

Recycled Hybrid Fiber Reinforced Concrete Modified with Nano Zirconia: Mechanical Performance and Pavement Application

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KEY WORDS	ABSTRACT
Hybrid Fibers Recycled Fibers Nano Modified Concrete Sustainable Rigid Pavement Pavement Thickness	Conventional plain concrete has a relatively low post cracking flexural resistance and therefore required larger pavement thickness. Hybrid fiber reinforced concrete using Recycled Tire Steel Fiber (RTSF) and Recycled Nylon Fiber (RNF) modified with Nano-ZrO ₂ is evaluated in terms of its mechanical, structural and sustainability performance for overcoming such limitations and decreasing the amount of natural materials used in production of concrete. To improve the multi-scale crack-bridging capabilities, a number hybrid combinations were made by utilizing 1.5% total fibre volume and Nano-ZrO ₂ 0.2% of weight of cement. All mixture's mechanical properties were assessed and utilized as input parameters for pavement thickness design in Street Pave software. The results showed that hybrid mixes' mechanical performance significantly improved in all areas, with compressive strength rising to around 127% and tensile strength in RTSF-rich blends reaching up to almost 200%. Flexural and residual flexural capabilities also dramatically boosted, especially in the hybrid RTSF1% + RNF0.5% combination that demonstrated the highest synergy in stiffness, ductility and post-crack load retention. Pavement slab thickness might be lowered by as much as 25–26% due to these strength benefits, which directly translated into enhanced structural efficiency. The cost analysis of basic concrete constituent materials showed that through optimization of thickness of slabs, about 25 percent of the cost of the material per unit pavement area could be reduced.

1. Introduction

Concrete is the most commonly utilized building material in the world, because of its affordability and adaptability. However, the ongoing expansion of rigid pavement construction and infrastructure development has resulted in a massive demand for cement and aggregates, which has contributed to the reduction of natural resources and an alarming increase in CO₂ emissions from the cement production industry [1–3]. In an effort to reduce the environmental effect of the concrete industry, recycled materials have been included in response to the demand for long-lasting and sustainable concrete

substitutes [4,5]. When it comes to enhancing the tensile resistance, crack management and post-cracking ductility of ordinary concrete, fiber-reinforced concrete (FRC) has shown great potential [6,7]. In recent years, there has been attention paid to the synergistic effects of fiber hybridization on the mechanical and fracture performance of concrete [8, 9]. Energy absorption and crack-bridging capacity under flexural and impact loading are improved when stiff metallic fibers are combined with ductile polymer fibers. Recycled fibers from pet bottles, paintbrushes, fishing nets and used tires have shown potential as environmentally benign reinforcements in sustainable

FRC [10–12]. Recycled tire steel fibers (RTSF), which are taken from used vehicle tires, have been shown to improve the flexural toughness and residual strength of concrete [13] and have a high tensile strength (~1100 MPa). Likewise, extra ductility and resistance to the spread of microcracks are offered by recycled nylon or polymer fibers derived from used paintbrushes or textile filaments [14]. Ahmad et al. reported that recycled nylon fibers (RNF) made from leftover paintbrush bristles can improve concrete's tensile, flexural and durability qualities at low doses, providing a sustainable substitute for manufactured fibers. The best results are obtained between 0.15% and 0.75% RNF, which increases flexural strength, decreases permeability, and improves fracture resistance. However, because of increased porosity and decreased fiber stiffness, larger fiber contents result in reduced density and compressive strength. [15]. In a literature, Zhong and Zhang [10] showed that the hybrid recycled tire steel and polypropylene fibers greatly improved the post-ultimate ductility and fracture resistance of concrete composites.

In addition to fiber reinforcing, the cement matrix has been strengthened but the pore structure refined by the introduction of nano-engineered additives such nano-zirconium dioxide (Nano-ZrO₂). Cement pastes and aggregates have better interfacial bonding and faster hydration due to nano ZrO₂'s high surface energy and pozzolanic reactivity [16,17]. The impact of nano modification on the mechanical behaviour of composite materials was examined and found that improved interfacial bonding at the nanoscale significantly increased strength and stiffness [18]. In a similar vein, it was noted that adding hybrid glass and basalt fibers to geopolymer mortars enhanced their structural integrity and durability at high temperatures, supporting the corresponding advantages of hybrid and nano-reinforced systems [19]. The combination of nano material modification and hybrid recycled fibers reinforced concrete can consequently result in a high-performance appropriate for structural uses like rigid pavements [20].

Fiber hybridization has a major impact on the performance of Hybrid Fiber Reinforced Self-Compacting Concrete. Compressive strength, flexural strength, toughness and fatigue resistance are all improved when steel and polypropylene fibers are combined. While differences in fiber amounts can impact fatigue behaviour and fracture management, a balanced fiber mix yields the best mechanical properties [21]. Fiber reinforcement can improve

flexural & residual flexural strengths and reduce pavement thicknesses by up to 15–20%, ultimately saving economy and materials while preserving the performance [22, 23].

The creation and performance assessment of Recycled Hybrid Fiber Reinforced Concrete (RHFRCC) (which incorporates Recycled Tire Steel Fibers (RTSF) and Recycled Nylon Fibers (RNF) modified with Nano-ZrO₂) are the main objectives of the current study. The composite's suitability for rigid pavement applications was evaluated by examining its mechanical properties such as its compressive, tensile and flexural strengths. Street Pave design software was used to forecast pavement slab thickness based on mechanical properties such as modulus of elasticity and residual flexural strength, due to this sustainable pavement design with lower material usage is made possible. This study provides a sustainable substitute for concrete infrastructure in the future by bridging the gap between performance-driven pavement engineering and the use of sustainable materials.

Unlike previous studies which have focused on individual fiber systems or limited their investigation to mechanical properties, this study has used hybrid recycled fibers RTSF and RNF to achieve multi scale crack bridging behaviour, modified with nano-ZrO₂ to improve matrix densification. Using Street Pave to translate these mechanical advantages to pavement thickness optimization provides an additional way to evaluate the structural and sustainability benefits of such a system.

2. Materials and Methodology

2.1 Materials

The materials employed in this study include recycled tire steel fibers (RTSF), recycled nylon fibers (RNF), fine and coarse aggregates, nano-ZrO₂ powder, ordinary Portland cement (OPC), superplasticizer and potable water.

2.1.1 Cement

The main binder was Maple Leaf Cement (Grade 53, Type I), which complies with ASTM C150 [24]. Chemical and physical properties of Ordinary Portland Cement are shown in Table 1.

2.1.2 Fine and Coarse Aggregates

Sand from the Lawrence Quarry (Attock) was used as the fine aggregate and crushed Sargodha stone utilized as the coarse aggregate. Both met the gradation limitations specified by ASTM C33. The gradation curves for both aggregates are presented in Fig. 1.

For the production of mixes, two types of aggregates were utilized: fine aggregates (0.075–4.75 mm) and coarse aggregates (4.75–12.5 mm). Fineness modulus of fine aggregate was 2.8. The fine aggregate's particle specific gravity and dry compacted density were 2.67 and 1.62 g/cm³, respectively. Crushed stone with a dry compacted density of 1.65 g/cm³ was utilized as coarse aggregate. The fine and coarse aggregates had corresponding water absorption rates of 1.16% and 0.80%.

2.1.3 Nano-Zirconium Oxide (Nano-ZrO₂)

Nano-ZrO₂ was utilized 0.2% of the cement weight, it was imported of commercially available Nano-ZrO₂ (from Zhengzhou Xinli Co., Ltd. China). Table 2 displays the physicochemical properties and composition of nano-ZrO₂. In order to improve hydration reactivity and decrease pore connectivity, the nano-additive functions as a micro-filler [16], [25]. Nano-ZrO₂ images are shown in Fig. 2.

2.1.4 Recycled Tire Steel Fibers (RTSF)

RTSFs were obtained from used automobile tires that were gathered from nearby recycling units. Each filament had a tensile strength of more than 1100 MPa [10], was around 12.5mm to 37.5mm in length, and had an average diameter of 1mm [15], [26-28] as shown in Fig. 3(a). Steel fibers generally are very susceptible to corrosion when exposed to moisture. However, in comparison with regular reinforcing bar, the recycled tire steel fibers (RTSF), embedded in a dense concrete matrix, are less susceptible to corrosion as they are discontinuous and are dispersed throughout the matrix which limits moisture and oxygen ingress into the matrix, thus reducing the potential for corrosion. Furthermore, the top surface of pavements typically has an applied protective coating (bituminous seal coat), which further protects the pavement from rain and reduces the chance of steel fiber corrosion. In addition, the authors have already worked on durability performance [20]. However, further study to evaluate long-term durability under extreme environmental conditions is recommended.

Table 1: Physical and chemical properties of Ordinary Portland Cement (OPC)

Chemical Properties (%)						
CaO	Al ₂ O ₃	SiO ₂	MgO	SO ₃	Fe ₂ O ₃	Ignition Loss
64.4	7.3	20.3	2.89	1.3	3.5	1.1
Physical Properties						
Specific Gravity	Specific Surface Area (m ² /kg)	Initial setting time (min)	Final setting time (min)	Soundness (%)		CS (MPa)
3.15	346	92	203	0.10		48.12

Table 2: Physicochemical properties of Nano Zirconia (ZrO₂)

Chemical Components (wt%)					
Zr(Hf)O ₂	Al ₂ O ₃	Fe ₂ O ₃	SiO ₂	TiO ₂	Na ₂ O
≥99.9	< 0.005	< 0.005	< 0.01	< 0.005	< 0.005
Physical Components					
L.O.I (wt%)	Water Composition (wt%)		Average Particle Size (nm)		Surface Area (m ² /g)
< 1	< 1		80nm		15-30

2.1.5 Recycled Nylon Fibers (RNF)

RNF was made from used paintbrush bristles. After cleaning, the bristles were trimmed in 12.5mm to 37.5mm lengths as shown in Fig. 3(b). Ahmad et al. [15] stated that the average tensile strength of nylon fibers was 357 MPa, and their specific gravity was

1.11 g/cm³. The fiber filament had a diameter of between 0.25 to 0.50 mm.

2.1.6 Superplasticizer and Mixing Water

Fiber-reinforced mixes were kept workable by using a high-range water reducer (Ultra Super Plast 437) at 1% of the cement weight. For both mixing and curing,

regular tap water that complied with ASTM C1602 standards was used.

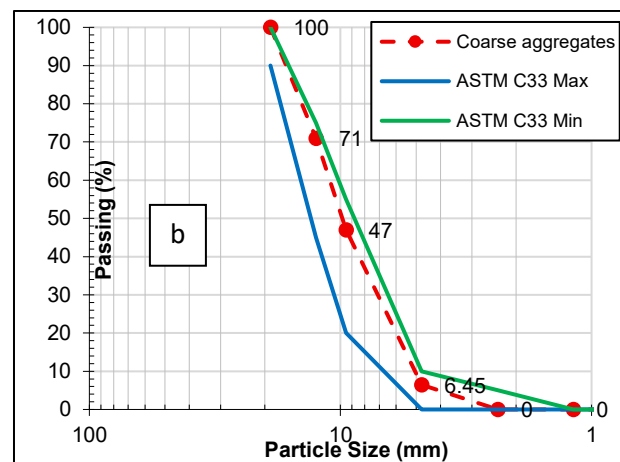
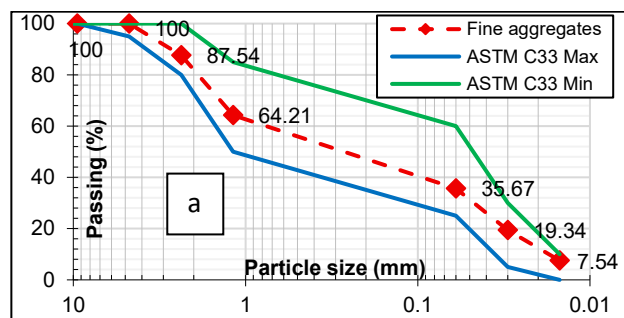


Fig. 1: Gradation analysis of (a) Fine Aggregates (b) Coarse Aggregate

2.2 Mix Design and Methodology

A target strength of 35 MPa for mix ratio 1:1.460:1.872 and W/C ratio 0.4% was chosen.

Table 3: Seven Concrete mix proportions

Mix IDs	Cement (kg/m ³)	Fine Aggregate (kg/m ³)	Coarse Aggregate (kg/m ³)	Water (kg/m ³)	SP (kg/m ³)	Nano ZrO ₂ (kg/m ³)	RTSF Fiber (kg/m ³)	RNF Fiber (kg/m ³)
(PC)	553.8	809.0	1037.2	221.5	5.5	0.00	0.0	0.0
PC + NM (0.2%)	553.8	809.0	1037.2	221.5	5.5	1.11	0.0	0.0
RTSF1.5% + 0 (RNF)	553.8	809.0	1037.2	221.5	5.5	1.11	117.0	0.0
RTSF1% + RNF0.5%	553.8	809.0	1037.2	221.5	5.5	1.11	78.0	5.6
RTSF0.75% + RNF0.75%	553.8	809.0	1037.2	221.5	5.5	1.11	58.5	8.3
RTSF0.5% + RNF1%	553.8	809.0	1037.2	221.5	5.5	1.11	39.0	11.1
RTSF0 + RNF1.5%	553.8	809.0	1037.2	221.5	5.5	1.11	0.0	16.7

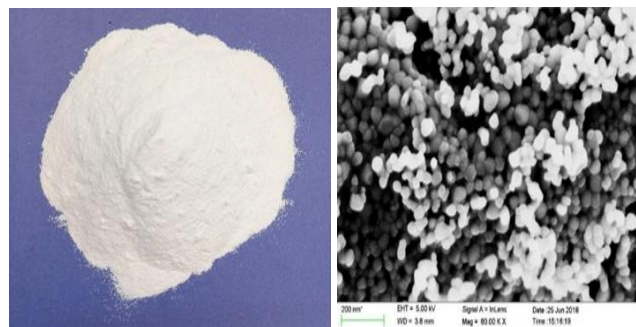


Fig. 2. Nano ZrO₂ and its SEM Micrograph

different kinds of mixes were made shown in Table 3. A mechanical mixer was used to prepare each mix. For the control mix that was Plain Concrete (PC), cement and aggregates were dry mixed for two minutes, then water was added gradually and mixed for an additional four minutes, for a total of six minutes. But in the 2nd mix, half of the water was introduced first, while the remaining water was pre-blended with nano-ZrO₂ and superplasticizer. For hybrid fiber mixes, cement and aggregates were blended for two minutes, fibres were dry mixed in it for another two minutes, and water was added in three

stages: half without admixtures, then the remaining water mixed with superplasticizer and nano-ZrO₂.

3. Results & Discussions

3.1 Experimental Program

For each concrete mix, three cylinders were tested for compressive strength, three cylinders for split tensile strength and three prisms for flexural strength, and the reported results represent average values.



Fig. 3. (a) RTSF & (b) RNF

3.1.1 Workability (Slump Test)

According to ASTM C143 [29], slump test was performed to assess the workability. Fig. 4 displays the slump values for each concrete mix. In comparison to

the PC, a decrease in slump was noted upon the addition of nano-ZrO₂ and fibers. The RNF1.5 mix had the smallest slump, measuring 35 mm, whereas the PC recorded a 75 mm slump. Because fibers increased internal friction and reduced the free movement of concrete particles during mixing resulted in lower slump [26], [30, 31]. Moderate slump values between 52 mm and 60 mm were shown by hybrid combinations like RTSF0.75 + RNF0.75 and RTSF0.5 + RNF1. Because of the enhanced fiber dispersion and decreased clustering, these mixes were able to maintain better flowability than single-fiber mixes. Overall, a homogeneous mixture with suitable workability for pavement applications was created by the hybridization of steel and nylon fibers.

3.1.2 Density of Fresh Concrete

In accordance with ASTM C138 [32], the density of freshly mixed concrete was tested in order to evaluate fiber dispersion and compaction effectiveness. Fig. 5 shows the mixes' fresh density trends. After adding nano-ZrO₂, the density of the control mix, which was 2365 kg/m³, slightly increased to 2380 kg/m³. The filler effect of nano-ZrO₂, which increases packing density and decreases air voids, is responsible for the improvement.

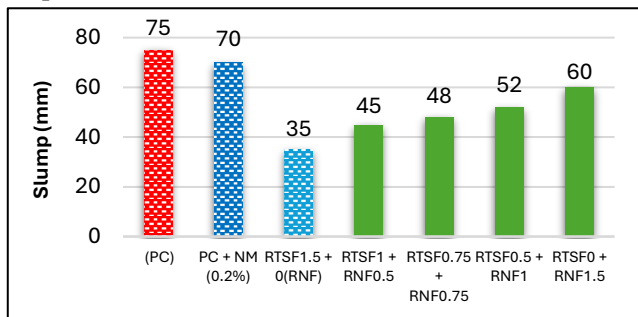


Fig. 4: Slump Values trend

The high specific gravity of steel fibres allowed the RTSF1.5 mix to achieve a maximum density of 2435 kg/m³. Because nylon has a much lower specific gravity than steel, mixes with a higher percentage of nylon fiber showed slightly lower densities. The hybrid mixes with intermediate densities (2410–2420 kg/m²) demonstrated that mixing the two different fiber types produces a mass distribution in the concrete matrix that is balanced.

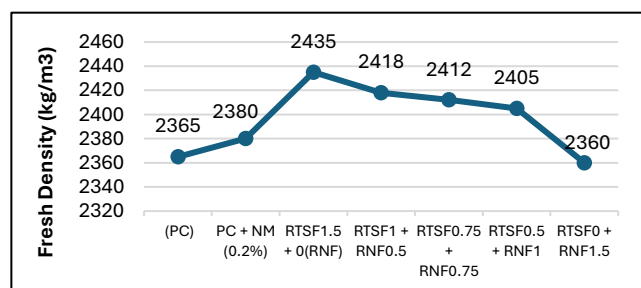


Fig. 5: Fresh Density of Mixes

3.1.3 Compressive Strength

After 28 days, cylindrical specimens of 100mm x 200mm were examined in compliance with ASTM C39 [33]. Fig. 6 shows the results for compressive strength, both nano-ZrO₂ and fibers clearly contribute positively. Because of matrix densification and enhanced hydration brought on by nano particles, the nano-modified combination (PC + NM) exhibits a 7% increase in comparison to the control mix (100%).

Because of the high stiffness and mechanical anchoring of steel fibers, which successfully limit lateral expansion under compression, RTSF1.5 shows the greatest rise of any blend, reaching 127%. Strong results are also obtained from hybrid mixes: RTSF1 + RNF0.5 boosts strength to 122%, while RTSF0.75 + RNF0.75 improves strength to 118%. By combining macro-crack resistance (RTSF) with micro-crack control (RNF), hybridization produces a balanced confinement effect, as these data verify. Because of the reduced stiffness of nylon and higher fiber clustering, strength marginally declines when RNF concentration rises over the ideal ratio, with RNF1.5 reaching 109%. Overall, the findings show that the ideal hybrid ratio (RTSF1 + RNF0.5) successfully improves compressive performance while preserving material homogeneity, which is consistent with observed experimental trends.

3.1.4 Splitting Tensile Strength

After 28 days of curing, tensile tests were conducted on 100 mm by 200 mm cylinders in accordance with ASTM C496 to assess split tensile performance [34]. Fig. 7 displays the results of the splitting tensile strength. When fibers and nanomaterials are added, the relative tensile strength findings clearly improve. Tensile performance is 100% in the control mix and 108.3% in the NM mix, mostly because of the densification of the Interfacial Transition Zone (ITZ) brought on by nano pores filling processes of Nano-ZrO₂. The combination containing RTSF1.5 + RNF0 has the highest tensile strength 4.80MPa which is 100% more than the PC. This significant increase is attributed to the high stiffness, remarkable crack-bridging ability, and mechanical anchoring of RTSF, which effectively inhibits the formation of macrocracks under tensile stresses. Hybrid fiber systems also demonstrate strong results. The RTSF1 + RNF0.5 combination performs 79% better than PC. This hybrid system's enhanced performance is due to its synergistic reinforcement mechanism: RTSF controls macrocracks, while RNF restricts the initial development of microcracks and enhances strain distribution. When combined, these processes

improve tensile ductility and stabilize the formation of cracks. The balanced hybrid mixes RTSF0.75 + RNF0.75 achieves 162.5%, indicating that tensile strength is also greatly increased by equal proportions of both fibers. However, RNF-dominant blends, such as RNF1.5 (129.2%), perform worse because of RNF's higher propensity for fiber clustering and decreased stiffness, which restricts its capacity to effectively bridge fractures.

Overall, the findings indicate a consistent trend in material performance, which showed that hybrid fiber systems (RTSF + RNF) modified with nano material exhibited superior tensile behaviour because of increased multi-scale crack reinforcing and ITZ quality.

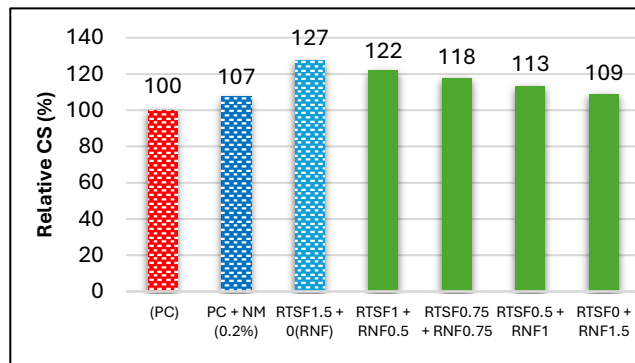
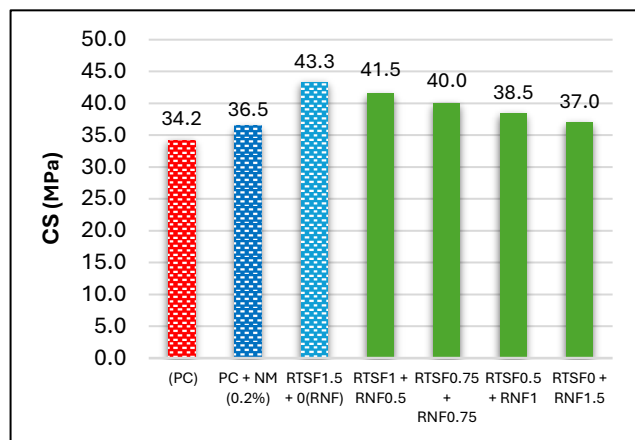
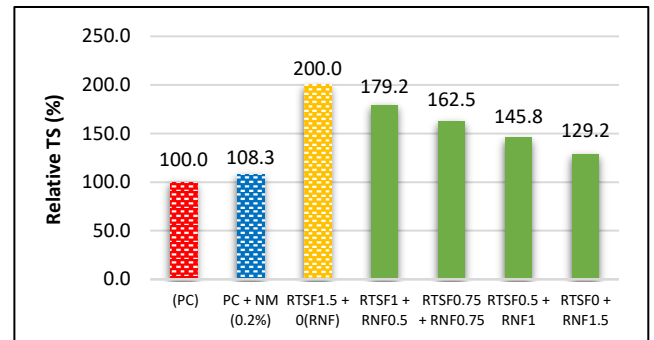
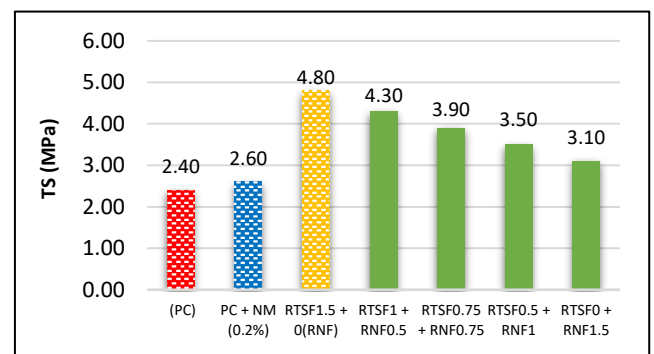


Fig. 6. Overview of Compression Testing & Results

3.1.5 Flexural Strength and Residual Flexural Strength

Using $100 \times 100 \times 50$ mm prisms, flexural



Tensile Failure Pattern

Fig. 7: Overview of Splitting Tensile Testing & Results

behaviour was tested under two-point loading in accordance with ASTM C1609 is standard [35]. The flexural strengths offered by hybrid fibers and Nano-ZrO₂ were evaluated by recording the first-crack and post-crack residual strength values. Fig. 8 displays the results of flexural and residual flexural strength. Relative Flexural Strength (FS) and Relative Residual Flexural Strength are significantly improved throughout fiber reinforced mixes, according to the results. The brittle post-cracking behaviour of plain concrete (PC) was demonstrated by its 100% FS with no residual strength. Although there was no contribution to residual FS in 2nd mix also but the addition of NM (0.2%) produced a modest rise to 110% FS, indicating that NM enhances matrix densification but is unable to hold load after breaking. Mixes containing RTSF showed the greatest improvements. The RTSF1.5 + RNF0 combination performed well, achieving 178% FS and 30% residual strength, due to RTSF's higher crack-bridging and post-crack load carrying properties. Hybrid combinations worked effectively. While the

RTSF0.75 + RNF0.75 and RTSF0.5 + RNF1 combinations obtained 156–161% FS and 22–23% residual strength, the RTSF1 + RNF0.5 combination demonstrated 166% FS and 28% residual strength. These findings verify that the combination of RTSF and RNF offers efficient multi-scale reinforcement, where RNF stabilizes microcracks and RTSF regulates macrocracks, improving flexural strength and post-crack ductility. With 146% FS and just 15% residual strength, the mix comprising RTSF0 + RNF1.5 showed the lowest performance. This restricted performance is explained by RNF's smooth surface and lower modulus of elasticity, which lessen its ability to control large fracture propagation or maintain higher load after breaking.

While NM improves matrix densification but has lowest impact on post-cracking behaviour than fiber reinforcement. Mixes with higher proportions of RTSF, either alone or in combination with RNF, produced the most significant improvements in both Relative Flexural Strength and Relative Residual Flexural Strength.

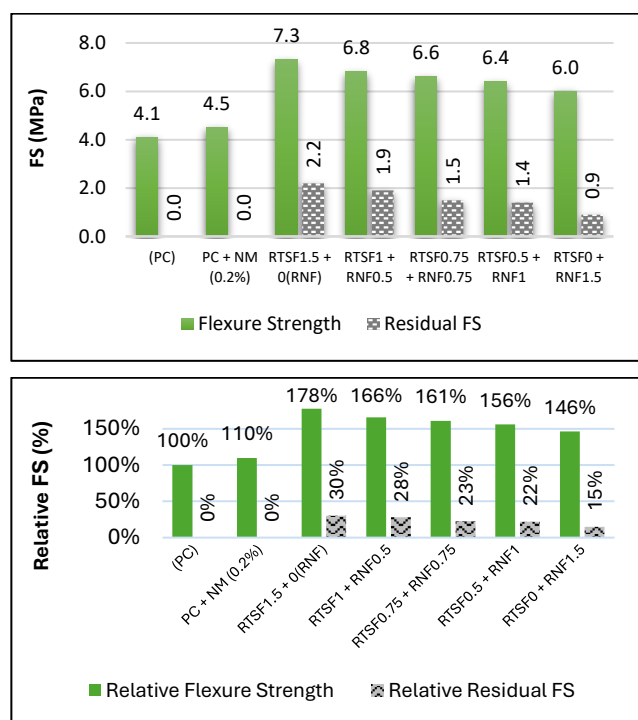


Fig. 8: Overview of Flexural Strength Testing & Results

3.1.6 SEM (Scanning Electron Microscopic) Analysis

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The interaction between RNF and the nano-modified cement matrix in the hybrid composite is clearly seen by the SEM micrographs Fig. 9. The RNF fibers, which are embedded in a densified framework, are clearly apparent in both pictures. Strong mechanical anchoring is indicated by the compact and well-bonded interface between the RNF and the surrounding matrix, which is consistent with the noted increases in tensile and flexural strength.



Fig. 9. SEM Images of RNF in Concrete Matrix

The refinement of the interfacial transition zone (ITZ) is one prominent aspect that can be seen in the pictures. The dense and uniform structure observed in the zones around the fibers is due to the incorporation of Nano-ZrO₂. These nanoparticles fill micropores and promote secondary hydration by providing active surfaces for hydration. The improved fiber-matrix adhesion and decreased porosity along the fiber surface of the modified ITZ are directly linked to the increased compressive strength and fracture resistance seen in the mechanical testing. Both micrographs show that microcracks arrested at the RNF surface, indicating the fibers' ability to prevent early crack propagation. This crack-bridging technique increases the composite's toughness by reducing the

concentration of stress along the fracture path. The roughened fiber surface shown in the high-magnification image further encourages frictional adhesion and prevents fiber pull-out. The matrix morphology surrounding the RNF indicates a multiscale reinforcing environment where RNF controls micro-cracking while RTSF manages macro-level crack opening in the composite, although the larger RTSF fibers are not captured within the same SEM frames. The improved post-cracking behaviour and high residual strength of the hybrid mixes are attributed to this synergistic reinforcement, which is supported by nano-ZrO₂ densification.

The combined effect of RNF, RTSF and Nano-ZrO₂ resulted in a denser matrix, stronger ITZ, and enhanced fracture resistance, as evidenced by the strong correlation between the SEM observations and mechanical performance.

3.2 Pavement Design Thickness (h_{Design})

Street Pave software was used to design the thickness of Jointed Plain Concrete Pavement (JPCP) for Major Arterial Street, which is subjected to the highest truck traffic. The design was based on the mechanical parameters (flexural strength, residual strength and modulus of elasticity) of each composite. Table 4 and Table 5 provide the remaining design input parameters. All general design inputs were kept constant for all composites except the mechanical properties while designing the pavement thickness.

The improvement in flexural and residual performance due to RTSF, RNF and NM directly contributes to the reduction in pavement design thickness. When NM (0.2%) was added to the plain concrete, then required design thickness reduced from 216.92 mm to 203.45 mm. Despite the fact that NM increased matrix densification but the absence of fibers restricted the post-cracking capacity, hence the decrease in h_{Design} was quite minor.

The inclusion of RTSF resulted in a significant reduction in h_{Design} . When compared to PC, the RTSF1.5 combination yielded the lowest design thickness (161.04 mm) with 55.88 mm reduction. This notable decrease is attributed to the enhanced crack-bridging capacity and post-cracking performance of RTSF, which improve the flexural and residual strength parameters that are directly utilized in pavement thickness design. Additionally, the hybrid mixes also exhibited the significant reduction in design thickness. Required thickness was reduced by 55.38 mm by the RTSF1 + RNF0.5 mix, 54.61 mm by

RTSF0.75 + RNF0.75, and 54.11 mm by RTSF0.5 + RNF1. These findings show that hybridization offers efficient multi scale reinforcement in which RNF stabilizes microcracks and RTSF controls macrocracks, thereby improving toughness and reducing the structural demand for pavement thickness. Additionally, the trend confirms the prominent role of RTSF in flexural-based pavement design, as a gradual reduction in RTSF content results in a slight but consistent decline in the effectiveness of h_{Design} improvement. RTSF0 + RNF1.5 showed the lowest amount of reduction among all fiber reinforced mixes, with a thickness decrease of 53.60 mm. While RNF improves ductility and helps manage microcracks, its lower stiffness and restricted capacity of crack-bridging limit its ability to reduce the required pavement thickness as compared to RTSF. Overall, the findings indicate that NM slightly reduces the design thickness, while mixes with higher RTSF fractions produce the greatest reduction. Although hybrid mixes provide notable reductions, they are slightly lower than RTSF dominant mix. These results align with the typical behaviour of fiber reinforced systems, where reductions in required pavement thicknesses are directly associated with improvements in flexural strength and residual load carrying capacity. Following is the equation for thickness of pavement obtained from regression analysis between flexural strength and design thickness.

$$h_{Design} = -18.794 FS + 287.87 \text{ where } R^2 = 0.9081$$

The high R^2 value confirms a strong correlation between flexural strength and pavement thickness. The negative coefficient indicates that increasing the flexural strength of RHFRC enables the use of thinner and more sustainable pavement sections.

3.3 Savings of Basic Concrete Constituents and Cost Analysis Based on Design Thickness

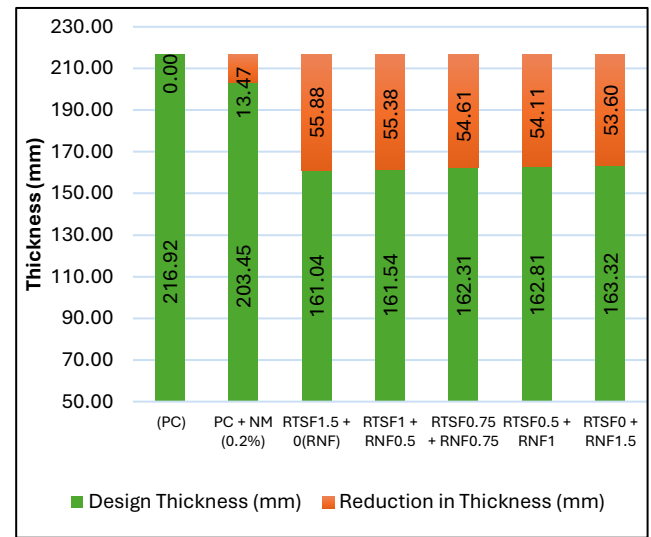
According to Table 6, It is clear from the material's percentage saving that a reduction in thickness results in a corresponding reduction in the usage of concrete constituents. PC exhibits no savings, The addition of Nano-ZrO₂ alone results in a minor 6.21% savings in concrete constituents, indicating that nano-modification slightly improves strength to allow a modest reduction in slab thickness. The introduction of recycled fibers results in a significant decrease in material utilization. Hybridization with RTSF and RNF greatly increases flexural capacity, enabling

Table 4: Design input parameters in Street Pave [36, 37].

Design input parameters including subgrade soil and concrete properties	
Final Terminal Serviceability	2.0
Reliability (percentage)	85.0
Resilient Modulus of Subgrade soil reaction (MPa)	28.0
Composite Modulus of Subgrade soil reaction (MPa)	28.0
At the end of design life, Slab cracked (percentage)	15 (typically taken value)
Edge support of pavement	Provided at Both sides
Elastic modulus of concrete - E_c (MPa)	Different for PC and HFRCs mixes
Flexural strength of concrete - FS (MPa)	Different for PC and HFRCs mixes
Residual strength of concrete - RS (%)	0% for PC mix Different for HFRCs mixes
Fibers	Considered for HFRCs mixes and Not Applicable for PC

Table 5: Input parameters in Street Pave for all Mixes

Input Parameters	Street Type
Traffic loading pattern*	Major Arterial
Trucks per day	700-1500
Traffic future growth (%)	2
Design life	25 Years
Lane distribution factor	100%
Directional distribution factor	50%
Total truck traffic over the design life throughout design life	11,113,545
Average trucks per day over the design life throughout design life	475-1,010

**Fig. 10.** Design Thickness & Reduction in thickness

the slab thickness to drop from 216.9 mm to around 161–163 mm, as attributed by the 24–26% constituents saving achieved by all fiber reinforced mixes. The RTSF1.5 + RNF0 combination achieves the highest concrete constituents saving (25.76%) which is closely followed by the hybrid mixes RTSF1 + RNF0.5 and RTSF0.75 + RNF0.75. Substantial savings of 24.7–24.9% are maintained even in blends with higher nylon content, demonstrating that both steel and nylon fibers contribute to structural optimization. These percentage savings demonstrate that improved mechanical performance directly translates into substantial material savings, ultimately reducing construction costs and environmental impacts by decreasing the use of cement, aggregates, water and admixtures by approximately 25 percent. Cost analysis of basic concrete constituents further showed that optimizing slab thickness could reduce material costs by about 25% per unit pavement area.

Table 6: Savings of Basic Concrete Constituents and Cost Analysis Based on Design Thickness

Mix IDs	h (m)	Cement (kg/m ²)	Fine (kg/m ²)	Coarse (kg/m ²)	Water (kg/m ²)	SP (kg/m ²)	Total (kg/m ²)	Material Saving (kg/m ²)	Material Saving (%)	Cost (USD /m ²)	Cost Saving (%)
PC	0.2169	120.13	175.49	224.99	48.05	1.19	569.85	0.00	0.00	23.25	0.00
PC + NM (0.2%)	0.2035	112.67	164.59	211.02	45.06	1.12	534.46	35.39	6.21	21.81	6.17
RTSF1.5 + RNF0	0.1610	89.18	130.28	167.03	35.67	0.89	423.05	146.80	25.76	17.27	25.70
RTSF1 + RNF0.5	0.1615	89.46	130.69	167.55	35.78	0.89	424.37	145.48	25.53	17.32	25.50
RTSF0.75 + RNF0.75	0.1623	89.89	131.31	168.35	35.95	0.89	426.39	143.46	25.18	17.39	25.18
RTSF0.5 + RNF1	0.1628	90.16	131.71	168.87	36.06	0.90	427.70	142.15	24.95	17.45	24.92
RTSF0 + RNF1.5	0.1633	90.45	132.13	169.45	36.17	0.90	429.06	140.79	24.71	17.51	24.68

4. Conclusions & Recommendations

Based on the analysis and experimental findings, the following conclusions may be drawn:

1. The incorporation of recycled fibers and nano-ZrO₂ had a significant influence on the fresh and hardened characteristics of concrete. The use of hybrid fiber combinations RTSF + RNF improved homogeneity of the mixes and minimized clustering as compared to single-fiber mixes; however, fiber addition reduced the workability due to increased internal friction.
2. Fresh density of concrete was considerably increased by adding nano-ZrO₂ because it improved the pore structure and filled the microvoids. Higher RTSF reinforced mixes had the maximum fresh density because steel has a greater specific gravity than nylon, while higher RNF mixes had slightly lower density because nylon has lower unit weight.
3. Compressive strength was improved by the inclusion of hybrid fibers and nano-ZrO₂. The maximum relative compressive strength of 127% was achieved by the RTSF1.5 + RNF0 mix while 122% was obtained by hybrid mix RTSF1 + RNF0, indicating effective stress transfer and improved fracture resistance within the matrix.
4. The splitting tensile strength was significantly increased with the use of hybrid fibers. Hybrid mix with RTSF1.5 + RNF0 exhibited the maximum relative tensile strength, nearly double as compared to the PC. Other hybrid mixes also showed considerable improvements in tensile performance.
5. The flexural and residual flexural strengths were significantly enhanced by the hybrid fiber reinforcement. RTSF1.5 + RNF0 mix achieved the highest relative flexural and residual strengths of 178% and 30%, respectively. While other hybrid mixes also provided notable enhancements in flexural performance. These improvements increase the post-cracking toughness and ductility.
6. According to pavement design analysis, the required slab thickness can be reduced by up to 26%, from 220 mm to 162 mm, due to the enhanced flexural performance of hybrid fiber nano modified concretes.
7. Hybrid fiber reinforcement with RTSF and RNF effectively governs the savings of basic concrete constituents by allowing the reduction in required pavement thickness and achieving about 24–26% material savings. Overall, the reduced required design thickness leads nearly to 25% savings in both material consumption and cost effectiveness.

8. The SEM results show that RNF is well embedded in a dense Nano-ZrO₂ modified matrix with a compact and well-bonded interfacial transition zone (ITZ). Reduced porosity, improved fiber matrix adhesion and crack arrest along the fiber interface confirm effective crack bridging and delayed propagation of cracks. Overall, the combined action of RNF, RTSF with nano-ZrO₂ modification produces a denser microstructure with enhanced bonding and improved fracture resistance.

Overall, a high performing and sustainable concrete suitable for rigid pavement applications was produced by combining recycled nylon and steel fibers with Nano-ZrO₂ modification. Among all mixes, the combination RTSF1.5 + RNF0 exhibited the best performance in terms of strength and efficiency. While in hybrid mixes RTSF1 + RNF0.5 was identified as the most balanced combination, offering an optimum compromise between strength and sustainability.

Although significant improvement has been demonstrated for the mechanical and structural aspects in this investigation and durability was also evaluated in a previous study by the authors [18]. But it is important to recognize that there were some limitations. This research was carried out under controlled laboratory conditions; therefore, it did not consider the effects of variable environmental exposure, traffic loadings and moisture levels on long term field performance. Consequently, these results are best suited for rigid pavement systems subjected to moderate to heavy traffic where the primary design objective is to optimize thickness. Future research may focus on evaluating the long-term durability of hybrid fiber reinforced concrete with Nano-ZrO₂ modification under various environmental conditions. Further research may also explore other recycled fibers and nano-additives to enhance mechanical performance and sustainability in rigid pavement applications.

The proposed hybrid fiber nano modified concrete system can be extended to industrial floors, airport pavement systems, precast pavement panels and bridge deck slabs, where enhanced flexural capacity and improved crack resistance are critical design requirements.

5. References

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