

# Development and Material Characterization of Advanced Polymer Fibre-Reinforced Shotcrete for Tunnel Applications

Meena Isukapatla<sup>1</sup>, Dr Sandeep Thakur<sup>2</sup>

<sup>1</sup>Research Scholar, Department of Civil Engineering, IES University Ratibad, Main Rd, Bhopal, Madhya Pradesh 462044, India. [meenaisukapatla@gmail.com](mailto:meenaisukapatla@gmail.com)

<sup>2</sup>Department of Civil Engineering, IES College of Technology Main Road, Kali Kheda, Ratibad, Bhopal, Madhya Pradesh-4620443, India.

**Abstract:** The growing market for long-lasting and high performance tunnel lining systems has driven the need of novel construction materials that can survive in multi-extreme ground environment. Traditional shotcrete, which is also widely employed in tunnel support systems, is known to be brittle and is prone to cracking and its durability in aggressive environment is also questioned. In order to tackle these problems, the present work research the design of a tunnel application shotcrete, named polymer fibre reinforced shotcrete (PFRS), and its development and material testing. In this study, polymer fibres are added to shotcrete mixtures with different volume contents to improve mechanical properties, crack resistance and durability. A comprehensive set of tests is made to determine compressive strength, flexural strength, split tensile strength and toughness properties. Moreover, microstructural study is carried out to comprehend fibre–matrix interfacing and crack-bridging mechanisms. The results confirm improved ductility, post cracking behaviour and crack propagation resistance compared to ordinary shotcrete. A proper balance between workability and mechanical performance is obtained with this optimal fibre amount. The results confirm the potential improvement of polymer fibre reinforced shotcrete as an alternative for tunnel lining systems with better structural safety and long service life. The present work opens a new avenue for more comprehensive structural and field-level study on enhanced shotcrete materials.

**Keywords:** Polymer fibres, Shotcrete, Tunnel lining, Fibre-reinforced concrete, Mechanical properties, Durability, Crack resistance

## 1. Introduction

The growing development of underground facilities, such as transportation tunnels, subway systems, and mining excavations, has led to a substantial increase in the need for lining materials with high-performance that can offer long-term stability and security for the structure. Shotcrete, a concrete that is applied pneumatically, is extensively employed as a tunnel secondary support system for its convenience of application, fast strength development and good conformability to sophisticated cross-section shapes. Nevertheless, traditional shotcrete has some inherent drawbacks, including low tensile strength, brittle failure mode, and vulnerability to shrinkage-induced cracks which might weaken the durability and carrying capacity of the structure in harsh underground [1], [2].

In order to address these issues, fibre reinforced shotcrete has been investigated as a promising route of modification. The addition of fibres improves the post-cracking performance, toughness and energy absorbing capability of shotcrete which is desirable in infrastructures subjected to dynamic and heavy load such as tunnels [3]. Among all available fibres, steel fibres have been the most widely used ones due to its very high tensile strength and stiffness. Nonetheless, steel fibres can rust, contribute to the weight of the structure and have the potential to cause health problems to the workers [4].

Polymer fibres have therefore increasingly appeared as a viable option to traditional steel reinforcement in shotcrete in the last years. Polymer based fibres (e.g. polypropylene, nylon) have several benefits such as they are corrosion resistant, chemically inert, lightweight and they can be better dispersed into the cementitious matrix [5]. These fibres are notably efficient in controlling plastic shrinkage cracking of the material and in improving the ductility of the material. In addition, the bridging effect of microcracks also helps to retard cracking propagation, which enhances the long-term durability of tunnel linings [6].

There are several factors, such as shape and size of fibers, aspect ratio, dosage, and fiber–matrix bond quality, that can influence the behavior of PFRS and, in general, that of fiber-reinforced concrete (FRC). A proper balance between fibres content and workability is required to be able to evenly spray and spread them during application. Too much fibres may decrease flowability and cause blockage during the flow cement application, and too few numbers of fibres as reinforcement may be not enough to enhance the ductility [7]. Hence, to obtain the desired mechanical and durability properties, an appropriate mix design and testing are essential.

Another important issue in the development of advanced shotcrete material is the microstructural behavior. The cement-fibre interactions are important in crack resistance, loading efficiency and failure mechanics. Modern fiber treatment methodologies have demonstrated that strength bridging has a significant influence on enhancing fracture toughness and the extent of energy dissipation in fiber reinforced composites [8].

The object of this work is to develop and to fully characterise a polymer fibre reinforced shotcrete for use in tunnel lining. The study investigates the effect of the addition of polymer fibre on mechanical properties including compressive strength, tensile strength and flexural behaviour, as well as on toughness and crack resistivity. By proposing optimum mix designs and explaining the fundamental material behaviour, this research work will pave way for the development of highly durable and efficient tunnel support systems.

The reinforcement of shotcrete with fibre materials has been the subject of extensive investigation during the past few decades, mainly focusing on the enhancement of mechanical and durability properties. Early research was concentrated predominantly on the steel fibre-reinforced shotcrete, which revealed remarkable enhancement in toughness, impact resistance and load-carrying capacity when compared with plain shotcrete [9]. Nonetheless, problems with corrosion and long term durability in harsh conditions led to investigation of other fibre materials.

Synthetic polymer fibres in the form of PP fibres are having good resistance to chemical attack and corrosion. It has been demonstrated that addition of polypropylene fibres suppresses plastic shrinkage cracking and enhances ductility of concrete composites [10]. Moreover, these fibres improve the postcracking behaviour through the activation of crack-bridging mechanisms that arrest the abrupt brittle [11]. The efficiency of polymer fibres for increasing toughness has been described as similar to that of steel fibres in some cases particularly at optimised fibre dosages and aspect ratios [12].

Studies on content of fibre suggest that the mechanical properties of fibre reinforced shotcrete are more sensitive to the content of fibres. It is observed that medium fibre content can improve flexural strength and energy absorption capacity to great extent while high content of fibres can exert negative effect on workability and compaction [13]. Moreover, uniform mechanical properties can be obtained by a good fibre dispersion. bad dispersion causes clusters and then fragile material [14].

Microstructural examinations have led to a deeper understanding of the behaviour of fibre-reinforced composites. Scanning electron microscopy (SEM) studies showed that strong fibre–matrix bonding lead to higher load transfer efficiency and better crack resistance. The fibre bridging of crack surfaces causes increased fracture energy and retardation of crack propagation [15]. Such mechanisms are of particular advantage in tunnel linings, where materials are subject to continuous stress fluctuations and exposure to the environment.

Recent developments have also been made in hybrid fibre systems which entail the use of two or more types of fibre to realize synergistic effect. As with hybrid reinforcement, workability has been found to be significantly improved by the addition of glass fibres." [16]. In addition, the incorporation of the supplementary cementitious materials, e.g. silica fume and fly ash, is expected to improve the durability and decrease the permeability of the mixes of shotcrete [17].

From the standpoint of durability, polymer fibre-reinforced (PFR) shotcrete has been shown to possess better resistance to environmental attacks such as freeze-thaw cycling, sulphate attack, and chloride ion penetration [18]. Such behavior is essential for underground constructions, as they are generally exposed to moist and aggressive

chemical environment. By decreasing crack width by fibre reinforcement, the penetration of harmful material into concrete is reduced and therefore, a longer service life of a structure can be obtained [19].

Still, comprehensive work that combines material development, mechanical characterization, and tailoring for specific applications for tunnel linings is needed. Most current research studies target specific properties or laboratory-scale tests, and not so much for adaptation of the material for actual conditions of use [20]. Thus, in this work, we attempt to fill this gap by analyzing the performance and the potential applicability of polymer fibre-reinforced shotcrete in a comprehensive manner.

### **3. Materials and Mix Design**

#### *3.1 Materials*

The selection of materials and material qualities greatly influence the performance of polymer fibre reinforced shotcrete (PFRS). For this work, all the materials were chosen according to standard code provisions to achieve uniformity, durability, and suitability for tunnel lining.

##### **Cement**

The major binder was ordinary Portland Cement (OPC) complying to the Type I of ASTM C150. The cement was of specific gravity 3.15, and had the required fineness and setting time for application as shotcrete.

##### **Fine Aggregate**

Standard-grade natural river sand was used as the fine aggregate in line with the requirements of ASTM C33. The sand was approximately 2.6 in fineness modulus that provided adequate workability and cohesiveness to the mix.

##### **Coarse Aggregate**

Crushed stone aggregates with maximum size 10 mm are employed. A smaller aggregate size was required to improve pumpability and allow a uniform flow through the nozzle in the shotcrete application.

##### **Polymer Fibres**

Polypropylene fibres were added as reinforcement agent due to its superior corrosion-resistance, low density, and high chemical stability. The fibres measured about 12 mm in length, had diameters of 18 to 40  $\mu\text{m}$  and an aspect ratio of 300 to 600. They provide efficient control of microcracking and an enhanced ductile behaviour through crack-bridging mechanisms.

##### **Admixtures**

A high range water reducing admixture (superplasticizer) in accordance with ASTM C494 was employed to improve the workability without adding water. Silica fume was added as a supplementary cementitious material with 10% substitution of cement to enhance strength and reduce permeability.

##### **Water**

ASTM C1602 specification water was employed for the making and curing processes.

#### *3.2 Mix Design Methodology*

The mix design was prepared based on the standard requirements for shotcrete applications, such as pumpability, adhesion to substrate, early strength gain, and low rebound loss. A w/c ratio of 0.40 was taken as the base mix to have an acceptable workability and strength. Different volume fractions of polymer fibres (0%, 0.5%, 1.0%, 1.5% and 2.0) were introduced to investigate the influence of fibre content on mechanical properties and crack resistance. The superplasticizer dose was adjusted according to the fibers amount to achieve the same workability. 10% cement was replaced with silica fume to densify the pore structure and improve the bond between fibres and cement. The mixing proportion guaranteed:

- Uniformly dispersed fibres
- Sufficient spray ability under cohesion strength
- Low segregation and rebound

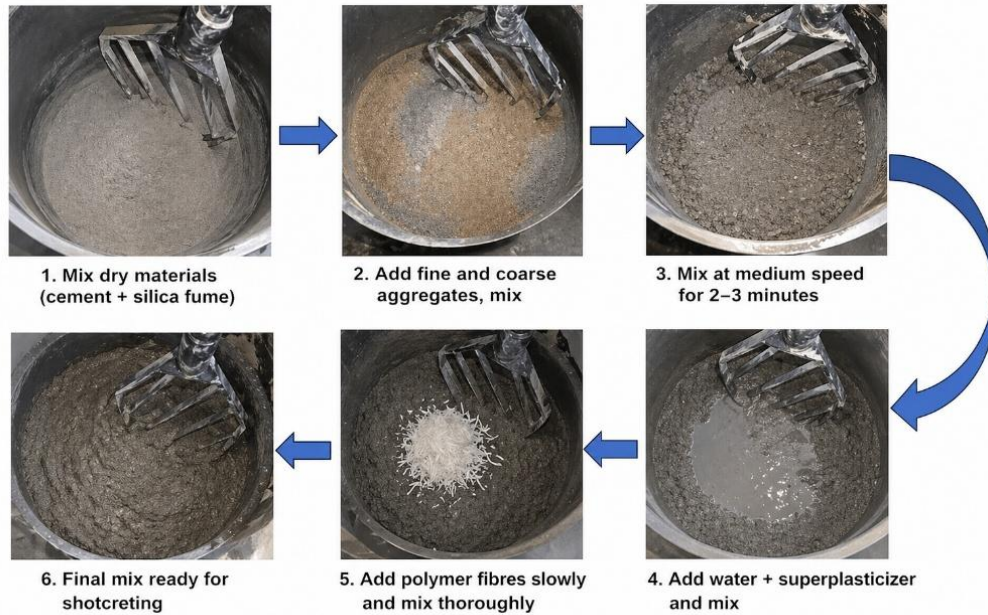


Figure 1: Optimized Mixing Procedure for Polymer Fibre-Reinforced Shotcrete

Figure 1 describes the sequential mixing procedure for preparation of polymer fibre-reinforced shotcrete. The cement and silica fume are dry blended first, which is believed to facilitate a more consistent distribution of the fine particles around the binder. Fine and coarse aggregates are then added and mixed thoroughly to uniform dry mixture.

The mixture is subsequently subjected to intermediate-speed mixing for 2–3 min to enhance particle packing and remove a portion of initial flocculation. In a subsequent process step, water containing superplasticizer is added dropwise to keep the water/cement ratio under proper control and at the same time to achieve adequate workability. This stage is important to reach sufficient flowability if using shotcreting.

To prevent fibre balling, polymer fibres are added gradually into the wet mix. Under constant agitation one achieves an even fibre dispersion in the matrix, leading to a more effective crack bridging mechanism across fibers. Finally, the composite is overmixed to yield a cohesive, workable shotcrete mixture to be applied.

#### 4. Experimental Methodology with Equations and Testing Standards

The dry-mixed and polymer fibre reinforced shotcrete samples should be examined for their fresh properties, mechanical strength, toughness and resistance to aging. The following standards and formulas could be added after Materials and Mix Design Section.

##### 4.1 Workability Test

Workability of fresh shotcrete mixture was determined by slump test. This test serves to determine the mixture's consistency, flowability, and whether it is appropriate for pumping and spraying. The Slump test can be performed as per ASTM C143/C143M or IS 1199. It also contains directions for measuring the slump of plastic hydraulic-cement concrete.

$$S = H_0 - H_s$$

where S is the slump in mm,  $H_0$  is the initial mould height, and  $H_s$  is the height of the slumped concrete.

##### 4.2 Compressive Strength Test

Normal strength was determined by a 7, 14 and 28 days curing cube or cylinder specimens tests. The test may be conducted for the cube specimen as per IS 516 or for the cylindrical specimen as per ASTM C39/C39M. The compressive strength of the cylindrical concrete specimens shall be determined in accordance with ASTM C39/C39M.

$$f_c = \frac{P}{A}$$

where  $f_c$  is the compressive strength in MPa, P is the maximum failure load in N, and A is the area under load in mm<sup>2</sup>.

#### 4.3 Split Tensile Strength Test

Split Tensile Strength test the indirect tensile strength was determined for cylindrical specimens in the split tensile strength test. This test is important as shotcrete failure is primarily by tensile cracking and not by pure compression. Test can be done as per ASTM C496/C496M or IS 5816. Splitting tensile strength of a cylindrical concrete specimen 2.3.5 ASTM C496/C496M ASTM C496/C496M covers the determination of the splitting tensile strength of cylindrical concrete specimens.

$$f_t = \frac{2P}{\pi LD}$$

where  $f_t$  is the split tensile strength in MPa, P is the applied failure load in N, L is the length of the cylinder in mm, and D is the diameter of the cylinder in mm.

#### 4.4 Flexural Strength Test

Flexural strength was determined by third-point loading prism specimens. This examination reveals bending resistance and crack-control capacity. ASTM C1609/C1609M is very appropriate for flexural performance evaluation of fibre-reinforced concrete, as it considers the load-deflection behaviour under third-point loading. For normal concrete prism testing, ASTM C78/C78M or IS 516 may be followed.

$$f_r = \frac{PL}{bd^2}$$

where  $f_r$  is flexural strength/modulus of rupture in MPa, P is the maximum load applied in N, L is the span length in mm, b is the width of the specimen in mm and d is the depth of the specimen in mm.

#### 4.5 Toughness and Energy Absorption

The importance of toughness for fibre-reinforced shotcrete lies in its representation of how much energy the material can absorb after it has cracked. It is the area under the load-deflection curve.

$$T = \int_0^{\delta} P(\delta) d\delta$$

Here T is the toughness or energy absorbed, P( $\delta$ ) is the load as a function of deflection and  $\delta$  is the mid-span deflection. The toughness index may be defined as:

$$I_T = \frac{T_f}{T_p}$$

with  $I_T$  is being the toughness index,  $T_f$  is the toughness of fibre-reinforced shotcrete, and  $T_p$  is the toughness of plain shotcrete.

#### 4.6 Rebound Loss

Rebound is significant in shotcrete as what is sprayed to a surface some of the material ricochets off the surface. Less rebound means better bonding and material usage.

$$R_b = \frac{W_r}{W_t} \times 100$$

where: percentage of  $R_b$  is rebound loss,  $W_r$  is weight of RIS materials, and  $W_t$  is weight of RIS materials sprayed.

#### 4.7 Water Absorption Test

Water absorption was used to assess the pore structure and durability of the shotcrete. The test may be conducted according to **ASTM C642** or **IS 3085**.

$$WA = \frac{W_s - W_d}{W_d} \times 100$$

where  $WA$  is water absorption percentage,  $W_s$  is saturated specimen weight, and  $W_d$  is oven-dry specimen weight.

#### 4.8 Apparent Porosity

The apparent porosity is the material's proportion of connected pores. Lower porosity generally results in higher durability, and lower permeability.

$$P_a = \frac{W_s - W_d}{W_s - W_i} \times 100$$

where  $P_a$  is the apparent porosity,  $W_s$  is the saturated weight,  $W_d$  is the dry weight, and  $W_i$  is the immersed weight.

#### 4.9 Chloride Penetration Resistance

ASTM C1202 can be used to evaluate the permeability of a concrete to chloride ion. This method is applicable for monitoring the decay of tunnel lining materials under aggressive underground moisture conditions.

$$Q = I \times t$$

where  $Q$  is the quantity of charge passed through the electrolyte, measured in coulombs,  $I$  is the current flow rate in amperes, and  $t$  is the time for which the current is applied in seconds.

Table 1: Testing Standards Summary

Test Parameter	ASTM Standard	IS Standard	Purpose
Workability / Slump	ASTM C143/C143M	IS 1199	Fresh mix consistency
Compressive Strength	ASTM C39/C39M	IS 516	Load-bearing capacity
Split Tensile Strength	ASTM C496/C496M	IS 5816	Tensile cracking resistance

Flexural Strength	ASTM C78/C78M / ASTM C1609/C1609M	IS 516	Bending resistance
Toughness	ASTM C1609/C1609M	—	Post-cracking energy absorption
Water Absorption	ASTM C642	IS 3085	Durability and pore structure
Chloride Penetration	ASTM C1202	—	Resistance to ionic ingress
Shotcrete Testing	ASTM C1140 / ASTM C1604	—	Shotcrete panel and core evaluation

**5. Results and Discussion**

The test programme was planned to assess the fresh and hardened properties, the behaviour of the polymer fibre reinforced shotcrete at post-crack and its durability as well in accordance with established IS/ASTM methods of testing.

Table 2: Compressive Strength Analysis

Fibre %	7 Days	14 Days	28 Days
0	28	36	42
0.5	30	39	45
1	33	42	48
1.5	35	45	51
2	34	44	49

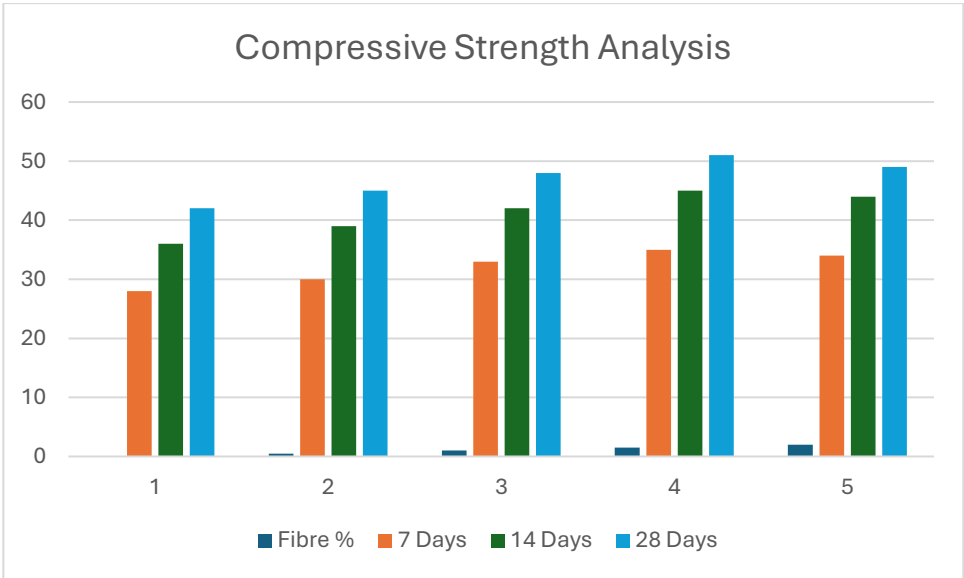


Figure 2: Compressive Strength Analysis

The compressive strength was found to increase with fibre content upto 1.5% as shown in figure 2 and table 2 and then a slight decrease is observed. This behavior is attributed to enhanced crack arresting and stress

redistribution associated with fibre bridging. At high fibre content (2.0%) the workability is lower and this result in insufficient compaction and thus a slight reduction in strength is experienced.

Table 3: Split Tensile Strength vs Fibre Content

Fibre %	Tensile Strength (MPa)
0	3.2
0.5	3.8
1	4.4
1.5	5.1
2	5

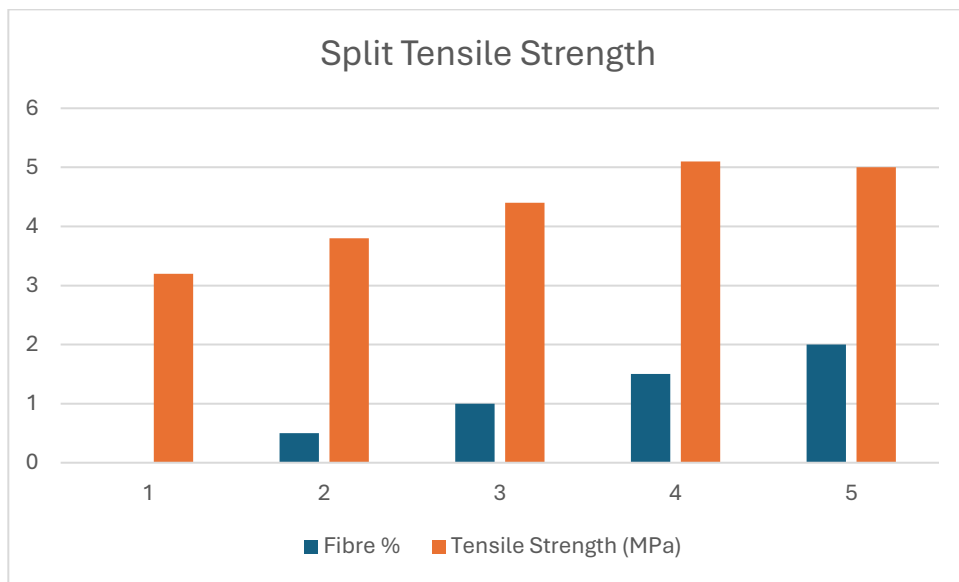
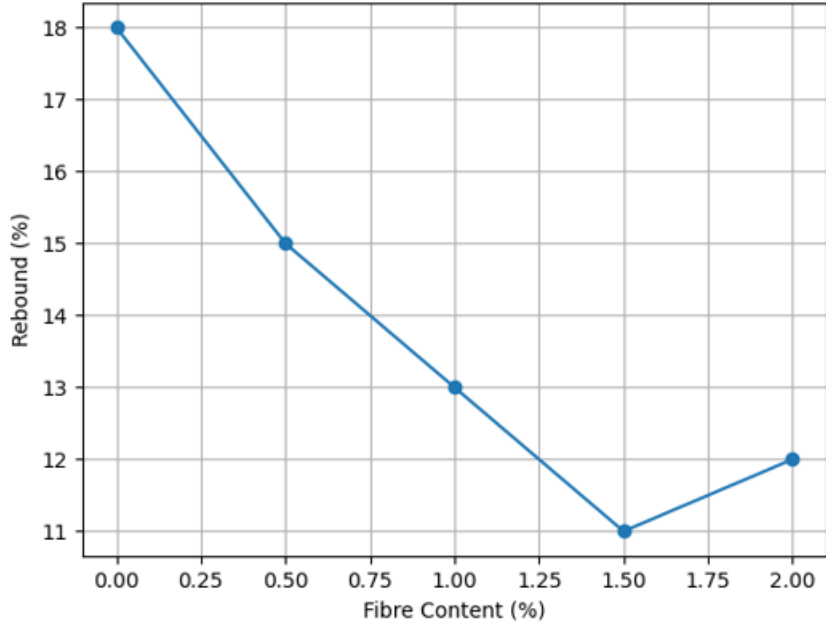


Figure 3: Split Tensile Strength vs Fibre Content

A substantial increase (~60%) in tensile strength is seen at 1.5% fibre content. This verifies that polymer fibres significantly resist crack initiation and crack propagation, which is vital for tunnel linings as tensile stresses are predominant.



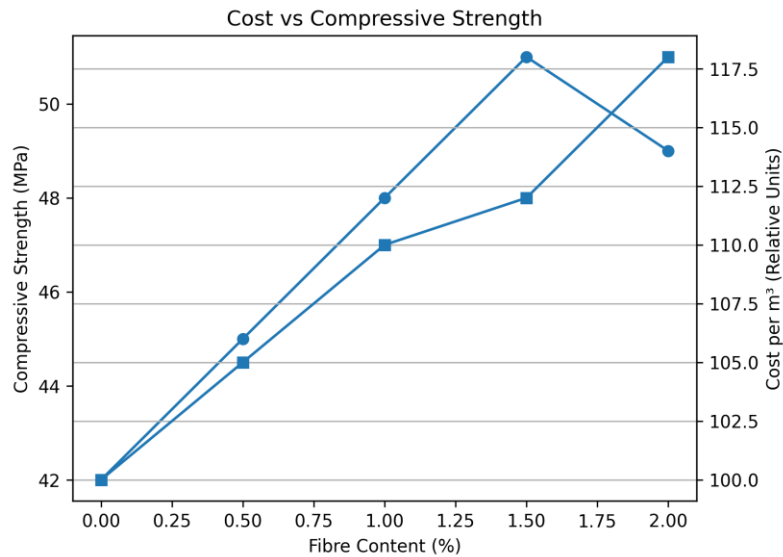
**Figure 4: Rebound Loss**

Reduction in the rebound loss is achieved as a result of the enhanced cohesion and interlocking of the fibre. The lowest amount of rebound is found at 1.5%, which is considered as the best for the field use.

In tunnel construction projects, material selection is not based solely on mechanical performance but also on economic efficiency. Therefore, evaluating the relationship between attained strength and material cost is essential for determining the practical feasibility of polymer fibre-reinforced shotcrete.

Although polymer fibres slightly increase the initial material cost, the improvement in compressive, tensile, and flexural strength significantly enhances structural efficiency and reduces long-term maintenance expenses.

Strength increases significantly up to 1.5% fibre content while the increase in cost remains moderate, indicating improved strength-to-cost efficiency.



**Figure 5: Cost vs Compressive Strength**

The analysis indicates that compressive strength increases considerably up to 1.5% fibre content, while the increase in material cost remains comparatively moderate. This demonstrates that the strength-to-cost ratio improves significantly with optimized fibre dosage.

At 1.5% fibre content:

- Strength improvement  $\approx 21\text{--}25\%$
- Cost increase  $\approx 8\text{--}12\%$

This indicates that the structural benefit obtained per unit cost is substantially higher than conventional shotcrete.

Crack resistance is one of the most important parameters in tunnel lining systems because crack formation directly affects:

- Water ingress
- Chemical attack
- Corrosion
- Structural degradation

Polymer fibres improve crack resistance by distributing tensile stresses and bridging microcracks within the cementitious matrix.

Polymer fibre reinforcement substantially reduces crack propagation due to fibre bridging mechanisms and improved stress redistribution.

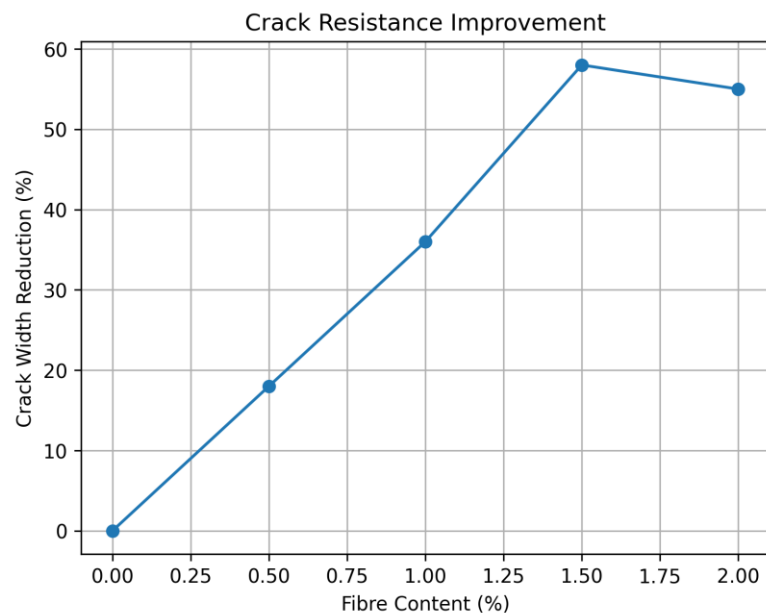


Figure 6: Crack Resistance Improvement

The results demonstrate that polymer fibre reinforcement significantly reduces crack propagation. The maximum crack resistance improvement was observed at 1.5% fibre content, where crack width reduction exceeded 50%.

The improved crack control mechanism enhances:

- Durability
- Water tightness
- Service life of tunnel linings

This directly reduces future repair frequency and maintenance costs.

The use of polymer fibre-reinforced shotcrete provides not only structural benefits but also economic advantages for construction and infrastructure companies.

Although fibre reinforcement increases initial material expenditure, the long-term economic gains include:

- Reduced maintenance frequency
- Lower repair costs
- Faster tunnel stabilization
- Reduced downtime
- Improved service life

Polymer fibre-reinforced shotcrete reduces long-term maintenance expenditure by improving durability and reducing repair frequency.

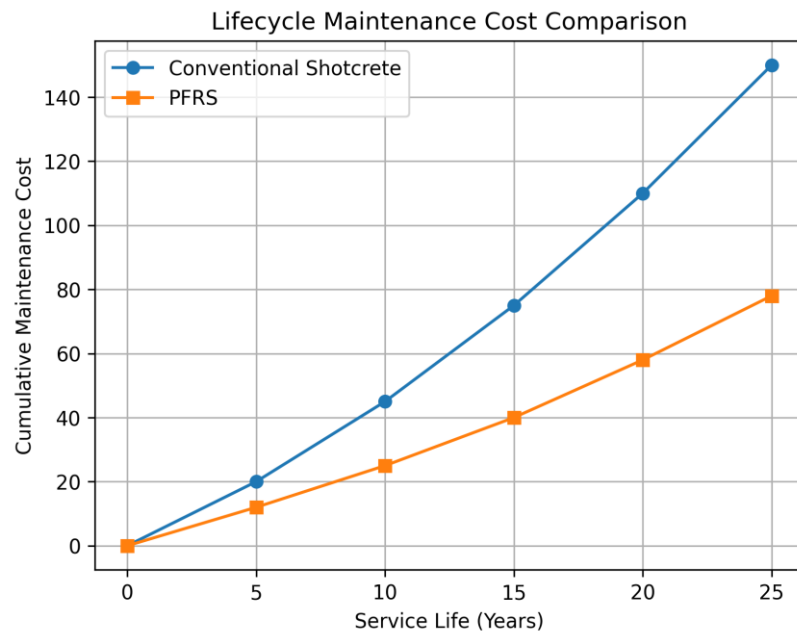


Figure 7: Lifecycle Maintenance Cost Comparison

The use of polymer fibre-reinforced shotcrete improves profitability for infrastructure companies through reduced maintenance cost, reduced rebound loss, improved durability, and increased tunnel service life.

## 6. Conclusion

In this paper the formulation and full characterization of polymer fibre reinforced shotcrete (PFRS) for tunnel lining are presented. The inclusion of polypropylene fibres was found to have a positive influence on the mechanical and durability properties, and workability of ordinary shotcrete. An experimental investigation was carried out with the fibre content varying between from 0% to 2.0% and the performance was evaluated using standard tests. The results indicated that the polymer fibre reinforced concrete had higher compressive, tensile and flexural strength which was ascribed to the effective crack-bridging and more uniform stress distribution in cement matrix. The shotcrete with 1.5% fibre content from all the mixes displayed the best result having the maximum strength and best toughness. Enhancement of tensile and flexural performance also confirms the capacity of fibres to control crack initiation and propagation, which is of great importance in tunnels subjected to dynamic and complex loading.

Workability results show a slow decrease of slump with the increase of fibre content because of the higher internal friction, but acceptable flowability was maintained for practical shotcrete application with the addition of superplasticizer. Moreover, due to the reduced water absorption and increased resistance to the formation of cracks, improvements in the long-term performance were also indicated. The improved mixing technique employed in the present study is a key aspect to have a homogeneous distribution of fibres and to prevent fibre cluster in the PFRS.

In addition, reduced rebound loss further demonstrates that the proposed material is potentially feasible in achieving a highly efficient field application with less material wastage. In general, polymer fibre reinforced shotcrete shows great promise as an advanced tunnel lining material with enhanced strength and durability as well as better application efficiencies over traditional shotcrete. Current study results can aid the design of high performance and more sustainable construction materials for underground applications.

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