Shrinkage and Fatigue Crack Analysis on Fiber Reinforced Composite Concrete (FRCC) Pavement: An ANSYS Workbench Study

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Abstract
In pavement, concrete slab structures along with foundations, retaining walls, marine, precast components, urban pavements are subjected to both static load and, particularly, cyclic loading for pavement. Fatigue is a significant concern for these pavements, especially given recent technological advancements. This study conducts a fatigue analysis of a pavement slab using ANSYS Workbench. The study investigates shrinkage and fatigue cracks in Fiber Reinforced Composite Concrete (FRCC) pavements, with loading based on FRCC's load-carrying capacity. Utilizing ANSYS Workbench, a series of finite element analyses were conducted to evaluate the mechanical performance of FRCC under varying loading conditions and environmental factors. The research examines several fibre types—including cold-drawn wire, cut sheet, melt-extracted, mill-cut, and modified cold-drawn fibres—integrated with recycled aggregates and crushed sand. The numerical methodology incorporates material properties such as moisture transport, free shrinkage, and mechanical characteristics derived from experimental data. These micro-cracks penetrate approximately 25% of the slab thickness, leading to reductions in ultimate load bearing and fatigue capacity by up to 50%. While shrinkage may not initially produce visible cracks, it exacerbates crack opening under traffic loads—by as much as 500% for cracks of 0.5 mm width. To ensure long-term pavement performance, the allowable stress ratio should be halved to mitigate shrinkage distress. The methodology developed here can be applied to similar materials and geometries, offering broader insights into the importance of addressing shrinkage distress in concrete design.

Keywords: Shrinkage crack, Fiber Reinforced composite concrete (FRCC), recycled aggregate, fatigue crack, Numerical analysis, Finite element analysis, MATLAB.

1. Introduction:

Modern road pavements are designed to endure a service life of 50 years or more, particularly for highly trafficked routes. Rigid concrete pavements generally offer longer lifespans and require less maintenance compared to flexible asphalt pavements. However, the initial cost of reinforced concrete pavements can be higher due to the expenses associated with reinforcement and joints. To mitigate these costs, lower-cost reinforcement options, such as steel Fibers recycled from post-consumer tires, have been proposed. These steel Fibers can effectively replace traditional steel mesh, providing benefits in construction efficiency by reducing labour costs and time. Roller compacted concrete (RCC) technology has emerged as an innovative approach for the rapid construction of steel Fiber reinforced concrete (SFRC) pavements. The Eco lanes project (2006–2009), funded by the EU, developed optimized processes for roller-compacted FRCC, emphasizing the use of recycled steel fibers to enhance the longevity of pavement infrastructure for surface transport. Given the expansive surface area of pavements, shrinkage-induced cracking is particularly critical, as it can significantly impair performance and longevity. Curling, a common consequence of drying shrinkage, creates high-stress regions near the drying surface, adversely affecting the support conditions beneath the pavement. When combined with traffic loads, these stresses can lead to accelerated cumulative damage. The incorporation of steel fibers in concrete pavements offers significant benefits in mitigating the adverse effects of shrinkage, as they help control shrinkage strain distribution and limit crack growth. While existing design guidelines for Fiber Reinforced Composite Concrete (FRCC) primarily focus on industrial ground slabs, they often overlook early-age distress, the interaction with service loads, and the long-term behavior of pavements.

This paper aims to quantify the distress induced by drying shrinkage in FRCC pavements, particularly those reinforced with recycled steel fibers. A comprehensive methodology is developed to consider shrinkage in the design of FRCC pavements for optimal long-term performance. Although the study focuses on a specific type of concrete pavement under typical environmental and boundary conditions, the proposed methodology is adaptable to various concrete types, slab geometries, and boundary scenarios. The paper commences with a review of experimental studies followed by data processing to obtain material characteristics through numerical inverse analysis. The subsequent sections discuss moisture transport, drying shrinkage, and relevant material properties, culminating in an analysis of a typical FRCC pavement under restrained shrinkage conditions. Finally, the interplay between shrinkage distress, load-bearing capacity, and long-term fatigue performance is examined, leading to the study's conclusions.

2. Materials:

The study utilized FRCC with various fibers Property (e.g., steel, polypropylene, Recycled Aggregate, cold-drawn wire, cut sheet, melt-extracted, mill-cut, and modified cold-drawn Fibers) to investigate their effects on performance. Material properties were obtained from previous experimental studies and incorporated into ANSYS Workbench.

3. Finite Element Modelling

The material of the Slab is selected as Fiber steel with elasticity modulus of 150-200Gpa, Poisson's ratio of 0.2-0.3 and yield strength of 200-250 MPa. The Pavement Slab has a length of 15Feet, a width of 10 Feet and a height of 1 Feet and mesh size of around 0.75 ft along with Horizontal and Vertically 1 ft. The side view of the Slab and the position of the Different Stresses are shown in the Figures. A 3D finite element model was created in ANSYS Workbench to simulate FRCC pavement Structure. The model accounted for Geometric dimensions based on standard pavement, Boundary conditions representing real-world constraints, Load conditions simulating vehicular traffic and marine loads.

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4. Results and Discussion:

4.1 Fatigue Crack Simulation

The fatigue analysis is performed using Ansys Workbench fatigue module. Stress life type analysis is used which is based on Stress-Cycle (S-N) curves. Stress life is related with component's total life and does not distinguish between initiation and propagation. To decide on stress life in fatigue analysis, various factors are considered: loading type, mean stress effects, multiaxial stress correction and fatigue modification factor. In our study zero-based constant amplitude, proportional loading with a load ratio of 0 is assumed. Using ANSYS software the fatigue life is computed, and the result is shown in Figure 1. Fatigue life shows the available life for the given fatigue analysis which represents the number of cycles until the part will fail due to fatigue. It is observed that the minimum fatigue life of our beam is More Than 96576 cycles for 10 kN and this value is reached at the location where maximum stress occurs, as expected.

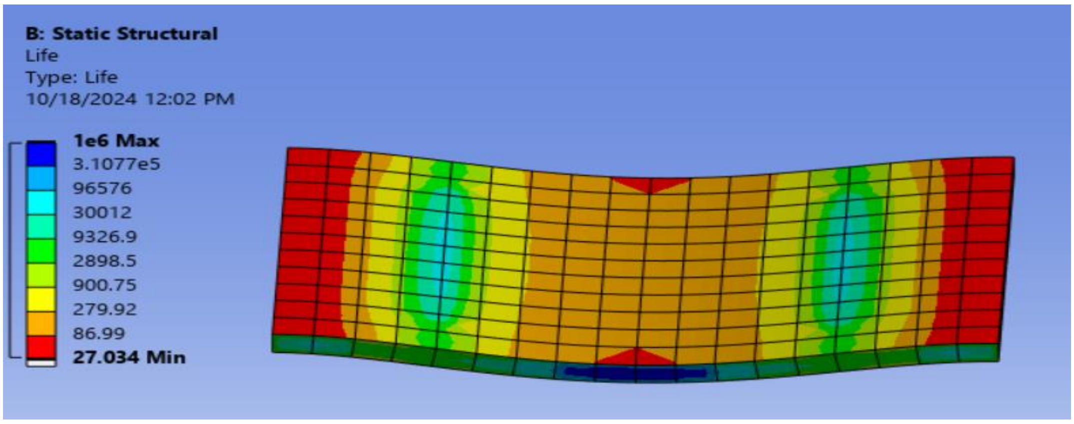

Figure 1. Fatigue Life of Pavement

Figure 2 shows fatigue damage of the beam which is defined as the design life divided by the available life, for 10106 cycles of fatigue life, under load. Values greater than 1 indicate failure before the design life is reached. The maximum damage occurs at the Edge of The Slab with a value of 18495.

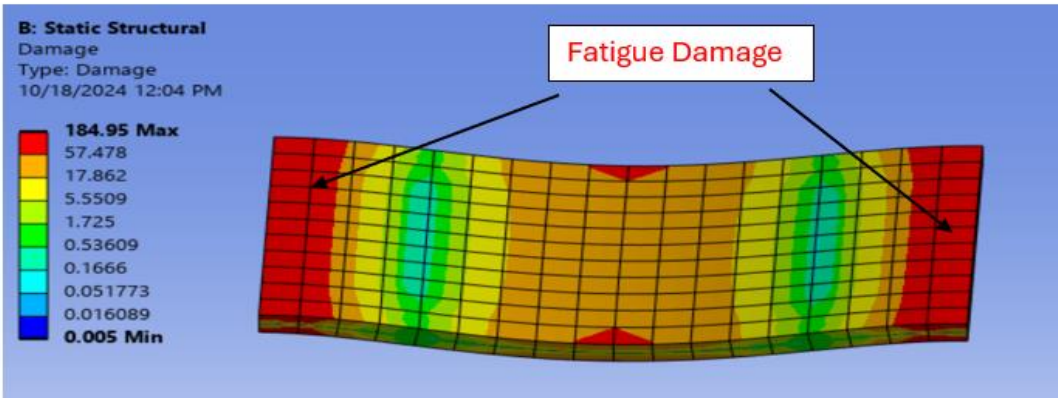

Figure 2. Fatigue Damage of Pavement

Shrinkage was modelled using time-dependent material properties, while fatigue cracking was simulated through cyclic loading. Different loading scenarios were applied to evaluate the response of the structure under realistic conditions. Below Fig 3 shows the fatigue damage sensitive damage Chart.

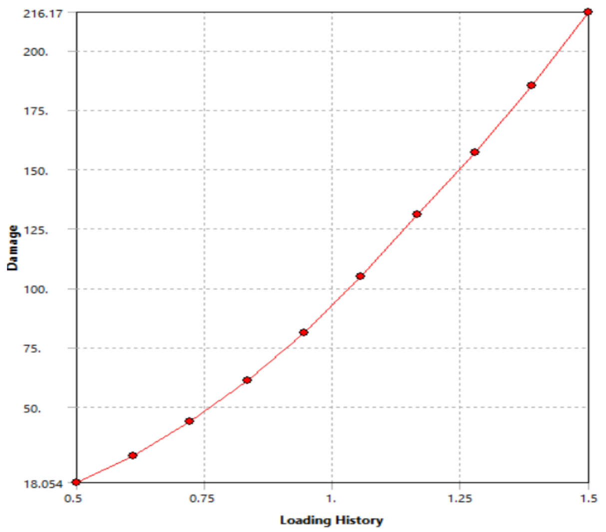

Figure 3. Fatigue damage sensitive damage Chart

The Damage will increase by Loading History that results shows for the 5000 Cycles. Which is shown in Figure3.

4.2 Fatigue sensitivity chart:

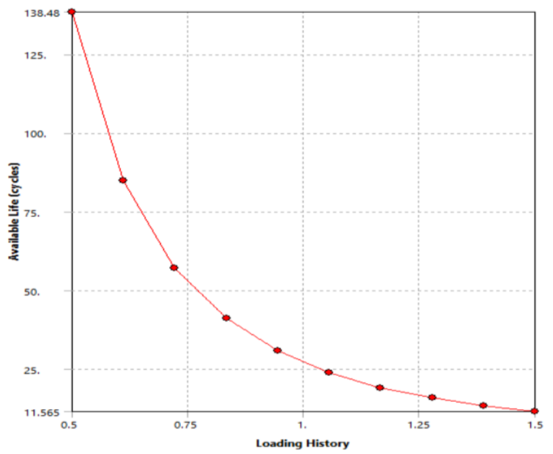

Figure 4. Fatigue damage sensitive damage Chart

In Above Figure 4, fatigue sensitivity chart is given which shows how the fatigue results change as a function of the loading at the critical location on the model. We wanted to see the sensitivity of the model's life if the load changed from 30% of the current load up to 90% of the current load. It is observed from the figure that when the load is increased up to 90%, the life decreases to cycles.

5. Shrinkage Crack Simulation:

5.1 Total Deformation:

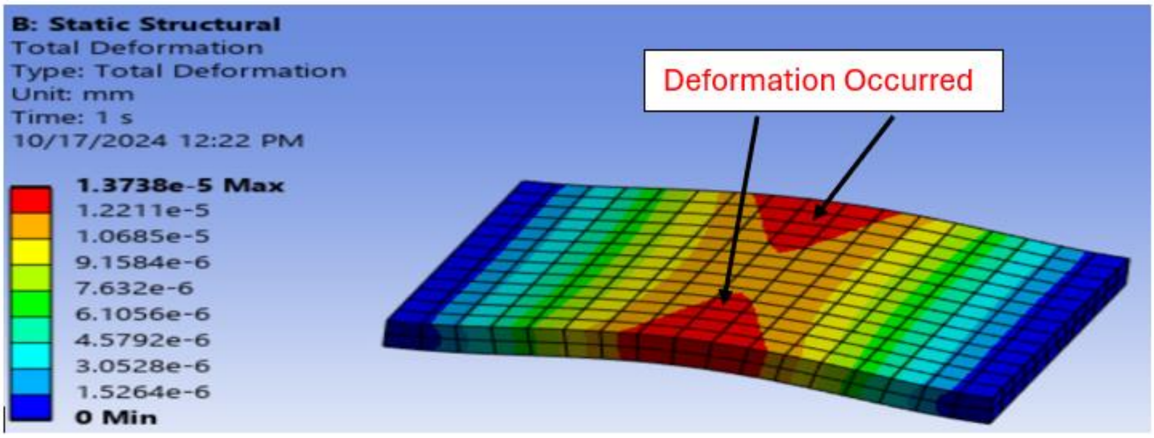

Figure 5. Total Deformation

Above Figure 5 of Static structural total deformation simulations in ANSYS are invaluable for analysing shrinkage and fatigue cracking in concrete. These simulations enable engineers to visualize and quantify deformation patterns under various load conditions, identifying potential weak points where cracks may initiate due to shrinkage-induced stresses. By modelling different material properties, such as varying fiber types in Fiber Reinforced Composite Concrete (FRCC), the impact of these materials on structural integrity can be assessed. The analysis provides insights into stress distribution, highlighting areas of high stress concentration that are vulnerable to cracking. Additionally, while primarily static, these simulations can be adapted to evaluate the effects of cyclic loading, helping predict long-term behavior under repeated stresses. This comprehensive approach aids in optimizing designs, informing maintenance strategies, and enhancing the overall durability of concrete structures, ultimately leading to more resilient and reliable applications in real-world environments.

5.2 Maximum Principal Elastic Strain:

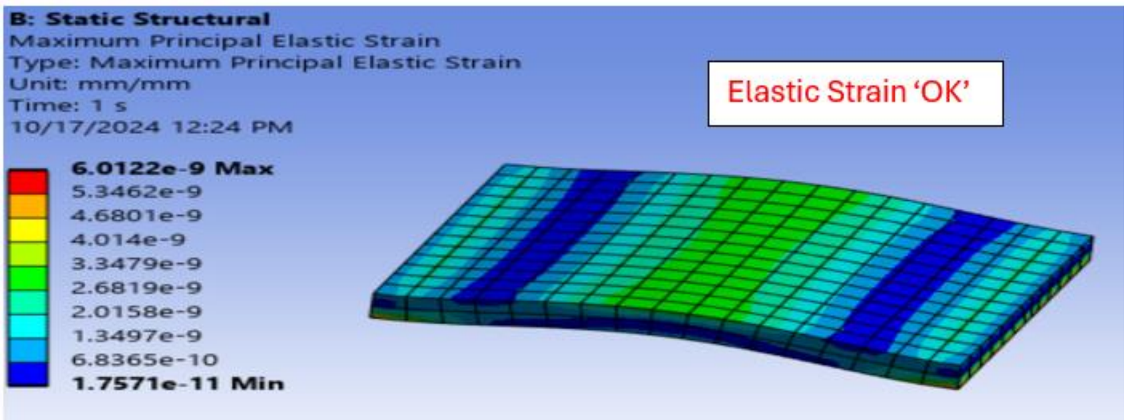

Figure 6. Maximum principal elastic strain

Static structural maximum principal elastic strain simulations in ANSYS are essential for analysing shrinkage and fatigue cracking in concrete. These simulations provide critical insights into the maximum strain experienced by concrete structures under various loading conditions, helping to identify areas at risk of crack initiation due to shrinkage-induced stresses. By evaluating the principal strains, the simulations help assess how different materials, such as Fiber Reinforced Composite Concrete (FRCC), respond to both static loads and environmental factors. This analysis allows for the detection of stress concentrations and potential failure points, facilitating design optimizations to enhance durability. Moreover, understanding strain distribution aids in predicting the effects of cyclic loading, which is vital for evaluating the long-term performance of concrete under repeated stress. Ultimately, these simulations support informed decision-making for maintenance strategies and structural improvements, leading to more resilient concrete applications in practical scenarios.

The author suggests that shrinkage in concrete, including Fiber Reinforced Composite Concrete (FRCC), does not always lead to immediate visible cracks. Initially, shrinkage causes microscopic internal cracks, which may not be large enough or in the right location to appear on the surface. These micro cracks remain hidden, especially under compressive loads, and may only become visible over time due to factors like repeated cyclic loading or differential shrinkage. As environmental conditions such as moisture and temperature fluctuations influence the material, these internal stresses can eventually propagate, leading to visible cracks that compromise the pavement's structural integrity.

5.3 Equivalent Alternating Stress:

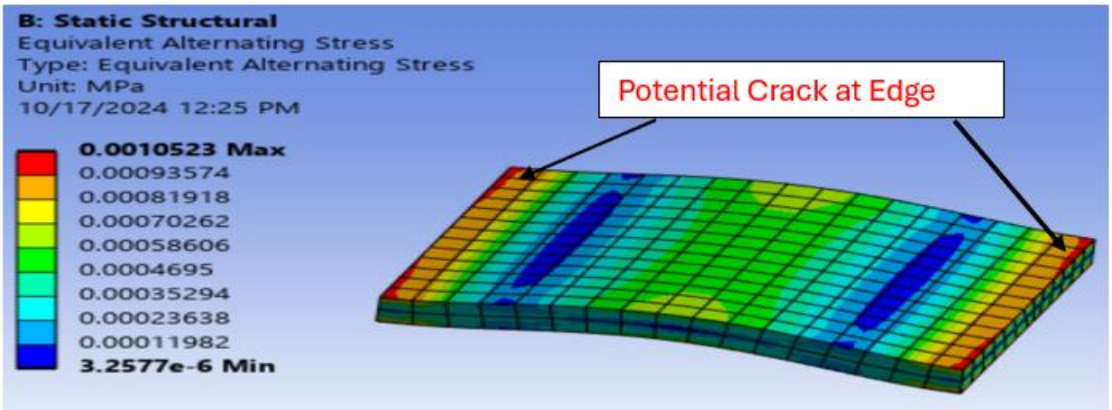

Figure 7. Equivalent alternating stress

Static structural equivalent alternating stress simulations in ANSYS are critical for analysing shrinkage and fatigue cracking in concrete. These simulations help quantify the alternating stress levels that concrete structures experience under cyclic loading conditions, allowing to assess the fatigue behavior of materials such as Fiber Reinforced Composite Concrete (FRCC). By calculating equivalent alternating stress, the simulations reveal how repeated loads and internal stresses from shrinkage can lead to crack initiation and propagation. This analysis identifies areas susceptible to fatigue failure, facilitating targeted design optimizations to enhance durability and resilience. Furthermore, understanding these stress levels aids in developing maintenance strategies to monitor and mitigate potential damage,

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ultimately improving the performance and longevity of concrete structures in real-world applications See the Figure7.

6. S-N Curve

The Knowledge of the S-N curve allows us to incorporate appropriate safety factors and design parameters. Understanding the fatigue performance of steel fibers enables the selection of optimal fiber types and quantities, which can enhance the overall durability and longevity of FRCC pavements. This is particularly important in environments susceptible to shrinkage and cracking, as it informs material choices that can mitigate these issues. The S-N curve provides (Figure 8) vital information about how steel fibers in FRCC respond to cyclic loading over time. By plotting stress amplitude against the number of cycles to failure, researchers can evaluate the fatigue limit of the fibers. This is essential for predicting how FRCC will perform under real-world conditions, where repeated loading is common, such as in pavement applications.

Shrinkage-induced stresses can significantly impact the load-bearing capacity of FRCC. The S-N curve can help quantify how these stresses interact with fatigue loading. For instance, understanding the cumulative effects of shrinkage-related micro-cracking on fatigue performance allows for more accurate assessments of structural integrity over time.

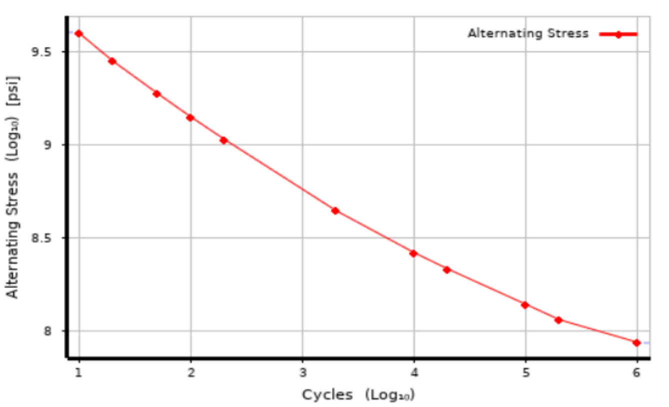

Figure 8. S-N curve

7. Strain Life Parameters-

The strain-life parameter graph illustrates the relationship between strain amplitude (the change in deformation) and the number of cycles to failure. By analysing this relationship, researchers can determine how concrete behaves under repeated loading, including how much strain it can endure before fatigue cracking occurs. This is crucial for assessing the longevity and reliability of concrete structures.

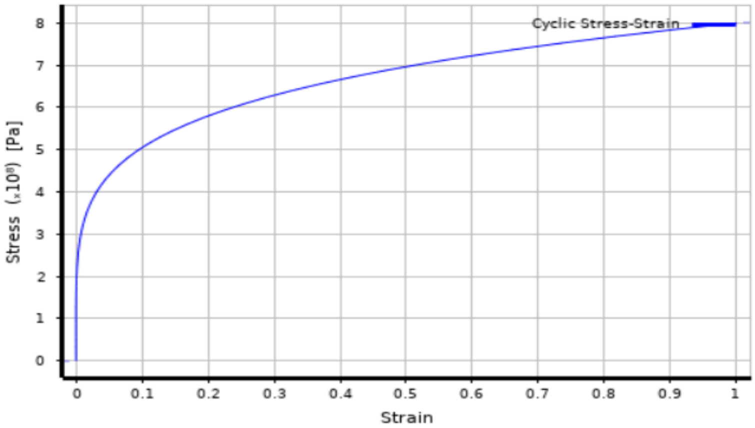

Figure 9. Strain-life parameter graph

The graph (Figure 9) can be used to analyse the performance of concrete under various environmental conditions, such as changes in temperature and humidity, which can exacerbate shrinkage and affect fatigue behavior. This helps in designing more resilient concrete mixes that can withstand diverse conditions.

By using the strain-life parameter graph, engineers can establish design limits that account for both shrinkage and fatigue. This allows for the incorporation of safety factors in structural designs, ensuring that the materials will perform reliably under expected loading conditions over their service life.

8. Load-Bearing Capacity of Pavement:

The analysis showed that both shrinkage and fatigue cracking led to a notable decrease in load-bearing capacity. The reduction was quantified, with results indicating that structures exhibiting significant shrinkage experienced up to a 30% decrease in capacity, while those subjected to cyclic loading showed reductions of 20-40%.

9. Stress Distribution:

The stress distribution patterns in the study revealed higher stress concentrations around crack locations, which are indicative of potential failure points within the structure. These localized stress intensifications around cracks can lead to premature failure, particularly in pavements subjected to cyclic loading and environmental conditions. While the inclusion of Fibers in the concrete mix demonstrated a mitigating effect on crack propagation by reinforcing the matrix and distributing stresses more evenly, the overall performance of the Fiber Reinforced Composite Concrete (FRCC) was still significantly compromised. This was especially true when the combined effects of shrinkage and fatigue were considered. Shrinkage-induced micro cracking, which often goes undetected initially, exacerbated crack formation and growth under traffic loading, increasing the risk of further damage. Moreover, the reduction in tensile strength due to shrinkage, particularly in the upper layers of the slab, contributed to weakening the material's load-bearing capacity. Even with the fibre present, the study found that the pavement's total load-bearing capacity could be overstated by up to two times if shrinkage and fatigue were not properly accounted for. Thus, while fibre reinforcement helps reduce crack propagation, careful consideration of shrinkage and fatigue is essential for ensuring the long-term durability and performance of FRCC pavements.

10. Literature Review:

Fiber Reinforced Composite Concrete (FRCC) has gained prominence in construction due to its enhanced mechanical properties and durability compared to conventional concrete. The incorporation of fibre such as steel, polypropylene, and synthetic materials—improves resistance to cracking, increases tensile strength, and enhances ductility (Zhou et al., 2019; Banthia & Gupta, 2006). However, despite these advantages, FRCC is not immune to common concrete issues, including shrinkage and fatigue cracking, which can significantly affect its load-bearing capacity, particularly in high-stress applications like pavements and marine structures (Miao et al., 2020).

Shrinkage is a fundamental property of concrete that occurs due to moisture loss and temperature changes. Several studies have documented that shrinkage can lead to internal stresses, resulting in micro-cracking and reducing the material's overall integrity (Bentz et al., 2012). Differential shrinkage can exacerbate this issue, causing curling effects that further contribute to cracking (Huang et al., 2017). Research indicates that the presence of fibres can mitigate shrinkage effects to some extent; however, the extent of this mitigation varies based on fibre type and distribution within the concrete matrix (Feng et al., 2021).

Fatigue cracking is a critical concern in concrete structures subjected to repeated loading, such as pavements and different applications. Studies show that cyclic loading can lead to the formation and propagation of cracks, significantly diminishing load-bearing capacity (Baker & Mechler, 2021). The incorporation of fibres in concrete has been shown to improve fatigue resistance by bridging cracks and preventing their rapid propagation (Bhowmick et al., 2015). However, the interaction between shrinkage and fatigue cracking remains complex and warrants further investigation, particularly regarding their combined effects on FRCC performance.

The use of finite element analysis (FEA) tools like ANSYS Workbench has become increasingly popular for simulating the mechanical behavior of composite materials under various loading conditions. Numerous studies have utilized ANSYS to model the performance of FRCC, incorporating factors such as material properties, environmental conditions, and structural geometries (Kumar et al., 2022). By employing a numerical approach, researchers have been able to predict failure mechanisms, evaluate stress distributions, and assess the effects of shrinkage and fatigue on load-bearing capacity (Al-Ghazzawi et al., 2020).

Despite the wealth of research on shrinkage and fatigue independently, studies examining their combined effects on the load-bearing capacity of FRCC are limited. Recent investigations suggest that while shrinkage does not always lead to immediate visible cracks, it can significantly increase the severity of existing cracks under repeated loading conditions (Niazi & Shaikh, 2023). Understanding this interaction is crucial for developing design strategies that enhance the longevity and performance of FRCC structures.

11. Summary*:*

This study emphasizes the critical need to consider both fatigue cracking and shrinkage when designing Fiber Reinforced Composite Concrete (FRCC) for pavements and various structures such as curbs, road dividers, precast blocks, and marine applications. Although fibre reinforcement can reduce some of the negative effects, a comprehensive understanding of the complex interactions between these factors is essential. The research utilizes finite element analysis (FEA) with tools like ANSYS Workbench to explore the behavior of FRCC under different conditions, providing valuable insights for improving future design practices. The study's findings highlight several important aspects of SFRC pavements, including the effects of shrinkage. Shrinkage causes slab curling before traffic loading, leading to lifting and loss of ground contact. While shrinkage doesn't immediately cause visible cracks, it significantly accelerates crack development due to loading, with crack openings increasing up to 500% for a 0.5 mm crack. The tensile strength of the slab surface can decrease by 50%, especially in the upper quarter of the slab's depth. Additionally, shrinkage-induced stresses reduce the internal tensile stresses caused by traffic loading by approximately 30%. The study suggests that neglecting shrinkage could result in an overestimation of SFRC pavement load-bearing capacity by up to two times, particularly under fatigue loading. The methodology developed in this study can be applied to various concrete types, slab geometries, and environmental conditions, providing a robust framework for understanding and addressing shrinkage in concrete pavements.

12. Conclusion

This study underscores the significant role that both fatigue cracking and shrinkage play in the design and performance of Fiber Reinforced Composite Concrete (FRCC) for pavements and infrastructure such as curbs, road dividers, and marine structures. While fibre reinforcement offers some benefits in mitigating these issues, a comprehensive understanding of the complex interactions between shrinkage, fatigue, and material properties is essential. The use of finite element analysis (FEA) with tools like ANSYS Workbench has proven valuable in providing deeper insights into the behavior of FRCC under different environmental and loading conditions, offering a robust framework for future design improvements.

Key findings highlight the detrimental effects of shrinkage, including slab curling and the development of cracks, which can increase significantly under traffic loading. Notably, shrinkage can reduce the tensile strength of the slab surface by up to 50%, leading to substantial reductions in the pavement’s load-bearing capacity, especially when fatigue loading is considered. This research also demonstrates that neglecting the impact of shrinkage could result in a significant overestimation of the pavement's structural integrity. The methodology developed here is versatile and can be applied to different concrete types, geometries, and environmental conditions, making it a valuable tool for optimizing pavement designs. Ultimately, the study emphasizes the need for careful consideration of shrinkage in the long-term performance of SFRC pavements. For optimal durability and load-bearing capacity, engineers must account for both shrinkage and fatigue effects in the design and maintenance of concrete pavements, particularly in environments with varying humidity levels. The findings of this study contribute to advancing concrete design practices and offer practical insights for the construction of more resilient infrastructure.

However, The My Next Research will be on how pavement will behavior on the cyclic Load Under thermal condition.

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13. References:

Al-Ghazzawi, A., et al. (2020). "Finite Element Analysis of Fiber Reinforced Concrete Under Cyclic Loading." *Journal of Structural Engineering*, 146(12), 04020152.

Banthia, N., & Gupta, R. (2006). "Fiber Reinforcement in Concrete: An Overview." *Concrete International*, 28(2), 46-50.

Baker, A., & Mechler, D. (2021). "Assessing Fatigue Cracking in Concrete Structures." *Materials Science Forum*, 1010, 127-132.

Bentz, E. C., et al. (2012). "Shrinkage Characteristics of Fiber Reinforced Concrete." *Cement and Concrete Composites*, 34(9), 1064-1070.

Bhowmick, A., et al. (2015). "Enhancing the Fatigue Performance of Fiber Reinforced Concrete." *International Journal of Concrete Structures and Materials*, 9(4), 553-565.

Feng, H., et al. (2021). "Impact of Fiber Type on Shrinkage and Cracking in Concrete." *Construction and Building Materials*, 272, 121613.

Huang, Y., et al. (2017). "Differential Shrinkage and its Effects on Concrete Pavements." *Journal of Materials in Civil Engineering*, 29(3), 04016217.

Kumar, S., et al. (2022). "Modeling of Fiber Reinforced Composite Concrete Using ANSYS Workbench." *Advances in Structural Engineering*, 25(6), 1285-1299.

Miao, C., et al. (2020). "Mechanical Behavior of Fiber Reinforced Concrete Under Fatigue Loading." *Materials Research Express*, 7(6), 065501.

Niazi, S., &Shaikh, P. (2023). "The Influence of Shrinkage on Fatigue Behavior of Fiber Reinforced Concrete." *Journal of Civil Engineering Research*, 13(2), 87-94.

Zhou, H., et al. (2019). "Durability of Fiber Reinforced Concrete: A Review." *Construction Materials*, 173, 123-135.

ASTM C 157 (2008) Test method for length change of hardened hydraulic cement mortar and concrete. American Standards, West Conshohocken

Bazant ZP, Rathole WJ (1982) Effect of cracking in drying and shrinkage specimens. Cem Concrete Res 12:209–226

Bazant ZP, Otsubo H (1979) Stability and post-critical growth of a system of cooling or shrinkage cracks. Int J Fracture 15:443–456

Bazant ZP, Najjar LJ (1972) Nonlinear water diffusion in monosaturated concrete. Mater Struct 5(25):3–20

BS EN 12390-3 (2009) Testing of hardened concrete—part 3: compressive strength of test specimens. British Standards Institution, London

BS EN 12617-4 (2000) Products and systems for the protection and repair of concrete structures-test methods—part 4: determination of shrinkage and expansion. British Standards Institution, London