits are especially crucial [15].

Additionally, in order to increase the microstructural durability of concrete, nanoscale additives are being added more frequently. Nano-zirconium dioxide (Nano-ZrO_2) enhances hydration, densifies the pore structure and strengthens the Interfacial Transition Zone (ITZ), resulting in reduced internal voids and better resistance to moisture penetration [16–18]. According to studies, the refined and denser microstructure of concrete containing Nano-ZrO_2 results in reduced water absorption, increased ultrasonic pulse velocity (UPV), and enhanced resistance to freeze-thaw deterioration [19], [20].

Few studies have examined the combined impact of recycled fibers and nano-modification on various durability aspects, despite the fact that both have been the subject of numerous investigations. It is still unclear how RTSF + RNF and Nano-ZrO_2 work together to improve impact resistance, shrinkage behavior, internal concrete quality through UPV, and overall mass transport behavior under freeze-thaw exposure [12], [18], [21], and [22]. To guarantee the long-term performance of pavement concrete, it is crucial to investigate these durability mechanisms collectively because rigid pavements are constantly subjected to repeated loading and environmental attack [3], [15], and [23].

Thus, the purpose of this study is to evaluate the durability performance of Recycled Hybrid Fiber-Reinforced Concrete (RHFRC) that has been modified with Nano-ZrO_2 for applications involving rigid pavement. Water absorption, UPV, drop-weight impact resistance, drying shrinkage, and freeze-thaw durability testing are used to assess durability. By fusing the advantages of recycled fiber with nanoscale microstructural improvement, the findings should contribute to the creation of a more resilient and sustainable pavement material.

This paper complements our previous investigation on the mechanical and structural performance of RHFRC, extending the analysis to durability aspects using the same optimized mix design."

2. Materials and Methodology

2.1 Materials

The materials used in this study include ordinary Portland cement (OPC), nano-ZrO_2 powder, fine and coarse aggregates, recycled tire steel fibers (RTSF), recycled nylon fibers (RNF), superplasticizer, and potable water.

2.1.1 Cement

The primary binder was ASTM C150-compliant Maple Leaf Cement (Grade 53, Type I) [24].

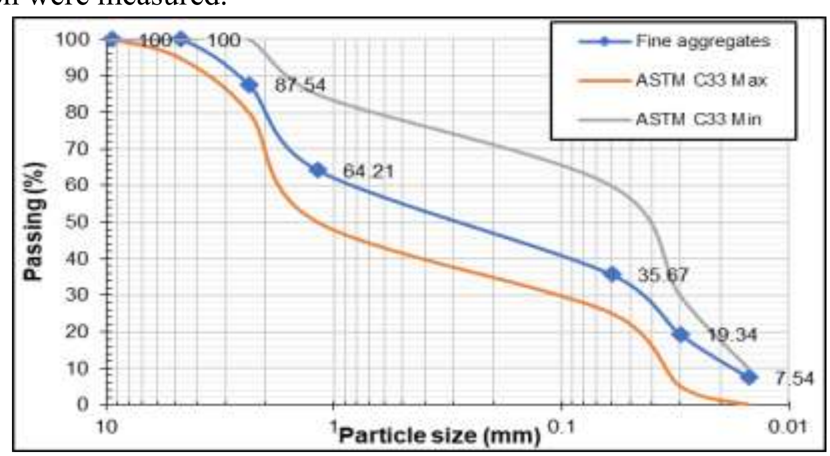
Table 1: Physical and Chemical Properties of OPC.

Chemical Properties						
Lime saturation Factor	Alumina Iron Ratio	Insoluble Residue	Magnesia	Sulphuric Anhydride	Total Chlorides	Ignition Loss
0.66-1.02	NR	1.5% max	4% max	3% max	NR	3% max
Physical Properties						
Specific Gravity	Consistency (%)	Initial Setting Time (min)	Final Setting time (mm)	Soundness (%)	28-days Compressive Strength (MPa)	
3.15	28.5	102	203	0.103	49.61	

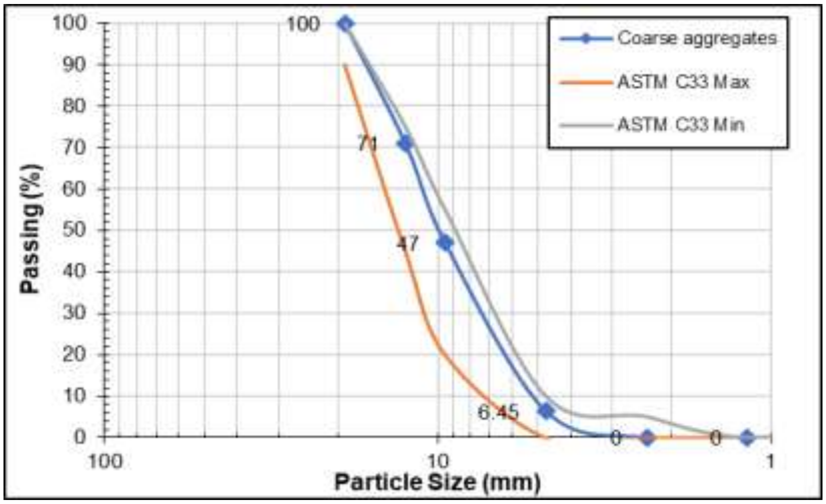
2.1.2 Fine and Coarse Aggregates

The coarse aggregate was crushed Sargodha stone up to 12.5 mm in size, and the fine aggregate was sand from the Lawrence Quarry River less than 4.75mm in size. Both satisfied ASTM C33's gradation restrictions [25]. Fig.1 shows the gradation curves for both aggregates.

In accordance with ASTM C128 and ASTM C127, physical attributes like bulk density, specific gravity, and water absorption were measured.



(a)



(b)

Fig. 1: Gradation Analysis of (a) FA, Quarry sand (b) CA, Crushed Aggregate

2.1.3 Nano-Zirconium Oxide (Nano-ZrO_2)

The commercially available Nano-ZrO_2 (from Zhengzhou Xinli Co., Ltd China) was used. It was used 0.2% of the cement weight. The particular surface characteristics and composition are shown in Table 2: Properties of nano-ZrO_2. As a micro-filler, the nano-additive reduces pore connectivity and increases hydration reactivity [15], [23].

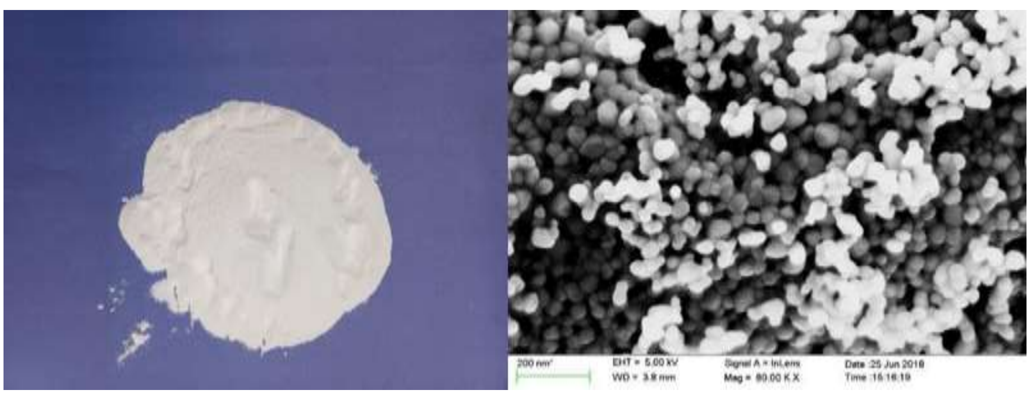


Fig. 2: Nano ZrO_2 and its SEM Micrograph

2.1.4 Recycled Tire Steel Fibers (RTSF)

RTSFs were extracted from used tires collected from local recycling facilities. Fiber measured approximately 0.5 to 1.5 inches in length, had an average diameter of 0.2 to 0.3 mm. According to Ali et al.'s findings [20], the recycled steel fibers improved flexural toughness and post-cracking strength. depicted in Fig. 3(a).

Table 2: Shows the physicochemical properties of Nano-ZrO_2.

Components		**Properties**
Chemical Component (wt%)	Zr(Hf)O2	≥99.9
	Al2O3	< 0.005
	Fe2O3	< 0.005
	SiO_2	< 0.01
	TiO_2	< 0.005
	Na_2O	< 0.005
L.O.I (wt%)		< 1
Water Composition (wt%)		< 1
Average Partical Size (nm)		80nm
Surface Area (m^2/g)		15-30

2.1.5 Recycled Nylon Fibers (RNF)

RNF was created using the bristles of an old paintbrush. The bristles were cleaned and then cut to a length of 0.5 to 1.5 inches. According to Ali et al. [13]. As shown in Fig. 3(b).

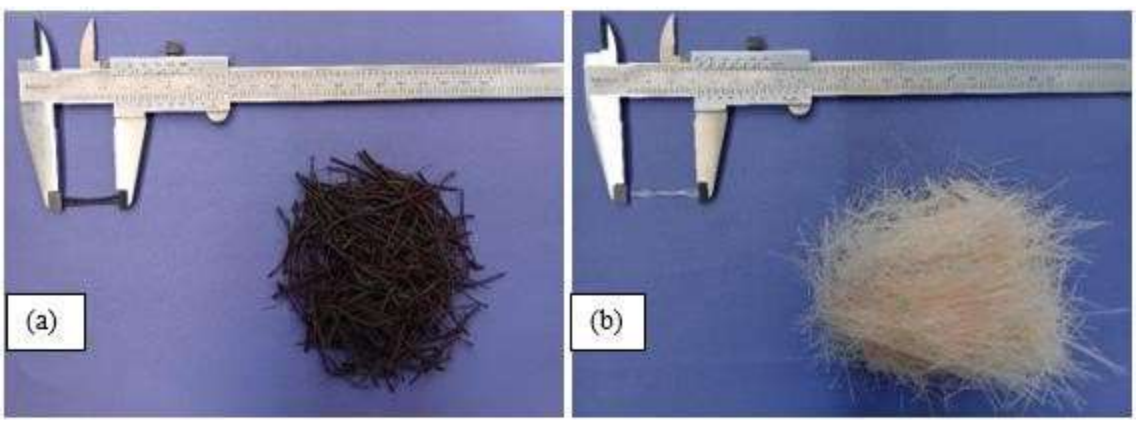


Fig. 3: Recycled Fibers (a) Recycled Tire Steel Fiber (b) Recycled Nylon Fiber

2.1.6 Superplasticizer and Mixing Water

A high-range water reducer (Ultra Super Plast 437) at 1% of the cement weight was used to keep fiber-reinforced mixtures workable. Regular tap water that met ASTM C1602 requirements was used for both mixing and curing.

2.2 Mix Design and Proportions

A target compressive strength of 35 MPa was selected at 28 days. There were seven types of mixes formed.

Table 3: Concrete Mix Proportions

Sr No	Fibers IDs	RTSF (%)	RNF (%)	Nano ZrO2 (%)
1	(PC)	0	0	0
2	PC + NM (0.2%)	0	0	0.2
3	RTSF1.5 + 0 (RNF)	1.5	0	0.2
4	RTSF1 + RNF0.5	1	0.5	0.2
5	RTSF0.75 + RNF0.75	0.75	0.75	0.2
6	RTSF0.5 + RNF1	0.5	1	0.2
7	RTSF0 + RNF1.5	0	1.5	0.2

To achieve uniform particle dispersion, the nano-ZrO_2 was dissolved in half of the water before being added to the mixer. After cement and aggregates had been dry mixed together, fibers were gradually added to prevent clumping. A total of six minutes were spent for mixing of each batch (2 minutes dry, 4 minutes wet). After finding fresh properties molds were filled. Casting and curing procedures followed ASTM C192. Samples were demolded after 24 hours and water-cured until testing.

3. Experimental Results & Discussions

3.1 Water Absorption of Concrete

Water absorption was measured by using samples of 100mm cubes according to the ASTM C642[26]. Reduced absorption indicates enhanced impermeability and microstructural densification. When fiber and nanoparticles were added, the water-absorption results consistently decreased. The RTSF1.5 + 0 RNF mixture had the lowest value (3.5%), indicating a 22% decrease in permeability, while the control mix absorbed 4.5%. The pore-refining function of ZrO_2 nanoparticles was confirmed by the improvement to 4.0% of the nano-modified control (PC + 0.2% NM) [3]. Steel fibers and Nano-ZrO_2 worked together to create a dense, fracture-free microstructure that limited capillary suction. While excessive nylon (RNF 1–1.5%) slightly increased absorption to 4.6–5.0% due to inter-fiber voids, hybrid mixes with a moderate nylon content (RTSF1 + RNF0.5) maintained low absorption (~3.9%) [4] as shown in **Fig. 4**. Therefore, the optimal impermeability was achieved at 1.5% steel fibers without nylon, indicating that nanopore filling and steel-fiber confinement are the main factors influencing permeability.

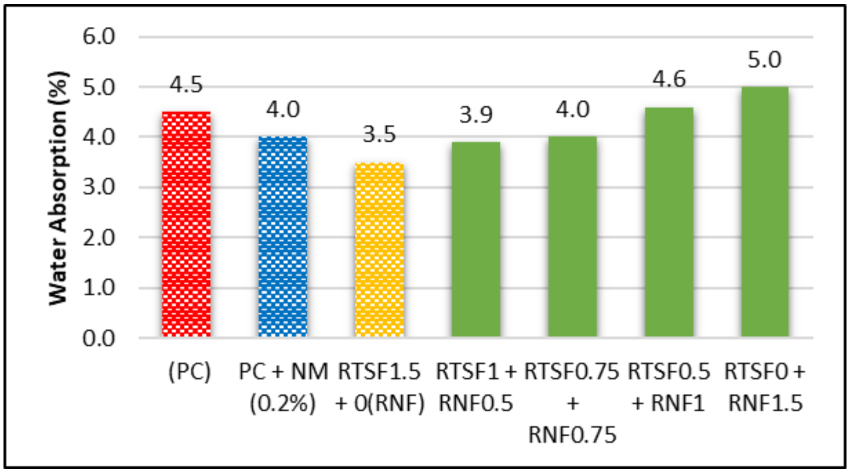


Fig. 4: Water Absorption Test Results

3.2 Freeze Thaw

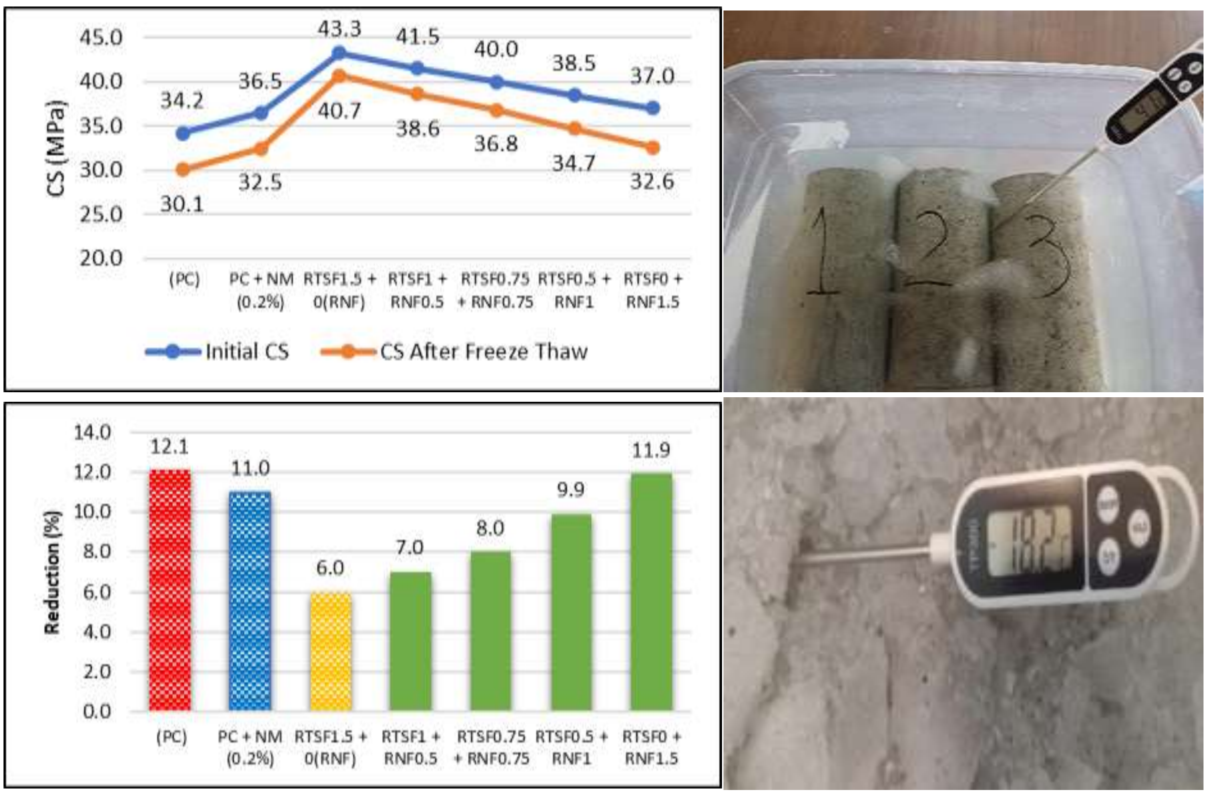


Fig. 5: Overview of Freeze Thaw Test & Results

Freeze-thaw tests on concrete were carried out in compliance with ASTM C666 [27]. Concrete cylinders measuring 100 mm by 200 mm were used for this test following a 14-day curing period. The samples underwent 200 cycles of freezing and thawing between -18°C and +4°C. Durability performance was evaluated by visual surface scaling and a decrease in compressive strength following cycling (ASTM C39). Improved resistance to microstructural degradation during freeze-thaw exposure was indicated by a lower loss of strength. Results for compressive strength before and after 200 freeze-thaw cycles showed in **Fig. 5** that fiber and nano modification significantly increased frost durability. From 34.2 MPa to 29.9 MPa, the control mix (PC) lost 12.1% of its initial strength. While mixes containing recycled fibers demonstrated significantly better retention, the addition of Nano-ZrO_2 alone reduced the loss to 11%. With only a 6% reduction, the RTSF1.5 + 0 RNF mix maintained 94% of its strength (43.3 → 40.7 MPa), demonstrating the best performance. With a 7–8% decrease, hybrid combinations like RTSF1 + RNF0.5 and RTSF0.75 + RNF0.75 came in second and third. Nano-ZrO_2 densifies the matrix and decreases water penetration, while steel and nylon fibers control microcracks, limiting internal stresses brought on by ice-crystal formation [1], [2]. Excessive nylon content (RNF ≥ 1.5 %) slightly weakened freeze–thaw resistance due to fiber clustering and lower stiffness. Overall, the hybrid fiber–nano composite improved microstructural stability and strength retention in a balanced manner.

3.3 Drop Weight or Impact Resistance of Concrete

To determine the impact resistance of concrete, a cylindrical sample of 150ϕ mm x 65h mm was prepared. A 4.45 kg weight is dropped onto the specimen surface from a predetermined height of 475 mm. This test calculates the number of drop cycles until the specimen fails in accordance with standard ACI 544 [28], which aids in assessing impact resistance. It was noted how many blows were needed to cause the first crack to appear and the ultimate failure. Better energy absorption and crack-arresting capabilities are indicated by higher blow counts. For every fiber-reinforced concrete, a noticeable improvement in impact behavior was noted. While the RTSF1.5 + 0 RNF mix absorbed 4623 J, or nearly 7.5 times the energy, after 230 blows, the control (PC) failed after 30 blows with a failure energy of 603 J. Closely behind were the hybrids RTSF1 + RNF0.5 and RTSF0.75 + RNF0.75 (failure energies of 4020 J and 4221 J, respectively) as shown in **Fig. 6**.

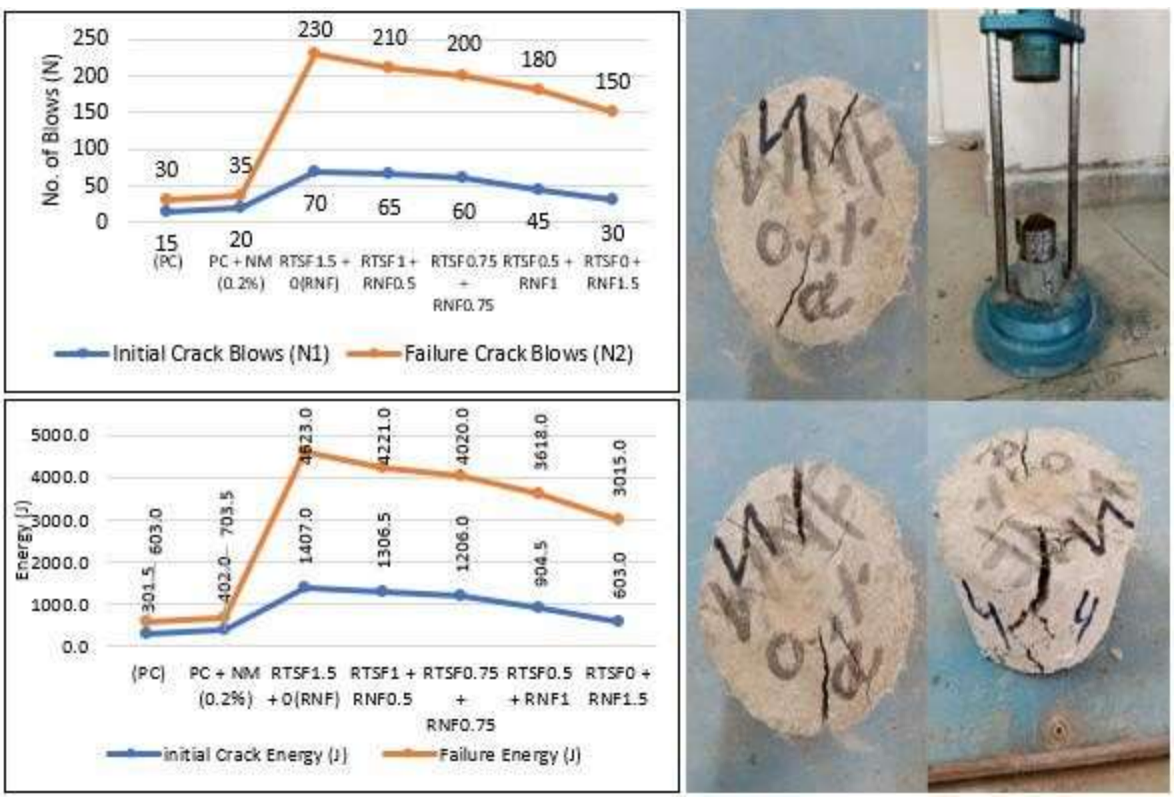


Fig. 6: Overview of Drop Weight Impact Resistance Test & Results

The enhancement results from the synergistic fiber network, wherein nylon fibers provide ductile energy dissipation by delaying post-crack propagation and steel fibers intercept macrocracks [8], [9]. By strengthening the bond at the fiber-matrix interface, nano-ZrO_2 improves stress transfer under impact loading. However, due to a lower modulus and more voids, the energy capacity and number of blows decreased at a high nylon dosage of 1.5%. According to the results, hybrid reinforcement maximizes toughness, which makes RHFRC especially useful for pavements subjected to high dynamic and impact loads.

3.4 Ultrasonic Pulse Velocity (UPV)

In accordance with ASTM C597, this test was conducted on cylindrical specimens measuring 100ϕ mm by 200h mm [29]. By calculating the speed and attenuation of an ultrasonic wave as it passes through the component under test, Ultrasonic Pulse Velocity (UPV) testing assesses the structural concrete's quality and integrity. Increased pulse velocity suggested less internal flaws and better integrity. All of the mixes fell into the "good–excellent" quality range, as indicated by the UPV values in **Fig. 7**, which varied from 3.80 km/s (PC) to 4.35 km/s (RTSF1.5 + 0 RNF) [5]. Better compactness and fewer internal voids are reflected in the steady increase in velocity with steel-fiber and nano addition. Recycled steel fibers prevented the formation of microcracks, while nano-ZrO_2 sped up cement hydration and improved the ITZ. Because nylon has a higher void probability and less stiffness, it has a slightly lower UPV in high-nylon mixes (RNF ≥ 1%). A balanced structure was provided by the hybrid mixture of 1% RTSF + 0.5% RNF (4.23 km/s), confirming that moderate polymer inclusion can preserve both density and ductility [6].

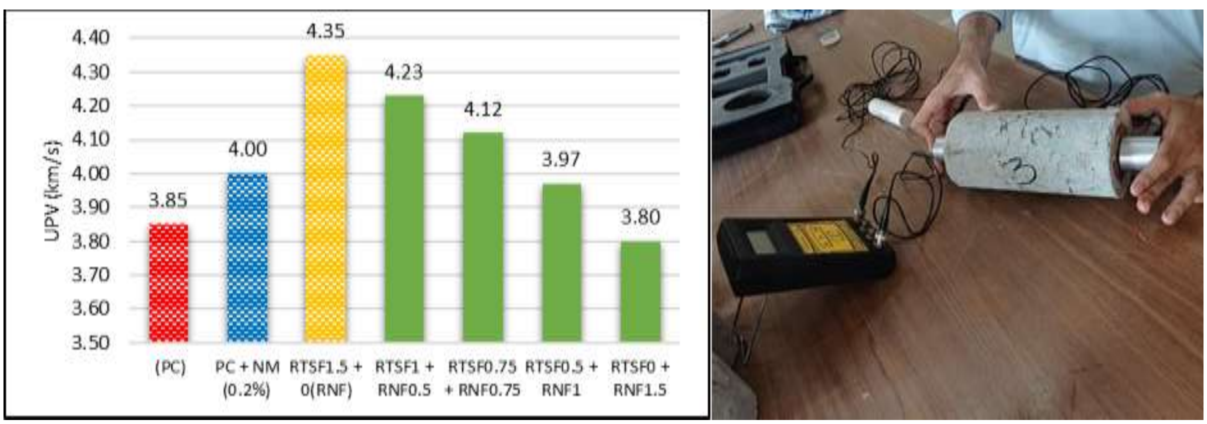


Fig. 7: Overview of UPV Test & Results

3.5 Drying Shrinkage

Shrinkage behaviour was evaluated following ASTM C157 [30]. Length change of prismatic specimens was monitored at regular intervals to determine the extent of shrinkage-induced microcracking control due to Fiber bridging. This test was performed on prismatic beams of 100mm x 100mm x 300mm after 7 days of curing. The readings were taken at 1, 2, 3, 5, 7, 14, 21, 28, 42, 56, 72, 90, 120, 150, 180 days. Fiber and nano inclusion resulted in a significant decrease in drying-shrinkage strains measured up to 180 days as shown in **Fig. 8.** The terminal strain of the nano-modified mix (PC + NM) was 470 με, whereas the control concrete showed roughly 505 με. Additional reductions were observed in all fiber-reinforced concretes; the RTSF1 + RNF0.5 and RTSF0.75 + RNF0.75 mixtures achieved ≈ 400 με, which is a 20%

decrease. By bridging microcracks, fibers effectively restrained internal volumetric contraction, and by densifying capillaries, Nano-ZrO_2 enhanced moisture retention [7]. Because of their higher water demand and flexibility, mixes containing more nylon fiber showed somewhat more shrinkage. Therefore, hybridization at balanced fiber ratios was the most effective way to reduce pavement slab cracking caused by drying.

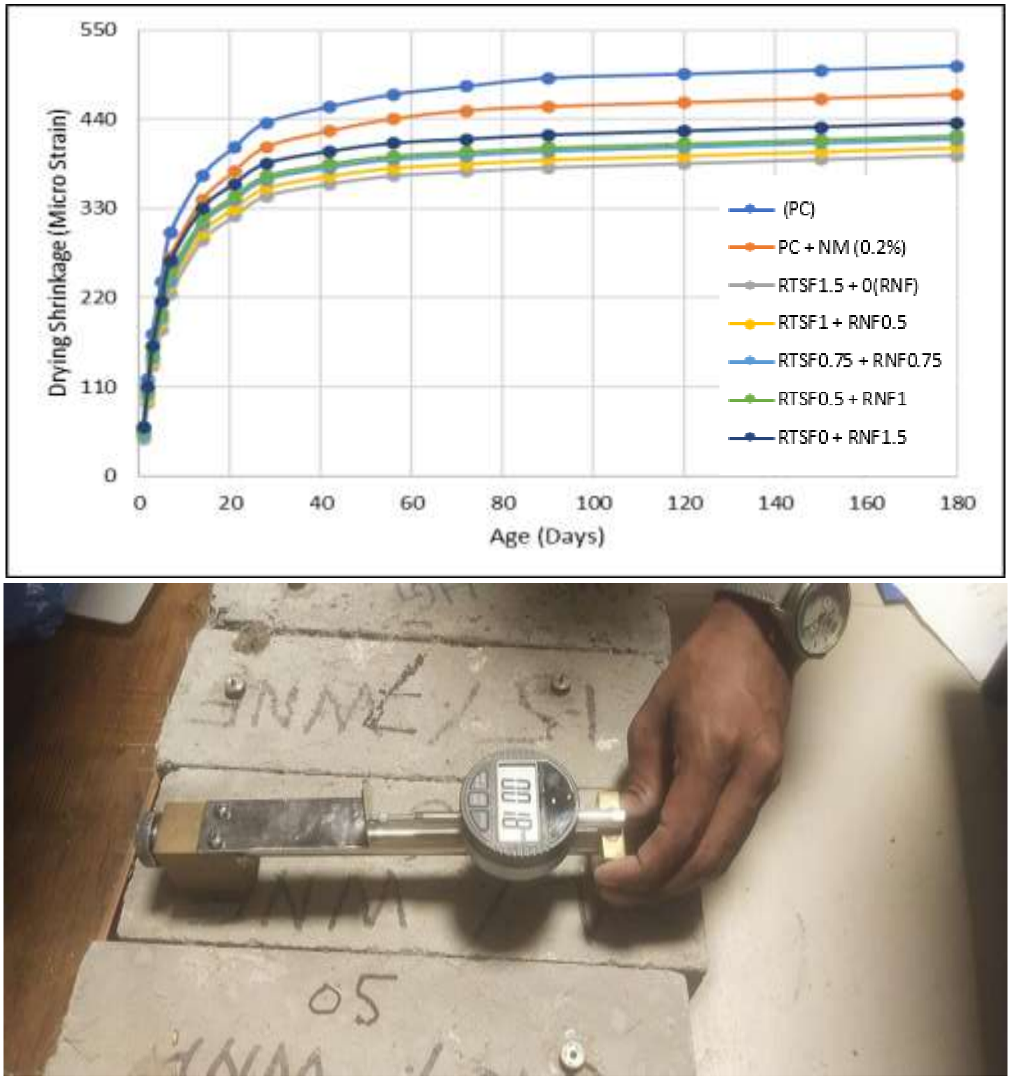


Fig. 8: Overview of Drying Shrinkage Test & Results

4. Conclusions & Recommendations

For rigid pavement applications, this study assessed the durability performance of Recycled Hybrid Fiber-Reinforced Concrete (RHFRC) modified with Nano-ZrO_2. The experimental results demonstrate that the combination of recycled tire steel fibers (RTSF), recycled nylon fibers (RNF), and nanoscale zirconium dioxide greatly enhances the long-term performance of concrete by improving crack control mechanisms and microstructural integrity.

1. When compared to the control mix, the addition of Nano-ZrO_2 and hybrid fibers decreased water absorption by more than 20%, indicating enhanced pore refinement and impermeability.

2. Because of the combined crack-bridging and densification effects, the RTSF1.5 + 0RNF mix demonstrated superior frost resistance, maintaining 94% of its initial compressive strength after 200 freeze-thaw cycles.
3. Because of the enhanced fiber–matrix interface that Nano-ZrO_2 provided and the synergistic energy absorption of steel and nylon fibers, impact resistance increased up to 7.5 times when compared to the control.
4. Excellent internal quality and compactness of the modified concrete were confirmed by UPV results (3.80–4.35 km/s), which showed reduced voids and increased homogeneity.
5. Drying shrinkage was about 20% lower in balanced hybrid mixes, demonstrating that better moisture retention and microcrack restraint effectively increase dimensional stability.

Overall, the combination of recycled fibers and Nano-ZrO_2 resulted in an impermeable, ductile, and long-lasting concrete that can be used to build rigid pavements in a sustainable manner. Long-term structural performance is supported by the suggested RHFRC mix, which also encourages resource recycling and cost reduction. In order to maximize its pavement applicability, future research should concentrate on field-scale validation, microstructural characterization, and resistance to chemical attacks like sulphate and chloride ingress.

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