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Review on Advancements in the Field of Macro Synthetic Fiber Reinforced Concrete Technology and its Application in Segmental Lining for Tunnels

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Abstract: In order to increase the crack resistance, durability and tensile stress resistance of conventional concrete it is a general practice nowadays to use fiber reinforced concrete. Macro synthetic fibers such as polypropylene are the latest improvement over traditional steel fibers in in this regard. The enhanced tensile stress resistance, crack resistance and energy absorption of structural members casted using macro fiber reinforced concrete makes it the best suitable material for precast as well as cast-in-situ segmental linings for tunnels and mine shafts. This paper attempts to consolidate all the innovations and improvements made over the past few years in the field of macro synthetic fiber reinforced concrete technology and its application in segmental tunnel linings by coursing through available research and literature related to the subject under consideration. The comprehensive review will be useful for future designers and tunnel engineers to achieve better stability, strength and performance during construction of segmental lining for tunnels.

Keywords: Macro Fiber Reinforced Concrete, Segmental Tunnel Lining, Steel Fiber, Crack Mouth Opening Displacement

1. INTRODUCTION

Tunnels are the most preferred mode of transportation when the roadways are obstructed by mountains. Underground tunnels for metro lines and undersea tunnels as an option over ferry lines are a common practice over the past few years. For protection of tunnels against collapse failure by improving structural stability and to provide confined surface free of entry of water, vegetation and dust the tunnels are required to be lined. Most advanced forms of tunnel lining include concrete linings consisting of either cast-in-situ lining using shotcrete or assembly of precast segmental linings casted in a controlled environment in workshops.

Conventionally the reinforcement is provided in concrete lining in the form of curved/semicircular rebar cages the transportation, assembly, execution and repair of which is a tedious, time consuming and costly task. For effective protection against cracks and for increasing the resistance against tensile stresses, energy absorption capacity while keeping the segments slender application of fiber reinforced concrete was adopted.

Initially steel fibers were the most frequently used fibers in fiber reinforced concrete but due to corrosion phenomena an improvement was made by replacing them with macro synthetic fibers such as polypropylene. This paper is an attempt to provide a comprehensive extract of all the recent research in the phenomena of macro fiber reinforced concrete technology and its application to segmental tunnel linings.

2. LITERATURE REVIEW

The available literature was divided in two groups with one group focusing on synthetic macro fiber reinforcement concrete technology and other group focusing on its application in segmental tunnel linings.

2.1 SYNTHETIC MACRO FIBER REINFORCED CONCRETE

Saber Fallah and Mahdi Nematzadeh (2016) (University of Mazandaran, Iran) [1] studied the effects of addition of macro polymeric fibers and polypropylene fibers to high-performance concrete consisting of nano-silica and silica fume. The authors prepared and tested specimens for 28 different groups containing polymeric fibers and polypropylene fibers as well as nano-silica and silica fume individually and then in combinations of varying percentages. The specimens were tested considering factors including compressive and tensile strengths, modulus of elasticity, water absorption and porosity.

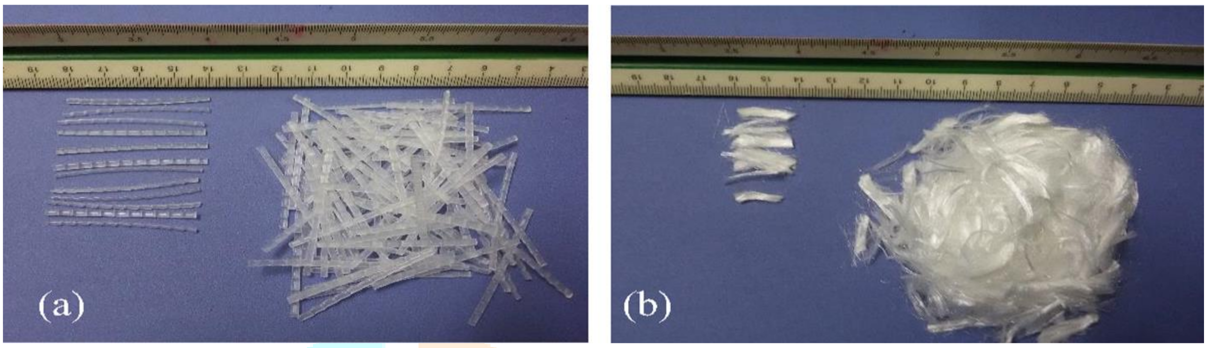

Figure 1 Macro Polymeric Fibres and Polypropylene Fibres

The authors concluded that addition of macro polymeric fibers and polypropylene fibers along with nano silica and silica fume decreases workability of fresh concrete but addition of PP and MP fibers up to a certain threshold percentage increases the tensile strength and modulus of elasticity compared to plain concrete. They also observed that replacement of cement with only nano silica and silica fume without adding fibers increases both the initial and secant modulus of elasticity of high-performance concrete. It was concluded that using a combination of fibers and pozzolanas the fresh state and hardened state properties of concrete can be improved.

Jong-Han Lee (2017) (Daegu University, South Korea) [2] worked on residual flexural strength of fiber reinforced concrete. hooked end type fibers were added to concrete in varying percentages. Beam elements were casted using this concrete mix and tested for flexural strength after initial cracking is over. Influence of fiber content was studied considering the parameters of limit of proportionality between load and displacement, residual flexural strength and energy absorption capacity. Grade of concrete was also varied and correlation analysis was performed to define a pattern in the observations.
The authors concluded that fiber content hardly affects the limit of proportionality between load and deformations while introduction of fibers in concrete causes strain hardening behavior in members upon cracking after a particular limit is reached. It was also observed that in case of fiber reinforced concrete the energy absorption capacity reduces with rise in the grade of concrete.

Veronica Guerini et al. (2018) (Carleton Laboratory, Columbia University) [3] studied the implications of addition of steel fibers and macro synthetic (polypropylene) fibers on the workability which is a fresh state property of fiber reinforced concrete. Multiple concrete mixes were prepared by keeping grade of concrete constant and varying the percentage of fibers. Influence of fibers on concrete mixes was observed on air content, slump and flow properties using formulae, slump cone tests and flow table tests respectively. Cubes were casted using same concrete mixes and compressive strength, flexural strength and residual flexural tensile strength along with flexural toughness were determined for cube specimen.

Figure 2 Steel fibres

Figure 3 Polypropylene Fibres

The authors observed that steel fibers provide more workability to fiber reinforced concrete than polypropylene fibers. It was also observed that steel fiber reinforced concrete flows less uniformly along the two directions on flow table than polypropylene fiber reinforced concrete as the steel fibers gets interlocked with each other along one direction and prevent the flow of mix in other direction.

Amin Noushini et al. (2018) (School of Civil and Environmental Engineering, University of New South Wales) [4] focused on use of polyolefin and polypropylene fibers in geopolymer concrete. The concrete mix was prepared using fly ash and ground granulated blast furnace slag acting as a source of silicate and aluminate while solution of sodium hydroxide and sodium silicate was used as an activator. The polypropylene and polyolefin fibers were added to this mix in varying percentages and fresh state properties of mix were determined. Cylindrical specimen casted from same mix were used for determination of hardened state properties.
The authors observed that the addition of polyolefin fibers to geopolymer concrete causes more reduction in compressive strength as compared to addition of polypropylene fibers while addition of both type of fibers increases the flexural strength of the casted member considerably.

Syed Minhaj Saleem Kazmi et al. (2019) (School of Engineering, RMIT University) [5] studied the behavior of recycled aggregate based concrete when macro synthetic fibers are added to it. The authors casted cylindrical specimen using varying percentages of recycled aggregates as well as polypropylene fibers. The specimen were then subjected to axial compression and the results were compared with normal aggregate concrete with same dosages of polypropylene fibers as well as normal and recycled aggregate concrete with addition of conventional steel fibers. The results were determined for peak stress, peak strain, elastic modulus and a modified numerical stress-strain model was prepared which can predict the behavior of steel as well as polypropylene fibers in normal as well as recycled aggregate concrete.
The authors observed an increase in peak stress, ductility and energy dissipation capacity as the fiber content increases and the adverse effects of using recycled aggregates are also lowered with an increase in dosage of macro-polypropylene fibers.

A Khalighi et al. (2020) (Imam Khomeini International University, Iran) [6] studied the effect of use of steel and hybrid-synthetic fibers in normal Reinforced concrete beams subjected to high temperatures. Beam specimen were casted using varying proportions of steel fibers as well as hybrid synthetic polypropylene fibers to Normal concrete and reinforced with steel bars. The beams were then subjected to temperatures of up to 800 degrees and 4-point loading test was executed to determine residual strength of specimens.
The authors concluded that steel fibers confined themselves around the steel reinforcement bars and provide better distribution of tensile stresses at high temperatures thereby increasing the fire resistance duration of concrete.

2.2 APPLICATION OF SYNTHETIC MACRO FIBER REINFORCED CONCRETE FOR SEGMENTAL LINING FOR TUNNELS

Kiachehr Behfarnia and Amir Behravan (2013) (Isfahan University of Technology, Iran) [7] tried to determine the effect of addition of High-Performance Polypropylene fibers on fresh state and hardened state properties of concrete and its suitability for lining of water tunnels. The authors prepared concrete mixes by adding steel fibers and High-Performance Polypropylene fibers along with polycarboxylate based High Range Water Reducing Admixtures. The casted specimens were tested for changes in compressive strength, tensile strength, flexural strength, toughness and energy absorption, water absorption of concrete and chloride ion penetration resistance as compared to normal concrete mixes.
The authors observed that High-Performance Polypropylene fibers reduced the workability of concrete mix due to fiber-aggregate interlocking phenomena while incorporating steel fibers lowered the water absorption of concrete mix. Addition of High-Performance Polypropylene fibers also improved the ductile behavior and energy absorption capacity of concrete as compared to normal concrete mixes. The High-Performance Polypropylene fibers provided greater resistance to penetration of concrete by chloride ions thereby making them more suitable to be used in segmental lining of underwater tunnels as opposed to steel fibers in which case accumulation of rust around fibers forms small gaps between fibers and cement paste making it easier for chloride ions to penetrate the concrete.

Lin Liao et al. (2016) (Taiyuan University of Technology) [8] redesigned the existing RCC segmental ring lining elements for Moncada vertical shaft (Barcelona) using fiber reinforced concrete. The authors first proposed a design formulation by replacing the entire steel reinforcement in vertical shaft by adding fiber reinforcement to concrete as per MC2010 design code criteria. Fibers were added to conventional as well as self-compacting concrete mixes in varying proportions and two full scale segments representing the mixes were casted. These segments were then tested using concentrated loading on critical points.

Figure 4 Precast segmental lining for vertical shaft subjected to concentrated loading

The authors observed that the members casted by replacement of main reinforcement by structural fibers were able to perform better when it comes to resistance to cracks and durability.

Antonio Conforti et al. (2016) (BASF Construction Chemicals, Italy) [9] assessed the suitability of polypropylene fiber reinforced concrete for hydraulic precast tunnel segments for Monte Lirio Hydraulic Tunnel (Panama). Concrete mixes prepared consisted of Conventional reinforcement, Polypropylene fiber reinforcement and a combination of both. Six full scale segments were casted and tested using 3-point bending test and one-point concentrated load test on various critical points.
The authors concluded that polypropylene fibers are best suited as flexural, splitting and minimum shear reinforcement of hydraulic precast tunnel segments. It was also observed that polypropylene fibers increases bearing capacity and ductility of concrete considerably compared to conventional reinforced concrete.

Antonio Conforti et al. (2019) (BASF Construction Solutions, Germany) [10] focused on suitability of polypropylene fiber reinforced concrete for Metro Tunnel Linings**.** The authors prepared full scale metro tunnel lining segments using polypropylene fiber reinforcement in combination with conventional steel rebars as well as using traditional rebars only. Three-point loading test and one point loading test ware performed for understanding flexural behavior of the members. The authors concluded that the combination of high polypropylene fiber reinforcement and low conventional reinforcement is able to resist the tensile cracks effectively than using polypropylene fiber reinforcement alone**.**

Safeer Abbas and Moncef L. Nehdi (2021) (University of Engineering and Technology, Lahore) [11] experimented to understand mechanical behavior of Ultra High-Performance Concrete with added Hybrid Steel Fiber Reinforcement and its suitability for Tunnel Lining Segments. The authors prepared the mix using Ordinary Portland Cement, Silica fume, Quartz powder, Quartz sand, Polycarboxylate superplasticizer and copper coated hybrid steel fibers in varying percentages and fresh state properties were observed. Three-point loading test and edge point load test was performed on casted scaled down specimens.
The authors observed that addition of fibers causes loss in flow of fresh concrete but at the same time compressive strength, splitting tensile strength and durability of casted specimen. It was thus concluded that using Ultra High-Performance Concrete in combination with Steel Fiber slender, more economical sections can be casted for segmental lining of tunnels as compared to cost and logistical as well as corrosion related issues associated with conventional concrete.

2.3 CASE STUDY: BLACKSNAKE CREEK STORMWATER TUNNEL, USA (2019)

The tunnel is part of the Blacksnake Creek Storm Water Separation Improvement Project of the City of St. Joseph, Missouri. Six trapezoidal segments were joined to make a single segmental ring. The technical specifications of segments are shown below.

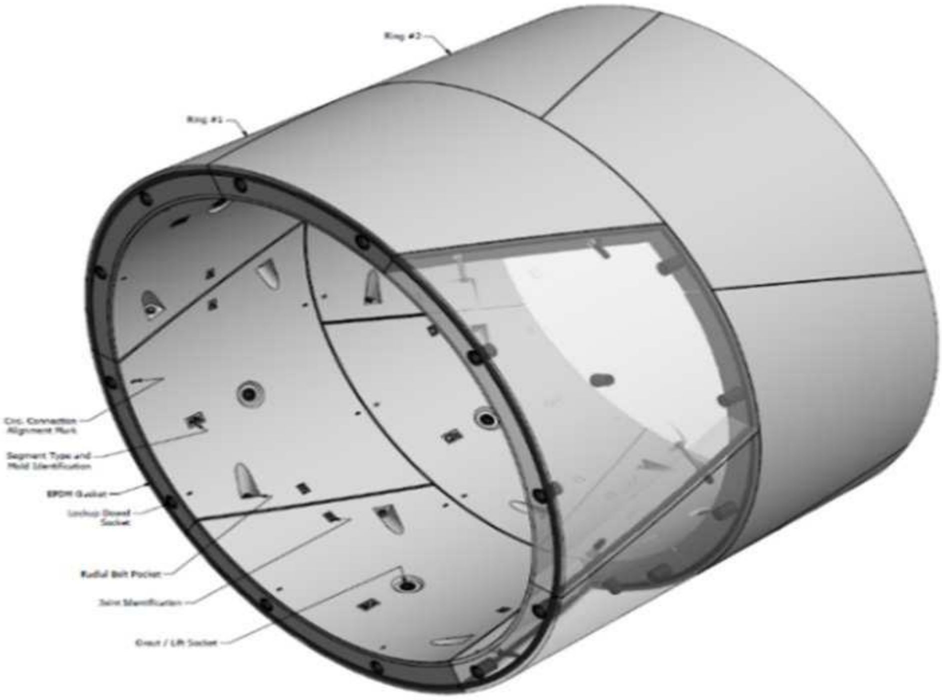

Figure 5 Completed segmental rings

- Internal diameter 2.743 m (108 in.)
- Thickness 190.5 mm (7.5 in.)
- Ring length 1.219 m (48 in.)
- Segmentation: 6 trapezoidal segments
- Ground conditions: predominantly shale & claystone
- Concrete specifications: Concrete class C45/55 (f'c = 48 MPa)
- Residual strength fD 600 = fD 150 = 3.20 MPa
- Reinforcement: 7 kg/m3 BarChip 54 macro synthetic fibers

Launch of the 78 m long TBM required construction of 18 m diameter segment pile shaft. During the launch of the tunnel the short launch screw conveyor was uninstalled and longer main screw conveyor was inserted. During this operation the precast tunnel segments consisting of BarChip 54 macro synthetic fibers were used as a lining to propagate forward the TBM.

The half ring segments were checked for deformations of defects if any after pushing operation for TBM was completed. It was observed that the fiber reinforced concrete tunnel segments were successfully able to resist the temporary loads such as loads due to transportation, hoisting, handling and installation without any significant damage. The fibers were also helpful in controlling the post construction cracks in the segments.

While driving through the hard strata the TBM experienced very high pressures but still the none of the fiber reinforced concrete segments gave in.

The case study proves the efficiency of the fiber reinforced concrete segments for tunneling operations considering the factors of crack resistance, flexural strength and robustness during TBM operations.

Figure 6 Completed segmental rings

3. CONCLUSION

Recent advancements in the field of fiber reinforced concrete technology were discussed. Furthermore, application of macro fiber reinforced concrete technology to segmental tunnel linings were also discussed in detail. The experiments, research and results of various esteemed researchers relevant to the topic were carefully listed out and referenced. This review should be able to serve as a valuable reference for future designers and engineers working within tunnel engineering regime.

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