# RECYCLED NYLON FIBERS FOR CRACK CONTROL IN HIGH STRENGTH CONCRETE- A USE CASE IN POWERHOUSE

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***Abstract-*** Shrinkage cracking in concrete structures, particularly in ultra-high strength concrete used in large-scale infrastructures such as hydropower powerhouse buildings, poses a significant threat to structural integrity and long-term durability. This review explores the effectiveness of nylon fiber-reinforced concrete (NFRC) in mitigating shrinkage-induced cracking. Findings from experimental studies show that incorporating nylon fibers (NF) at concentrations above 2% by volume reduces shrinkage by up to 5% compared to conventional concrete. Additionally, using an optimized water-cement ratio, such as 0.42, in combination with carefully selected NF content, was shown to significantly reduce crack length with an increase of just 0.05% in NF content lowering crack length to 52 mm. The review highlights the critical role of fiber length and type, demonstrating that synthetic fibers (12–54 mm) improve shrinkage resistance, with 54 mm fibers achieving a 62.4% reduction. However, excessive fiber dosage (beyond 1.5%) may lead to void formation and reduced compaction. The incorporation of recycled nylon fibers from waste materials such as fishing nets and textiles not only improves post-cracking toughness and tensile strength but also promotes environmental sustainability. Field applications in hydropower projects have validated NFRC's resilience under thermal and moisture variations, achieving a significant reduction in maintenance costs over a decade. In conclusion, NFRC presents a promising solution for enhancing durability and sustainability in high-performance concrete structures, particularly in critical infrastructure applications.

***Keywords-*** Shrinkage cracks; Nylon fibers; NFRC; Hydropower

## 1 Introduction

Concrete is a fundamental construction material due to its high strength, but it lacks ductility. Despite being a major component in construction, concrete is prone to cracking to various types of cracks which impact its structural integrity, accelerates fatigue-mode failures and thereby results in significant repair costs and wastes [1], [2]. United States alone bears an annual cost of $20 billion for the concrete repairs whereas, for Australia it turned out be $8 billion per annum for steel corrosion repairs and maintenance in concrete [2]**.** Considering the economics of the issue, many researchers are developing techniques to mitigate the risks of concrete cracking, including the use of polyamide or polypropylene fibers (nylon thread) as reinforcing agent in the concrete mixture design.

Although, in the presence of various other cracking issues, shrinkage remains a critical phenomenon in mix design deals with both plastic and hardening properties of concrete. Cracks resulting due to shrinkage, mostly occur on the surface of the concrete due to moisture loss and temperature fluctuations, posing significant challenges in maintaining the durability and strength of concrete structures [3, 4]. This phenomenon is generalized into three basic categories, plastic shrinkage, autogenous shrinkage, and drying shrinkage [5]. Plastic shrinkage crack occurs in initial hours of laying concrete usually from within a day up to 3 days after concrete placement and appear as narrow, hairline cracks due to rapid moisture loss. Whereas, autogenous also termed as hydration shrinkage is a result of self-desiccation process [6] when concrete experience decreases in internal humidity due to rapid hydration of cement. On the other hand, drying shrinkage refers to reduction on concrete volume when water bleeds from the surface, leaving internal concrete mass dried. Drying shrinkage cracks, develops weeks or months after hardening and are typically wider and deeper due to gradual moisture loss [7].

The primary mechanisms behind shrinkage include capillary stress, interlayer water evaporation, surface energy, and disjoining pressure. This study systematically reviews the potential of nylon fiber-reinforced concrete (NFRC) in reducing shrinkage cracks, highlighting the importance of selecting appropriate fiber types and sizes.

# 2 Shrinkage Mechanism

## *2.1 Shrinkage Dynamics in Cement Matrix*

The primary reasons for shrinkage in concrete include capillary stress, interlayer water evaporation, surface energy, and disjoining pressure [8, 9] . When moisture is evaporated from cement mix it creates an imbalance between saturated pressure and vapor. Capillary pressure thus exerting hydrostatic tensile stress leading to irreversible shrinkage as shown in figure-01 [5] . Similarly, capillary pressure also contributes to shrinkage when water is absorbed and desorbed, on the outer film of calcium silicate and hydrate (C-S-H) particles. The interlayer water which is closely bounded with the C-S-H particles, undergoes shrinkage strain on each C-S-H monolayer results in moisture content drop by 25%, The interconnected layer narrows further with substantial volumetric reduction if the moisture further reduces to 12% [8]. This densification of C-S-H particular leads to irreversible shrinkage with the collapsing of small pores.

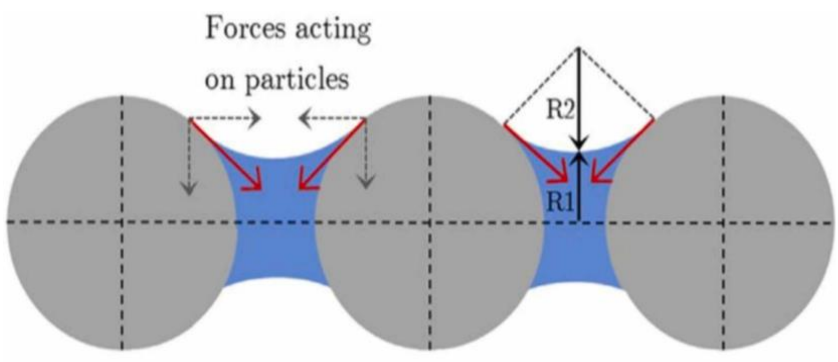



*Figure 1: Schematic illustration showing the presence of partially empty pores exerting hydrostatic tensile stress in concrete [2]*

## *2.2 Shrinkage cracking issues in ultra-high strength concrete*

The primary reason behind various types of shrinkage cracks (plastic shrinkage, thermal shrinkage, autogenous shrinkage, and drying shrinkage) is loss of water in concrete. This water loss is mainly controlled through effective curing or trapping moisture to leave from the surface of the concrete, as indicated in the figure-02. Where certain approaches can easily prevent the shrinkage cracks appearing immediately after concrete pouring. However, shrinkage cracks which are thermally induced due to sudden temperature variations on massive construction elements in dams and powerhouse buildings are unavoidable. This could be one of the two reasons either extremely hot climate conditions where one side of elements exposed to high temperature changes than the other or use of high-strength concrete. In hydropower construction of powerhouse high-strength concrete is very common nevertheless, curing with water or wetting the surface will prevent penetration in the concrete due to low permeability [10]. Comparison of ordinary concrete and high-strength concrete autogenous shrinkage and drying shrinkage in total is illustrated in the figure-03a and 03b.

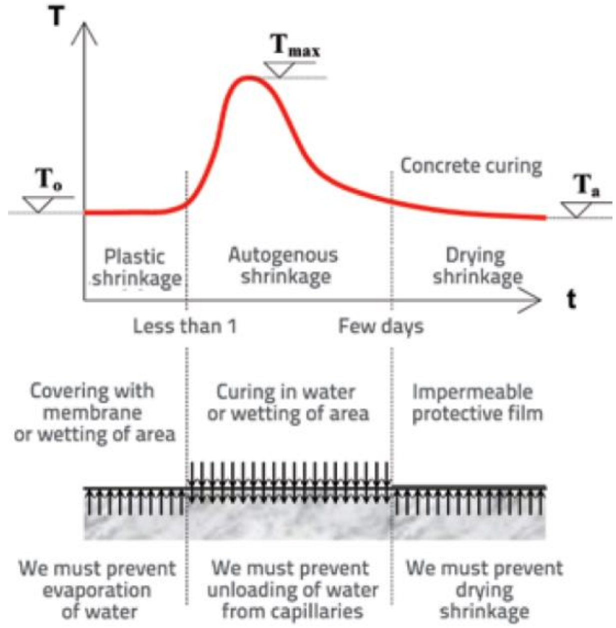
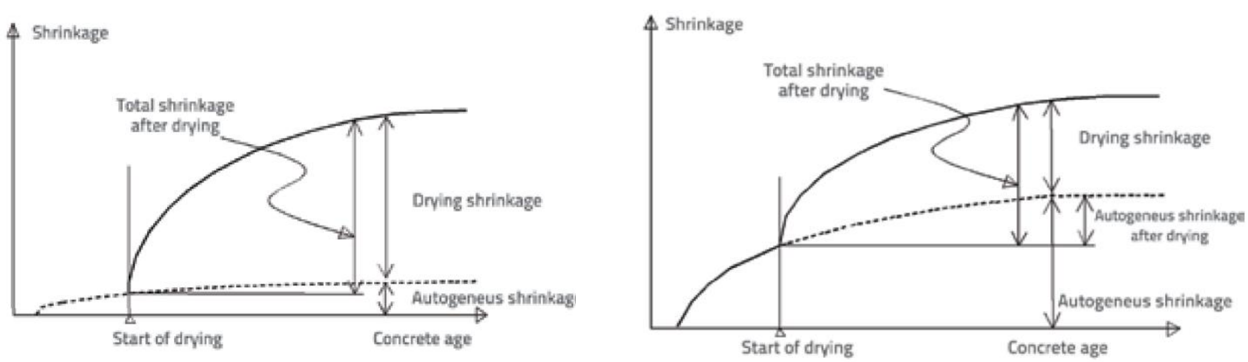



*Figure 2: Necessary curing conditions during temperature changes in concrete constructive elements [11]*

Shrinkage cracks are a prevalent issue in ultra-high-strength concrete, especially when used in large-scale concrete pours for hydro powerhouse buildings. Various factors contribute to concrete cracks in such structures, including the large size of the concrete mass, high stress concentrations, thermal changes due to humid conditions, and inadequate curing. These factors, either individually or in combination, contribute to shrinkage cracks in hydro powerhouse buildings.

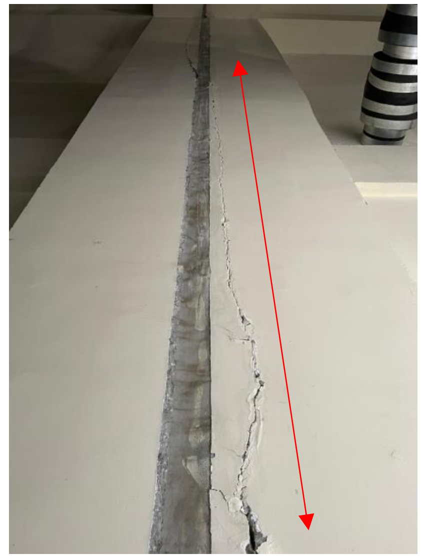



a) Shrinkage in ordinary concrete b) Shrinkage concrete in ultra-high-strength concrete

*Figure 3: Shrinkage in (a) ordinary concrete; (b) ultra-high-strength concrete [11]*

For example, shrinkage cracks were observed along the expansion joints due to high stress concentrations in units 16 and 17 of Tarbela Dam. Figure-4a shows the cracks on the concrete surface developing from upstream to downstream, possibly due to plastic shrinkage of the concrete, while figure-04b illustrates crack widening with the concrete ageing. The volumetric addition of fibers as fiber reinforced concrete (FRC), preferably nylon or polyamide, could have prevented crack propagation on these expansion joints.

a) Surface crack appearing along expansion joint



b) Crack propagation along unit 17 expansion joint

*Figure 4: Shrinkage crack along the expansion joints of Tarbela Dam's 4th Extension (a) unit-16; (b) unit-17*

# 3 Selection of fiber

## 3.1 Natural and Synthetic fiber

To limit the shrinkage crack propagation in high-strength concrete in the construction of powerhouse, possible solutions can be use of admixtures, internal curing agents, and fibers. Before selecting either natural or synthetic fibers for concrete reinforcement, it is crucial to first identify and understand the underlying causes of shrinkage cracks. It has been reported that crack propagation in high strength concrete is primarily due to impermeability, water absorption and rapid temperature changes [12]. Hence, any fiber exhibit high water absorption should not be a preferred option. For example, natural fibers such as jute, coir, sisal, and abaca exhibit high water absorption abilities as compared to synthetic fibers, polypropylene (PP) fibers as illustrated in figure-05 [12]. Amongst all, abaca has the highest water absorption at 95% RH, which could impact the workability of concrete as compared to PP fiber which has the lowest water absorption rate. Other factors in deciding the selection of fiber are their availability nearest to the site location and recycling of these materials.

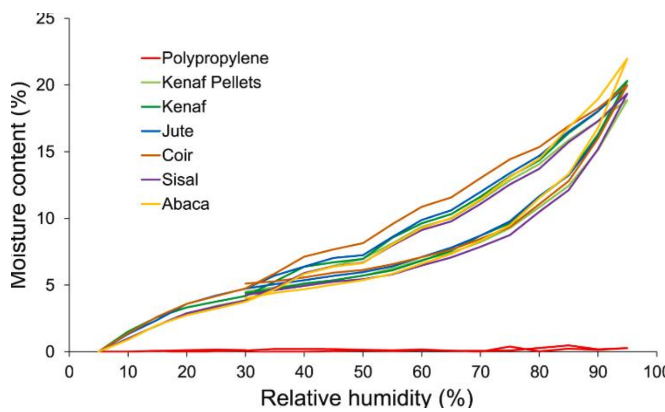



*Figure 5: Sorption isotherms of fibers measured at 20 °C [12]*

### *3.2 Recycled nylon fiber reinforced concrete (NFRC)*

In addition to use as a reinforcement material nylon fiber (NF) offers a variety of uses in other sectors. NF possess good wear resistance and high tensile strength, and has excellent water absorption properties [13]. There is an increasing trend in use of synthetic fiber with rapid urban development (estimated at 150–200 MJ/kg of virgin nylon fiber production [14]), whilst the production of large fiber quantities inevitability causing energy consumption and environment pollution eventually generating large amounts of waste to landfills. Not all the NF can be treated to reduce its environmental impact, and recycling often increases its embodied energy. However, if the fiber is recovered from waste materials such as clothes, ropes, fish nets and cots (charpai) from nearby locations, we can achieve better environmental and economic benefits. Previous studies have demonstrated promising contribution of NFRC in improving the compressive properties of concrete [15], [16]. Recycled nylon fiber as NFRC from fishing nets can enhance the tensile strength of motor [17] and toughness as compared to non-fiber reinforced material [18] . Furthermore, waste fiber fabrics from carpets can also influence the permeability of cracked concrete [10], [15]. 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 [18, 19], without increasing self-weight of concrete [20].

Studies have shown that NF added by 2% of concrete volume, not only exhibits enhanced mechanical properties but also reduce the permeability and shrinkage by 5% as compared to conventional concrete [20] . NFRC can also control formation of micro crack in large-sized ultra-high-strength [21] used in hydro powerhouse [18, 20] . As opposed to micro-sized nylon fibers, macro nylon fibers offer the same benefits as steel fibers without added weight, suitable for light weight concrete applications. However, when effective stress transfer is essential then macro synthetic fibers are a preferred choice. Therefore, it is critically important to choose the optimal type and size of fiber, whether natural or synthetic, to address the prevalent issues in concrete. Flow chart illustrates in figure-06 governing properties of concrete and proposed solution for controlling shrinkage cracks in ultra-high-strength concrete.

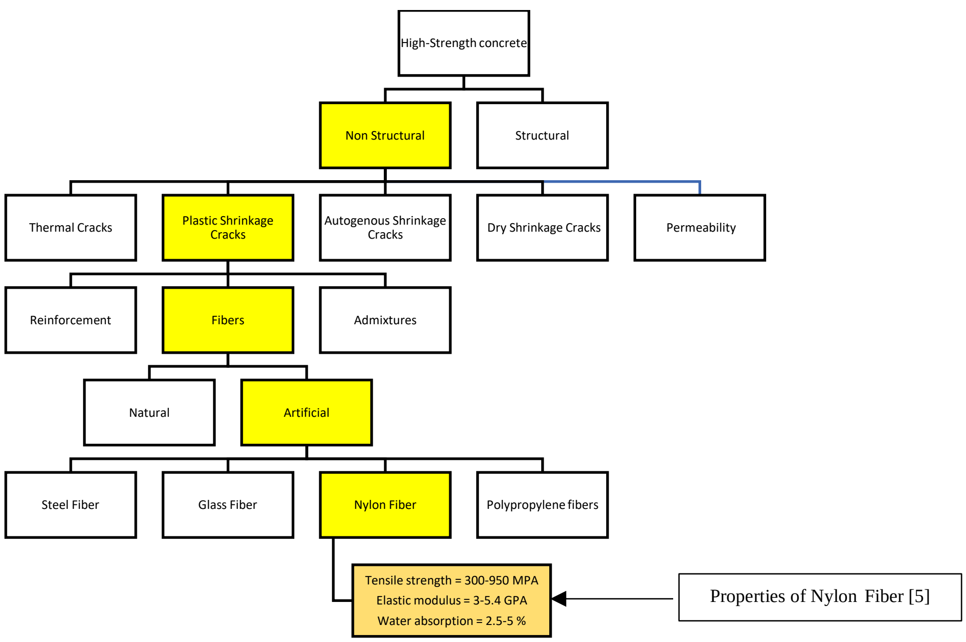



*Figure 6: Flow chart representing governing properties for concrete cracking and control with Nylon fibers*

### *3.3 Fiber preparation*

To produce nylon fiber-reinforced concrete (NFRC), the fiber is first cut into uniform lengths of 54 mm with straight ends, 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. Additionally, another sample of fiber is cut to a length of 75mm, maintaining the same nominal diameter as the 1.01mm fiber. Nylon fiber in raw bundle is illustrated in figure-7a, while the preparation of fiber was visually documented in series of figures as illustrated in figure-7b.

a) Raw nylon fiber b) Nylon fiber cut to form straight fiber

*Figure 7: (a) Extraction of raw nylon fiber; and (b) cut in to uniform lengths*

# 4 Factors affecting Shrinkage in NFRC

## *4.1 Water-cement ratio*

Water binder ratio is critical in reducing the concrete shrinkage. Increase in water cement ratio can provide sufficient water for evaporation resulting in residual strength improvement. Studies show that addition of 54 mm Nylon fibers with a 0.55 mm diameter reduces shrinkage cracks in concrete by 24.7% and 29.9% at 0.35% and 0.42% ratios, respectively [2]. Table-01 demonstrates using nylon fiber in combination of 12 and 54mm sizes with water cement ratio of 0.42 can mitigate the shrinkage cracks up to 62.4% [2].

*Table 1 Impact of Water-Binder Ratio on Concrete Shrinkage [2]*

| Fiber type - size | Water-Cement Ratio | Shrinkage reduction than the control (%) |
|---|---|---|
| Nylon – 54mm | 0.35 | 24.70 |
| Nylon – 54mm | 0.42 | 29.90 |
| Nylon – 12 mm | 0.35 | 8.8 |
| Nylon – 12mm | 0.42 | 21.40 |
| Nylon 12 & 54mm | 0.42 | 62.4 |

## *4.2 Volumetric size of fiber*

Using fiber lengths in different variation can have significant impact on the shrinkage behavior of concrete. Studies reported that increase in fiber length from 6mm to 12mm can reduce shrinkage to 30% [20]. Other findings indicate that 12 mm fibers reduce shrinkage cracks in concrete by 45.8%, while 19 mm fibers achieve up to 30.41% reduction [22], [23]

An increase in fiber volume notably decreases shrinkage in textile fiber-reinforced concrete. For example, incorporating 0.15% fiber volume fraction with 54 mm fibers reduces shrinkage by 30%, while a 0.35% fraction achieves a 60% reduction [20]. However, excessive fiber content can cause agglomeration, leading to voids and increased permeability [2]. Optimum fiber volumetric content in concrete is critical for its shrinkage reduction.

# 5 Applications of Nylon Fiber-Reinforced Concrete (NFRC) in Hydropower Structures

The inclusion of nylon fibers improves crack resistance by effectively bridging microcracks and redistributing stresses, reducing the risk of shrinkage-induced damage [24]. This is particularly beneficial in hydropower applications, where uncontrolled cracking can lead to seepage, structural weakening, and increased maintenance costs. In canal linings and dam spillways, NFRC with 2–3% fiber content has demonstrated a significant reduction in thermal and drying shrinkage cracks, improving service life and minimizing water loss [25]. The fibers enhance tensile strength, reducing crack propagation under axial and split tensile stresses, which is critical in hydropower infrastructure subjected to cyclic hydraulic loading. Additionally, NFRC offers corrosion resistance, making it a sustainable alternative to steel reinforcement in aggressive water environments. Unlike steel fibers, nylon fibers and some natural and organic fibers do not rust, ensuring long-term durability in tailrace tunnels, culverts, and spillway aprons [26]. The use of recycled nylon fibers (e.g., from discarded fishing nets) further enhances sustainability, reducing embodied energy while maintaining mechanical performance. Field applications confirm that NFRC is particularly effective in thin-shell structures like tunnel linings, where shrinkage cracking is a major concern [27, 28].

# 6 Conclusion

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

- Use of nylon fiber can reduce shrinkage in concrete by 5%
- Increasing the concentration of nylon fibers from 0.05% to 0.1% can reduce the crack length from 115.2mm to 52mm.
- Exceeding the optimal fiber dosage (>1.5%) can result in adverse effect, disrupting concrete compaction and increasing the number of entrapped voids, which in turn increases shrinkage in concrete.

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

# Appendix

N/A

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