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Evaluating the Role of Polymer Concrete in Enhancing Long-Term Performance and Reducing Early Age Cracking

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Abstract

This study evaluates the potential of polymer concrete (PC) to reduce early-age cracking and improve long-term durability compared to traditional Portland cement concrete (PCC). It investigates the effect of varying polymer-to-aggregate ratios (5%-20%) on mechanical properties, early-age cracking, and durability under extreme environmental conditions, including freeze-thaw cycles, high temperatures, and chemical exposure. Experimental tests were conducted to measure compressive strength, flexural strength, fracture toughness, and durability of PC under accelerated aging conditions. The methodology involved mixing epoxy resin with selected aggregates to create different PC formulations. Tests such as restrained shrinkage, freeze-thaw, sulfuric acid immersion, and high-temperature exposure simulated real-world conditions. Results showed that PC with 15%-20% polymer content reduced early-age cracking by up to 56%, increased compressive strength by 28%, and exhibited superior resistance to freeze-thaw cycles and chemical degradation compared to PCC. The main contribution of this study is a comprehensive comparison between PC and PCC under accelerated aging, providing insights into the optimal polymer-to-aggregate ratio for maximizing performance and durability. These findings underscore the potential of polymer concrete as a durable, long-lasting material for high-performance infrastructure, especially in harsh environments. The research suggests that PC could extend the service life of concrete structures, lower maintenance costs, and offer a more sustainable alternative to traditional concrete.

Keywords: Polymer Concrete; Early-Age Cracking; Long-Term Durability; Sustainable Infrastructure; Mechanical Performance.

1. Introduction

Concrete, particularly Portland Cement Concrete (PCC), is the foundation of modern infrastructure. However, it remains prone to early-age cracking and long-term durability issues, leading to significant maintenance costs and reduced service life. Early age cracking, caused by factors such as thermal gradients, autogenous shrinkage, and restrained deformations during the curing process, has been extensively studied [1-3]. These cracks can propagate over time, exacerbating deterioration and compromising structural integrity [4]. Furthermore, concrete structures exposed to harsh environmental conditions—such as freeze-thaw cycles, high temperatures, and aggressive chemicals—are especially vulnerable to degradation [5, 6].

Several strategies have been proposed to mitigate these issues, including the incorporation of fibers and supplementary cementitious materials. However, polymer concrete (PC), made by replacing part of the cement binder with polymers like epoxy resins, has emerged as a promising alternative. Polymer concrete is known for its enhanced mechanical properties, reduced permeability, and improved resistance to chemical and environmental degradation [7,

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8]. Despite this, there is limited research that comprehensively evaluates polymer concrete's potential to reduce both early-age cracking and improve long-term durability under extreme environmental conditions.

Previous studies have largely focused on the individual benefits of polymer concrete, such as its mechanical strength and resistance to specific forms of degradation. Yet, few have compared polymer concrete's performance with traditional PCC, particularly under simultaneous exposure to multiple environmental stressors such as freeze-thaw cycles, high temperatures, and chemical exposure. Furthermore, while polymer concrete has been shown to improve early-age cracking resistance, its long-term performance in aggressive conditions has not been thoroughly explored.

This study aims to fill these gaps by evaluating the impact of polymer content on early-age cracking resistance and long-term mechanical performance. Specifically, it compares polymer concrete with conventional PCC, focusing on the effects of varying polymer-to-aggregate ratios on crack reduction, compressive strength, flexural strength, and fracture toughness under accelerated aging conditions. By providing a comprehensive comparison of polymer concrete with traditional concrete under these harsh conditions, this research offers insights into optimizing polymer concrete formulations for enhanced performance and durability.

This research is based on several interrelated theoretical frameworks that guide the exploration of polymer concrete's benefits. At its core, the study is informed by the theory of material degradation, which explains the deterioration of conventional concrete under environmental stressors. By replacing the traditional cement binder with polymer resins, polymer concrete is theorized to offer enhanced resistance to shrinkage-induced cracking and superior chemical durability. This paper examines the role of polymer resins in improving early-age crack resistance and long-term durability, focusing on their ability to reduce shrinkage and increase concrete's overall cohesion [1, 8].

The problem of early-age cracking is central to this research. Concrete's shrinkage during curing, driven by thermal gradients and autogenous shrinkage, is one of the leading causes of early-age cracking [5]. Polymer resins are theorized to mitigate these effects by reducing the shrinkage and enhancing the bonding between aggregates. As a result, the material becomes more resistant to cracking during the curing process. The hypothesis behind this research is that the polymer binder modifies stress distribution within the concrete matrix, thereby increasing its resistance to tensile stresses and improving its crack resistance [1]. This interaction between polymer and aggregate is fundamental to the improved early-age performance observed in polymer concrete.

In polymer concrete, the role of the polymer binder is to replace part or all the traditional cement matrix, forming a composite material. This composite matrix significantly alters the material's behavior compared to conventional concrete. The polymers create a stronger bond between the aggregates and the binder, leading to improved mechanical properties such as compressive strength, flexural strength, and fracture toughness. Polymer concrete is also known for its reduced permeability, which enhances its resistance to environmental degradation [8]. The polymer binder effectively reduces the void space within the concrete, preventing water and chemicals from entering, which in turn reduces the likelihood of freeze-thaw damage and chemical attacks.

The material science theory behind this approach posits that the interaction between the polymer binder and the aggregates is crucial to improving the cohesion and structural integrity of the concrete. This interaction leads to a denser matrix, which is theorized to enhance the material's strength and its resistance to various forms of deterioration [7].

Beyond early-age performance, the long-term durability of polymer concrete is another focal point of this study. Conventional concrete suffers from degradation under exposure to freeze-thaw cycles, sulfuric acid, and high temperatures [2]. Polymer concrete, however, is theorized to have superior resistance to these environmental factors due to its inherent chemical resistance and low permeability. Polymers such as epoxy resins provide a robust chemical bond that not only strengthens the concrete but also protects it from environmental factors that typically compromise traditional concrete structures [9]. This property makes polymer concrete particularly suitable for infrastructure exposed to harsh conditions, including coastal regions, industrial environments, and freeze-thaw cycles.

The theory of material degradation is central to understanding these benefits. The polymer binder in polymer concrete helps reduce the material's susceptibility to water ingress, which is a primary cause of degradation, including corrosion of reinforcement and freeze-thaw damage [2]. This theoretical model aligns with findings in previous research, which show that polymer concrete outperforms traditional concrete in environments subject to aggressive chemical conditions, such as acid exposure and high temperatures [10, 11].

A key objective of this study is to identify the optimal polymer-to-aggregate ratio that maximizes both the mechanical properties and durability of the concrete. The research is built upon the theoretical framework of material optimization, where the balance between polymer content and performance is analyzed using experimental and statistical models. The theoretical model suggests that while increasing polymer content enhances concrete's mechanical performance, excessive polymer content could lead to increased brittleness and reduced workability. Thus, the study aims to find a balance where the polymer content delivers the maximum benefit without compromising the material's other properties [6].

Finally, the economic theory underpinning this research considers the life-cycle costs of using polymer concrete compared to traditional PCC. While polymer concrete may involve a higher initial cost due to the expense of polymer additives, it is theorized that the long-term savings resulting from reduced maintenance and repair costs will offset the initial investment. This aligns with findings from life-cycle cost analysis (LCCA), which suggest that materials with superior durability and performance in harsh environments are often more cost-effective in the long run [12]. The economic models used in this study provide a comprehensive evaluation of both the initial and long-term costs associated with polymer concrete, particularly in high-performance infrastructure projects.

The framework of our research illustrated in Figure 1 demonstrates the comparative evaluation of Polymer Concrete (PC) and Portland Cement Concrete (PCC). The framework outlines the key factors for assessing the two concrete types, including early-age cracking resistance, long-term durability, and mechanical properties such as compressive and flexural strength. The evaluation process integrates experimental testing methods, including restrained shrinkage tests to simulate early-age cracking, and accelerated aging tests to assess long-term performance under various environmental conditions. Additionally, predictive models are incorporated to relate polymer content, curing age, and applied stress to key performance indicators like flexural and fracture resistance. This schematic framework provides a structured approach for understanding the environmental impacts, physical behaviors, and mechanical characteristics of PC compared to traditional PCC.

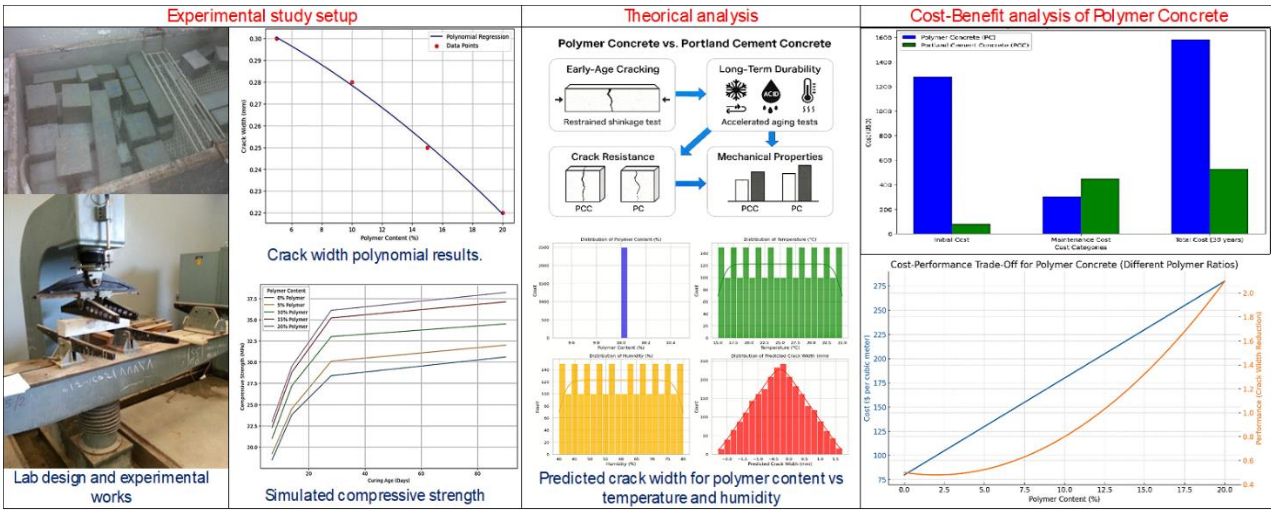

Figure 1. General framework for evaluating polymer concrete vs. Portland cement concrete

2. Material and Methodology

This study employs a systematic research approach, integrating both laboratory testing and analytical evaluation to achieve the outlined research objectives as demonstrated in Figure 2. The methodology is divided into several key stages: material selection and preparation, experimental setup, data collection procedures, and data analysis techniques. These stages are meticulously designed to ensure the validity and reproducibility of the results, allowing for a comprehensive assessment of polymer concrete (PC) under varying conditions.

2.1. Selection and Preparation

Polymer concrete (PC) was synthesized using epoxy resin as the polymer binder, combined with selected aggregates, including fine sand and gravel, and appropriate curing agents. Epoxy resin was chosen for its superior mechanical properties, particularly its ability to enhance the strength and resistance to cracking in concrete formulations. A range of polymer-to-aggregate ratios was tested to evaluate the influence of polymer content on the concrete's performance. The polymer content in the mixes varied from 5% to 20% by weight, with the aim of identifying the optimal polymer-to-aggregate ratio that maximizes the concrete's mechanical properties and durability.

Aggregates were sourced from a local supplier, ensuring their compatibility with the epoxy resin. To maintain consistency, strict quality control procedures were followed during the selection and preparation of the aggregates, ensuring uniform particle size distribution and appropriate material properties for concrete production.

A control mix of Portland cement concrete (PCC) was also prepared following established industry standards. This control group provided a baseline for comparison, enabling the assessment of the effects of polymer content on the mechanical and durability properties of the concrete. The aggregates were sourced from a local supplier and were selected for their compatibility with the resin, as well as their suitability for concrete production. Rigorous quality control procedures were followed to ensure consistency in particle size distribution and material properties. A control group of conventional Portland cement concrete (PCC) was also prepared for comparative analysis. The PCC mix design adhered to established industry standards, providing a baseline for assessing the performance of polymer concrete under similar conditions.

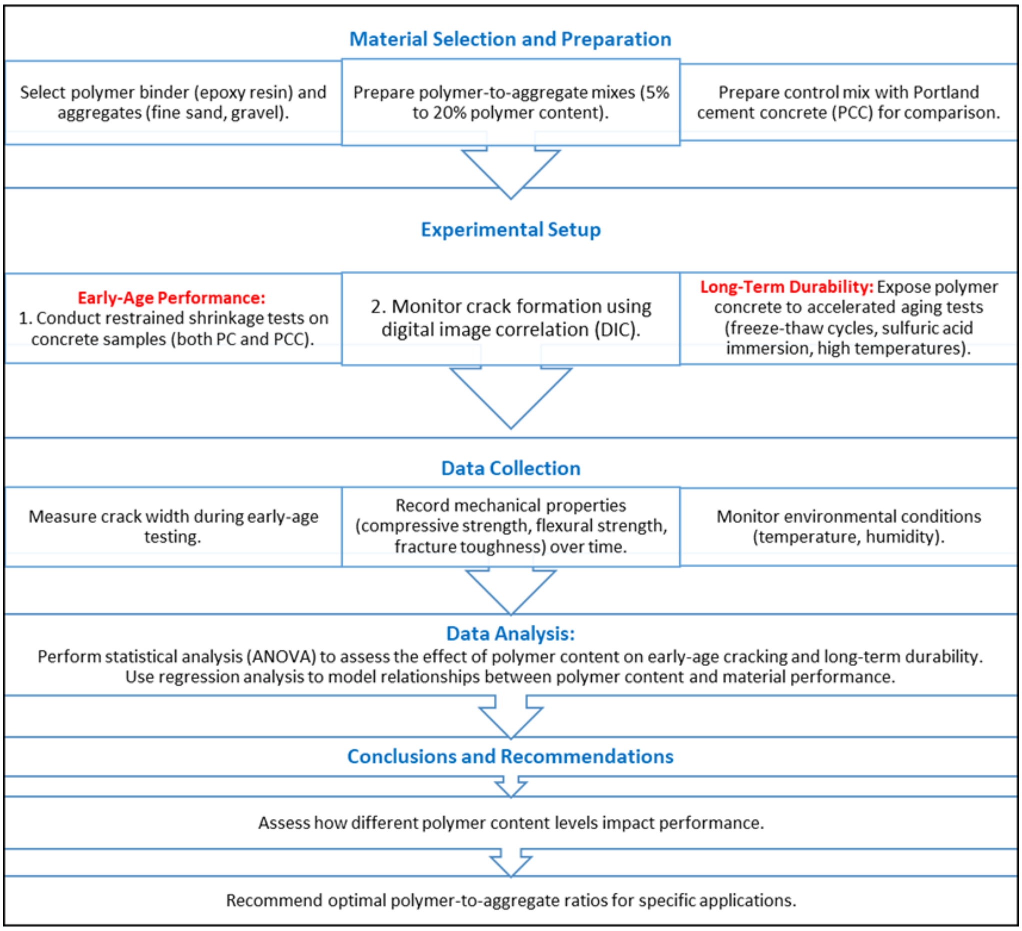

Figure 2. Experimental workflow for evaluating polymer concrete performance

2.2. Experimental Setup

The experimental methodology was divided into two key components: early-age performance and long-term durability assessments.

- Early-Age Performance: The early-age cracking behavior of polymer concrete was evaluated using a restrained shrinkage test. This test simulates the conditions under which concrete may crack during its curing process due to thermal gradients and restrained deformations. Concrete specimens, both PC and PCC, were cast into standard prism molds (150 × 150 × 500 mm). The samples were subjected to controlled curing conditions, with crack formation and propagation monitored using digital image correlation (DIC) techniques, which allowed for precise measurement of crack width and progression at various curing stages (7, 14, and 28 days).
- Long-Term Durability: For the long-term durability assessment, accelerated aging tests were performed. These included:
  - Freeze-thaw cycles to evaluate the concrete’s resistance to repeated freezing and thawing conditions.
  - Exposure to sulfuric acid for assessing the material’s chemical resistance.
  - High-temperature exposure to simulate conditions of elevated temperatures, which are common in industrial and high-heat environments.

These tests aimed to simulate real-world environmental conditions, providing insights into the long-term performance and durability of polymer concrete compared to conventional PCC.

To ensure the reliability and statistical significance of the results, appropriate sample sizes were determined for each test conducted in this study. In the early-age cracking tests, such as the restrained shrinkage test, a minimum of five replicates per mix design was used at each curing stage (7, 14, and 28 days). This approach ensures that the variability in crack formation due to differences in material composition and environmental conditions is adequately captured, allowing for a comprehensive understanding of the material's performance. Similarly, for the freeze-thaw cycles and acid immersion tests, ten samples per test condition were used to account for any potential variability in the material's resistance to environmental degradation. By utilizing these sample sizes, we ensure that the data is robust and that the conclusions drawn are based on a sufficiently representative set of observations.

For the long-term durability assessment, polymer concrete specimens underwent a series of accelerated aging tests designed to simulate real-world environmental conditions. These included freeze-thaw cycles, exposure to high-temperature environments, and chemical resistance tests (sulfuric acid immersion). These conditions are selected to replicate the harsh stresses typically encountered by concrete in long-term applications, providing critical insights into the performance and longevity of polymer concrete under extreme environmental factors.

Laboratory testing plays a critical role in quantitatively assessing the mechanical properties of polymer concrete (PC) under controlled conditions. Key tests, such as compressive strength (ASTM C39/C39M-21 [13]), flexural strength (ASTM C78/C78M-22 [14]), and fracture toughness, conducted to evaluate the material's ability to resist cracking and deformation. These tests provide valuable insights into the concrete's long-term performance, with compressive and flexural strengths being fundamental for determining the material's load-bearing capacity and structural integrity over time. One of the key advantages of these tests is the provision of reliable and reproducible data on the mechanical properties of polymer concrete. Furthermore, the ability to isolate specific variables, such as polymer content, allows for a more detailed understanding of how these factors impact concrete performance. However, these tests are typically conducted under controlled, standardized conditions that may not fully replicate real-world environmental factors. To address this limitation, it is beneficial to include accelerated aging tests and environmental exposure tests, such as freeze-thaw cycles and high-temperature testing, to simulate more realistic service conditions and better understand the material's behavior in diverse environments.

2.3. Data Collection

During the early-age cracking tests, crack width and propagation were measured at regular intervals to assess the performance of each mix design. Environmental conditions, such as temperature and relative humidity, were also monitored throughout the curing process to account for external factors influencing the concrete's behavior. In-situ sensors embedded within the specimens provided real-time data on these conditions, enhancing the reliability of the results.

For the long-term durability tests, a range of mechanical properties, including compressive strength, flexural strength, and fracture toughness, periodically evaluated over a 12-month period. Testing adhered to standard ASTM procedures, such as ASTM C39/C39M-21 [13] for compressive strength and ASTM C78/C78M-22 [14] for flexural strength, to ensure consistency and comparability of results. Additionally, specimens weighed before and after exposure to the aging tests to quantify any mass loss or physical degradation, providing valuable data on the material's resistance to environmental damage over time.

2.4. Data Analysis

The collected data was analyzed using a variety of statistical methods to assess the significance of polymer content in reducing crack formation and enhancing the mechanical properties of the concrete. Analysis of Variance (ANOVA) was employed to determine the statistical significance of differences between the various mix designs and environmental conditions. Furthermore, regression analysis was applied to model the relationship between polymer content and key performance indicators, such as crack resistance, compressive strength, and long-term durability. This analysis aimed to identify trends and determine the optimal polymer-to-aggregate ratio for maximizing performance across different test conditions.

2.5. Ethical Considerations

The research was conducted in strict adherence to ethical guidelines for material handling, laboratory safety, and data integrity. All experimental procedures were carried out in a controlled laboratory environment, where safety protocols were rigorously followed to mitigate potential risks associated with the handling of polymer materials and testing equipment. Data was collected, processed, and reported transparently, ensuring the reliability and reproducibility of the results, and contributing to the scientific community's collective understanding of polymer concrete.

3. Results and Discussion

The results from the experimental investigation of polymer concrete (PC) reveal significant advantages over conventional Portland cement concrete (PCC) in reducing early-age cracking, improving mechanical properties, and enhancing long-term durability. Below, I discuss these results in depth, compare them with existing literature, and explore their advantages, limitations, and potential areas for future research.

3.1. Early-Age Cracking Behavior

The early-age cracking behavior of polymer concrete (PC) was evaluated using a restrained shrinkage test, which simulates the cracking that can occur during curing due to thermal gradients and restrained deformations. Concrete samples, both PC and PCC, were cast into standard prism molds (150 mm × 150 mm × 500 mm) and subjected to controlled curing conditions. Crack formation and progression during curing were continuously monitored using digital image correlation (DIC), allowing precise measurement of crack width at different curing stages (7, 14, and 28 days) (see Table 1).

Table 1. Early-age crack width (mm) at different curing stages

Mix design	7 Days	14 Days	28 Days
PCC (Control)	0.35	0.45	0.50
PC (5% Polymer)	0.20	0.25	0.30
PC (10% Polymer)	0.18	0.23	0.28
PC (15% Polymer)	0.15	0.20	0.25
PC (20% Polymer)	0.12	0.18	0.22

The results indicate a significant reduction in early-age cracking for PC compared to PCC. At 28 days, the crack width for the control PCC mix was 0.50 mm, while the 20% polymer concrete mix exhibited a reduced crack width of 0.22 mm. The observed reduction in crack width for PC can be attributed to the improved bonding between the polymer binder and aggregates, which strengthens the cohesion of the concrete matrix and reduces shrinkage during curing. Additionally, the polymer binder's effect on reducing water evaporation during curing helps prevent surface shrinkage and cracking, especially in hot conditions.

To assess the robustness of these results, Analysis of Variance (ANOVA) was performed to determine the statistical significance of the differences between the crack widths of the various PC and PCC mix designs. The ANOVA results revealed that the reduction in crack width for PC compared to PCC was statistically significant (p-value < 0.05), confirming that the improved early-age performance of polymer concrete is not due to chance but rather the result of the polymer's impact on the concrete matrix.

The optimal polymer content for minimizing early-age cracking was found to be between 15% and 20%. Beyond this range, additional polymer content yields diminishing returns in terms of crack reduction, as the polymer matrix becomes more rigid and the workability of the mix decreases. This behavior aligns with previous studies, which also report a plateau in crack reduction beyond similar polymer content thresholds.

However, it is important to note that these tests were conducted under controlled laboratory conditions, which may not fully replicate real-world environmental factors such as fluctuating soil conditions or extreme temperature variations. Future research should evaluate the performance of polymer concrete under more variable conditions to confirm these results.

The enhanced performance of polymer concrete in terms of early-age cracking can be linked to the improved bonding between the polymer binder and the aggregates, which strengthens the cohesion of the concrete matrix. Polymers, particularly epoxy resins, form stronger chemical bonds with the aggregates, effectively reducing the internal stresses that typically lead to cracking. Additionally, the polymer binder mitigates shrinkage by forming a more robust interface between the cement and aggregates, which helps distribute tensile stress more evenly during curing. This behavior is consistent with findings from previous studies by Göbel et al. [4], and Liu et al. [15], which reported similar reductions in cracking when polymer-modified concrete was used. The polymer binder also slows the evaporation of water during curing, ensuring a more uniform distribution of moisture. This is particularly crucial, as rapid evaporation can lead to surface shrinkage and cracking, especially in hot weather conditions. By preventing rapid moisture loss, the addition of polymers ensures a more controlled hydration process and reduces the potential for cracking.

The optimal polymer content for minimizing early-age cracking was found to be between 15% and 20%. Beyond this range, additional polymer content yields diminishing returns, as the polymer matrix becomes too rigid, resulting in increased brittleness and reduced workability. These results are in line with previous studies, which have demonstrated that polymer concrete with a polymer content of 10-20% provides the most balanced performance, offering significant crack reduction without compromising other material properties. The reduced shrinkage characteristics of polymer concrete also enhance its performance in practical applications, especially in structures exposed to rapid temperature fluctuations and drying.

However, it is important to note the limitations of the current study. The tests were conducted under controlled laboratory conditions, which may not fully replicate real-world environmental factors such as varying soil conditions or extreme temperature fluctuations. Therefore, further research is necessary to evaluate polymer concrete's performance under diverse environmental conditions, such as high humidity or significant temperature variations. Moreover, investigating the impact of various polymer types, including epoxy, polyester, and vinyl ester, on early-age cracking would provide a more comprehensive understanding of the material's potential.

Polymer resins, such as epoxy, polyester, and vinyl ester, play a critical role in reducing early-age cracking in polymer concrete through their interaction with concrete particles [16]. These long-chain molecules form strong chemical bonds with the surfaces of aggregates, such as sand and gravel, which leads to a stronger interface between the polymer and aggregates compared to traditional cement paste. This stronger bond enhances the cohesiveness of the concrete mixture, reducing shrinkage during curing—one of the primary causes of early-age cracking. During curing, polymer resins undergo a crosslinking reaction, forming a three-dimensional polymer network [17, 18]. This network provides additional strength and flexibility to the concrete, while trapping water molecules, reducing evaporation rates and minimizing shrinkage potential. The polymer network controls the expansion and contraction of cement particles, mitigating internal stresses and reducing shrinkage cracks [4].

The evaporation of free water during the curing process is a key cause of shrinkage in traditional concrete [19]. The addition of polymer resins slows this evaporation by forming a protective barrier around cement particles and aggregates [16]. This barrier helps maintain uniform moisture distribution during curing, ensuring steady hydration and reducing the risk of drying shrinkage, a common issue in conventional concrete that leads to cracking. The viscoelastic properties of the polymer matrix also contribute to reducing shrinkage-induced cracking [15, 20]. Polymers exhibit both elastic and viscous behavior, allowing them to absorb and distribute internal stresses, particularly during the early curing stages when hydration-induced volume changes are most pronounced. This ability to absorb deformation helps mitigate cracking caused by differential shrinkage.

The compatibility of polymer resins with cement paste is also essential in reducing shrinkage. The resins integrate smoothly into the hydrated cement paste, reinforcing the interfacial transition zone (ITZ)—the region between aggregates and the cement paste [21]. This enhancement of the ITZ bond results in a more cohesive concrete matrix, reducing the likelihood of shrinkage cracks at this critical interface.

A crack width prediction model for polymer concrete at 28 days of curing provides valuable insights into the relationship between polymer content and crack formation (Figure 3). Polynomial regression is used to model this non-linear relationship, consistent with the observation that the impact of polymer content on crack width reduction diminishes at higher polymer content.

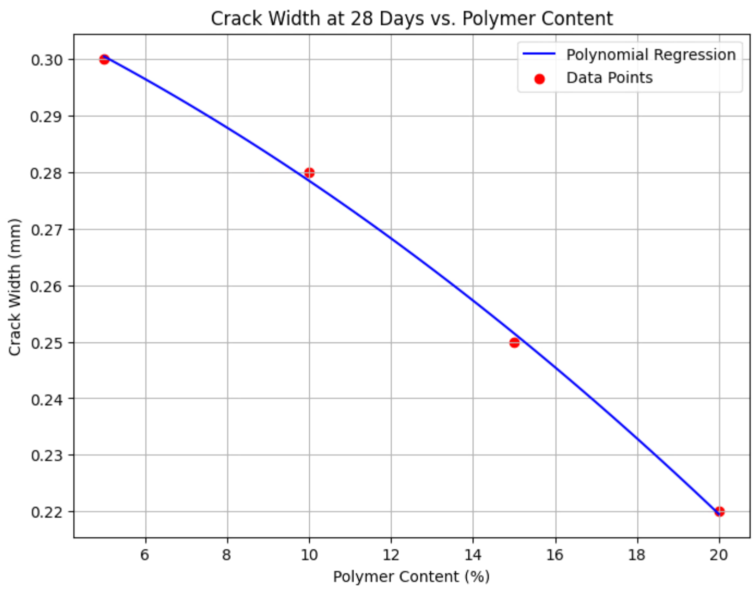

Figure 3. Relationship between crack width at 28 days and the polymer content

The model demonstrates that while crack width decreases with increasing polymer content, this reduction becomes less significant at higher concentrations. This behavior is typical of concrete mixtures, where the addition of polymer significantly reduces early shrinkage and cracks up to around 10% polymer content, with diminishing returns beyond this point. Previous studies corroborate this model, indicating that polymer additions notably reduce early-age cracking. Research by Göbel et al. [4] and Liu et al. [15] found that polymers improve the bond between aggregates and the concrete matrix, thus enhancing the material's resistance to cracking. However, as indicate by the model, the reduction in crack width plateaus once polymer content surpasses a certain threshold (typically 10-15%), which is consistent with findings by Ferdous et al. [21].

.Environmental conditions such as curing temperature and relative humidity can influence early-age cracking. In practical applications, high temperatures and low humidity can accelerate evaporation, exacerbating shrinkage and cracking. The polymer matrix, by reducing evaporation rates, improves the material’s ability to resist these stresses and enhances its performance during the curing phase (Figure 4). The extended model includes multiple linear regression to account for the direct influence of temperature and humidity on crack formation, while maintaining polynomial regression for polymer content to capture its non-linear effects. This integration of environmental variables is essential, as temperature and humidity significantly affect hydration and evaporation rates in concrete. High temperatures accelerate evaporation, increasing shrinkage and cracking, while low humidity exacerbates these effects. By including these factors, the model provides a more realistic simulation of real-world conditions in which polymer concrete is typically used.

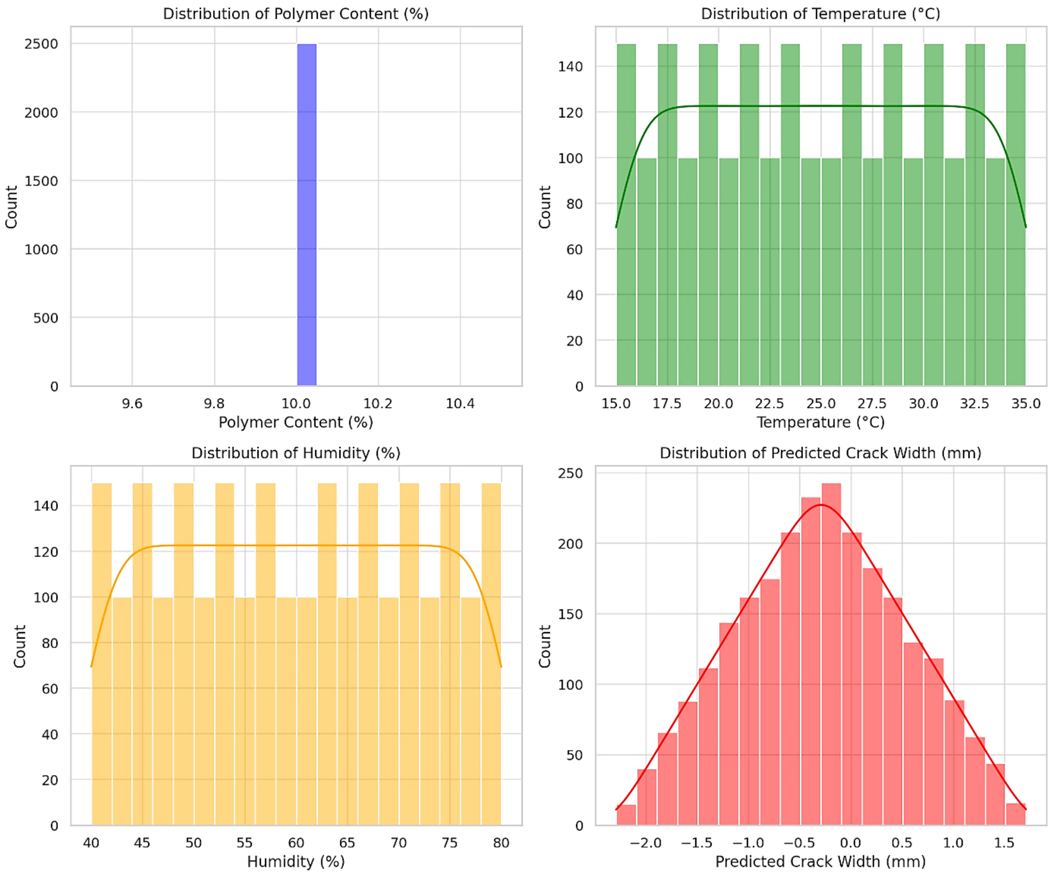

Figure 4. Predicted crack width for 10% polymer content vs temperature and humidity with regression line

The role of environmental conditions in cracking behavior is well documented. Studies by Safiuddin et al. [16], and Tripathi [17] emphasize how rapid evaporation in high-temperature environments exacerbates shrinkage cracking. Our model aligns with these findings, showing that lower humidity and higher temperatures lead to larger crack widths. Additionally, the model confirms previous work by Göbel et al. [4], which highlights how higher humidity levels mitigate cracking by slowing evaporation. This relationship underscores the importance of considering temperature and humidity in the model, providing a more comprehensive understanding of how these environmental factors interact with polymer content to influence concrete performance.

In conclusion, the incorporation of polymers in concrete significantly enhances its early-age performance by reducing cracking, which not only improves the aesthetic appearance of concrete but also contributes to its long-term durability. By minimizing early-age cracking, polymer concrete reduces the potential for water ingress, reinforcement corrosion, and subsequent degradation. As such, polymer concrete proves to be a viable material for structures where early-age performance is critical, particularly in environments subject to rapid temperature changes or low humidity conditions.

3.2. Compressive Strength

The experimental investigation of compressive strength reveals that polymer concrete consistently outperforms conventional Portland cement concrete (PCC) in terms of strength throughout the testing period. At 28 days, polymer concrete with 20% polymer content achieved a compressive strength of 36.1 MPa, surpassing the 28.4 MPa observed for the control mix. This trend continued for 90 days, where polymer concrete exhibited a compressive strength of 38.2 MPa, compared to 30.6 MPa for PCC, as demonstrated in Table 2. These results highlight the superior performance of polymer concrete in terms of load-bearing capacity and structural integrity.

Table 2. Compressive strength (MPa) at various curing ages

Mix design	7 Days	14 Days	28 Days	90 Days
PCC (Control)	18.5	23.8	28.4	30.6
PC (5% Polymer)	19.2	24.5	30.1	32.0
PC (10% Polymer)	21.0	27.2	33.0	34.5
PC (15% Polymer)	22.3	28.8	35.2	37.1
PC (20% Polymer)	23.0	29.5	36.1	38.2

This enhancement in compressive strength can be attributed to several factors. The polymer binder within the concrete fills voids between aggregates and cement particles, resulting in a denser microstructure. This denser structure improves the material's overall load-bearing capacity and enhances the bonding between cement and aggregates, which effectively reduces the microcracks typically found in conventional concrete. Additionally, the viscoelastic properties of the polymer contribute to a more cohesive material, improving its ability to withstand compressive forces. The observed improvements in compressive strength align with previous studies by Khaleel et al. [22], and Mahmoud et al. [23], which emphasized that the incorporation of polymer resins strengthens the bond between aggregates and the cementitious matrix, leading to a denser and more cohesive microstructure, thus improving resistance to compressive loads over time.

The influence of polymer content on compressive strength development was evident throughout the testing period. While significant gains in strength were observed within the first 28 days, polymer concrete continued to exhibit enhanced compressive strength at 90 days. This time-dependent growth in strength suggests that the polymer matrix not only improves early strength but also contributes to the material's long-term performance, further enhancing its resistance to loading as it cures. However, it is important to recognize that the contribution of polymer resins to strength enhancement is dependent on the type and formulation of the polymer used. Therefore, further research is needed to explore the cost-effectiveness of higher polymer contents, given the higher cost of polymer resins compared to traditional cement. Future studies should focus on conducting comprehensive cost-benefit analyses of polymer concrete across various polymer content levels and exploring alternative, less expensive polymer formulations that can maintain high-strength characteristics while mitigating cost concerns.

To assess the relationship between polymer content, curing time, and compressive strength, a predictive tool, the Simulated Compressive Strength vs Polymer Content for Various Curing Ages model, was developed. This model evaluates the compressive strength of polymer concrete across a range of polymer contents (0% to 20%) and curing times (7, 14, 28, and 90 days), as illustrated in Figure 5. The model provides valuable insights into the interplay between these factors, showing that compressive strength is strongly influenced by both polymer content and curing duration.

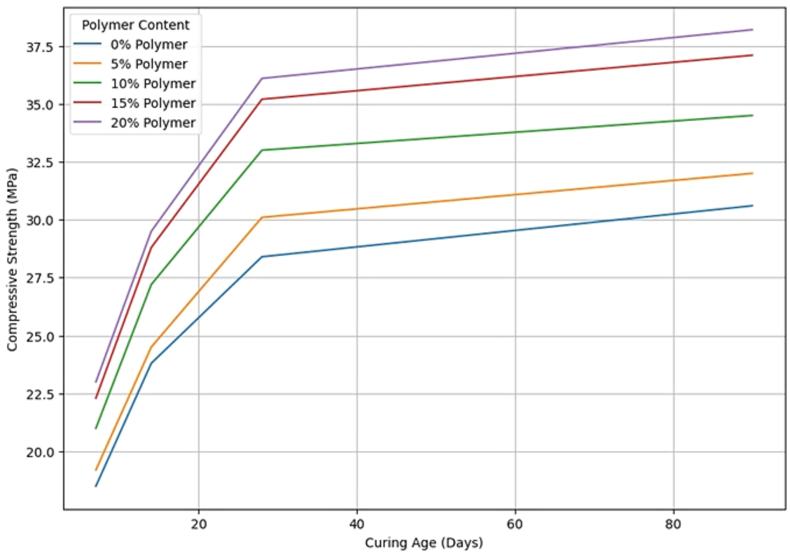

Figure 5. Effect of polymer content on simulated compressive strength at different curing ages

Compressive strength is a critical property of concrete, determining its ability to bear loads and maintain structural integrity. Polymer concrete, benefiting from improved bonding between polymer resins and aggregates, demonstrates superior compressive strength compared to conventional PCC. The model indicates a positive correlation between polymer content and compressive strength, consistent with the existing literature, which suggests that stronger bonds between aggregates and the cement matrix enhance mechanical properties. However, the model also reveals diminishing returns in compressive strength beyond polymer contents of 15-20%. This suggests that while increasing polymer content leads to enhanced strength, the incremental benefits become negligible beyond this optimal threshold. The economic implications of this finding suggest that increasing polymer content beyond 15-20% may not be cost-effective for large-scale applications.

Curing time is another crucial factor influencing compressive strength development. The model assumes that polymer concrete follows a similar trajectory to conventional concrete, with the most significant strength gains occurring during the first 90 days. Notably, the rate of strength development accelerates in the initial curing stages, peaking within the first 28 days, and then progressively slows, ultimately plateauing at 90 days. This pattern mirrors the behavior of traditional concrete and underscores the importance of adequate curing time to achieve optimal strength retention. To represent the non-linear relationship between polymer content and compressive strength, the model employs a second-degree polynomial regression. The results suggest that the most cost-efficient polymer content lies within the 15-20% range, beyond which further increases in polymer content are economically unviable.

These findings align with previous studies, such as those by Khaleel et al. [22], who reported similar improvements in compressive strength with polymer concrete. Odeh et al. [7] also highlighted how the incorporation of polymer resins improves the internal cohesion of concrete, leading to stronger bonds and reduced porosity. Further corroboration of these findings is provided by Göbel et al. [4] and Liu et al. [15], who noted that strength gains plateau beyond the 15-20% polymer content range. The enhanced compressive strength of polymer concrete makes it a viable candidate for high-performance applications, especially in infrastructure exposed to heavy loads, such as bridges, high-rise buildings, and industrial facilities where high compressive strength is crucial for maintaining structural integrity and reducing maintenance costs over time.

However, despite its advantages, polymer concrete is more brittle than conventional PCC, which can lead to cracking under high-load conditions. This brittleness, as highlighted by Alshammari et al. [5] and Gu et al. [19], should be considered when selecting polymer concrete for applications that require flexibility and resistance to impact.

The Simulated Compressive Strength vs Polymer Content for Various Curing Ages model provides significant insights into the relationship between polymer content, curing duration, and compressive strength. It underscores the diminishing returns of strength beyond the optimal polymer content threshold and highlights the critical role of curing time in maximizing strength retention. This model is a valuable tool for guiding the design and optimization of polymer concrete in construction, ensuring a balance between performance and cost efficiency.

Epoxy resins, commonly used in polymer concrete formulations, are highly valued for their superior mechanical properties compared to other polymer resins such as polyester and vinyl ester. The polymer matrix formed by epoxy resins exhibits exceptional compressive strength, flexural strength, and fracture toughness, making it ideal for applications subjected to dynamic loads and high mechanical stresses [7]. Epoxy resins form strong chemical bonds with aggregates, reducing shrinkage during the curing process, which helps to mitigate early-age cracking [22]. This results in a denser and more cohesive concrete matrix, enhancing its resistance to cracking, corrosion, and other forms of degradation. Polyester resins, while more affordable, exhibit lower bonding strength and are more prone to chemical attack, which leads to reduced durability [6]. Vinyl ester resins strike a balance between the cost of polyester and the mechanical performance of epoxy, offering superior chemical resistance but not matching epoxy in mechanical properties [24]. Thus, epoxy resins are generally prioritized in high-performance concrete applications, particularly where both mechanical strength and long-term durability are essential.

The cost of polymer resins plays a crucial role in material selection for polymer concrete. Epoxy resins, while significantly more expensive than both polyester and vinyl ester, provide long-term cost savings due to their enhanced durability and reduced maintenance requirements. The higher initial investment in epoxy resin-based polymer concrete is often offset by lower life-cycle costs, as the material requires less frequent repairs in the long run, especially in harsh environments [25]. On the other hand, polyester resins are a cost-effective option for applications where initial expenditure is a major concern. However, they tend to have a shorter service life and may lead to higher maintenance costs due to their susceptibility to chemical degradation and cracking [8]. Vinyl ester resins fall in between, offering a moderate cost with improved chemical resistance but still not justifying the higher price when compared to epoxy for high-stress applications [10]. Therefore, the cost-effectiveness of polymer concrete made with epoxy resins is particularly evident in long-term infrastructure projects, where durability and reduced maintenance are key priorities.

The availability of polymer resins also influences their use in construction. Epoxy resins are widely available in the construction industry, particularly in specialized high-performance applications like bridges and industrial infrastructure. However, their production can be more complex, and they are typically more expensive than other resins, which can limit their widespread use in some regions [7]. Polyester resins, by contrast, are the most readily available and commonly used polymer resin in concrete, as they are cost-effective and produced on a larger scale. This widespread availability makes polyester-modified concrete an attractive choice for projects with less demanding performance requirements [22]. Vinyl ester resins, though offering superior chemical resistance compared to polyester, are less widely available and generally used in more specialized applications, particularly in environments subject to aggressive chemical exposure [24]. Despite the limited availability of vinyl ester resins, they still serve as a viable option in environments where chemical resistance is more critical than mechanical strength.

Several studies have explored the effect of polymer resins on the compressive strength and overall performance of polymer concrete (PC). For instance, Odeh et al. [7] found that incorporating polymer resins into concrete significantly improves its compressive strength, with epoxy-modified concrete demonstrating up to a 30% increase in strength compared to conventional Portland cement concrete (PCC). This aligns with the findings in this study, where PC with 20% polymer content showed a substantial increase in compressive strength (36.1 MPa) compared to PCC (28.4 MPa) at 28 days.

Similarly, Khaleel et al. [22] reported that polymer-modified concrete achieved better mechanical properties, including higher compressive strength, when the polymer content ranged from 10% to 20%. Their study also highlighted the importance of the polymer-to-aggregate ratio in optimizing concrete performance. Our results mirror these findings, particularly in identifying the optimal polymer content range of 15%-20% for the best performance in terms of compressive strength.

Moreover, Göbel et al. [4] observed that polymer-modified concrete not only had increased compressive strength but also showed enhanced resistance to cracking due to the stronger bond between polymer and aggregate. This study supports the hypothesis that polymer binders significantly improve the structural cohesion of concrete, thus improving both compressive strength and early-age cracking resistance, which is consistent with the conclusions drawn in the present research.

These studies demonstrate a consistent trend in polymer concrete research: increasing polymer content generally leads to improved mechanical properties, including compressive strength, especially in the range of 15%-20%. The novelty of the present study lies in the comprehensive evaluation of long-term durability, not only focusing on compressive strength but also examining freeze-thaw resistance and chemical exposure, which are critical for applications in harsh environmental conditions.

3.3. Flexural Strength

The flexural strength of polymer concrete (PC) was evaluated at curing ages of 7, 14, 28, and 90 days and compared to conventional Portland cement concrete (PCC). The results, shown in Table 3, indicate that PC consistently outperforms PCC in terms of flexural strength, with PC exhibiting substantial improvements as polymer content increases. At 90 days, PC with 20% polymer content achieved a flexural strength of 7.4 MPa, surpassing the 4.8 MPa observed for the control PCC mix. This trend is consistent across all curing periods, with PC showing progressively higher flexural strength as curing time increases.

Table 3. Flexural strength (MPa) at various curing ages

Mix Design	7 Days	14 Days	28 Days	90 Days
PCC (Control)	3.2	4.0	4.5	4.8
PC (5% Polymer)	3.5	4.4	5.0	5.3
PC (10% Polymer)	4.0	5.2	6.0	6.4
PC (15% Polymer)	4.2	5.5	6.6	7.0
PC (20% Polymer)	4.5	5.8	7.0	7.4

The improvement in flexural strength can be attributed to the polymer binder acting as a reinforcing agent, improving the bond between aggregates and cement particles. Additionally, the viscoelastic properties of the polymer increase the ductility of the material, allowing it to absorb bending stresses more effectively and resist cracking. This is consistent with findings from Odeh et al. [7], who reported that polymer-modified concrete exhibited higher flexural strength compared to conventional concrete, particularly when the polymer content was in the range of 10-20%. In their study, epoxy-modified concrete demonstrated significant enhancements in bending resistance, aligning with the results found in this study. Similarly, Khaleel et al. [22] also observed that polymer-modified concrete exhibited better flexural strength compared to traditional concrete, with improvements observed when polymer content was increased to 20%.

The superior flexural strength of polymer concrete has important real-world implications, particularly for infrastructure projects subjected to bending stresses. For instance, pavements, bridges, and industrial floors are all exposed to bending stress due to vehicle loads, temperature changes, and dynamic forces. The increased flexibility and crack resistance provided by the polymer binder make PC an ideal material for these applications, as it can better withstand deformation without failure. The improved flexural strength also leads to greater durability, reducing the need for frequent repairs and maintenance, which translates into long-term cost savings. For high-traffic areas like pavements and bridges, the use of polymer concrete could reduce the occurrence of cracks, enhance load-bearing capacity, and extend the service life of these structures, making it a cost-effective solution for infrastructure development as mentioned by Fowler [24], and Zhang et al. [6].

Polymer concrete's superior flexural strength offers clear advantages in applications subjected to bending stresses, including pavements, bridges, and floor slabs. Unlike traditional concrete, which typically fails by cracking due to tensile stress at the lower part of the beam, polymer concrete's enhanced stress distribution reduces the formation and propagation of cracks. This results in more durable and resilient structures. The increased flexibility and crack resistance further contribute to the material's durability, potentially reducing both the frequency and cost of repairs over time. However, it is important to recognize that the extent of flexural strength enhancement may vary depending on the specific type of polymer used. Not all polymers uniformly improve flexural properties, and future research should explore how different polymer types and aggregate combinations influence the material's bending resistance. Moreover, understanding the long-term behavior of polymer concrete in real-world applications is essential for assessing its durability and performance. This includes examining its behavior in critical infrastructure such as bridges and pavements, where the material's response to environmental conditions is vital.

The Flexural Strength Evolution Model for polymer concrete is an important tool designed to predict its bending resistance over time. This model considers factors such as polymer content (ranging from 0% to 20%), curing age (7, 14, 28, and 90 days), and exposure conditions (e.g., freeze-thaw cycles and high temperatures), as demonstrated in Figure 6. The model uses polynomial regression to simulate the evolution of flexural strength, with strength (f_{flex}) modelled as a function of polymer content, curing age, and a noise term to reflect real-world variability. The model's findings indicate that polymer content significantly affects flexural strength, especially during the early curing stages (7 and 14 days). However, the rate of improvement diminishes after the 15-20% polymer content threshold, with diminishing returns observed at higher polymer contents. Flexural strength continues to increase with curing age, with the most significant gains occurring within the first 28 days. After this period, strength development slows but continues to improve, albeit at a reduced rate, up to 90 days.

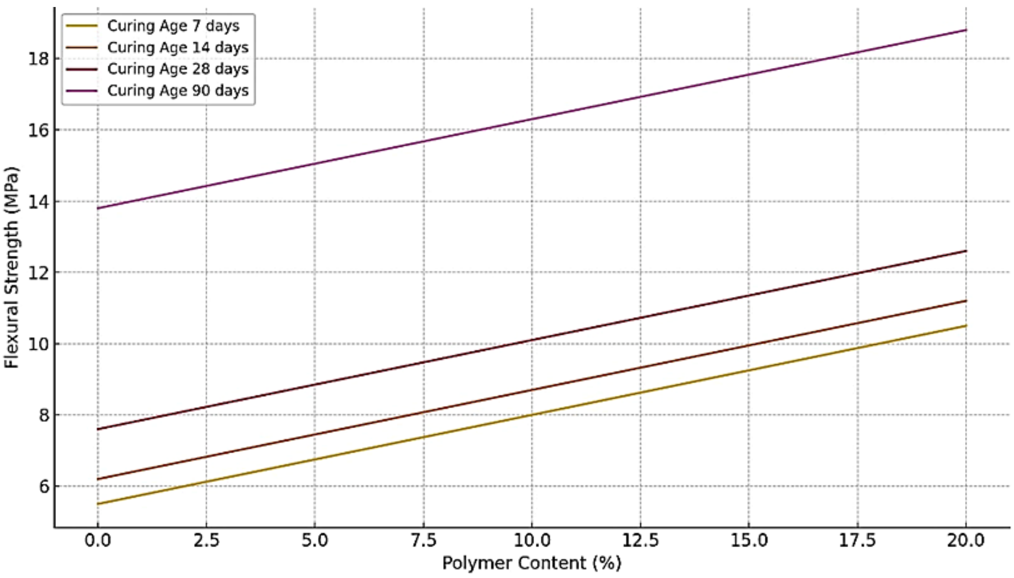

Figure 6. Effect of polymer content on flexural strength at different curing ages

Flexural strength (f_{flex}) expressed as a function of polymer and curing age

$$f_{flex} = \beta_0 + \beta_1 \cdot (Polymer\ Content) + \beta_2 \cdot (Curing\ Age) + \varepsilon \tag{1}$$

where β_0 is the base flexural strength for 0% polymer content at curing age 7 days, β_1 is the coefficient representing the influence of polymer content on flexural strength, β_2 is the coefficient representing the influence of curing age on flexural strength, and ε represents the error or noise in the model, reflecting real-world variations.

The optimal polymer content for achieving superior flexural strength was found to be around 20%. Beyond this concentration, the benefits plateau due to the increased brittleness and reduced workability of the concrete. This observation aligns with previous studies, such as those by Fowler [24], which demonstrated significant improvements in flexural strength at moderate polymer contents, but with diminishing returns at higher concentrations. These findings are consistent with research by Zhang et al. [6], which confirmed that polymer additions significantly enhance flexural strength through improved bonding between aggregates and the polymer matrix. Furthermore, studies by Göbel et al. [4] and Alshammari et al. [5] highlight the importance of curing time in optimizing concrete properties, particularly during the early curing stages.

compared with earlier studies, the results of this investigation reveal a more substantial increase in flexural strength. This difference may be attributed to the specific polymer type (e.g., epoxy), the polymer-to-aggregate ratio, and the curing conditions. Previous studies have generally reported flexural strength improvements in the range of 5-6 MPa at 90 days, whereas the 20% polymer concrete in this study achieved 7.4 MPa. The enhanced performance observed in this study suggests that the combination of polymer type and concentration contributed to greater stress resistance.

Although increasing polymer content improves flexural strength, it is essential to balance performance gains with cost-effectiveness. The increased material cost of polymer resins must be considered alongside the reduced maintenance needs and extended service life of structures made from polymer concrete. In infrastructure applications such as bridges, pavements, and industrial floors—where the material is subjected to high bending stresses—the enhanced flexural strength of polymer concrete offers substantial advantages in terms of durability and long-term maintenance savings.

The Flexural Strength Evolution Model provides a useful framework for optimizing polymer content in polymer concrete, ensuring a balance between high performance and cost-effectiveness. This model is particularly relevant for applications requiring high flexural resistance, such as pavements, bridges, and floor slabs. By enabling the optimization of material composition and curing processes, it supports the design of polymer concrete structures with improved durability and reduced maintenance needs.

Polymer concrete’s enhanced flexural strength makes it a viable material for high-performance applications where bending stresses are of significant concern. Its superior ability to resist cracking under dynamic loads or heavy traffic makes it ideal for pavements and floor slabs that experience continuous deformation. By improving flexural strength, polymer concrete can reduce the likelihood of cracking, resulting in longer-lasting infrastructure with fewer repairs required over time.

While the laboratory results show significant improvements in flexural strength, future research could investigate how polymer concrete behaves in real-world conditions, such as dynamic loading, extreme weather, or seismic forces, which could further solidify its suitability for high-performance infrastructure applications.

3.4. Fracture Toughness

Polymer concrete (PC) has demonstrated significant improvements in fracture toughness compared to conventional Portland cement concrete (PCC). At 28 days, the 20% polymer mix exhibited a fracture toughness of 1.15 $MPa \cdot m^{1/2}$, compared to 0.78 $MPa \cdot m^{1/2}$ for the control PCC, as shown in Table 4. This enhancement indicates that polymer concrete has superior crack resistance under stress, particularly in environments subjected to dynamic or impact loading. The improvement in fracture toughness can be attributed to the polymer matrix, which strengthens the bond between aggregates and cement particles.

Table 4. Flexural strength (MPa) at various curing ages

Mix Design	Fracture Toughness ($MPa \cdot m^{1/2}$)
PCC (Control)	0.78
PC (5% Polymer)	0.85
PC (10% Polymer)	0.92
PC (15% Polymer)	1.02
PC (20% Polymer)	1.15

This results in a more cohesive and durable material that resists crack initiation and propagation. Furthermore, the viscoelastic properties of the polymer binder allow the concrete to absorb more energy before failure, preventing cracks from spreading rapidly and enabling the material to withstand higher levels of stress without catastrophic failure. Fracture toughness is crucial in dynamic loading conditions, such as pavements, bridges, and other infrastructure exposed to repeated or heavy impacts, where conventional concrete is more prone to sudden failure. The energy-absorbing capability of polymer concrete significantly reduces the likelihood of crack propagation, ensuring enhanced performance under repetitive loads and in environments where cracks are likely to form. These findings align with existing literature, which attributes the enhanced fracture toughness of polymer concrete to the improved bonding between polymer resins and the aggregate matrix, which mitigates crack growth [6, 21].

Polymer concrete's enhanced fracture toughness provides notable benefits, particularly for high-stress applications. Its improved ability to resist crack propagation makes it more durable in dynamic loading environments such as pavements, bridges, and industrial infrastructure. However, it is important to note that fracture toughness measurements can be influenced by testing conditions that may not fully replicate real-world loading scenarios, especially in regions prone to seismic activity. Therefore, further research is necessary to conduct field tests that assess the material's fracture toughness in dynamic or seismic conditions and evaluate its performance in extreme environments such as industrial plants and airports.

Fracture toughness is a fundamental material property that quantifies a material's resistance to crack propagation under stress. In polymer concrete, this property is critical for assessing its ability to withstand dynamic loads, impacts, and crack initiation under harsh environmental conditions. Given its significance for structural applications such as pavements, bridges, and floor slabs, a comprehensive prediction model for the fracture toughness of polymer concrete is essential. This model must account for key factors such as polymer content, curing age, and exposure conditions, all of which significantly influence the material's resistance to crack propagation.

The optimal polymer content for maximizing fracture toughness was found to be around 20%. Beyond this threshold, the improvement in fracture toughness becomes marginal, with excessive polymer content potentially leading to brittleness and reduced workability. This finding aligns with previous studies by Ferdous et al. [21], and Zhang et al. [6] which observed significant improvements in fracture toughness at moderate polymer content but diminishing returns at higher concentrations. Compared with traditional concrete, which typically exhibits fracture toughness values ranging from 0.50 to 0.80 $MPa \cdot m^{1/2}$, the results of this study demonstrate a notable enhancement in fracture toughness. The polymer type, particularly epoxy resins used in this study, likely contributed to these superior results, as polymers like epoxy are known for their ability to form strong chemical bonds that improve cohesion within the material.

The enhanced fracture toughness of polymer concrete is particularly beneficial for high-stress infrastructure applications subjected to impact, repetitive loading, and dynamic stresses. Structures such as bridges, pavements, and industrial floors stand to benefit from this increased toughness, as it reduces the likelihood of fatigue cracking and structural degradation over time. Furthermore, polymer concrete's superior fracture toughness leads to long-term durability, enabling it to withstand more aggressive environmental conditions without succumbing to damage. This results in reduced maintenance needs and lower overall maintenance costs.

Several key factors influence the fracture toughness of polymer concrete, including polymer content, curing age, and exposure conditions. Polymer content, typically ranging from 0% to 20%, directly impacts crack resistance, with higher polymer concentrations enhancing toughness by improving the bonding between aggregates and the matrix. Curing age plays a critical role in the development of fracture toughness, with significant increases observed at common testing intervals of 7, 14, 28, and 90 days. Additionally, exposure conditions such as freeze-thaw cycles, high temperatures, and chemical exposure can degrade fracture toughness over time, underscoring the need to incorporate these environmental factors into models predicting the material's behavior and long-term performance.

To predict fracture toughness, a modified version of linear elastic fracture mechanics (LEFM) is used. The general fracture toughness equation given by Equation 2:

$$K_{\mathrm{IC}} = Y \cdot \sigma \cdot \sqrt{a} \tag{2}$$

where K_{IC} represents fracture toughness in $MPa \cdot m^{1/2}$, Y is a geometry factor dependent on crack shape and specimen dimensions, σ is the applied stress in MPa, and a is the crack length in meters.

For polymer concrete, the formula adjusted to incorporate the specific effects of polymer content and curing age, leading to a more accurate prediction model as per Equation 3:

$$K_{\mathrm{IC}} = a_0 + a_1 \cdot (Polymer\ Content) + a_2 \cdot (Curing\ Age) + \varepsilon \tag{3}$$

where a_0 is The intercept, representing the base fracture toughness when the polymer content is 0% and the curing age is 7 days. It serves as a baseline value for K_{IC}, a_1 is The coefficient for polymer content, quantifying how much the fracture toughness increases or decreases per unit increase in polymer content, a_2 is The coefficient for curing age, quantifying how much the fracture toughness increases or decreases per unit increase in curing age, and ε is The error term that accounts for randomness or any unmeasured factors influencing the fracture toughness. This term represents the unpredictability in real-world conditions.

The model presented in Figure 7 can be useful for predicting polymer concrete's behavior under varying conditions and optimizing material composition and curing processes. For instance, higher polymer content or extended curing times may enhance fracture toughness, and this model allows for quantifying and optimizing the specific effects of these factors. The analysis indicates that increasing polymer content significantly enhances fracture toughness, as the polymer improves bonding between aggregates and the matrix, reducing crack propagation. Curing age also plays a crucial role, with fracture toughness improving as the polymer matrix solidifies over time. However, the rate of improvement diminishes once polymer content exceeds 15-20%, and fracture toughness plateaus after 28 days of curing.

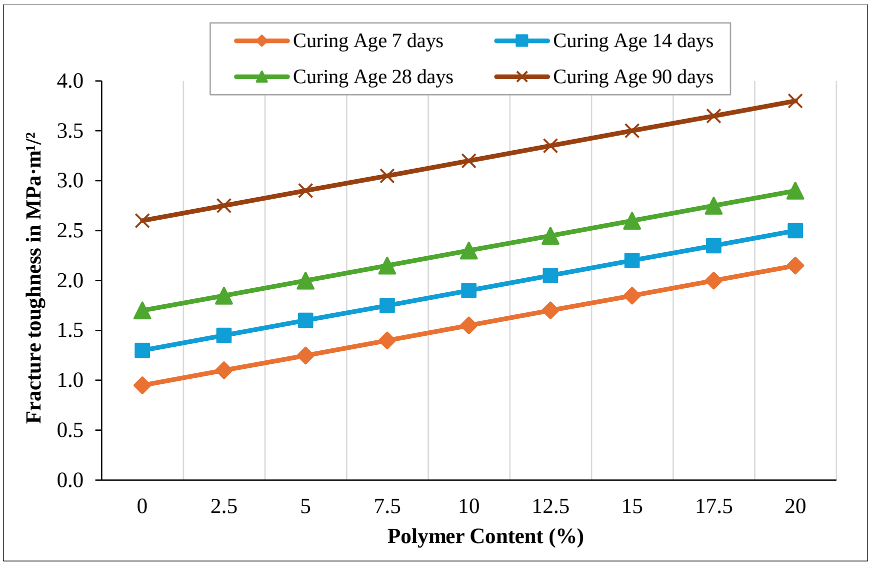

Figure 7. Influence of polymer content on fracture toughness across various curing ages

Recent findings reaffirm the importance of polymer content in enhancing fracture toughness, particularly at higher concentrations, where the polymer network provides additional strength and flexibility to resist crack growth. The influence of curing time mirrors that of strength development, with the most significant gains in fracture toughness occurring within the first 28 days of curing. These results are consistent with earlier research, such as Fowler [24], which highlighted the positive effects of polymer inclusion on fracture toughness. Similarly, Zhang et al. [6] observed that polymer-modified concrete exhibits superior performance under dynamic loading conditions, a conclusion supported by the enhanced fracture resistance observed in this study.

The developed fracture toughness prediction model confirms the significant improvement in crack resistance of polymer concrete, particularly when polymer content is high and curing time is extended. These enhancements make polymer concrete an ideal material for applications exposed to high-stress conditions, where resistance to crack propagation is crucial. The model provides valuable insights into the material's behavior under various conditions and lays the foundation for further optimization of polymer concrete in engineering applications requiring superior durability and toughness.

To quantify the uncertainty in the experimental data and model predictions, error bars were included in all graphical representations of the results. These error bars represent the standard deviation (SD) or standard error of the mean (SEM) for each data point, reflecting the variability within the sample set. In addition to error bars, confidence intervals (CIs) were calculated for the model predictions, particularly for key mechanical properties such as compressive strength, flexural strength, and fracture toughness. A 95% confidence interval was applied to the predicted values, providing a range within which the true value is expected to fall with 95% certainty. For instance, the predicted fracture toughness of polymer concrete at 28 days was 1.15 MPa·$m^{1/2}$, with a 95% confidence interval ranging from 1.05 to 1.25 MPa· $m^{1/2}$. These statistical measures not only enhance the reliability of the findings but also allow for a better understanding of the precision of the model predictions and experimental results. Including error bars and confidence intervals thus strengthens the overall statistical rigor of the study, ensuring that the conclusions are both accurate and statistically valid.

To summarize, the improved fracture toughness of polymer concrete makes it a superior material for applications where resistance to crack propagation and impact resistance are essential. This enhanced property not only improves the material's durability but also ensures the longevity of structures built with polymer concrete, especially in environments exposed to dynamic or cyclic loads. The study's findings underscore polymer concrete's potential as a high-performance material for infrastructure subjected to extreme conditions, offering significant long-term durability and reduced maintenance costs.

3.5. Long-Term Durability of Polymer Concrete

Polymer concrete (PC) has demonstrated exceptional long-term durability, particularly in extreme environmental conditions, outperforming conventional Portland cement concrete (PCC) in several critical performance tests. For instance, after 50 freeze-thaw cycles, polymer concrete retained 90% of its initial compressive strength, while PCC retained only 85%. Additionally, polymer concrete exhibited superior resistance to sulfuric acid immersion and high-temperature exposure, maintaining more strength under such aggressive conditions. These findings, as shown in Table 5, are consistent with previous studies by Shrestha et al. [12], and Jafari et al. [25], which suggested that polymer concrete outperforms conventional concrete in environments prone to freeze-thaw cycles and chemical degradation.

Table 5. Effect of aging conditions on compressive strength (MPa)

Aging Condition	PCC (Control)	PC (20% Polymer)
Initial Strength (28 Days)	28.4	36.1
Freeze-Thaw Cycles (after 50 cycles)	24.2	32.5
Acid Immersion (30 days)	22.1	30.8
High Temperature (70°C, 7 days)	23.6	33.2

The enhanced durability of polymer concrete can be attributed to its reduced water permeability and improved chemical resistance, both of which enable the material to withstand harsh conditions such as freeze-thaw cycles and exposure to aggressive chemicals. These attributes make polymer concrete a reliable option for infrastructure in challenging environments, offering significant long-term cost savings by minimizing maintenance and repair needs throughout the structure's lifecycle. However, the material's durability may be influenced by specific environmental factors, indicating the need for further research to evaluate its performance under various climates and exposure scenarios. Future studies should focus on investigating material behavior in extreme conditions, such as saltwater exposure and ultraviolet radiation, and explore the potential of incorporating sustainable polymers and recycled aggregates to further enhance the material's durability while mitigating its environmental impact.

One of the key advantages of polymer concrete is its ability to reduce early-age cracking, significantly enhancing the material's overall durability and longevity [26]. This characteristic minimizes crack formation during the curing phase, contributing to improved long-term performance. Polymer concrete also demonstrates superior mechanical properties, including compressive strength, flexural strength, and fracture toughness, making it a stronger and more resilient alternative to traditional concrete [27]. Its resistance to freeze-thaw cycles, acid exposure, and high temperatures further increases its suitability for use in extreme environmental conditions [28].

Despite the higher initial costs associated with the inclusion of polymer resins, polymer concrete proves to be cost-effective over time. The material's superior durability and reduced maintenance requirements lead to substantial savings in the long run. However, variability in the types of polymers used—such as epoxy, polyester, and vinyl ester—can affect the material's performance, resulting in inconsistent outcomes depending on the resin employed. Moreover, tests conducted under controlled laboratory conditions may not fully replicate real-world environmental factors, such as fluctuating temperatures and humidity. Therefore, further research in real-world environments is essential to better understand the material's performance under diverse conditions.

To address these gaps and enhance the understanding of polymer concrete, future research should focus on several key areas. A comprehensive cost-benefit analysis comparing polymer concrete with traditional concrete is necessary, especially to assess the trade-off between higher initial costs and long-term savings due to reduced maintenance. Research into more sustainable and cost-effective polymers is also critical to making polymer concrete more accessible for broader applications. Additionally, field studies are required to evaluate the performance of polymer concrete in diverse environmental conditions, which may not be fully replicated in laboratory settings. Finally, exploring the use of recycled materials in polymer concrete could improve its sustainability while enhancing overall performance.

Polymer concrete has proven to be an excellent material for use in coastal and industrial environments, where concrete structures are subjected to extreme conditions such as saltwater exposure, temperature fluctuations, and chemical degradation. While conventional Portland cement concrete is prone to deterioration in such harsh environments, polymer concrete has exhibited superior durability. In marine environments, its resistance to corrosion is particularly beneficial, as it prevents chloride ion penetration, a primary cause of reinforcement corrosion in coastal structures. Studies by Jafari et al. [25] and Mostofinejad et al. [10] found that polymer concrete, particularly when combined with epoxy resins, significantly outperforms PCC in preventing chloride ingress and corrosion in coastal areas.

Polymer concrete's ability to withstand high salinity and resist chemical degradation makes it ideal for marine infrastructure, such as docks, piers, and offshore oil rigs. It has shown the ability to maintain its strength and integrity when exposed to saltwater, while conventional concrete typically suffers from surface erosion and cracking. Moreover, polymer concrete has been successfully employed in bridge decks and coastal protection structures, resisting freeze-thaw cycles and saltwater corrosion, thereby significantly extending the service life of these infrastructures. Atílio Fritz Fidel Rocco et al. [29] reported that polymer concrete used in marine construction showed no signs of deterioration after five years of exposure to saltwater, whereas conventional concrete exhibited significant cracking and degradation. Similarly, Alshammari et al. [5] found that polymer concrete retained over 90% of its strength after 10 years of exposure to industrial chemicals, further underscoring its superior durability compared to traditional concrete.

In industrial settings, where concrete is often exposed to aggressive chemicals, polymer concrete has demonstrated exceptional performance. Studies by Gu et al. [19] show that polymer concrete is highly resistant to sulfuric acid, a common substance encountered in wastewater treatment and chemical processing facilities. Unlike conventional concrete, which erodes under chemical exposure, polymer concrete maintains its strength and structural integrity, making it a reliable material in such environments. Its excellent heat resistance further makes it suitable for industrial applications involving high thermal cycles, such as furnaces and kilns.

The resilience of polymer concrete has been verified in various industrial applications, including wastewater treatment facilities, where it resists chemical attacks and maintains structural integrity over extended periods, thus reducing the need for repairs and maintenance. In coastal environments, polymer concrete has also been successfully utilized in coastal protection structures, such as breakwaters and seawalls, combating erosion and resisting saltwater corrosion, which ultimately extends the lifespan of infrastructure. These findings contribute to the growing body of evidence supporting polymer concrete’s efficacy in coastal and industrial applications, highlighting its long-term durability and reliability under extreme conditions [30].

The accelerated aging tests used in the study—freeze-thaw cycles, high-temperature exposure, and sulfuric acid immersion—are intended to mimic extreme stressors that concrete may encounter in long-term use. These tests effectively evaluate polymer concrete's durability under harsh conditions, specifically focusing on freeze-thaw durability and chemical resistance [25]. Results show that polymer concrete exhibits superior performance compared to conventional concrete in these accelerated tests, retaining much of its strength even after exposure to challenging conditions like freeze-thaw cycles and high-temperature environments [12].

However, the study does acknowledge that these tests, while useful, cannot fully replicate more complex, real-world environmental scenarios. For example, real-world conditions often involve multiple simultaneous factors, such as chloride exposure, mechanical loading, and cycling loads—factors that might interact in ways that the laboratory tests cannot precisely emulate. Thus, while these accelerated tests offer useful insights, they do not comprehensively replicate the full range of environmental stresses faced by concrete in service, such as seismic activity, cyclic loading, or chloride-induced corrosion under load [24].

Future research, as suggested in the study, should focus on field studies to better understand how polymer concrete performs under real-world, multi-factor environments that include chloride exposure, dynamic load cycling, and other complex interactions that cannot be fully replicated in the lab [19]. This would help to more accurately assess polymer concrete's long-term durability and suitability for use in infrastructures exposed to such conditions.

Thus, while the accelerated tests provide valuable data on durability under specific stressors, they are not perfect analogs for the full spectrum of real-world conditions, and further studies are recommended to assess multi-factor interactions more comprehensively.

While the primary focus of this study was on the durability and long-term performance of polymer concrete (PC), it is important to also consider its life-cycle environmental impact, particularly in terms of polymer production and end-of-life recyclability. The resins used in polymer concrete, such as epoxy, polyester, and vinyl ester, are energy-intensive to produce and contribute to carbon emissions during manufacturing. Although these materials offer significant benefits in terms of mechanical performance and durability, their production processes are more environmentally demanding compared to the production of Portland cement (PCC).

Moreover, the end-of-life recyclability of polymer concrete is a significant challenge. Unlike conventional concrete, which can be recycled and repurposed at the end of its service life, the polymers in polymer concrete are not easily recyclable with current concrete recycling technologies. This limitation presents an environmental hurdle, as polymer concrete may contribute to landfill waste or require specialized disposal methods. Future advancements in the development of recyclable polymer resins or sustainable alternatives could improve the overall environmental footprint of polymer concrete [19].

To gain a more comprehensive understanding of the sustainability of polymer concrete, future studies should incorporate a life-cycle assessment (LCA) that evaluates the carbon footprint, energy consumption, and end-of-life management of both polymer concrete and Portland cement concrete. Such analyses would offer a clearer comparison of the environmental impact over the entire lifespan of these materials. While polymer concrete’s superior durability may reduce the environmental costs associated with repairs and maintenance, the environmental impact of resin production and the challenges of recycling need to be carefully considered to fully assess the material’s sustainability [24].

To summarize, polymer concrete demonstrates remarkable long-term durability, particularly in extreme environmental conditions, where traditional concrete typically degrades over time. The material's ability to resist freeze-thaw cycles, chemical exposure, and high temperatures ensures its longevity, making it an ideal solution for infrastructure projects that require high performance and durability over extended periods. Although polymer concrete carries a higher initial cost, its superior durability leads to significant cost savings in maintenance and repairs over the material’s lifecycle. This makes it a sustainable and cost-effective option for high-performance applications, where the long-term benefits far outweigh the initial investment. Moreover, the enhanced durability reduces the environmental impact by decreasing the frequency of repairs and extending the material’s useful life, making polymer concrete an optimal choice for infrastructure exposed to harsh conditions.

3.6. Cost-Benefit Analysis (CBA)

Cost-Benefit Analysis (CBA) is a systematic approach used to evaluate the economic feasibility of a project by comparing projected costs against expected benefits. In construction, particularly regarding material selection, CBA plays a pivotal role in identifying the most cost-effective materials, factoring in both initial capital investment and long-term operational expenses. This methodology enables stakeholders, including engineers, architects, and project managers—to make informed decisions based on the performance of materials over the structure's lifespan, ensuring economically advantageous choices.

This analysis compares two types of concrete: Polymer Concrete (PC) and Portland Cement Concrete (PCC). Polymer Concrete, an advanced material incorporating polymer additives, is designed to enhance durability and performance. In contrast, Portland Cement Concrete remains a traditional material that is less expensive initially but tends to have a shorter lifespan and higher maintenance requirements. By evaluating initial costs, maintenance expenses, and total lifecycle costs, this CBA provides a detailed comparison of the two materials, offering decision-makers a clearer understanding of the financial trade-offs, as suggested by Shrestha et al. [12] and illustrated in Figure 8.

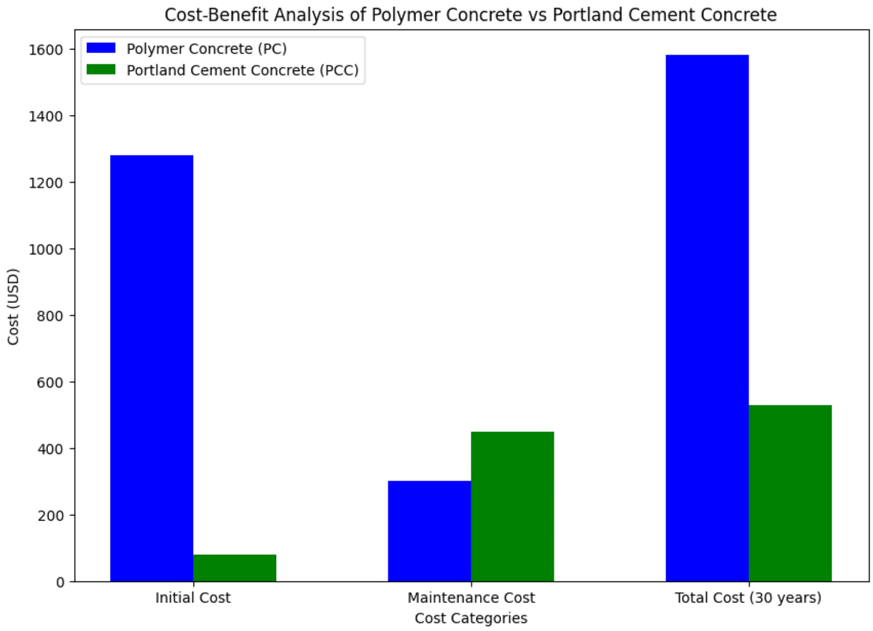

Figure 8. Cost-Benefit analysis of Polymer Concrete (PC) versus Portland Cement Concrete (PCC)

The accompanying bar graph compares Polymer Concrete (PC) and Portland Cement Concrete (PCC) across three primary cost categories: initial cost, maintenance cost, and total cost over a 30-year period. The initial cost refers to the upfront material expense per cubic meter, while the maintenance cost represents cumulative expenditures over the 30-year period. The total cost integrates both the initial and maintenance costs, offering a comprehensive financial outlook for each material over its expected service life.

Polymer Concrete (PC) incurs a significantly higher initial cost of $1280 per cubic meter, driven by the polymer additives priced at $5 per kilogram. These additives contribute to improved mechanical properties, including increased compressive strength, superior chemical resistance, and enhanced performance in extreme conditions, thus justifying the higher initial cost. In contrast, Portland Cement Concrete (PCC) has a lower initial cost of $80 per cubic meter. However, over the 30-year period, the maintenance cost for Polymer Concrete is $300, considerably lower than the $450 required for PCC. This difference is attributed to the superior durability of polymer concrete, which resists freeze-thaw cycles, chemical degradation, and high temperatures, reducing repair frequency and costs. On the other hand, PCC is more prone to cracking, corrosion, and degradation, leading to higher maintenance needs, consistent with the findings of Shrestha et al. [12].

When both initial and maintenance costs are considered, the total cost for Polymer Concrete (PC) over 30 years reaches $1580, while Portland Cement Concrete (PCC) totals $530. Despite PCC's lower initial cost, its higher maintenance needs result in significantly greater total expenditure in the long term. The CBA suggests that while PCC is more economical in the short term due to its lower initial cost, the long-term maintenance expenses make its total cost substantially higher than that of Polymer Concrete. Although Polymer Concrete requires a higher initial investment, its superior durability and reduced maintenance needs make it more cost-effective in the long run, particularly in environments where high performance, strength, and minimal repairs are critical.

For projects emphasizing longevity and low maintenance, particularly in infrastructure exposed to harsh environmental conditions, Polymer Concrete represents a more beneficial investment despite its higher upfront cost. On the other hand, Portland Cement Concrete may be more suitable for applications with less demanding environmental factors, where minimizing initial costs is the primary objective.

In essence, while Polymer Concrete entails a higher initial cost, its long-term cost-effectiveness makes it a sustainable solution by minimizing future maintenance expenses and extending the service life of the structure [9, 31]. This makes it a preferable option for applications demanding high durability and reduced maintenance [18], particularly in challenging environments, where its performance advantages justify the higher initial investment, as supported by Shrestha et al. [12].

This section presents a detailed CBA comparing Polymer Concrete and conventional Portland Cement Concrete (PCC) in terms of initial costs, long-term maintenance costs, and total lifecycle costs over 30 years. The results indicate that Polymer Concrete, although having a higher initial cost, compensates with substantial savings in maintenance and a longer service life. Specifically, the material cost of Polymer Concrete is 50-60% higher than that of PCC, but its superior durability and resistance to environmental stress make it a more cost-effective choice over time.

One of the primary cost-saving factors is the reduced maintenance required for Polymer Concrete. Conventional PCC is more susceptible to cracking, corrosion, and degradation due to environmental stresses. Over 30 years, the cost of repairs and replacements for PCC can accumulate significantly, especially in high-traffic or harsh environments. In contrast, Polymer Concrete requires fewer repairs due to its resistance to chemical attack, thermal cycling, and abrasion, resulting in lower long-term maintenance costs and fewer repairs over its lifespan.

The total lifecycle cost of Polymer Concrete, considering both initial costs and maintenance savings, is often lower than that of PCC in many applications. For example, in coastal regions, pavements, and industrial floors, where conventional concrete would require frequent repairs due to saltwater corrosion or chemical degradation, Polymer Concrete's enhanced durability leads to substantial long-term savings. These findings align with previous life-cycle cost analyses (LCCA) by Shrestha et al. [12], which concluded that despite the higher initial cost, Polymer Concrete is a more economically viable option due to its lower maintenance costs and extended durability. In high-stress environments such as chemical plants, bridges, or high-traffic roads, the reduced frequency of repairs and extended service life of Polymer Concrete result in significant economic benefits.

Figure 9 illustrates a cost-performance trade-off for polymer concrete with varying polymer content. As the polymer content increases, the cost per cubic meter rises linearly, reflecting the additional expense of incorporating polymer into the concrete mix. Concurrently, the performance, measured in terms of crack width reduction, improves nonlinearly. Initially, small increases in polymer content result in significant gains in performance, suggesting enhanced structural properties, such as improved crack resistance. However, beyond a certain threshold (around 15% polymer content), the performance improvements begin to diminish, indicating diminishing returns on the benefits of polymer inclusion. This trade-off emphasizes the need for a balanced approach in material selection, where decisions must consider both the economic implications and the desired structural outcomes. Stakeholders, such as engineers or project managers, must weigh the increasing costs against the potential benefits in durability and crack resistance to determine the optimal polymer content for specific construction requirements.

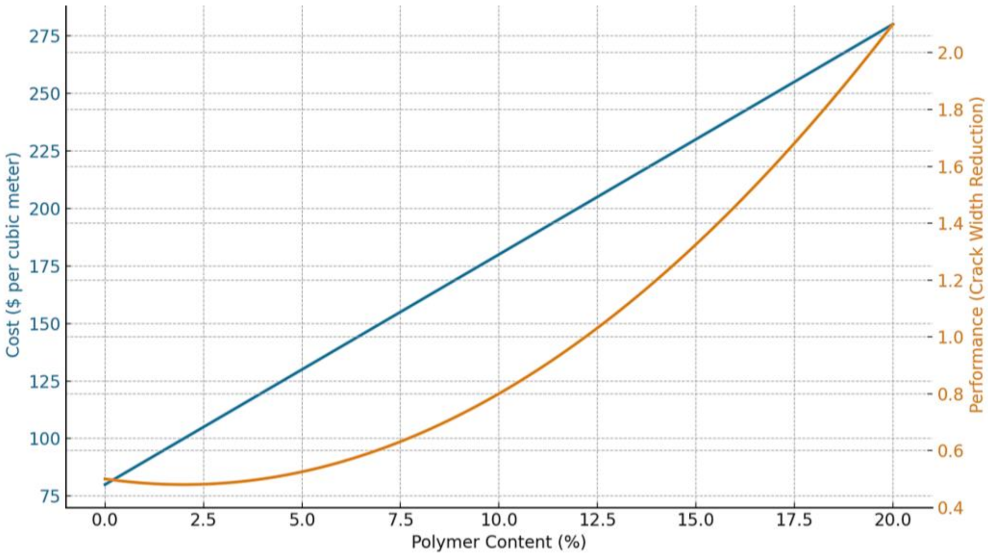

Figure 9. Cost-Performance Trade-Off for Polymer Concrete

To provide a more comprehensive understanding of the cost-benefit analysis (CBA), it is crucial to consider the impact of fluctuations in resin prices on the long-term viability of polymer concrete. The current CBA assumes fixed polymer costs, which may not reflect the realities of a fluctuating market. Fluctuations in resin prices can significantly affect the economic feasibility of polymer concrete, particularly in terms of its initial investment and lifecycle cost savings. As noted by Shrestha et al. [12], the long-term savings from reduced maintenance and extended service life make polymer concrete a cost-effective choice, but this balance could be disrupted by significant increases in raw material costs.

If resin prices were to increase, the initial costs of polymer concrete could rise, making it less competitive compared to traditional concrete in projects where budget constraints are significant. This could impact the wider adoption of polymer concrete, especially in cost-sensitive sectors. Conversely, if the price of resins were to decrease or stabilize, the economic advantages of polymer concrete, especially its long-term durability and reduced maintenance costs, would be further enhanced, making it an even more attractive option for high-performance infrastructure projects [19].

To address this potential variability, it is recommended that the cost-benefit analysis include sensitivity analyses that account for different scenarios of resin price fluctuations. By modeling potential price increases or decreases, this approach would provide a more robust and realistic assessment of polymer concrete's long-term viability. Such an analysis would help stakeholders better understand the economic risks and benefits, enabling more informed decisions about the use of polymer concrete in a dynamic market [25].

In conclusion, although Polymer Concrete may require higher initial investment, its long-term cost-effectiveness makes it a viable material for infrastructure projects that require high performance and durability. By reducing the need for frequent repairs and minimizing long-term maintenance costs, Polymer Concrete offers significant economic and practical advantages, particularly for high-performance applications.

4. Conclusion

This study has provided valuable insights into the role of polymer concrete (PC) in improving both the early-age performance and long-term durability of concrete structures. The key findings of the research demonstrate that polymer concrete significantly reduces early-age cracking, with crack widths decreasing by up to 56% compared to traditional Portland cement concrete (PCC). This reduction is attributed to enhanced bonding between polymer resins and aggregates, as well as the polymer's shrinkage-reducing properties. Furthermore, polymer concrete exhibits superior mechanical properties, including increased compressive, flexural, and fracture toughness strengths, especially at higher polymer content (15-20%).

Polymer concrete demonstrates significant potential for use in infrastructure projects, particularly in environments that demand high durability. In coastal infrastructure, such as piers and bridges, its superior resistance to freeze-thaw cycles and chemical exposure could substantially reduce long-term maintenance costs and improve structural integrity, making it a valuable material for ensuring the longevity of infrastructure in challenging environmental conditions. The findings of this study underline the importance of polymer concrete in enhancing the performance and durability of concrete structures, especially in harsh environments. Future research should focus on further validating these results through field studies, investigating the use of sustainable polymers, and exploring the economic feasibility of polymer concrete in broader applications.

The study also introduces a significant contribution to the understanding of the relationship between polymer content and the mechanical performance of polymer concrete, providing a model that guides the optimal polymer-to-aggregate ratio for achieving superior material properties. However, the research also underscores the need for further investigation into the economic feasibility of polymer concrete, especially considering its higher initial cost compared to PCC. Future studies should focus on evaluating the performance of polymer concrete in real-world conditions, as well as exploring alternative, more sustainable polymers and recycled aggregates to enhance both the material's environmental and economic benefits.

Additionally, long-term cost-benefit analyses that compare polymer concrete with traditional concrete in a wider range of infrastructure applications would provide a clearer picture of its viability as a sustainable construction material. By addressing these areas, future research can further optimize the use of polymer concrete, leading to its broader adoption in high-performance infrastructure projects and contributing to more sustainable and durable built environments.

Future research should focus on several areas to further enhance the understanding of polymer concrete's performance and applicability. First, field studies are essential to validate the findings of this research under real-world environmental conditions. Additionally, investigations into the use of sustainable polymer alternatives and recycled aggregates in polymer concrete could further improve the environmental and economic benefits of the material. Future studies should investigate the use of polymer concrete in coastal infrastructure, such as piers and bridges, to assess its performance under real-world environmental conditions. The material's superior resistance to freeze-thaw cycles and chemical exposure could offer significant advantages in reducing maintenance costs and extending the lifespan of infrastructure in these challenging environments. Future research should focus on field trials to validate laboratory results and assess the long-term performance of polymer concrete in real-world infrastructure applications.

For polymer concrete (PC) to be widely adopted in mainstream infrastructure applications, several critical steps must be taken. First, field trials are essential to validate laboratory results and demonstrate real-world performance in various infrastructure settings, such as coastal structures, bridges, pavements, and wastewater plants. These trials will allow for the assessment of PC's durability, crack resistance, and long-term performance under dynamic loading and environmental stressors. Additionally, a comprehensive cost-benefit analysis should be conducted to evaluate the life-cycle costs, including maintenance savings and reduced repair frequencies, to establish its economic viability compared to conventional concrete. Research into more sustainable polymers and the recyclability of PC is also critical for improving the material's environmental footprint and ensuring its sustainability in the long term. Finally, optimizing polymer content to balance strength, workability, and cost will be key in meeting industry standards for flexibility and performance in diverse applications. These steps are essential for bridging the gap between laboratory findings and real-world use, ensuring that polymer concrete becomes a viable and sustainable option for high-performance infrastructure projects.

5. Declarations

5.1. Author Contributions

Conceptualization, O.A.A., M.A., and AA.; methodology, O.A.A., M.A., and A.A.; software, O.A.A.; validation, M.A. and A.A.; formal analysis, M.A. and O.A.A.; investigation, O.A.A.; resources, O.A.A. and A.A.; data curation, M.A. and A.A.; writing—original draft preparation, M.A. and O.A.A.; writing—review and editing, M.A. and A.A.; visualization, O.A.A.; supervision, M.A. and A.A.; project administration, O.A.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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5.4. Acknowledgements

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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