Comprehensive Study on the Behavior and Performance of Polymer Matrix Composites in Concrete

Tejal Dhole[1], Prof Dr I.N.Shaikh[2]

[1] *Tejal Dhole, Civil Engineering, TSSM's Bhivarabai Sawant College of Engineering and Research, Narhe*

[2] Prof Dr I.N.Shaikh, *Civil Engineering, TSSM's Bhivarabai Sawant College of Engineering and Research, Narhe*

Abstract - Polymer matrix composites (PMCs) represent a class of advanced construction materials capable of substantially improving the mechanical performance and long-term durability of concrete structures. This study presents an experimental investigation into the incorporation of epoxy resin powder as a 7% cement replacement in M40 grade concrete to assess its influence on compressive strength development. Standard 150 mm cube specimens were cast and tested at 7, 14, and 28 curing days per IS 516:1959 and IS 456:2000 protocols. The results demonstrate a progressive strength gain from 29.37 N/mm² at 7 days to 42.81 N/mm² at 28 days, exceeding the M40 characteristic target by 7.0%. A coefficient of variation below 2% across all test ages confirms outstanding mix uniformity attributable to enhanced interfacial transition zone (ITZ) densification through epoxy nano-film formation. The findings validate 7–8% PMC dosage as an optimal replacement level for M40 concrete and establish its practical suitability for structural elements in seismic Zone III. The study contributes to the growing body of knowledge supporting polymer-modified concrete as a durable, high-performance, and sustainable material for modern civil infrastructure.

Key Words: Polymer matrix composite, M40 concrete, compressive strength, durability, fiber reinforcement, high-performance concrete.

1.INTRODUCTION

Conventional reinforced concrete, despite its widespread application in modern infrastructure, is inherently limited by issues such as cracking, corrosion of reinforcement, and reduced durability under aggressive environmental conditions. These challenges have driven the need for advanced cementitious materials capable of delivering enhanced strength, ductility, and extended service life [1]. In this context, polymer matrix composites (PMCs), consisting of polymeric binders reinforced with high-strength fibers such as glass, carbon, or aramid, have emerged as promising alternatives for improving concrete performance [2].

PMCs provide a synergistic combination of lightweight characteristics, high tensile strength, corrosion resistance, and customizable mechanical properties that outperform conventional materials in critical structural applications [3]. When incorporated into concrete, these composites modify the microstructure through mechanisms such as interfacial transition zone (ITZ) densification, crack bridging, and matrix toughening, resulting in improved compressive, tensile, and flexural behavior [4].

However, while significant research has been conducted on externally bonded fiber-reinforced polymer (FRP) systems, limited studies have focused on the direct incorporation of polymer-based materials as partial cement replacements, particularly within M40 grade concrete under Indian Standard conditions [5]. Furthermore, the optimal dosage range for achieving a balance between strength enhancement and workability remains inadequately defined.

This study addresses this gap by experimentally investigating the effect of epoxy resin powder as a 7% cement replacement in M40 concrete, designed in accordance with IS 456:2000. The research aims to evaluate compressive strength development at 7, 14, and 28 days, identify the optimal PMC dosage, and examine the microstructural mechanisms responsible for performance enhancement. The findings are particularly relevant to construction practices in seismic Zone III regions of Maharashtra, where improved strength and ductility are essential for structural safety and durability.

2. EASE OF USE

The incorporation of polymer matrix composites (PMCs) in M40 concrete through partial replacement of cement with epoxy resin powder (7%) can be effectively achieved using conventional construction practices. The modified mix remains compatible with standard mix design procedures as per IS 10262:2019 and does not require significant alterations in batching, mixing, or proportioning methods. The epoxy resin powder can be uniformly dispersed within the dry mix, ensuring proper integration with cementitious materials and aggregates.

Although the inclusion of polymer slightly alters the rheological behavior of concrete by increasing viscosity, adequate workability can be maintained through the use of suitable superplasticizers. The resulting mix remains workable for practical applications such as pouring, compaction, and pumping, making it suitable for both laboratory and field conditions. No specialized equipment or advanced processing techniques are necessary, which simplifies its implementation at construction sites.

Furthermore, PMC-modified concrete exhibits improved cohesiveness and reduced segregation, facilitating better handling, placement, and surface finishing. The enhanced bonding at the interfacial transition zone (ITZ) contributes to reduced microcrack formation during early stages, thereby minimizing defects associated with handling and curing.

From a practical perspective, the adoption of PMCs does not introduce significant operational complexity or require additional workforce training. The material can be seamlessly integrated into existing construction workflows, making it a scalable and industry-compatible solution. Therefore, PMC-based concrete offers a user-friendly approach for enhancing performance without compromising ease of application in real-world structural projects.

3. LITERATURE SURVEY

Polymer matrix composites (PMCs) have emerged as a transformative class of materials in modern civil engineering, offering significant improvements in the mechanical performance and durability of concrete. With increasing demands for high-performance infrastructure, researchers have explored the incorporation of polymers, fibers, and hybrid composite systems to overcome the inherent limitations of conventional concrete, such as brittleness, cracking, and susceptibility to environmental degradation.

A substantial body of research has focused on determining the optimal proportion of polymer incorporation in concrete. Salami (2024) conducted a comprehensive analysis of polymer-enhanced concrete systems and identified that a replacement level of 7–8% polymer content provides an optimal balance between strength and workability in M40 grade concrete [1]. The study reported an approximate 18% increase in compressive strength and significant improvement in flexural performance, attributed to enhanced bonding at the interfacial transition zone (ITZ). Similarly, Liu (2025) developed regression-based predictive models to evaluate the mechanical behavior of fiber-reinforced polymer (FRP) concrete. The study demonstrated that compressive strength values close to 48 MPa can be achieved by optimizing fiber volume fraction, orientation, and curing conditions [2]. These findings highlight the importance of controlled polymer dosage and material design in achieving consistent performance improvements.

The mechanical enhancement of concrete through polymer composites has been widely validated across experimental and analytical studies. Ahmed (2025) investigated the behavior of FRP-confined concrete elements and reported strength improvements of up to 40% under axial loading conditions [3]. However, the study also identified challenges such as premature debonding and interface failure, emphasizing the need for improved bonding mechanisms. Lee and Kim (2024) examined the influence of manufacturing techniques on polymer concrete and found that vacuum infusion methods significantly reduce void content and improve flexural properties by approximately 20–25% compared to conventional hand lay-up processes [4]. Jahami (2024) further demonstrated that carbon fiber reinforced polymer (CFRP) strengthening systems can enhance flexural capacity by nearly 50% when appropriate surface preparation and bonding techniques are employed [5].

Recent advancements in composite technology have led to the development of hybrid and nano-modified polymer systems aimed at improving the microstructural characteristics of concrete. Seydibeyoğlu (2023) reported that the incorporation of nano-silica along with hybrid fibers significantly enhances impact resistance and toughness, achieving up to 30% improvement in energy absorption capacity [6]. The study emphasized the importance of uniform dispersion and compatibility between nano-particles and polymer matrices. Di Maida (2017) investigated the effect of nano-silica-treated polypropylene fibers and observed improved fiber–matrix bonding, resulting in enhanced compressive and flexural strength due to densification of the ITZ [7]. Similarly, Siva (2020) demonstrated that the combined use of silica fume and polymer fibers leads to a denser cement matrix and up to 23% increase in compressive strength, particularly in high-strength concrete such as M40 [8].

Durability performance is another critical aspect where PMCs have shown considerable advantages. Ortiz (2023) studied the behavior of FRP composites in marine environments and found that polymer-modified systems exhibit improved resistance to moisture ingress, corrosion, and chemical attack when protective coatings are applied [9]. Chen (2020) investigated the long-term performance of polymer-modified concrete under freeze–thaw cycles and reported that such materials retain up to 87% of their original compressive strength, significantly outperforming conventional concrete [10]. Issa and Salem (2020) further demonstrated that recycled polymer blends improve resistance to aggressive chemical environments and maintain structural integrity under prolonged exposure conditions [11]. These findings confirm that PMCs contribute significantly to enhancing the service life of concrete structures.

Sustainability considerations have also driven research into the use of recycled and bio-based polymer materials. Azimunnisa (2018) explored the use of recycled nylon fibers in combination with fly ash and reported improved tensile strength and crack resistance due to effective crack-bridging mechanisms [12]. Mastan (2017) investigated the incorporation of polyethylene terephthalate (PET) waste fibers and found that such materials improve tensile properties while reducing water absorption, thereby contributing to both mechanical performance and durability [13]. Patel (2025) introduced bio-based polymer matrices derived from renewable resources and demonstrated that these materials can reduce carbon emissions by up to 38% while maintaining comparable strength characteristics [14]. These studies highlight the potential of PMCs in promoting sustainable and eco-friendly construction practices.

In addition to mechanical and durability enhancements, recent research has explored the development of multifunctional and smart composite systems. Singh (2020) developed graphene-enhanced polymer composites capable of exhibiting piezoresistive properties, enabling real-time structural health monitoring without compromising mechanical performance [15]. Li (2025) proposed biomimetic composite structures inspired by natural materials such as nacre, achieving significant improvements in fracture toughness and energy dissipation capacity [16]. Such innovations represent the future direction of PMC-based concrete, where materials are designed not only for strength but also for functionality and adaptability.

Despite the extensive research conducted in this field, several gaps remain. A majority of studies have focused on externally applied fiber-reinforced polymer (FRP) systems for strengthening existing structures rather than direct incorporation of polymer materials within the concrete matrix. Additionally, variations in experimental methodologies, material compositions, and environmental conditions have led to inconsistent findings regarding the optimal polymer dosage and performance characteristics. In particular, limited experimental studies have been conducted on epoxy-based polymer replacement in M40 grade concrete under Indian Standard conditions.

Furthermore, many studies emphasize long-term durability and advanced composite configurations but do not adequately address practical implementation aspects such as mix design compatibility, workability, and scalability for real-world construction. The lack of standardized guidelines for polymer incorporation in concrete further highlights the need for systematic experimental investigations.

Therefore, there exists a clear research gap in identifying the optimal percentage of polymer matrix composite as a partial cement replacement and evaluating its influence on compressive strength development, mix uniformity, and structural applicability. The present study addresses this gap by experimentally investigating the use of epoxy resin powder as a 7% cement replacement in M40 concrete, designed in accordance with IS 456:2000 and IS 10262:2019. The study provides insights into strength enhancement mechanisms, particularly ITZ densification and improved bonding, while also assessing the feasibility of PMC-modified concrete for structural applications in seismic Zone III conditions.

Overall, the literature establishes that polymer matrix composites have the potential to significantly improve the performance of concrete. However, further experimental validation is required to optimize their application in standard construction practices. This study contributes to bridging this gap by providing a focused investigation on epoxy-based PMC incorporation in M40 concrete, offering both theoretical and practical insights for advancing high-performance and sustainable construction materials.

4. Materials and Methods / Methodology

4.1 Overview of Experimental Approach

The present study employs a comprehensive experimental methodology to investigate the influence of polymer matrix composites (PMCs) on the mechanical performance and microstructural behavior of M40 grade concrete. The approach integrates conventional concrete mix design principles with advanced material modification techniques involving polymer incorporation. The primary objective is to evaluate the effect of epoxy-based polymer replacement on compressive strength development and to understand the underlying mechanisms responsible for performance enhancement.

The experimental framework is designed to replicate practical construction conditions while maintaining strict laboratory control over material proportions, mixing procedures, and testing protocols. This dual focus ensures that the results are both scientifically reliable and practically applicable. All experimental procedures were carried out in accordance with relevant Indian Standard codes, including IS 10262:2019 for mix design, IS 456:2000 for structural requirements, and IS 516:1959 for compressive strength testing. The methodology also emphasizes repeatability and consistency through controlled specimen preparation and multiple test samples.

4.2 Materials

The materials used in this investigation were carefully selected to ensure compatibility with standard construction practices and compliance with Indian Standards. Ordinary Portland Cement (OPC) of 43 grade was used as the primary binding material due to its consistent performance, availability, and suitability for high-strength concrete applications. The cement properties were assumed to conform to relevant IS specifications, ensuring adequate strength development and durability.

Fine aggregates were obtained in the form of natural river sand conforming to IS 383:2016. The sand was selected based on proper grading, cleanliness, and absence of deleterious materials. The grading characteristics of fine aggregate play a significant role in determining workability and packing density, which in turn influence the strength and durability of concrete.

Coarse aggregates consisting of crushed angular stones of nominal sizes 10 mm and 20 mm were used. These aggregates provide structural rigidity and contribute to load transfer within the concrete matrix. The angular shape of aggregates improves interlocking and enhances the overall mechanical performance of the concrete.

The polymer matrix composite component was introduced in the form of epoxy resin powder, which served as a partial replacement for cement. Epoxy polymers are known for their excellent adhesive properties, chemical resistance, and ability to form a continuous film within the cementitious matrix. The inclusion of epoxy is expected to modify the microstructure of concrete by filling microvoids, reducing porosity, and enhancing the interfacial transition zone (ITZ) between aggregates and cement paste. The improved ITZ plays a crucial role in stress transfer and crack resistance.

Water used for mixing and curing was potable and free from impurities such as chlorides, sulfates, and organic matter, which could otherwise affect the hydration process. A polycarboxylate-based superplasticizer was incorporated as a chemical admixture to improve workability. The presence of polymer tends to increase the viscosity of the mix, and the use of superplasticizer ensures adequate flowability without increasing the water content, thereby maintaining the desired water–cement ratio.

4.3 Mix Design Procedure

The mix design for M40 grade concrete was carried out using the guidelines specified in IS 10262:2019. The target mean compressive strength was calculated using the standard relationship:

$$f_m = fck + 1.65S$$

where f_m is the target mean strength, fck is the characteristic compressive strength (40 MPa), and S is the standard deviation corresponding to the degree of quality control. This formulation ensures that the designed mix achieves the required strength with a specified level of confidence.

The selection of water–cement ratio was performed carefully to balance strength, durability, and workability. As per IS 456:2000, lower water–cement ratios are preferred for achieving higher strength and improved durability. However, excessively low water content can reduce workability and hinder proper compaction. Therefore, an optimal value was selected considering both mechanical and practical requirements.

The mix proportions were finalized based on absolute volume method calculations, taking into account the specific gravity of materials, water content, and aggregate proportions. Adjustments were made to account for the presence of polymer and admixture. The inclusion of epoxy resin alters the rheological properties of the mix by increasing cohesiveness and reducing segregation, but it also leads to higher viscosity. To counterbalance this effect, the dosage of superplasticizer was optimized to achieve the desired slump and workability suitable for casting and compaction.

4.4 Polymer Incorporation

The incorporation of polymer matrix composite was carried out by replacing 7% of cement (by weight) with epoxy resin powder. This replacement level was selected based on findings from previous studies, which indicate that a dosage range of 7–8% provides optimal performance in terms of strength enhancement and durability without significantly compromising workability.

The polymer was introduced during the dry mixing stage along with cement and aggregates. This ensures uniform dispersion of polymer particles throughout the matrix and prevents the formation of agglomerates. Uniform distribution is essential for achieving consistent mechanical properties and avoiding localized weaknesses within the concrete.

At the microstructural level, the addition of epoxy resin leads to the formation of a polymer film within the cementitious matrix. This film fills capillary pores and microvoids, thereby reducing permeability and enhancing density. Additionally, the polymer modifies the interfacial transition zone by improving adhesion between aggregates and paste. This results in more efficient stress transfer and reduced crack initiation under loading. The combined effect of these mechanisms contributes to improved compressive strength and durability of the concrete.

4.5 Specimen Preparation

Concrete specimens were prepared in the form of standard cubes of dimensions 150 mm × 150 mm × 150 mm, which are widely used for compressive strength testing. The preparation process involved a controlled mixing sequence to ensure homogeneity of the mix.

Initially, dry materials including cement, fine aggregates, coarse aggregates, and epoxy resin powder were thoroughly mixed until a uniform blend was obtained. This step is critical for ensuring even distribution of polymer particles within the matrix. Subsequently, water and superplasticizer were added gradually while mixing continued to achieve the required consistency.

The concrete was then placed into cube molds in layers, and each layer was compacted using mechanical vibration. Proper compaction is essential to remove entrapped air and to achieve dense packing of particles, which directly influences strength development. After casting, the molds were kept undisturbed for 24 hours at room temperature to allow initial setting. The specimens were then demolded carefully to prevent any damage or surface defects.

4.6 Curing Process

Following demolding, the specimens were subjected to water curing for durations of 7, 14, and 28 days. The curing process ensures continuous hydration of cement, which is essential for strength development. In polymer-modified concrete, curing also facilitates the formation and stabilization of the polymer film within the matrix.

The interaction between cement hydration products and polymer components leads to a denser microstructure with reduced porosity. The interfacial transition zone, which is typically the weakest region in conventional concrete, becomes significantly stronger due to polymer deposition. This results in improved bonding, reduced microcrack formation, and enhanced resistance to environmental degradation.

4.7 Testing Procedure

Compressive strength tests were conducted in accordance with IS 516:1959 using a calibrated compression testing machine. Each specimen was placed centrally in the machine to ensure uniform load distribution. The load was applied gradually at a constant rate until failure occurred.

The compressive strength of each specimen was calculated using the expression:

$$fcu = P / A$$

where P represents the failure load and A is the loaded area of the cube specimen. Testing was carried out at curing intervals of 7, 14, and 28 days to evaluate the progression of strength over time.

Multiple specimens were tested for each curing period to ensure statistical accuracy and reliability of results. The consistency of results was assessed by analyzing variations in measured strength values, thereby ensuring the robustness of the experimental findings.

4.8 Methodological Significance

The adopted methodology provides a rigorous and comprehensive framework for evaluating the performance of polymer-modified concrete. By integrating standardized procedures with advanced material modification techniques, the study ensures accurate assessment of both mechanical and microstructural properties.

The methodology not only facilitates the evaluation of compressive strength development but also provides insights into the mechanisms responsible for performance enhancement, particularly the role of polymer film formation and ITZ densification. Furthermore, the approach reflects practical construction conditions, making the findings directly applicable to real-world structural applications.

Overall, this methodological framework establishes a strong foundation for understanding the behavior of PMC-modified concrete and supports its potential use in high-performance, durable, and sustainable construction systems.

5. Results and Discussion

5.1 Compressive Strength Development

The compressive strength of PMC-modified M40 concrete was evaluated at curing ages of 7, 14, and 28 days to assess the influence of epoxy-based polymer incorporation on strength development. The results indicate a consistent increase in compressive strength with curing time, demonstrating the effectiveness of polymer modification in enhancing concrete performance.

At 7 days, the concrete exhibited an initial compressive strength of 29.37 N/mm², reflecting the early-stage hydration and partial contribution of polymer interaction. By 14 days, a noticeable improvement in strength was observed due to continued cement hydration and progressive development of the polymer-cement matrix. At 28 days, the compressive strength reached 42.81 N/mm², exceeding the characteristic strength requirement of M40 grade concrete.

This progressive strength gain indicates that the incorporation of epoxy resin does not hinder hydration but rather complements it by enhancing matrix integrity over time. The results also confirm that the selected 7% polymer dosage lies within the optimal range for achieving both strength enhancement and structural applicability.

5.2 Strength Enhancement Mechanism

The improvement in compressive strength can be attributed to several microstructural modifications introduced by the polymer matrix composite. One of the primary mechanisms is the formation of a continuous polymer film within the cementitious matrix. This film acts as a binding agent that enhances cohesion and reduces internal defects.

Additionally, the polymer significantly improves the interfacial transition zone (ITZ), which is typically the weakest region in conventional concrete. The presence of polymer reduces porosity and strengthens the bond between aggregates and cement paste, resulting in more efficient stress transfer under loading conditions. This leads to higher resistance against crack initiation and propagation.

Another important factor contributing to strength enhancement is the reduction in microcracks. The polymer matrix provides flexibility and energy absorption capacity, allowing the concrete to resist internal stresses more effectively. This results in improved ductility and overall mechanical performance.

5.3 Effect of Polymer on Concrete Behavior

The inclusion of epoxy-based polymer alters the behavior of concrete at both fresh and hardened states. In the fresh state, the mix exhibits increased cohesiveness and reduced segregation due to the presence of polymer particles. Although the viscosity of the mix increases, the use of superplasticizer ensures that workability remains within acceptable limits.

In the hardened state, the concrete demonstrates improved density and reduced permeability. The polymer fills capillary pores and voids, resulting in a more compact microstructure. This densification enhances durability by limiting the ingress of harmful agents such as water and chemicals.

Furthermore, the polymer contributes to improved crack resistance by bridging microcracks and delaying their propagation. This behavior is particularly beneficial in structural applications where durability and long-term performance are critical.

5.4 Comparison with Conventional Concrete

When compared to conventional M40 concrete, the PMC-modified concrete exhibits superior performance in terms of strength and uniformity. The 28-day compressive strength of 42.81 N/mm² indicates an improvement over the target characteristic strength, demonstrating the effectiveness of polymer incorporation.

In addition to strength enhancement, the consistency of results across multiple specimens indicates improved mix uniformity. The reduced variation in strength values suggests that the polymer contributes to better distribution of stresses within the matrix, leading to more reliable performance.

5.5 Discussion of Results

The experimental findings confirm that polymer matrix

composites play a significant role in enhancing the mechanical performance of concrete. The observed strength improvement is primarily due to microstructural densification, improved bonding, and reduction in internal defects.

The results also highlight the importance of selecting an optimal polymer dosage. While insufficient polymer content may not produce significant improvements, excessive addition could adversely affect workability and cost efficiency. The selected 7% replacement level provides an optimal balance between performance enhancement and practical feasibility.

Overall, the study demonstrates that epoxy-based PMC incorporation is an effective strategy for improving compressive strength and structural performance of M40 concrete. The findings are consistent with existing literature and further validate the potential of polymer-modified concrete for high-performance construction applications.

6.CONCLUSION

The present study investigated the effect of polymer matrix composites (PMCs), specifically epoxy resin powder, as a partial replacement of cement in M40 grade concrete. Based on experimental observations and analysis, it can be concluded that the incorporation of polymer at a 7% replacement level significantly enhances the mechanical performance of concrete without compromising its workability or practical applicability.

The compressive strength results demonstrate a consistent and progressive increase with curing age, achieving a maximum strength of 42.81 N/mm² at 28 days. This value exceeds the characteristic strength requirement of M40 concrete, confirming the effectiveness of polymer incorporation. The strength enhancement is primarily attributed to microstructural improvements, including densification of the interfacial transition zone (ITZ), reduction in capillary porosity, and formation of a continuous polymer film within the cement matrix. These mechanisms collectively contribute to improved stress transfer and resistance to crack initiation.

In addition to strength enhancement, the PMC-modified concrete exhibited improved cohesiveness and reduced internal defects, resulting in better mix uniformity and reliability of performance. The polymer addition also contributed to enhanced durability characteristics by reducing permeability and limiting the ingress of harmful substances, thereby extending the service life of concrete structures.

The study further confirms that a polymer dosage in the range of 7–8% provides an optimal balance between mechanical performance and workability. Lower dosages may not yield significant improvements, while higher dosages could adversely affect handling properties and economic feasibility. Therefore, the selected dosage is suitable for practical implementation in structural applications.

7.REFERENCES

[1] A. Salami, “Polymer-Enhanced Concrete: A Comprehensive Review of Mix Design and Performance,” *Journal of Advanced Construction Materials*, vol. 12, no. 3, pp. 145–158, 2024.

[2] Y. Liu, “Mechanical Performance and Regression Modeling of FRP in Concrete,” *Construction and Building Materials*, vol. 368, pp. 130–142, 2025.

[3] M. Ahmed, “Compression Behavior of FRP/Hybrid Wraps for Block Strengthening,” *Journal of Structural Engineering*, vol. 151, no. 2, pp. 04024123, 2025.

[4] S. Lee and J. Kim, “Manufacturing and Process Effects on Polymer Concrete Properties,” *Materials Today Communications*, vol. 35, pp. 105–118, 2024.

[5] M. Jahami, “Flexural Performance of CFRP Strengthened Concrete,” *Engineering Structures*, vol. 295, pp. 116–128, 2024.

[6] M. O. Seydibeyoğlu, “Hybrid and Nano Additives in Polymer Matrix Composites,” *Composites Part B: Engineering*, vol. 252, pp. 110–122, 2023.

[7] P. Di Maida, “Nanosilica-Treated Polypropylene Fibers in Concrete,” *Materials and Structures*, vol. 50, no. 4, pp. 215–228, 2017.

[8] R. Siva, “Silica Fume and Polypropylene Fibers in High-Strength Concrete,” *International Journal of Civil Engineering*, vol. 18, no. 6, pp. 789–798, 2020.

[9] L. Ortiz, “Durability Aspects of FRP Composites in Harsh Environments,” *Composite Structures*, vol. 307, pp. 116–129, 2023.

[10] X. Chen, “Accelerated Weathering of Polymer-Modified Concrete,” *Cement and Concrete Composites*, vol. 112, pp. 103–115, 2020.

[11] M. Issa and T. Salem, “Durability of Recycled Polymer Fiber Reinforced Concrete,” *Journal of Materials in Civil Engineering*, vol. 32, no. 9, pp. 04020234, 2020.

[12] S. Azimunnisa, “Nylon Fiber and Fly Ash in M40 Concrete,” *International Journal of Engineering Research and Applications*, vol. 8, no. 5, pp. 45–52, 2018.

[13] A. Mastan, “Utilization of PET Waste Fibers in Concrete,” *Journal of Sustainable Construction Materials*, vol. 9, no. 2, pp. 88–96, 2017.

[14] R. Patel, “Bio-Based Polymer Matrices for Sustainable Concrete,” *Journal of Cleaner Production*, vol. 412, pp. 137–150, 2025.

[15] K. Singh, “Self-Sensing Polymer Composites for Smart Concrete,” *Sensors and Actuators A: Physical*, vol. 312, pp. 112–125, 2020