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EFFECTIVENESS OF NYLON FIBERS IN CONTROLLING SHRINKAGE CRACKING IN CONCRETE PAVEMENTS

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Abstract- The road infrastructure is a vital component of national economic development; however, it is increasingly challenged by sustainability concerns stemming from material deterioration, insufficient maintenance, and harsh environmental exposure. Although rigid pavements are valued for their extended service life, they are susceptible to premature cracking, primarily due to drying shrinkage. This phenomenon occurs when volumetric reduction in concrete induces tensile stresses that exceed its capacity, leading to early-age cracking. These cracks are further exacerbated by repeated traffic loads, compromising both performance and longevity. This study aims to identify the underlying factors contributing to shrinkage-induced cracking in rigid pavements and to evaluate strategies for enhancing their post-cracking resistance. In particular, the effectiveness of nylon fibers as a reinforcement material is explored. An experimental framework is employed to investigate the fibers' role in controlling crack propagation through bridging mechanisms and improved tensile behaviour. The results demonstrate that nylon fiber integration significantly enhances resistance to shrinkage stresses, leading to improved durability and an extended lifespan for rigid pavement systems.

Keywords- NFRC, Rigid Pavement, Shrinkage Cracking, Tensile Strength

1 Introduction

Rigid pavements play a critical role in modern transportation infrastructure, particularly in areas subjected to high traffic volumes. They are designed to offer a durable, smooth, and long-lasting surface, providing consistent performance under heavy vehicular loads. Although the initial construction cost of rigid pavements is typically higher than that of flexible pavements, their minimal maintenance requirements and extended service life make them a cost-effective option over time [1]. The inherent high flexural strength of concrete facilitates the even distribution of traffic loads across the pavement structure, thereby reducing stress on the subgrade and improving overall structural performance. Moreover, rigid pavements exhibit significantly higher elastic and shear modulus compared to flexible pavements, enhancing their ability to resist deformation and sustain repeated loading [2]. Despite these advantages, concrete pavements are prone to early-age microcracking, which often marks the beginning of long-term deterioration. This issue is particularly critical in highways, where pavements are expected to remain functional for four decades or more [3]. Compared to asphalt alternatives, concrete pavements generally require fewer repairs throughout their service life [4]. However, the inclusion of reinforcement and joint systems may add to construction costs; exploring cost-efficient reinforcement strategies, such as fiber reinforcement, presents a promising approach to optimize both performance and economy [5].

2 Shrinkage cracks in Concrete

Shrinkage is widely recognized as one of the primary factors contributing to the development of early-age cracks in rigid concrete pavements [2]. Concrete pavements, by nature, are more susceptible to shrinkage-induced cracking compared to other structural components. This heightened vulnerability can be attributed to the substantial surface area exposed to atmospheric conditions, which accelerates moisture loss and exacerbates shrinkage-related stresses [6, 7]. As concrete undergoes changes in volume due to drying or thermal fluctuations, internal tensile stresses are generated within the material. These stresses continue to build up until they surpass the concrete's inherent tensile strength, leading to the formation of surface cracks. These early cracks can significantly reduce the overall performance and durability of the pavement. The situation is further aggravated by the exposure of the top surface of the pavement to drying, while the underlying layers remain somewhat insulated. This differential drying rate results in a phenomenon known as differential shrinkage, where the surface layer shrinks more rapidly than the deeper layers. As a consequence, the disparity in shrinkage between the surface and the underlying concrete leads to internal strain, ultimately causing the formation of cracks, which often appear in the form of longitudinal or transverse fissures across the pavement surface [8].

Once shrinkage cracks form on the surface of rigid pavements, they create a pathway for various environmental factors to further deteriorate the structure. Water infiltration is one of the most significant threats, as rainwater can easily enter the cracks, reach the underlying layers and cause damage to the subgrade material. This water infiltration can lead to partial settlement, weakening the structural foundation and promoting thermal cracking due to fluctuations in temperature [9]. The process of early-age shrinkage begins during the curing phase when moisture begins to evaporate from the concrete. During this phase, the material experiences tensile stresses that often exceed its tensile strength, resulting in the formation of microcracks. Research has shown that concrete can develop between 500 to 700 micro-strains of shrinkage within the first week of curing, which can already lead to the initiation of microscopic cracks within the concrete matrix. These microcracks are not immediately visible but serve as the starting point for more substantial damage under traffic loading. As these cracks continue to grow and propagate, they form larger visible cracks that allow more water to penetrate, accelerating the process of deterioration. Over time, the presence of moisture can lead to spalling, the corrosion of embedded steel reinforcement, and further weakening of the pavement structure. Without appropriate preventive measures, shrinkage cracking becomes a primary cause of premature pavement failure, significantly reducing the pavement's lifespan and structural integrity. In the long term, this damage compromises the ability of the pavement to carry heavy traffic loads, leading to costly repairs or complete reconstruction(figure-1) [10].

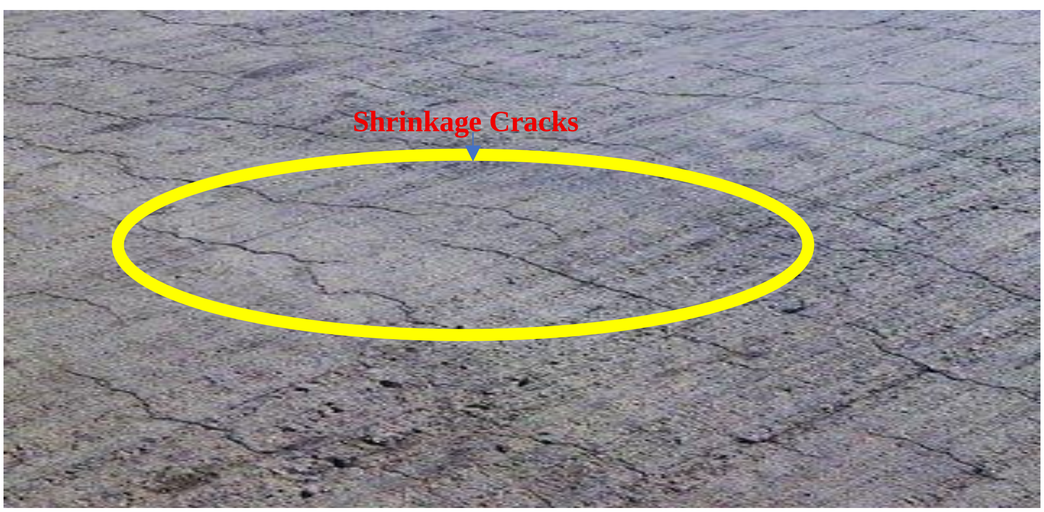

Figure 1. Visible shrinkage cracks reduce structural integrity of pavement due to moisture infiltration.

3 Governing Factors

In light of the challenges associated with shrinkage-induced cracking, understanding the governing factors that influence concrete resistance to such deterioration becomes critically important. The durability and performance of rigid pavements under shrinkage stress depend significantly on aspects such as the concrete mix design, environmental exposure during curing and most notably the type and effectiveness of reinforcement embedded within the structure. While conventional steel reinforcement has long been the standard for improving concrete structural strength, especially against externally applied loads, it often proves insufficient in mitigating early-age shrinkage cracking. This is largely because shrinkage stresses emerge during the plastic and initial hardening stages of concrete phases in which the bond between the steel bars and the surrounding concrete matrix has not yet fully developed. As a result, the reinforcement cannot effectively counteract the tensile strains that initiate microcracks(figure-2)[10].

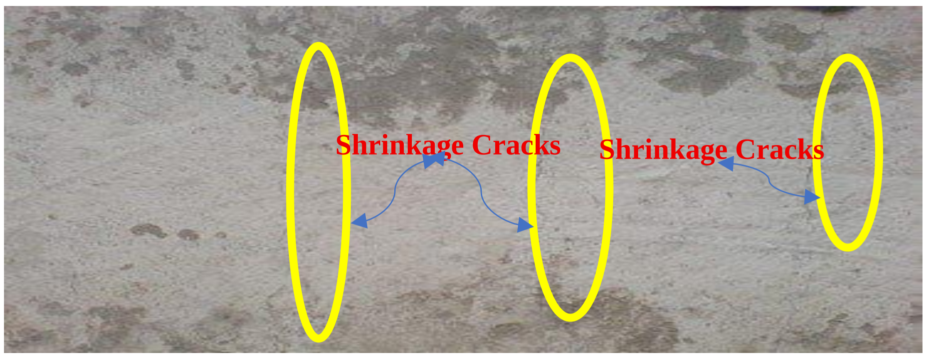

Figure 2. Tradition reinforcement can't control micro-cracking.

4 Fibres Selection

This limitation has prompted a shift in research focus toward more advanced reinforcement solutions that can perform effectively from the earliest stages of concrete setting. Among these, fiber-reinforced concrete has gained significant attention for its potential to enhance shrinkage resistance. The inclusion of discrete fibers, dispersed uniformly throughout the concrete matrix, helps control crack formation by bridging microcracks and redistributing internal stresses and behave concrete more ductile under axial load (figure-3). Researchers have identified this approach as a promising way to improve early-age performance and overall durability, thereby extending the service life of rigid pavements in demanding environmental and load-bearing conditions [11].

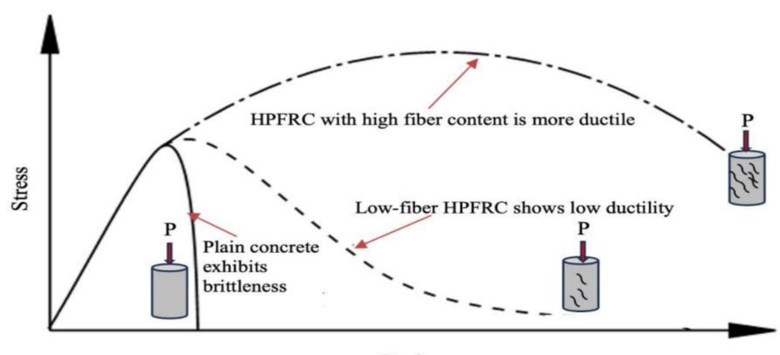

Figure3. Representation of stress–strain behaviour for plain concrete and HPFRC under axial load [11].

Building upon the need for effective shrinkage crack mitigation, the selection of optimal fiber reinforcement systems requires a multidimensional evaluation approach, as detailed in ACI 544.5R (2023). Chief among the criteria are mechanical properties such as tensile strength, elastic modulus, and the interfacial bond between fiber and matrix, which collectively determine the overall behaviour of fiber-reinforced concrete (FRC). Simultaneously, durability under aggressive environmental conditions is crucial resistance to chemical degradation in alkaline environments, corrosion resistance particularly for metallic fibers, and UV stability in polymer-based fibers must all be carefully considered. Equally important are economic factors: life-cycle cost analysis plays a key role in evaluating fiber systems' practicality in comparison to conventional steel reinforcement, taking into account not only initial installation costs but also potential long-term maintenance savings[10].

5 Nylon Fibre Reinforcement Concrete (NFRC)

Among synthetic fibers, nylon has emerged as a highly promising alternative due to its favorable mechanical properties and chemical stability[12]. Research has shown that nylon fiber-reinforced concrete (NFRC) exhibits enhanced tensile as well as superior post-cracking, effectively reducing the likelihood of crack propagation. Studies shown among others, affirm that nylon fibers significantly mitigate early-age shrinkage cracking, making them ideal for rigid pavement applications. Beyond mechanical performance, nylon fibers offer additional advantages they are corrosion-resistant, lightweight, and easily integrable into concrete mixes[13]. Importantly, nylon is also one of the most abundantly available synthetic fibers in daily use, found in textiles such as clothing, ropes, and socks. With the growing emphasis on sustainability, the reuse of waste nylon fibers presents a viable opportunity to address both environmental and infrastructural challenges. A substantial amount of nylon waste is currently disposed of through landfilling or incineration, contributing to ecological degradation. However, incorporating recycled nylon fibers into concrete offers a dual benefit: it reduces environmental burden while enhancing the structural resilience of concrete[14]. Recent field trials by the Federal Highway Administration (2024) revealed that rigid pavements reinforced with 1.5% nylon fiber content exhibited up to 60% fewer cracks over a five-year period compared to conventional concrete. Similarly, 30 to 40% reduction in plastic shrinkage cracking in lab-scale tests[12]. Studies have shown that NF added to concrete not only exhibits enhanced mechanical properties but also reduce the permeability and shrinkage by 5% as compared to conventional concrete[15].

Therefore, it is critically important to choose the type and size of fiber, whether natural or synthetic, to address the prevalent issues in concrete pavement shown in figure 4. These findings underscore the potential of nylon fibers not only as an effective technical solution for shrinkage crack control and increase tensile strength but also as a sustainable alternative aligned with modern environmental goals.

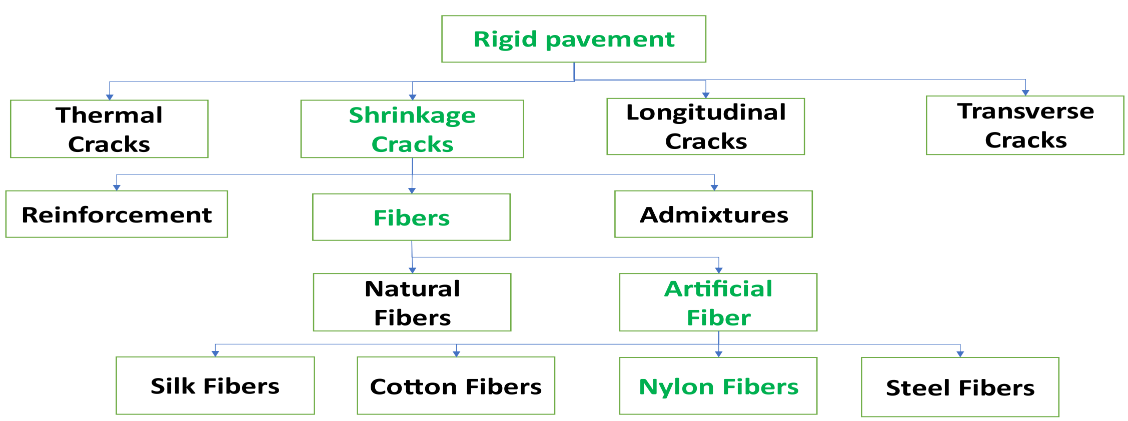

Figure 4. Flow Chart Representing Pavement issues, Governing properties and its solution

6 Conclusion

The study explores shrinkage cracking in rigid pavements, revealing that incorporating nylon fibers significantly enhances tensile strength compared to non-fiber-reinforced pavements. The conclusions derived from the research are as follows:

- Pavements are typically designed to fail eventually, but the incorporation of nylon fibers alters the failure behaviour of concrete, changing it from brittle to a more ductile response.
- Nylon fibers create a bridging effect in the concrete, enhancing its post-cracking behaviour in rigid pavements.
- Nylon fiber can reduce shrinkage in concrete by 5% as compared to conventional concrete.
- Nylon fiber 30 to 40% reduction in plastic shrinkage cracking in lab-scale tests.

Optimizing fiber content can enhance the tensile strength of rigid pavements. The increased strength and improved post-cracking behaviour of nylon fiber-reinforced rigid pavements help limit crack propagation and widening, thereby slowing down pavement deterioration.

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