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Recent Developments in Polymer Concrete: Considerations for Materials, Performance, and Sustainability

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Abstract

In modern infrastructure Growing need of durability and environmental has driven interest in polymer concrete (PC) as an alternative to conventional cement-based materials. This review critically evaluates recent developments in polymer concrete with emphasis on material innovations, performance characteristics, and sustainability aspects. Demonstration of Advanced polymer binders (e.g. epoxy, polyester and vinyl ester resins) shown significant improvements in mechanical strength, adhesion and chemical resistance. Investigation indicates that use of nanomaterials (e.g., carbon nanotubes (CNTs), graphene oxide and nano-silica) densificify microstructurally and increases strength (by about 10–35%). The integration of recycled materials (such as fly ash, slag and plastic waste) has been seen to decrease CO_2 emissions (by about 15–25%). In addition, bio-based binders obtained from renewable sources such as lignin, cellulose and chitosan are emerging as sustainable alternatives that reduce dependence on petrochemical resins while retaining competitive strength and durability. Despite these advantages, challenges such as high initial cost, thermal sensitivity and lack of standardized mix design protocols limit large-scale adoption. This review identifies critical knowledege gaps (in respect of long-term durability, nano-material dispersion and sustainability quantification) that outlines future research directions for the development of high-performance and environmentally sustainable polymer concrete systems. Beyond laboratory performance, the reviewed studies confirm the value of polymer concrete in structural repair, precast elements, marine structures and industrial flooring. By consolidating evidence reported between 2016 and 2025, this review provides a structured benchmark of present capabilities and a focused agenda for future innovation.

Keywords: Polymer concrete, polymer binders, nano-silica, carbon nanotubes (CNTs), graphene oxide, recycled materials, biopolymers, mechanical properties, durability, sustainable construction

INTRODUCTION

Polymer concrete (PC) is a complex composite material (Figure 1) in which there is a replacement of primary binder i.e., of conventional Portland cement by polymeric resins which gained considerable attention in modern construction due to durability, corrosion resistance and environmental impact. Extensive research since decade explored high-performance, durable and environmentally sustainable formulations incorporating nanotechnology, recycled materials and bio-based polymers.

This review focuses on advancements in polymer binders, nanomaterial integration, recycled material utilisation and biopolymer applications which aims to identify current performance benchmarks and future research directions.

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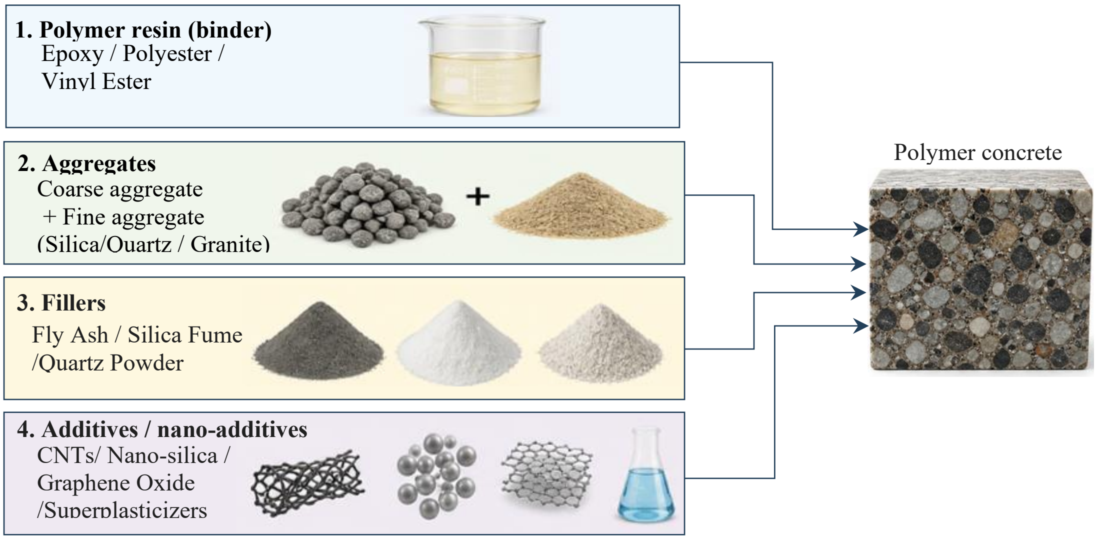


Polymer concrete is a composite material formed by combining polymer resin with aggregates, fillers, and additives to achieve enhanced strength, durability, and chemical resistance.

Figure 1. Schematic representation of polymer concrete composition showing polymer binder, aggregates, fillers, and nano-additives.
(Source: *Author)*

REVIEW OF THE LITERATURE

This section synthesises the published literature on polymer concrete, organised around four interrelated themes: polymer binders, nanomaterials and nano-modification, recycled and waste materials, and biopolymers. For each theme, the most significant experimental findings reported over the past decade are summarised, and the comparative strengths and limitations of the documented approaches are critically examined to establish the current state of knowledge.

Polymer Binders

The performance of polymer concrete is fundamentally governed by the characteristics of its polymer binder (Figure 2). Polymer binders are used with regular cement and enhance mechanical strength, chemical resistance, and long-term durability. Extensive research efforts have focused on improving binder performance over the past decade (2016–2025) to make binders work better and last longer.

Prevalent Polymer Resins

Experimental investigations reported in the literature indicate that some polymer binders can greatly improve the performance of polymer concrete. Singh S. B. [1] (2016) stated that epoxy-based polymer concrete had better adhesion, much better durability and higher compressive strength. Tayeh B. A. [2] (2018) found that polyester based polymer concrete (a cheaper material) is a good material for the use of non-structural and precast. Gupta T. [4] (2020) claimed that in chemical environment the vinyl ester resins are more resistant to corrosion and long later. Haddad R. H. [5] (2021) showed that thermosetting resins (such as vinyl ester, polyester and epoxy) make a dense cross-linked polymer matrix which makes less permeable and more durable material. The compiled results demonstrated that consistently the traditional polymer binders improves the strength and durability of polymer concrete (Table 1).

Critical Synthesis: Polymer Binder Performance

A critical comparison of the reviewed studies shows several important differences. Epoxy resins (Singh [1], 2016) always give the highest compressive strength (80-100 MPa) but brittle under impact loading is a well-documented limitation which is not observed in polyester-based systems (Tayeh [2], 2018). The contrasting results of Gupta [4] (2020) and Haddad [5] (2021) on permeability reduction, attributes different resin to aggregate ratios and curing temperatures in those studies which underscores direct cross-study comparison without standardized test protocols. Future studies should be performed using standardized testing according to ASTM C39 and EN 12390-3, which will allow meaningful comparison between studies.

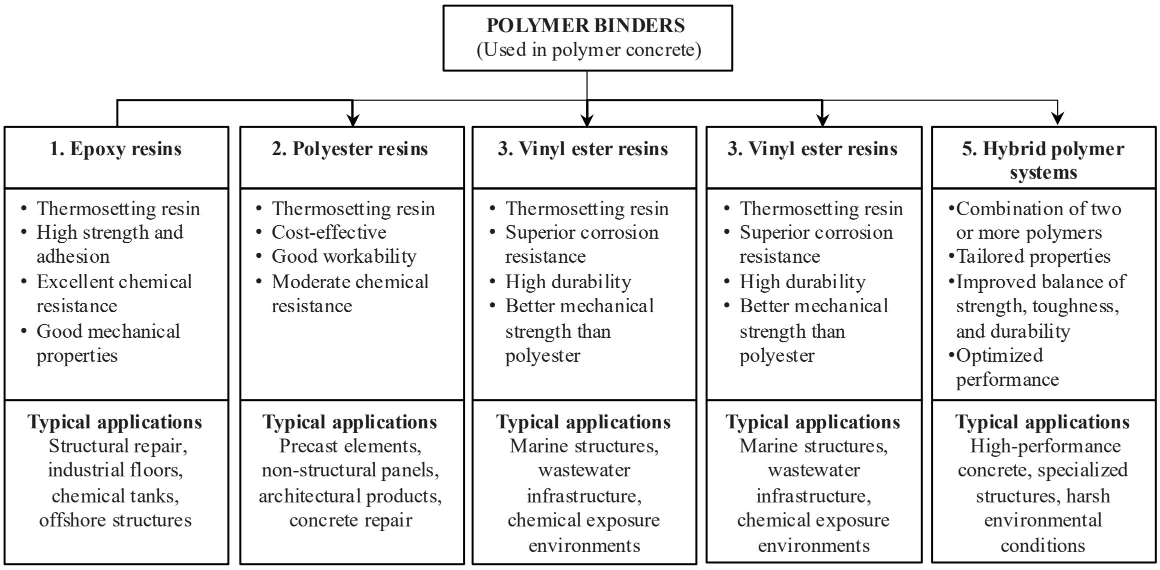


Figure 2. Classification of polymer binders used in polymer concrete systems.
***(Source:** Author)*

Table 1. Overview of polymer binder categories, standard compressive strengths, and essential performance attributes.

Type of Binder	Compressive Strength	Principal Asset	Source
Epoxy	80 to 100 MPa	Superior adherence and durability	Singh S. B. [1], 2016
Polyester	60 to 80 MPa	Economically viable, appropriate precast	Tayeh B. A. [2], 2018
Vinyl Ester	70 to 90 MPa	Superb corrosion resistance	Gupta T. [4], 2020
Bio-based (Lignin)	50 to 70 MPa	Eco-friendly, compostable	Fiore V. [3], 2019
Epoxy–Polyester Hybrid	75 to 95 MPa	Decreased brittleness, enhanced toughness	Almeshal I. [10], 2022
Polymer–Geopolymer Hybrid	80 to 100 MPa	Thermal stability and strength	Muthukumar M. [11], 2023

***Source**: Aggregated from analyzed literature.*
***Note:** Compressive strength values were obtained under varying experimental conditions. Unless otherwise stated, specimens were cured at ambient temperature (20–25°C) with natural silica or quartz aggregate and a resin-to-aggregate ratio of approximately 1:4 by weight. Cross-study comparisons should account for these differences.*

Emerging Polymer Materials

Recently, the high performance and sustainable polymer binders become a focus. Fiore Vito [3] (2019) studied bio-based polymers with lignin and natural fibers, highlighting the improved mechanical properties and the greater sustainability features. As Farooq Fawad [6] (2021) pointed out that bio-based resins can decrease environmental impact while keeping adequate strength and durability. Almeshal Ibrahim [10] studied hybrid epoxy-polyester systems in 2022 and reported lower brittleness and higher toughness. Muthukumar M. 2023. Study on polymer–geopolymer hybrid systems. The study showed a significant improvement in thermal stability and mechanical strength. Recent research has been focused on a prominent movement towards hybrid and sustainable polymer binders that enhance both structural and environmental performance.

Performance Features of Polymer Binders

Recent research has thoroughly characterised the performance properties of polymer binders. Singh S. B. [1] (2016) reported strong adhesion between binder and aggregates, thereby enhancing structural integrity. Haddad R. H. [5] (2021) further confirmed this finding, emphasising that the dense polymer matrix is instrumental in achieving superior bond strength. Tayeh B. A. [2] (2018) noted low permeability, which confers improved durability against environmental exposure and reduced water absorption. Gupta T. [4] (2020) identified enhanced chemical resistance, contributing to extended service life against acids, salts, and other corrosive substances. Farooq F. [6] (2021) observed rapid strength development, attributed to the accelerated polymerisation and curing processes of polymer binders. Taken together, the reviewed studies suggest demonstrate the superior performance of polymer concrete relative to conventional cement-based materials.

Nanomaterials and Nano-Modification

Recent investigations have concentrated on nano-scale modifications (Figure 3) to enhance the microstructural and mechanical performance of polymer concrete like graphene oxide, carbon nanotubes (CNTs), and nano-silica to improve performance at the microstructural level. Siddique Rafat [12] (2016) stated that nano-silica fills in nano-voids and makes microstructural densification much better, which makes the material stronger and more durable. Research by Maria S. Konsta-Gdoutos in 2017 showed that carbon nanotubes improve tensile strength and fracture resistance because they have a high aspect ratio and a mechanism for bridging cracks. Lv Shuang [14] (2018) observed that graphene oxide enhances interfacial bonding, leading to improved mechanical properties and reduced permeability. Chuah Siang Huat [9] (2021) affirmed that nano-modification enhances resistance to wear and corrosion (Table 2).

Table 2. Nanomaterials incorporated in polymer concrete and their performance effects.

Nanomaterial	Effect on PC	Strength Gain (%)	Reference
Nano-silica	Microstructure densification	10–20%	Siddique R. [12], 2016
Carbon Nanotubes (CNTs)	Tensile & fracture resistance	15–30%	Konsta-Gdoutos [13], 2017
Graphene Oxide	Interface bonding, ↓ permeability	20–35%	Lv Shuang [14], 2018
Nano-modification (general)	Wear & corrosion resistance	10–25%	Chuah S. H. [9], 2021

Source: *Compiled from reviewed literature.*
Note: *Strength gain percentages refer to improvement over unreinforced polymer concrete baseline. Nanoparticle dosages ranged from 0.5–2.0 wt% in the cited studies; curing was conducted at ambient temperature (20–25°C) unless otherwise stated by original authors.*

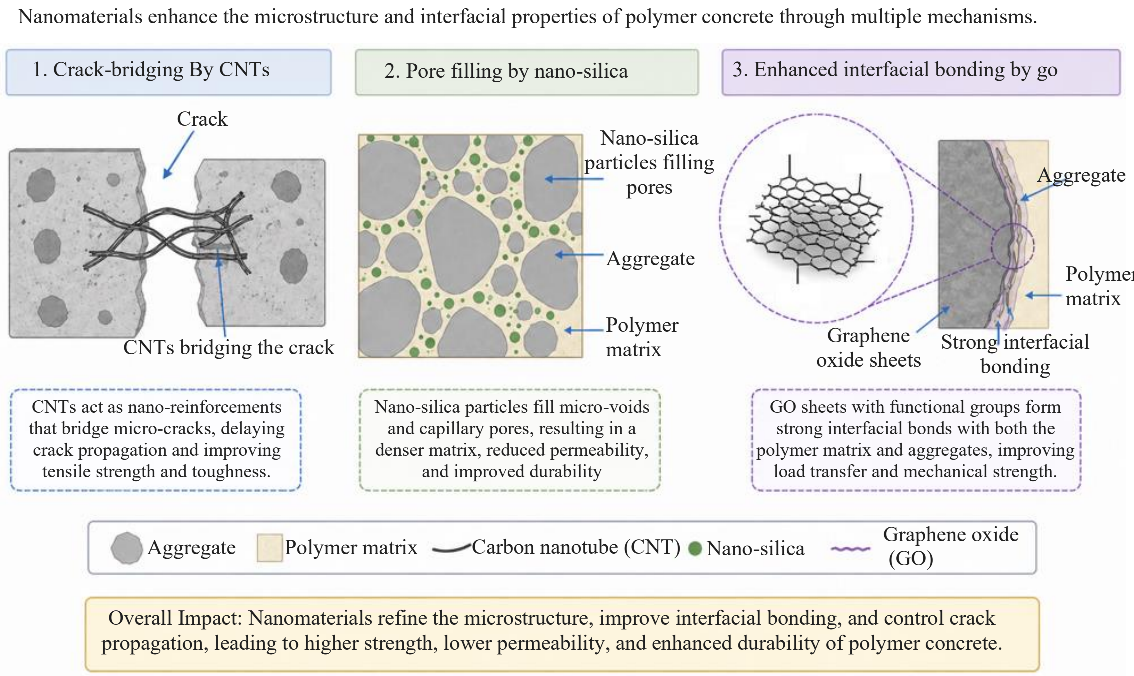


Figure 3. Mechanisms of nano-modification in polymer concrete including crack-bridging, pore filling, and interfacial bonding enhancement.
(Source: *Author)*

Nanoparticles improve mechanical strength, durability, and microstructural densification, making polymer concrete more suitable for advanced structural applications. In a recent contribution, Dabral and Babbar [8] (2025) demonstrated that the combined use of nano-silica and natural Pinus fibre in concrete paver blocks—a fibre-reinforced polymer-cement composite—improved mechanical performance while introducing a renewable reinforcing phase.

Critical Synthesis: Nanomaterial Integration

While all three nanomaterials reviewed—nano-silica, CNTs, and graphene oxide—improve PC performance, the mechanisms and trade-offs differ significantly. Nano-silica (Siddique [12], 2016) primarily densifies the microstructure through pore-filling, yielding modest strength gains (10–20%) at relatively low cost, making it the most practically viable option. CNTs (Konsta-Gdoutos [13], 2017) offer the highest tensile strength improvement (15–30%) through crack-bridging, but their dispersion in viscous polymer matrices remains a critical unresolved challenge. Graphene oxide (Lv [14], 2018) achieves the greatest strength gain (20–35%) through interfacial bonding enhancement, yet its high cost and complex functionalisation requirements limit scalability. Notably, no reviewed study directly compared all three nanomaterials under identical mix design and curing conditions, representing a significant knowledge gap. Combined nano-additive systems also remain largely unexplored, and the long-term stability of nanoparticle–polymer interfaces under cyclic loading has not been characterised.

Recycled and Waste Materials

Environmental concerns and sustainability objectives have attracted significant research attention towards the integration of recycled and waste materials in polymer concrete (Figure 4). Increasing research attention has been directed toward materials like fly ash, slag, silica fume, recycled aggregates, and plastic waste (PET, PVC). Khaled S. Rebeiz [15] (2016) demonstrated that recycled plastic can be utilized as aggregate, reducing material costs and environmental impacts. Gupta T. [16] (2019) demonstrated that the incorporation of fly ash and slag improves workability and long-term strength

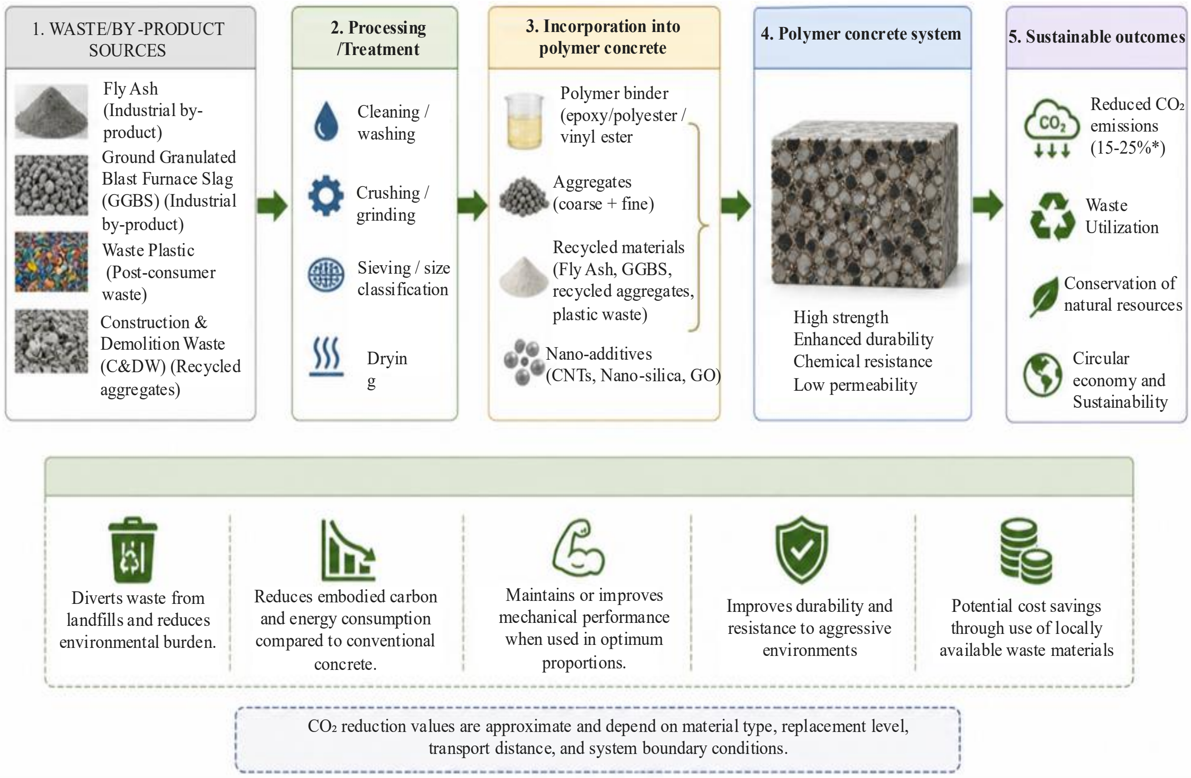


Figure 4. Integration of recycled and waste materials in polymer concrete within a circular economy framework.
***(Source:** Author)*

gain while reducing CO_2 emissions by approximately 15–20% compared to ordinary Portland cement concrete, as reported in associated life cycle assessments. Singh N. [17] (2020) established that correctly processed recycled aggregates achieve compressive strengths comparable to those of virgin aggregates. Kumar R. [18] (2022) affirmed that these materials are consistent with circular economy principles, converting industrial waste streams into viable construction feedstocks (Table 3). The adoption of these materials promotes environmentally responsible construction practices and reduces the overall ecological footprint of concrete production.

Critical Synthesis: Reclaimed and Waste Materials

The combined results of the reviewed studies suggest that PC can be formulated with recycled materials without significant penalty to mechanical properties, but that significant differences exist depending on the type of material. Rebeiz [15] (2016) noted a reduction in cost and landfill waste when recycled PET plastic is used as aggregate, but also realized a 5–10% decrease in compressive strength when compared to natural aggregate systems, a tradeoff not seen in the sustainability discussion of previous studies. Gupta [16] (2019) reported reductions of CO2 of around 15-20% with incorporation of fly ash. However, these are based on process level assessments and may not capture the full life cycle impacts such as material transport . Singh [17] (2020) found that recycled aggregates only achieve comparable strength if pre-treated to remove surface contaminants, but no standard pre-treatment protocol exists across the literature reviewed. This inconsistency is a critical knowledge gap that hinders the reproducibility of findings and the development of generally applicable mix design guidelines for sustainable PC.

Biopolymers

Figure 5 illustrates the structured pathway of bio-based polymers from biomass extraction to binder formulation and into polymer concrete, allowing better sustainability performance.

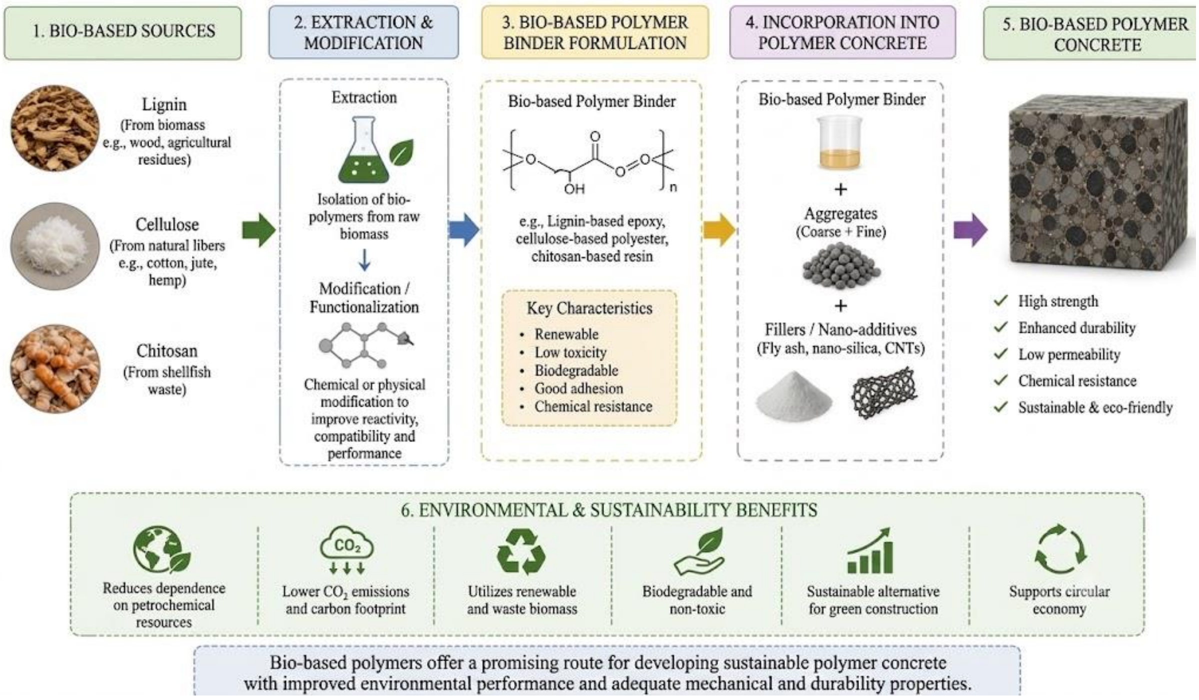
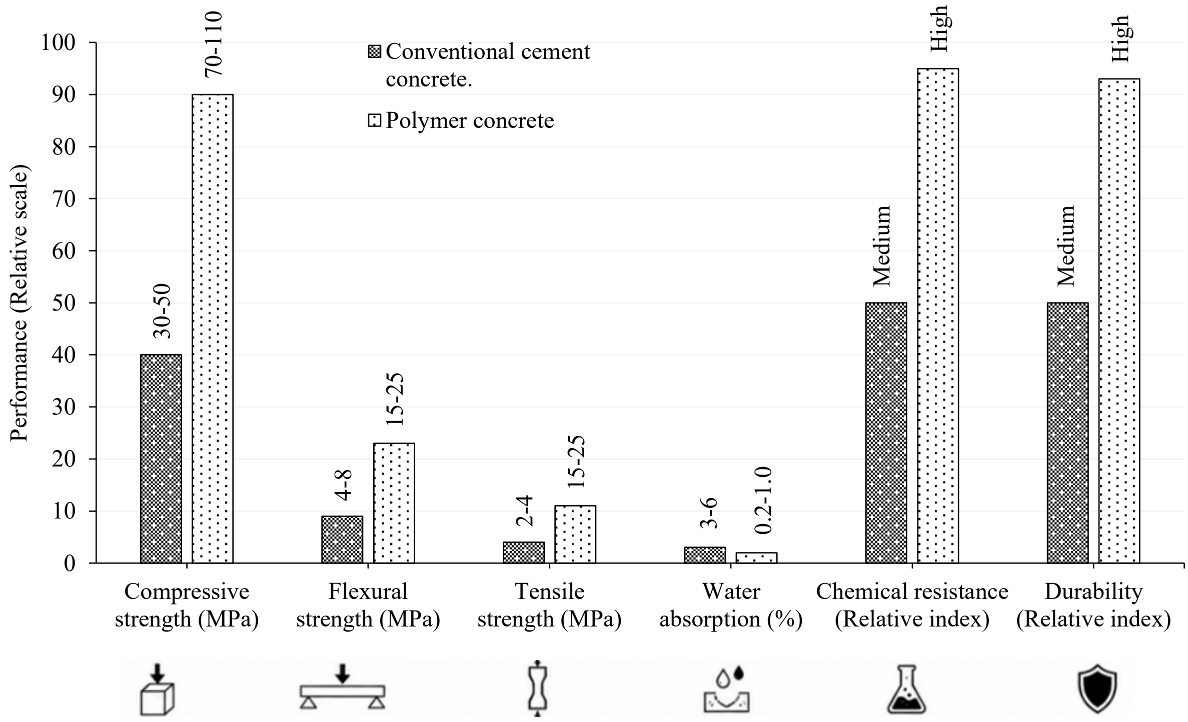


Figure 5. Schematic overview of the integration of bio-based polymers in polymer concrete with source materials (lignin, cellulose, chitosan), extraction and modification processes, formulation of bio-based polymer binders and their integration in polymer concrete systems with aggregates and additives. The figure also points out the major sustainability benefits such as lower CO_2 emissions, the use of renewable resources and better environmental performance.
(Source: *Author)*

Biopolymers have been shown to be a viable alternative to conventional synthetic resins in polymer concrete. The functional and environmental benefits of natural polymers such as cellulose, chitosan and lignin have been studied. Fiore V. [3] (2019) demonstrated that lignin based polymers have satisfying mechanical properties with better environmental performances. Farooq F. [6] (2021) found that biopolymers are more biodegradable and less dependent on petrochemical feedstocks. Alavijeh M. K. [19] (2022) showed that the chitosan-based modifications enhance the fracture resistance and overall durability. Zhang J. [20] (2023) confirmed long-term structural stability and sustained performance of bio-based binders. Biopolymers are a class of materials with a great potential for use in sustainable construction applications that offer better durability, biodegradability and longevity compared to traditional synthetic alternatives.

CRITICAL DISCUSSION AND EVALUATION

Drawing on the thematic survey presented above, this section critically evaluates the performance of polymer concrete in comparison with conventional cement-based systems (Figure 6). The assessment is organised around four interrelated dimensions—mechanical behaviour, long-term durability, thermal and shrinkage response, and emerging functional capabilities—in order to weigh the documented benefits against the practical constraints reported across the reviewed studies.



Polymer concrete exhibits significantly higher strength, lower permeability, and superior resistance to aggressive environments compared to conventional cement concrete.

Common testing standards used for property evaluation						
ASTM C39	ASTM C78	ASTM C496	ASTM C642	ASTM C1202	ASTM D543	EN 12390 Series
Compressive strength	Flexural strength	Splitting tensile	Water absorption	Chloride Ion permeability	Chemical resistance	Mechanical testing (Alternative)

Note: Values represent typical ranges from higher strength, lower permeability, and superior resistance to aggressive environments compared to conventional cement concrete.

Figure 6. Comparative performance characteristics of polymer concrete and conventional cement concrete.
(Source: Author)

Table 3. Recycled and waste materials employed in polymer concrete.

Material	Role in PC	Environmental Benefit	Reference
Recycled Plastic (PET/PVC)	Aggregate replacement	Reduces landfill waste	Rebeiz K. S. [15], 2016
Fly Ash & Slag	Filler/binder supplement	Lowers carbon emissions	Gupta T. [16], 2019
Recycled Aggregates	Coarse/fine aggregate	Conserves virgin resources	Singh N. [17], 2020
Industrial By-products	Circular economy feedstock	Waste valorisation	Kumar R. [18], 2022

Source: *Compiled from reviewed literature.*

Table 4. Comparison of mechanical and durability properties between ordinary concrete and polymer concrete.

Property	Ordinary Concrete	Polymer Concrete	Reference
Compressive Strength (MPa)	20–40	60–120	Singh S.B. [1], 2016
Tensile Strength (MPa)	2–5	5–15	Tayeh B.A. [2], 2018
Water Absorption (%)	5–10	< 1	Gupta T. [4], 2020
Flexural Strength (MPa)	3–5	8–20	Farooq F. [6], 2021
Chemical Resistance	Moderate	Excellent	Haddad R.H. [5], 2021

Source: *Compiled from reviewed literature.*
Note: *Compressive strength tested per ASTM C39 / EN 12390-3; tensile strength per ASTM C496; flexural strength per ASTM C78 / EN 12390-5; water absorption per ASTM C642 / ISO 15148. Values represent ranges reported across studies conducted at ambient curing conditions (20–25°C) with silica or quartz aggregate.*

Mechanical Properties

Polymer concrete has much higher mechanical properties than that of conventional cement concrete. Singh S. B. [1] (2016) reported that epoxy-based formulations gave compressive strengths of 90–100 MPa together with excellent adhesive properties when tested according to ASTM C39. Tayeh B. A. [2] (2018) reported that the PC has higher flexural and tensile strength than normal concrete and it can be used in precast and structural applications. The flexural strength was evaluated based on ASTM C78. Gupta T. [4] (2020) has shown that better bonding between aggregate and reinforcement improves load transfer. Farooq Fawad [6] (2021) reported better flexibility and greater strength-to-weight ratio than traditional concrete (Table 4). More recently, Antima and Babbar [7] (2025) investigated polymer-cement composite hollow bricks incorporating aerated aggregates and reported favourable mechanical performance suitable for lightweight structural masonry.

Longevity

Polymer concrete has the advantages of being durable. The resistance to chemical attack, acids and harsh environments was found to be excellent and because of the dense polymer matrix [5] Haddad R. H., 2021. As shown by Gupta T. [4] (2020), low permeability decreases infiltration of water and improves long-term performance. Chuah S. H. [9] (2021) confirmed improved resistance to freeze-thaw cycles, making PC suitable for severe climates. These properties make polymer concrete highly suitable for industrial floors, marine constructions and sewage systems.

Thermal and Shrinkage Behaviour

Polymer concrete exhibits unique temperature and shrinkage characteristics during the process of polymerization than that of traditional concrete. Almeshal Ibrahim [10] (2022) showed that the faster chemical reactions in polymer binders lead to faster curing rates. Muthukumar M. [11] (2023) concluded that shrinkage cracking may be reduced by an appropriate mix design. Farooq Fawad [6] (2021) reported that polymer concrete has a higher thermal expansion than regular concrete and it needs to be considered in the structural design process.

Functional Features

Recent research has produced polymer concrete with improved functional properties. Maria S. Konsta-Gdoutos In 2017, a research announced the development of self-sensing (smart) concrete for structural health monitoring with the use of nanoparticles. Lv Shuang [14] (2018) presented the development of self-healing materials with autonomous reparability for microcracks. Zhang Jian [20]

(2023) highlighted the advancements in lightweight polymer composites, which can maintain strength and reduce the dead weight of structures.

POLYMER CONCRETE APPLICATIONS

The varied performance characteristics of polymer concrete have led to its use in a variety of infrastructure applications (Table 5). The main application domains are indicated below.

PC [1] provides better adhesion and rapid strength gain which is useful in applications such as crack filling, patching and bridge deck overlays for structural repair and rehabilitation. Due to its high early strength and dimensional stability, polymer concrete is used in the production of precast elements such as wall panels, manholes, railway sleepers and drainage pipes [2]. Their resistance to chlorine corrosion and harsh environmental conditions are utilized in marine and coastal constructions [4]. Polymer concrete is used for chemical facilities and industrial flooring applications because of its low permeability and acid resistance [5]. Wastewater and sewage systems are advantageous because they are resistant to chemical and biological deterioration [6]. Transportation infrastructure (bridge decks, road repairs and airport pavements) benefits from rapid construction and outstanding durability [10]. Innovative smart applications include self-sensing, self-healing and 3D-printed polymer concrete composites [11].

ADVANTAGES AND LIMITATIONS

Polymer concrete combines a number of compelling performance benefits with several practical and economic constraints that together determine its suitability for a given application. Weighing these competing factors is therefore essential when selecting polymer concrete over conventional alternatives and when prioritising areas for further development. Table 6 summarises the principal advantages and current limitations of polymer concrete.

FUTURE RESEARCH DIRECTIONS

Based on the reviewed literature, the following priority research directions have been identified, each grounded in specific gaps noted across Sections 2–3 (Table 7):

Table 5. Key application areas of polymer concrete.

Application Area	Specific Uses	Reference
Structural Repair	Crack filling, bridge deck overlays, patching	Singh S.B. [1], 2016
Precast Components	Manholes, pipes, railway sleepers, wall panels	Tayeh B.A. [2], 2018
Marine Structures	Offshore platforms, coastal protection	Gupta T. [4], 2020
Industrial Flooring	Chemical plants, storage facilities	Haddad R.H. [5], 2021
Wastewater Systems	Sewer pipes, drainage channels, treatment plants	Farooq F. [6], 2021
Transportation	Bridge decks, road repairs, airport pavements	Almeshal I. [10], 2022
Smart/Emerging	Self-sensing, self-healing, 3D-printed composites	Muthukumar M. [11], 2023

Source: *Compiled from reviewed literature.*

Table 6. Advantages and limitations of polymer concrete.

Advantages	Limitations
High compressive & tensile strength	High initial material cost
Excellent chemical & corrosion resistance	Heat/fire sensitivity of polymer matrix
Low permeability and water absorption	More complex mixing and curing process
Rapid curing and strength development	Limited standardisation of mix design
Durability in extreme environments	Thermal expansion larger than OPC concrete
Enables use of recycled/waste materials	Restricted large-scale adoption

Source: *Authors.*

Table 7. Future research directions and expected outcomes for polymer concrete.

Research Direction	Expected Outcome
Bio-based and green polymer binders: comparative studies of lignin vs. chitosan under freeze-thaw cycling (gap identified in Sections 2.1.2 and 2.4)	Quantified CO_2 reduction (LCA-based); reduced petrochemical dependence with maintained compressive strength ≥ 60 MPa
Optimisation of CNT and graphene oxide dosage in PC: no study has established a universal optimal loading; dispersion methods remain inconsistent across studies (gap from Section 2.2)	Standardised dosage protocols; consistent strength gains of 20–35% with reproducible dispersion methods
Polymer–geopolymer hybrid systems: thermal performance above 200°C has not been systematically characterised; cost modelling absent from existing studies (gap from Section 2.1.2)	Validated performance at elevated temperatures; cost-benefit analysis demonstrating feasibility for large-scale infrastructure
Self-sensing smart PC: existing studies (Konsta-Gdoutos [13], 2017) demonstrate proof-of-concept; field validation under cyclic loading and corrosive environments is absent	Field-validated sensing performance under cyclic loading and chemical exposure; prototype deployment in bridge deck monitoring
Self-healing PC: microcrack repair has been demonstrated (Lv [14], 2018) but healing efficiency under repeated loading cycles and long-term structural performance remain unquantified	Quantified healing efficiency (≥80% strength recovery) after repeated loading; validated long-term durability over 10+ year service life
3D printing with PC: printability of high-viscosity polymer binders and layer adhesion under field conditions are not yet characterised (gap from Section 3.4)	Printability protocols for high-viscosity PC binders; inter-layer adhesion strength ≥85% of cast specimens per ASTM C1140
AI/ML for PC mix design: no validated predictive model exists for multi-variable PC formulations incorporating nano-additives and recycled aggregates simultaneously (gap from Sections 2.2 and 2.3)	Validated ML model with $R^2 \geq 0.95$ for multi-variable PC mix design, covering nano-additives, recycled aggregates, and polymer binder type simultaneously

Source: *Authors.*

CONCLUSION

There are certain limitations to this review. Differences in experimental conditions such as curing temperature, resin composition and aggregate type make direct quantitative comparison between different studies impossible. Furthermore, the lack of long-term field performance data and standardized reporting frameworks leads to uncertainty in evaluating durability and sustainability outcomes.

The present review has proved that polymer concrete is a better alternative to conventional cement concrete by giving better mechanical strength, better durability and more toughness in extreme environmental conditions. The main findings arising from the literature reviewed are:

- The performance of polymer concrete has been greatly improved by combining advanced polymer binders, nanomaterials, recycled materials and biopolymers.
- Singh S. B. [1] (2016), Gupta T. [4] (2020) and Haddad R. H. [5] (2021) reported progressive improvements in the compressive strength, reduction in permeability and enhanced chemical resistance in polymer concrete formulations.
- The incorporation of carbon nanotubes and graphene oxide significantly improves tensile strength and microstructural densification in polymer concrete.
- The use of recycled and waste materials is in the context of the circular economy concept and is not relevant for the mechanical behavior.

However, the benefits of high initial material costs, susceptibility to high temperatures and lack of standardisation of mix design still hinder widespread adoption.

Future research should be directed towards bio-based binders, AI-optimized mix design, intelligent concrete technologies, and 3D printing applications to expand the use of polymer concrete in sustainable infrastructure.

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