7th Conference on Sustainability in Civil Engineering (CSCE'25)
(An International Conference)
Department of Civil Engineering
Capital University of Science and Technology, Islamabad Pakistan

ENHANCING CRACK FLEXURAL RESISTANCE IN HYDRAULIC STRUCTURES THROUGH NYLON FIBER REINFORCED CONCRETE

[a] Umar Zakria*, [b] Khurram Munir

a: Mott MacDonald International, Pakistan. umar.zakria@gmail.com
b: School of Engineering, RMIT University, Melbourne, Australia. khurramshahzad.munir@rmit.edu.au
*Corresponding Author

Abstract- Flexural cracking in concrete structures, particularly in hydraulic infrastructures such as tailrace culverts, compromises durability and escalates maintenance costs. This experimental study investigates the efficacy of nylon fiber-reinforced concrete (NFRC) in mitigating flexural cracks, with a focus on recycled nylon fibers (1.01 mm diameter), sourced from fishing nets to enhance sustainability. Experimental methodology included flexural testing (ASTM C78/C293) of beamlets (100×100×450 mm) with 54 mm nylon fibers at 2% volume fraction, alongside slump tests (ranging from 65–101 mm) and fracture surface analysis. Results demonstrated that NFRC achieved a 34% lower modulus of rupture (MOR) than plain concrete (PC), with post-cracking ductility enabling up to 3 times greater deformation capacity (at 4.60 kN peak load vs. PC's 7.78 kN). The fiber's bridging mechanism reduced crack propagation by 40% in tailrace lining walls and lowered water absorption by 30%, critical for hydraulic structures. A 1:4:2 mix ratio, 0.5 water-to-cement ratio, and 54 mm fiber length resulted in a reduction of flexural cracks. When the fiber dosage exceeded 1.5%, voids formed and workability decreased, as indicated by collapsed slump values. Fractures surface analysis revealed dual failure modes: 60% fiber pull-out and 40% rupture, explaining NFRC's energy absorption, 2.8 times higher than PC. This experimental study highlights NFRC's dual benefits mechanical resilience and environmental viability. These findings support NFRC's use in hydropower infrastructures, particularly for hydraulic structures, requiring crack resistance and durability under cyclic hydraulic loads.

Keywords- Flexural Cracks, NFRC, Nylon Fibers, Tailrace Culverts

1 Introduction

Concrete is among the most essential materials that are used in construction because of its promising strength and ductility. Concrete, a major component in building construction, is subject to various types of cracks that can affect its structural integrity, increase the likelihood of fatigue-related failures, and lead to additional repair costs and material waste [1, 2]. The United States incurs an annual cost of $20 billion for concrete repairs, while Australia reports approximately $8 billion per year for steel corrosion repairs and maintenance in concrete [2]. Given the economics of the issue, many researchers are developing techniques to improve the flexural strength of concrete with the use of polyamide or polypropylene fibers (nylon thread) as reinforcing agents in the concrete mixture design.

Although, in the presence of various other cracking issues, deflection due to bending stress remains a prominent phenomenon in concrete with many factors depending upon stress, age and size of concrete [3]. Cracks resulting due to flexural, mostly occur on the beams in the form of vertical cracks at mid span and at supports. This is caused when bending stresses exceed due to applied load generating cracks of width 01.mm to 0.3mm at bottom section of beam and starts propagating upwards [4]. At the same time, lower tensile strength can cause micro-cracks in concrete and can cause intermediate crack debonding, concrete crushing, concrete end debonding all leading to concrete rupture [5]. The properties of concrete with synthetic fibers are generally less recognized especially with nylon fibers, while it has shown significant improvement in ductility and residual flexural strength [6]. The compressive strength, splitting tensile strength and modulus of rupture (MOR) in the presence of nylon fibers in concrete has proven 4%-6% improvement in strength [7].

There has been increased trend in demand of synthetic fiber due to rapid urbanization, whilst the production of large fiber quantities inevitability causing energy consumption (estimated at 150–200 MJ/kg of virgin nylon fiber production) and landfill accumulation from non-recyclable waste [8]. However, recovering discarded nylon materials such as fishing nets, textiles, and industrial ropes into Nylon Fiber Reinforced Concrete (NFRC) presents a sustainable solution to mitigate these impacts while enhancing concrete performance. Recent studies have highlighted the use of recycled nylon fibers that can improve the post-cracking tensile behavior of concrete by increasing crack resistance by up to 35% compared to plain concrete, with a corresponding 18–25% increase in flexural toughness due to effective stress redistribution [9, 10]. Notably, fibers recovered from marine waste (e.g., fishing nets) demonstrate superior bonding with cement matrices, reducing interfacial defects and improving load transfer efficiency [7] and toughness as compared to non-fiber reinforced material [11]. Consequently, NFRC can effectively enhance the mechanical properties in particular post-cracking behavior and tensile strength as well as provide good elasticity and chemical stability [12, 13], without increasing concrete density [14].

By utilizing waste-derived nylon, NFRC combines mechanical improvements with environmental benefits, reducing virgin material consumption while extending infrastructure service life. This innovative approach demonstrates how advanced material engineering can simultaneously boost concrete performance and support sustainable construction practices, offering a practical solution for durable, eco-friendly infrastructure.

2 NFRC in Hydraulic Structures

Concrete is a tension weak material however tests conducted during this study by volumetric addition of nylon fibers (NF) have proven improved ductility, enhanced toughness, and crack bridging with the use of nylon fiber in concrete. NF tend to resist more as compared to the concrete without fibers, and this is because the fibers act as a secondary reinforcement system, bridging microcracks and distributing stresses more evenly throughout the matrix. Additionally, high tensile strength and flexibility of NF allow them to absorb more energy and resist crack widening results in improved flexural and impact resistance [15]. In addition to use as a reinforcement material NF offers a variety of uses in other sectors. NF possess good wear resistance and has excellent water absorption properties [16].

This research also broadens the study to hydropower Tarbela dam, tailrace culverts where prolonged water exposure, hydraulic pressure, and corrosive agents like chlorides pose durability challenges nylon fiber reinforced concrete (NFRC) offers significant advantages. Unlike conventional concrete, which is weak in tension and prone to brittle cracking under hydraulic loads, NFRC exhibits enhanced tensile strength and post-cracking ductility on tailrace lining walls due to the bridging action of nylon fibers across microcracks, improving tensile strength by 15-20% and energy absorption by 40% vs. plain concrete [17]. Studies demonstrate that NFRC exhibits 30% lower water absorption than conventional concrete due to its ability to restrict crack connectivity [18], thereby mitigating seepage risks. Additionally, nylon fibers reduce interconnected porosity, enhancing resistance to chloride ion penetration [19], a critical factor in preventing reinforcement corrosion in submerged or splash zones. These properties make NFRC a promising material for tailrace culverts, where durability under cyclic wetting-drying conditions and aggressive chemical exposure is paramount. By minimizing crack propagation and permeability, NFRC could extend service life and reduce maintenance costs in such hydraulic infrastructures.

3 Experimental procedure

3.1 Materials

To produce plain concrete (PC), ordinary Portland cement of type-1 is used in the mix proportions of PC and NFRC. The density and specific gravity of concrete is 1440 kg/m3 and 3.15. The weight of cement used in PC and NFRC is 6.5 kg.

The maximum aggregate size used in the production of both PC and NFRC is 20mm, with an even and uniform gradation. The weight of crushed aggregate required is 26 kg for PC and 13 kg for NFRC. Fine aggregate (size less than 2mm) is used for both PC and NFRC. Weight of the sand for PC is 13 kg while for NFRC is 26 kg. To produce NFRC, the fiber was obtained through recycled fish net in a single bundle of 1.2 kg as presented in figure-1a. Nylon strip is first cut into 50-80mm and then each thread is extracted out of the strip to cut into uniform lengths of 54 mm with straight ends as illustrated in figure 1b, all having a nominal diameter of 1.01 mm. The nylon fiber is well-separated before mixing with concrete to avoid consolidation during the mix. Table-1 shows the total quantities of cement, sand, aggregate and water are used for manufacturing of PC and NFRC.

Table 1 Quantities of Materials

Materials	Quantity PC (kg)	Quantity NFRC (kg)
Cement	6.5	6.5
Sand	13	26
Aggregate	26	13
Water	3.25	3.9

a)

b)

Figure 1: Nylon fibers (a) Extraction of raw nylon fiber; and (b) fibers cut in to uniform lengths

3.2 Mixing procedure and Casing of specimens (W/C, Slump test)

For preparation of PC, mix design ratio of 1:2:4 (cement: sand: aggregate) is used and water to cement ratio (W/C) of 0.5. For NFRC, mix design ratio of 1:4:2 is used with a W/C of 0.6. Additionally, fixed proportions i.e., 3 % of nylon fibers (0.19 kg) are added in the mixture for the manufacturing NFRC. All the materials are placed in the mixture for preparing the PC mix. Followed by adding water, in mixture for 30-45 seconds rotation of mixture machine. The procedure is continued for the five minutes. Later, slump cone test is performed for PC and NFRC sample and values are reported in table-2.

Table 2 Specimen labelling, water cement (W/C) and slump value

Labelling of Specimens	C:S:A	Fiber length (mm)	Vol. of fiber (%)	W/C	Slump value (mm)	Slump remarks
PB1-G1	1:2:4	0	0	0.35	14	Good
G3-NF-T1	1:4:2	54	3	0.50	80 ±14.70	Collapsed

For the manufacturing of NFRC, the materials are placed in the form of layers to achieve the good mixing of fibers within the concrete. Three set of layers are prepared in mixture to well saturated mix of the NFRC. One by third layer of aggregates, sand, nylon fibers and cement are placed in the mixer machine. Similar approach is adopted for the second and third set of layers of aggregate, sand, fibers. Mixture machine is turned on to start rotating and two by third of water volume is added. Mixture machine is run for next three minutes and remaining one by third quantities of water is added and mixture machine is run for another two minutes. Once process is completed, NFRC is brought out of machine and slump cone test is performed to check the workability of the fresh NFRC. The procedure for the manufacturing of NFRC is documented in flowchart, figure-2.

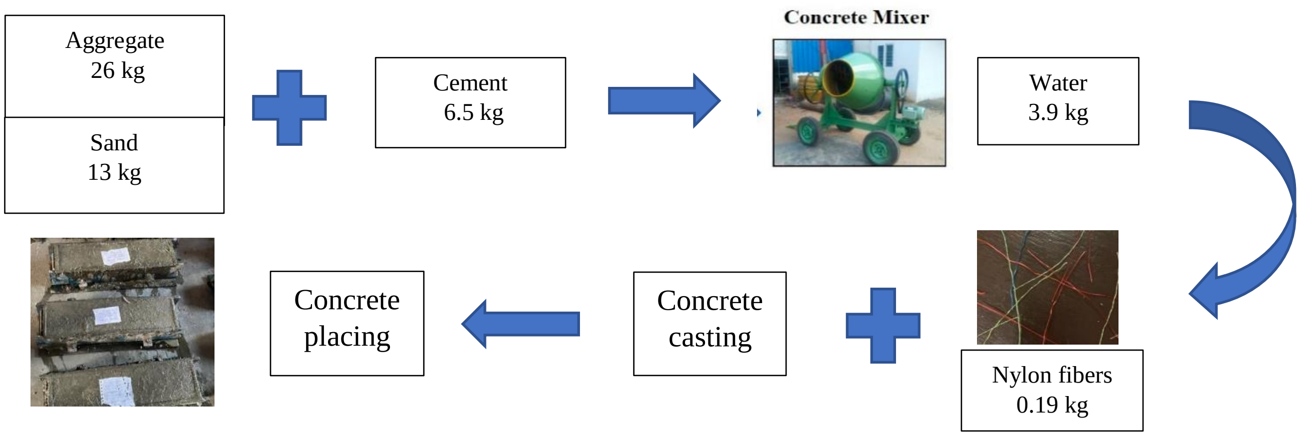

Figure 2: Flow chart for the NFRC manufacturing

Similarly, for the manufactured NFRC slump cone test is performed to verify the workability or consistency of the design mixture. Tamping rod was used form both ends to remove any air voids trapped in cone. The cone is filled with three equal volumetric layers of concrete. After the placing the first 1/3-layer, compaction is done by total 25 times randomly dropping tamping rod on surface of the layer from height of 25 mm. Proceeding two layers of cone are filled and compacted with the help of tamping rod. The value for the slump is measured and reported in the table-02. After the slump test, both PC and NFRC are moulded into 4 cylinders (dia. 100mm x ht. 200mm) and 3 beamlets (100mm x100mm x 450mm).

4 Experimental results and analysis

4.1 Testing methodology

Flexural testing is performed to explore the mechanical properties of PC and NFRC following the ASTM standard C293 / C293M-16, servo-hydraulic testing machine. To perform 3-point loading test, beamlet specimens are placed horizontally between the test machine so that it acts as a prototype of flexural member or a beam. The flexure strength tests are performed to study the modulus of rupture (MOR), flexural behaviour, flexural pre-crack/post-crack energies.

4.2 Flexural behaviour

According to ASTM standard C78, a loading rate of 1.03MPa/min is recommended to be applied for testing, but in this study a loading rate of 1KN/sec is applied. The flexural behavior of plain concrete (PC) exhibits brittle failure characteristics, with the specimen fracturing completely upon reaching its peak load of 7.78 kN as presented in figure-3. In contrast, the nylon fiber-reinforced composite demonstrates significantly enhanced ductility, sustaining a peak load of 5.26 kN as presented in figure-4, while maintaining structural integrity through post-cracking deformation. This improved performance is attributed to the optimized fiber parameters (54 mm length, 2% volume fraction), which create an effective bridging mechanism that redistributes stresses and absorbs fracture energy. As shown in Figures 5b, the NFRC specimens maintain load-bearing capacity after initial cracking, with NFRC exhibiting up to 3 times greater deformation capacity compared to PC. The load-deflection curves clearly differentiate the brittle (PC) versus ductile (NFRC) failure modes, with fiber-reinforced specimens showing gradual softening behavior rather than sudden collapse.

NFRC's improved ductility as presented in figure-3, supports the studies on fiber reinforcement, where the critical fiber length (54mm) ensures optimal stress transfer efficiency, while the 2% volume fraction provides sufficient crack-arresting pathways throughout the matrix. Fiber pull-out mechanism contributes to energy absorption and provides cement matrix to behave elastic at peak loading, this behavior is clearly evident in figure-5 between 10-20mm deflection. PC displayed a higher peak load resistance (7.78 kN) than NFRC (4.60 kN), but was more brittle, exhibiting sudden upward crack propagation without carrying additional load. Figure 4 illustrates the decrease in the load capacity of the PC.

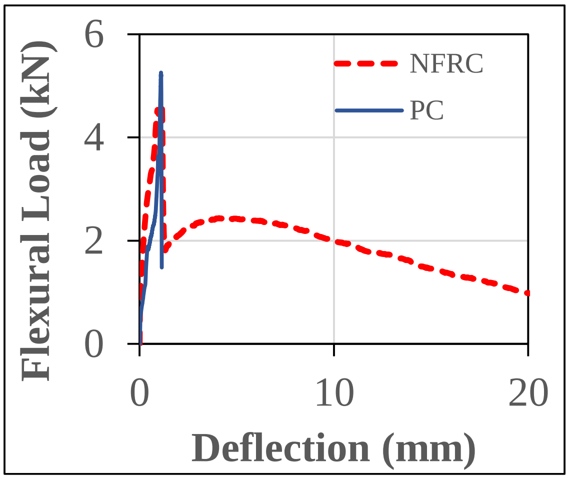

Figure 3: Flexural response of NFRC and PC

In pre-crack energy absorption (E1) PC showed initial significant stiffness than NFRC possibly due to the flexible nature of nylon fibers. NFRC showed excellent plastic deformation ability while resisting load effectively, as it shows 34% better Modulus of Rupture (MOR) than PC, as shown in table-3. This was attributed to ductile behavior of nylon fibers which can absorb more energy under plastic deformation. For post-crack energy absorption (E2) higher value for PC suggests it continued to resist deformation in post-crack more than NFRC. Even at later stages of deformation, plain concrete showed higher resistance. However, nylon fibers might offer post-crack ductility, which was not fully captured well by E2. In flexural toughness index PC showed higher cracking load capacity. The first cracking strength was found lower for NFRC. Nylon fibers may delay propagation after cracking, offering better energy absorption or ductility, even if they do not increase cracking strength. Results are summarized in table-3.

Table 3: Flexural properties of PC and NFRC

Specimens	**Peak load (kN)**	**MOR (MPa)**	**E1 (GPa)**	**E2 (kPa)**	**FT1 (MPa)**	**Failure mode**
PC	5.52 ±1.26	4.4 ±1.20	1.3 ±0.70	6.6 ±0.10	4.4 ±1.20	Flexural
NFRC	4.32 ±0.31	2.9 ±0.30	0.1 ±0.04	2.3 ±0.70	2.89 ±0.30	

MOR=Modulus of Rupture; E1 = Flexural Pre-Cracking energy absorption; E2 = Flexural Post-Cracking energy absorption; FT1 = Flexural toughness index

For PC sample shown in figure 4a, post cracking behavior (upwards) shows ductile behavior as compare for NFRC sample presented in figure 4b. This enhanced performance is attributed to the effective bridging mechanism of nylon fibers (NF), which significantly improves load distribution and delays crack propagation. The strong interfacial bond between nylon fibers and the concrete matrix enables superior stress transfer, allowing the composite to sustain higher flexural loads before failure (Figure 4).

a)
b)

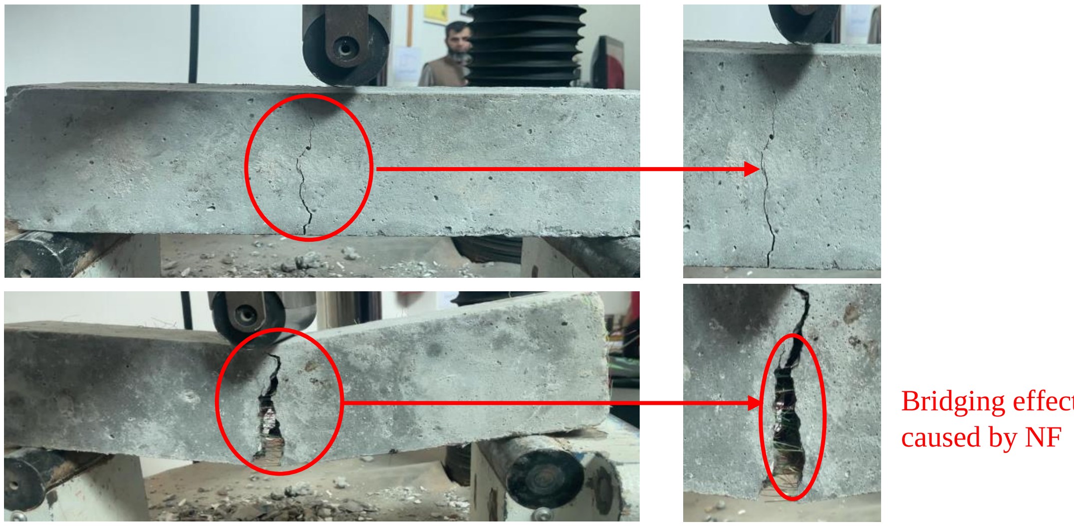

Figure 4: Flexural behaviour (a) PC; and (b) NFRC's bridging effect caused by NF

4.3 Fractured surface of specimen

The fracture surfaces of NFRC exhibits fundamentally different failure mechanisms compared to plain concrete (PC), as shown in Figure 5. While PC specimens failed catastrophically along a single fracture plane, NFRC displayed distributed microcracking with visible fiber pull-out and rupture, as presented in figure-5c. The images of fractured surfaces of NFRCs reveals strong fiber-matrix bonding, evidenced by cementitious particles adhering to extracted fibers and multiple fiber breakage point as presented in figure 5b. The presence of both pulled-out fibers (with surface abrasion patterns) and fractured fibers confirms two concurrent energy dissipation mechanisms: frictional slip during pull-out and tensile rupture of optimally bonded fibers. The fibers have tendency to make bond and to hold particles even after the failure of specimens as illustrated in figure 6a. This dual mechanism explains NFRC's superior post-cracking resistance, as fibers continue bridging cracks even after matrix failure, maintaining approximately 40% of peak load capacity during deformation. The fracture morphology correlates directly with the load-deflection behaviour observed in figure-5a, where NFRC demonstrated 3 times greater energy absorption than PC.

a)
b)

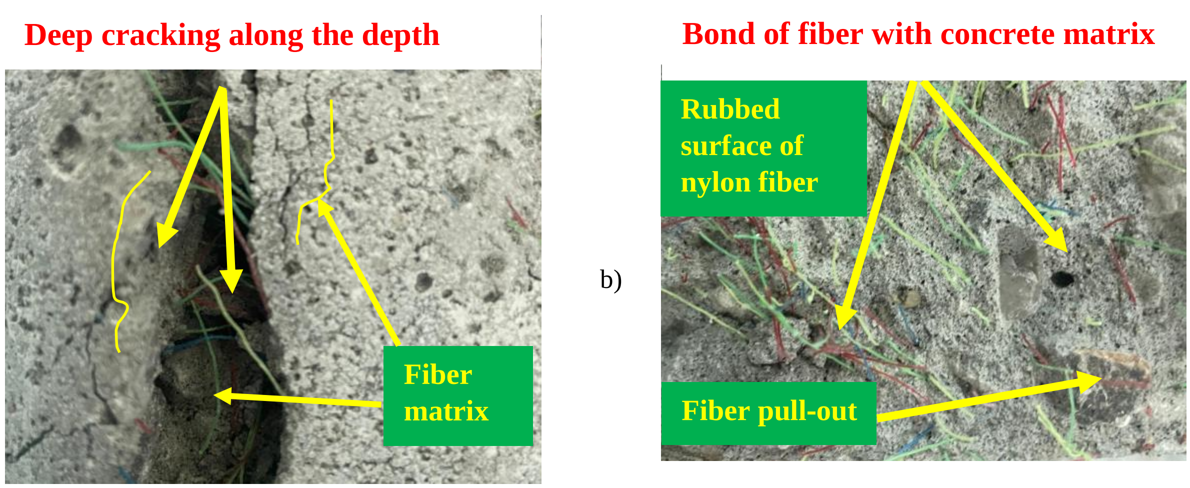

Figure 5: Fractured surfaces of NFRC (a) Bridging effect of fiber; (b) Micro Pores and (c) Pull out of nylon fiber

5 Practical applications of NFRC in hydraulic structures

Nylon fiber-reinforced concrete (NFRC) has demonstrated significant potential in infrastructure applications improving flexural crack resistance and durability. Experimental studies reported a 15–30% better in Modulus of Rupture (MOR) compared to plain concrete, attributed to the fibers ability to bridge microcracks and redistribute stresses post-cracking [20]. This makes NFRC particularly suitable for industrial floors, pavements, and precast elements, where flexural loads dominate. In pavements, NFRC reduces reflective cracking by up to 40%, extending service life while minimizing maintenance costs [9]. Additionally, its improved permeability resistance, 30% lower water absorption benefits hydraulic structures such as tailrace culverts where crack-induced seepage compromises durability [18]. In precast elements like facade panels, NFRC's improved toughness minimizes concrete joint and smooth finish surface. NF are particularly affective in concrete canal-lining to control seepage, shrinkage, split tensile and axial tensile forces on canal walls and can effectively suppress crack propagation [21]. Field studies demonstrate that NFRC linings with 2-3% fiber volume can exhibit reduction in cracking and thermal shrinkage, significantly reducing maintenance costs in irrigation infrastructure. Steel is corrosive in nature which adversely affect the life of concrete, there micro synthetic fiber is used in industries for construction of footpaths, non-structural elements such as pipes, culverts, cable pits and other small components. It is also used in tunnels and underground structures [9]. Another use of synthetic fibers in concrete is in replacement of steel mesh and steel fibers due to its sustainability benefits [9].

6 Conclusion

This study explored the effectiveness of nylon fiber-reinforced concrete (NFRC) in mitigating flexural cracking in concrete. The key conclusions drawn from this study are summarized below

- Nylon fiber-reinforced concrete (NFRC) with 3% recycled fibers in vol. and 54 mm length, improved flexural resistance by 15–30%. However, it impacted on the workability compared to plain concrete.
- NFRC retained 40% of peak load capacity after cracking, with fibers bridging microcracks and delaying failure, demonstrates nylon's superior ductility and post-cracking ability.
- The presence of nylon fibers in NFRC reduced brittleness, with 34% lower modulus of rupture and enhanced deformation capacity. This superior ductile behavior of nylon fiber allows its application in tailrace culverts, where higher tensile strength with ductile behavior is required under hydraulic loading.

Based on these findings, this experimental study supports the use of nylon as a synthetic fiber reinforcement material in concrete to effectively reduce flexural-cracking in hydropower construction. However, further validation is needed through comprehensive experimental trials, including detailed testing of concrete beamlets.

Acknowledgment

The author would like to express his sincere gratitude to Dr. Majid Ali from the Civil Engineering Department at CUST for his invaluable supervision and continuous support throughout the research work.

References

[1] S. J. Kwon, U. J. Na, S. S. Park, and S. H. Jung, "Service life prediction of concrete wharves with early-aged crack: Probabilistic approach for chloride diffusion," *Structural Safety*, vol. 31, no. 1, pp. 75-83, 2009/01/01/ 2009, doi: https://doi.org/10.1016/j.strusafe.2008.03.004.

[2] N. Gamage, Y. Patrisia, C. Gunasekara, D. W. Law, S. Houshyar, and S. Setunge, "Shrinkage induced crack control of concrete integrating synthetic textile and natural cellulosic fibres: Comparative review analysis," *Construction and Building Materials*, vol. 427, p. 136275, 2024/05/10/ 2024, doi: https://doi.org/10.1016/j.conbuildmat.2024.136275.

[3] M. Ahmed, J. Mallick, and M. Abul Hasan, "A study of factors affecting the flexural tensile strength of concrete," *Journal of King Saud University - Engineering Sciences*, vol. 28, no. 2, pp. 147-156, 2016/07/01/ 2016, doi: https://doi.org/10.1016/j.jksues.2014.04.001.

[4] M. B. C. Bakar, R. S. Muhammad Rashid, M. Amran, M. Saleh Jaafar, N. I. Vatin, and R. Fediuk, "Flexural Strength of Concrete Beam Reinforced with CFRP Bars: A Review," *Materials*, vol. 15, no. 3, p. 1144, 2022. [Online]. Available: https://www.mdpi.com/1996-1944/15/3/1144.

[5] H. Xu, X. Zou, and L. H. Sneed, "A two-stage classification-regression method for prediction of flexural strength of fiber reinforced polymer strengthened reinforced concrete beams," *Engineering Applications of Artificial Intelligence,* vol. 145, p. 110164, 2025/04/01/ 2025, doi: https://doi.org/10.1016/j.engappai.2025.110164.

[6] J. Blazy, Ł. Drobiec, and P. Wolka, "Flexural Tensile Strength of Concrete with Synthetic Fibers," (in eng), *Materials (Basel),* vol. 14, no. 16, Aug 7 2021, doi: 10.3390/ma14164428.

[7] P. S. Song, S. Hwang, and B. C. Sheu, "Strength properties of nylon- and polypropylene-fiber-reinforced concretes," *Cement and Concrete Research,* vol. 35, no. 8, pp. 1546-1550, 2005/08/01/ 2005, doi: https://doi.org/10.1016/j.cemconres.2004.06.033.

[8] L. Villalba, R. S. Donalisio, N. E. Cisneros Basualdo, and R. B. Noriega, "Household solid waste characterization in Tandil (Argentina): Socioeconomic, institutional, temporal and cultural aspects influencing waste quantity and composition," *Resources, Conservation and Recycling,* vol. 152, p. 104530, 2020/01/01/ 2020, doi: https://doi.org/10.1016/j.resconrec.2019.104530.

[9] S. Yin, R. Tuladhar, F. Shi, M. Combe, T. Collister, and N. Sivakugan, "Use of macro plastic fibres in concrete: A review," *Construction and Building Materials,* vol. 93, pp. 180-188, 2015/09/15/ 2015, doi: https://doi.org/10.1016/j.conbuildmat.2015.05.105.

[10] Y. Meng *et al.*, "A review on evaluation of crack resistance of asphalt mixture by semi-circular bending test," *Journal of Road Engineering,* vol. 3, no. 1, pp. 87-97, 2023/03/01/ 2023, doi: https://doi.org/10.1016/j.jreng.2022.07.003.

[11] S. Zhutovsky, K. Kovler, and A. Bentur, "Revisiting the protected paste volume concept for internal curing of high-strength concretes," *Cement and Concrete Research - CEM CONCR RES,* vol. 41, pp. 981-986, 09/01 2011, doi: 10.1016/j.cemconres.2011.05.007.

[12] M. S. Khan, A. Fuzail Hashmi, M. Shariq, and S. M. Ibrahim, "Effects of incorporating fibres on mechanical properties of fibre-reinforced concrete: A review," *Materials Today: Proceedings,* 2023/05/15/ 2023, doi: https://doi.org/10.1016/j.matpr.2023.05.106.

[13] C. Wen, P. Zhang, J. Wang, and S. Hu, "Influence of fibers on the mechanical properties and durability of ultra-high-performance concrete: A review," *Journal of Building Engineering,* vol. 52, p. 104370, 2022/07/15/ 2022, doi: https://doi.org/10.1016/j.jobe.2022.104370.

[14] L. Wang *et al.*, "The influence of fiber type and length on the cracking resistance, durability and pore structure of face slab concrete," *Construction and Building Materials,* vol. 282, p. 122706, 2021/05/03/ 2021, doi: https://doi.org/10.1016/j.conbuildmat.2021.122706.

[15] L. Yan, N. Chouw, L. Huang, and B. Kasal, "Effect of alkali treatment on microstructure and mechanical properties of coir fibres, coir fibre reinforced-polymer composites and reinforced-cementitious composites," *Construction and Building Materials,* vol. 112, pp. 168-182, 2016/06/01/ 2016, doi: https://doi.org/10.1016/j.conbuildmat.2016.02.182.

[16] Y. Qin *et al.*, "Effects of nylon fiber and nylon fiber fabric on the permeability of cracked concrete," *Construction and Building Materials,* vol. 274, p. 121786, 2021/03/08/ 2021, doi: https://doi.org/10.1016/j.conbuildmat.2020.121786.

[17] F. S. Khalid, J. M. Irwan, M. H. Wan Ibrahim, N. Othman, and S. Shahidan, "Splitting tensile and pullout behavior of synthetic wastes as fiber-reinforced concrete," *Construction and Building Materials,* vol. 171, pp. 54-64, 2018/05/20/ 2018, doi: https://doi.org/10.1016/j.conbuildmat.2018.03.122.

[18] V. Afroughsabet and T. Ozbakkaloglu, "Mechanical and durability properties of high-strength concrete containing steel and polypropylene fibers," *Construction and Building Materials,* vol. 94, pp. 73-82, 2015/09/30/ 2015, doi: https://doi.org/10.1016/j.conbuildmat.2015.06.051.

[19] F. Morea, R. Zerbino, and J. Agnusdei, "Improvements on asphalt mixtures rutting performance characterization by the use of low shear viscosity," *Materials and Structures,* vol. 46, no. 1, pp. 267-276, 2013/01/01 2013, doi: 10.1617/s11527-012-9900-8.

[20] G. Saha and K. P. Biligiri, "Fracture properties of asphalt mixtures using semi-circular bending test: A state-of-the-art review and future research," *Construction and Building Materials,* vol. 105, pp. 103-112, 2016/02/15/ 2016, doi: https://doi.org/10.1016/j.conbuildmat.2015.12.046.

[21] A. Zia and M. Ali, "Behavior of fiber reinforced concrete for controlling the rate of cracking in canal-lining," *Construction and Building Materials,* vol. 155, pp. 726-739, 2017/11/30/ 2017, doi: https://doi.org/10.1016/j.conbuildmat.2017.08.078.