



Review

Evolutionary process and mechanical properties of polymers: A comprehensive review

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ABSTRACT

The growing demand for innovative construction materials has driven the exploration of polymer-based composites due to their enhanced mechanical performance and potential environmental benefits. However, a clear understanding of the historical development, classification, and structural behavior of polymers in construction remains limited. This review aims to bridge this gap by synthesizing current knowledge on the historical evolution, mechanical benefits, chemical benefits, drawbacks and real world applications of polymers in construction. The study focuses on key thermosetting resins such as polyester, epoxy, vinyl ester, and PET and assesses their mechanical properties relevant to structural applications. To address the lack of integrated insight in the literature, the review compiles and compares data from various primary sources. Mechanical properties such as tensile, compressive, and flexural strength are evaluated to determine the suitability of each polymer for construction use. The outcomes indicate that epoxy resins demonstrate superior tensile and flexural strength, while polyester and polyethylene terephthalate PET offer notable advantages in compressive resistance and sustainability. Overall, the findings provide a consolidated understanding of polymer development and performance, offering valuable guidance for researchers and engineers aiming to enhance material efficiency, durability, and environmental responsibility in the construction industry.

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1. Introduction

The rapid industrialization of the modern era has led to an increased demand for materials that are not only strong and lightweight but also flexible and durable. Historically, natural polymers such as rubber, wool, cotton, and silk were widely used to meet these needs. However, their limited availability, high costs, and inconsistent performance posed significant challenges. One of the primary concerns was the scarcity and expense of natural rubber, which prompted researchers to explore synthetic alternatives. This shift led to the rapid expansion of the polymer industry following World War II, resulting in the development of various synthetic plastics such as polyethylene, polystyrene, and polyvinyl chloride

(PVC) (Feldman 2008). These materials quickly gained popularity due to their affordability, versatility, and broad applicability in industries ranging from packaging and household appliances to construction.

Polymers, in essence, are materials that can be molded into various shapes during manufacturing, making them essential structural components in a wide range of applications. They consist of one or more types of synthetic or chemically modified natural polymers, which are built from individual functional units known as monomers and combined with chemical additives (Seewoo et al. 2024). A monomer is a small molecule that bonds with others to form a larger structure, creating a polymer, a macromolecule composed of repeated subunits. The structural arrangement of polymers influences

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their physical properties, such as strength, transparency, and flexibility. For instance, polymers containing ethylene and terephthalate can exist in different forms amorphous, semi-crystalline, or colorless depending on their molecular organization (Soni et al. 2024). The ability to manipulate polymer structure and composition has allowed for the development of materials with enhanced mechanical and chemical properties tailored to specific applications.

Due to their diverse properties, polymer materials are selected based on various factors, including strength, flexibility, resistance to corrosion, thermal stability, electrical conductivity, and cost. In addition to performance requirements, material selection is influenced by safety concerns such as the risks associated with monomers, their potential migration in food-contact plastics, and the presence of additives or microplastics (Seewoo et al. 2024). Commonly used polymers such as polyethylene, polypropylene, polystyrene, PVC, and nylon have been widely integrated into industrial and consumer applications, with ongoing research dedicated to improving their sustainability and performance (Salami et al. 2024).

In the construction industry, polymer concrete emerged as a solution to address the limitations of traditional concrete, particularly its susceptibility to cracking,

low chemical resistance, and high permeability. The composition of polymer concrete plays a crucial role in determining its overall performance. Studies indicate that an optimal polymer content of 12–14% by weight enhances flexural strength (4 to 50 MPa) and increases compressive strength (40 to 150 MPa) (Ali and Ansari 2013). The integration of polymers into concrete mixtures gained significant attention in the 1950s, leading to the development of polymer-modified concrete, which offers improved flexibility, reduced permeability, and enhanced durability (Bulut and Şahin 2017; Waysal et al. 2023).

One of the primary advantages of polymer concrete is its ability to reduce material consumption while offering significantly enhanced performance compared to conventional cement concrete, as shown in Table 1. For example, polymer concrete exhibits much higher compressive strength (40–150 MPa) than traditional concrete (10–60 MPa), as well as superior flexural and tensile strengths. Additionally, it absorbs less water (0.5–3%) and demonstrates excellent chemical resistance, in contrast to the higher water absorption (4–10%) and poor-to-average chemical resistance of traditional concrete. These improved properties contribute to greater durability and making polymer concrete a more efficient and long-lasting construction material.

Table 1. Comparison of the properties of traditional and polymer concrete (Ali and Ansari 2013).

Properties	Traditional concrete	Polymer concrete
Compressive	10–60 MPa	40–150 MPa
Flexural strength	1.5–7 MPa	4–50 MPa
Tensile strength	0.6–3.0 MPa	4.0–20.0 MPa
Water absorption	4–10%	0.5–3%
Chemical resistance	Poor–Average	Very good–Excellent

In addition, polymer concrete demonstrates enhanced drainage properties, making it a preferred choice in applications requiring high permeability control. As illustrated in Fig. 1, these benefits stem from the material's unique pore structure, which influences water movement within the concrete matrix. In conventional concrete, refer Fig. 1(a), permeability is facilitated by interconnected voids between aggregate particles allowing water to flow freely. In contrast, polymer concrete exhibits a significantly lower permeability, as its polymer binder effectively fills or minimizes voids within the structure as shown in Fig. 1(b). As a result, water tends to accumulate on the surface rather than seeping through the material (Tabatabaeian et al. 2019). This reduced permeability plays a crucial role in preventing internal deterioration, minimizing chemical attacks, and enhancing resistance to moisture-related damage, thereby extending the lifespan and structural integrity of polymer concrete.

The composition of polymer concrete is another defining factor that differentiates it from traditional concrete types such as Portland cement concrete, polymer-modified concrete, and polymer-impregnated concrete.

A critical component of polymer concrete is its aggregate system, which provides mechanical strength and influences the overall performance of the material. Aggregates are typically categorized into coarse aggregates (larger than 5 mm) and fine aggregates (smaller than 5 mm), both of which contribute to the material's stability and durability. In polymer concrete, aggregates and fillers generally account for 75–80% of the total volume, serving as a structural framework within the polymer matrix (Bedi et al. 2013). The choice of aggregate type, in addition to factors such as polymer selection, curing temperature, and dosage of key components, significantly affects the mechanical performance and long-term behavior of polymer concrete (Kumar 2016).

Although extensive research has been conducted on various types of polymers and their applications, there is still a lack of comprehensive reviews that link the history of polymer development to their structural advantages, limitations and evolving roles in the construction industry. Most of the existing literature tends to focus on isolated aspects such as material performance or environmental impact. Therefore, this review aims to bridge this

gap by synthesizing current knowledge on the historical evolution, mechanical benefits, chemical benefits, drawbacks and real world applications of polymers in construction. By offering an integrated perspective, this pa-

per aims to support researchers, engineers, and policymakers in understanding the broader context and future potential of polymer-based materials in building and infrastructure development.

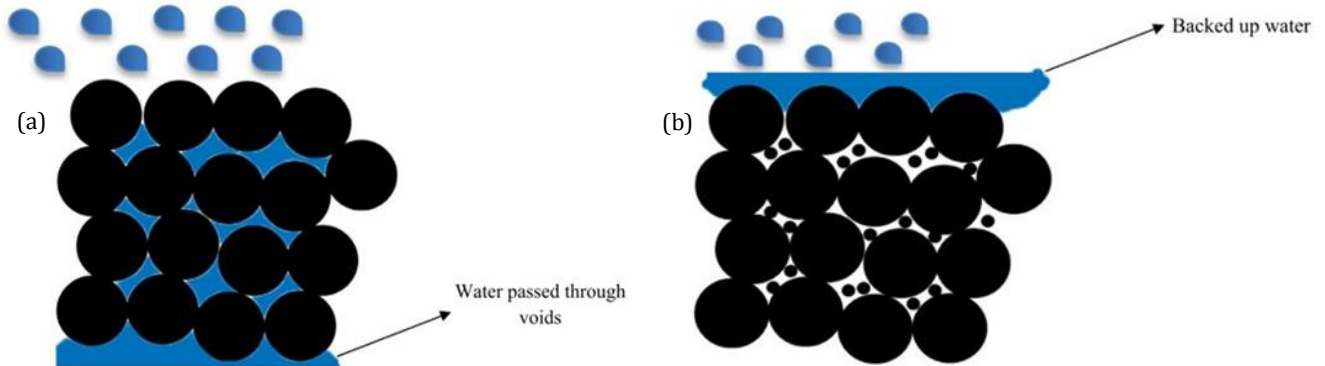


Fig. 1. The comparison of (a) conventional concrete and (b) polymer concrete (Tabatabaeian et al. 2019).

2. Development and Application of Polymer Concrete

The existence and production of polymers have been an integral part of scientific and industrial development for over a century. A significant milestone in polymer-based construction materials was achieved in 1923 when Cresson and Lefebure secured a patent for polymer-modified mortar, marking an early innovation in the field (Nodehi 2022). Since then, polymers have continued to gain attention for their versatility, durability, and diverse applications, making them an essential component in modern construction materials. Researchers play a critical role in optimizing the use, modification, and

production of polymer-based materials to improve their performance, particularly for on-site construction applications.

The evolution of polymer composites in construction has been well-documented, with notable advancements shaping the industry over the decades. As highlighted in Nodehi (2022), the continuous refinement and development of polymer-based materials have resulted in substantial improvements in strength, durability, and sustainability. The progression of polymer concrete, from its early development stages to present applications, can be better understood through the timeline of key advancements (Fig. 2) and the historical evolution of composite materials (Table 2).

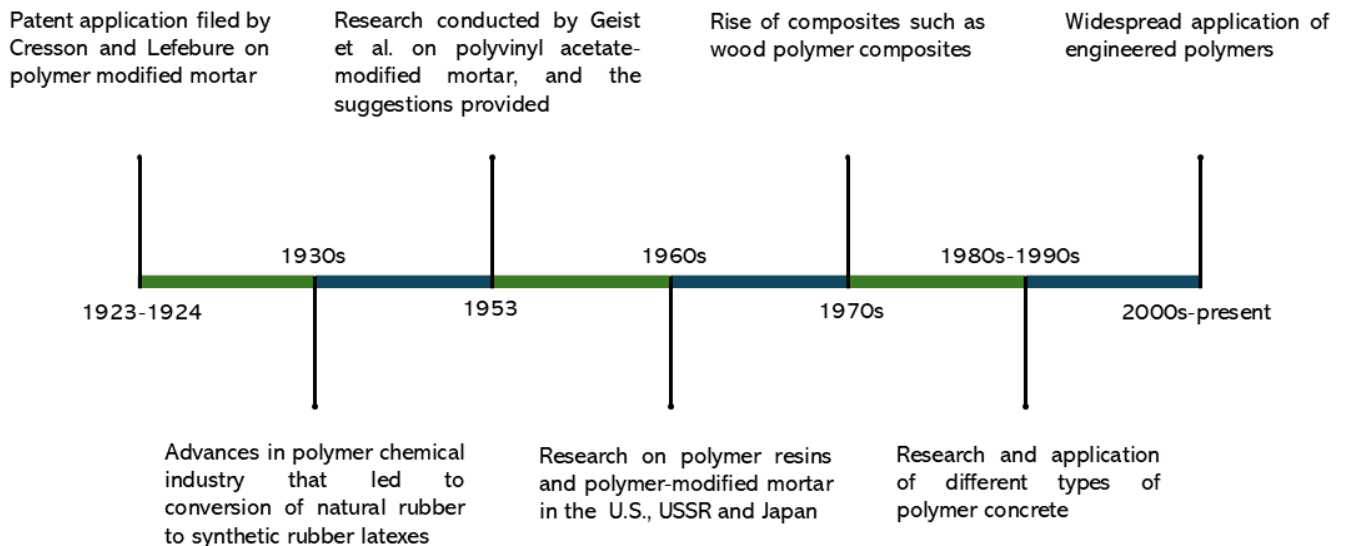


Fig. 2. Timeline of polymer concrete development (Nodehi 2022).

The historical development of polymer concrete reflects major advancements in both material science and practical applications. It started in the early 20th century. The milestone occurred in 1923–1924 when Cresson and Lefebure filed a patent for polymer-modified

mortar. This innovation coincided with progress in polymer chemistry, particularly the shift from natural to synthetic rubber latexes, laying the groundwork for polymer use in cement-based materials. By the 1930s, the growing polymer industry enabled more structured ex-

perimentation in construction. In 1953, Geist et al. conducted a notable study on polyvinyl acetate-modified mortar. The highlight of the study is on how polymers could enhance bonding and flexibility in traditional sys-

tems. The 1960s saw expanded research in the U.S., USSR, and Japan on polymer resins and polymer-modified mortars, deepening the understanding of polymer cement interactions.

Table 2. Polymer composite history (Godara et al. 2021).

Time	Development of composite material
In 3400BCE	Man created plywood around 3400 BCE by adhering timber strips at different angles.
2181–2055BCE	Egyptians courted as early as 2181–2055 BCE by creating cartonnage out of layers of linen or papyrus wet in plaster.
Around 1500BCE	The earliest people used grass to strengthen pots, canoes, and dust bricks.
Around 1200 CE	The first composite bows were created by the Mongols using a mixture of bamboo, bone, horns, cattle tendons, silk, and wood that had been bound together with herbal pine resin.
1870s–1890s	New synthetic resins were able to change from a liquid to a solid state in a pass-connected molecular shape thanks to polymerization.
Early 1900s	Vinyl, polyester, polystyrene, and phenolic are examples of plastics that have evolved.
1930s	By introducing the first glass fibre, Owens Corning started the fibre giving a boost to polymer (FRP) business. Unsaturated polyester resins were patented in 1936.
1940s	The FRP company transitioned from research to practical manufacturing during World War II. A fully composite frame car had been created and tested by 1947.
Early 1950s	Large-scale filament winding, vacuum bag molding, and covered pultrusion are examples of sophisticated manufacturing techniques. The concept for the enormous rocket vehicles that drove space research in the 1960s and beyond was filament winding.
1960s	After a few years, carbon fibre composites were employed commercially after the original carbon fibre was patented in 1961. In the 1960s, the marine industry became the largest consumer of composite materials.
1970s–1980s	The automobile industry overtook the maritime industry as the biggest market for composite materials in the 1970s, and it continues to hold this position today.
1990–2000	By the middle of the 1990s, composites were widely used in production and manufacturing as a strong substitute for conventional materials. Every day, consumers come into contact with composite materials in the form of handles and exquisitely stained entryways at their homes. Composite materials were evaluated for high-energy and rigid applications during the development of the 787 Boeing Dreamliner in the mid-2000s.
Present day	The use of composite materials in the automobile, appliance, and consumer goods industries is continuously growing due to their growth. Furthermore, composites are only now beginning to find their way into nanotechnology. According to industry statistics, the global market for composite materials is expected to expand at a compound annual growth rate (CAGR) of 7.04% between 2016 and 2021, from USD 69.50 billion in 2015 to USD 105.26 billion by 2021.
The future	Governments, businesses, and academic institutions are becoming increasingly interested in the study of composite materials. This may put pressure on additional funding to help develop new fibres and resins. This might lead to more composite material uses in both new and existing sectors. Additionally, it is highly likely that environmentally friendly composite materials such as bio-based polymers and recycled plastics will become increasingly popular.

The 1970s began with improvement on hybrid materials such as wood polymer composites gained attention, signaling broader interest in combining polymers with conventional binders. A major shift occurred in the 1980s–1990s, when polymer concrete moved from experimental phases to structural applications, driven by its superior mechanical properties, durability, and resistance to corrosion particularly in harsh environments. Since the 2000s, the innovations in engineering polymers and advanced resins have further improved concrete performance, offering greater design flexibility and supporting sustainable construction practices. This evolution illustrates how developments in polymer chemis-

try have transformed concrete into a high-performance and multifunctional material suited for modern infrastructure needs.

Early examples of composite materials include plywood (circa 3400 BCE), cartonnage used by the Egyptians (2181–2055 BCE), and Mongolian composite bows (1200 CE), all of which incorporated natural fibers, resins, and adhesives to enhance structural performance. The emergence of synthetic resins in the late 19th century and early 20th century laid the foundation for the development of modern polymer composites, which eventually led to the widespread use of fiberglass-reinforced polymers (FRP) in the 1930s.

The mid-20th century marked a turning point, as polymer composites transitioned from laboratory research to commercial and industrial applications. During World War II, the development of lightweight, high-strength composites accelerated, leading to their use in military and aerospace applications. By the 1960s, the marine industry became the largest consumer of composite materials, followed by the automotive sector in the 1970s and 1980s. By the 1990s and early 2000s, polymer composites were widely used in production and manufacturing, serving as a strong substitute for conventional materials in various industries.

In the present day, the automotive, appliance, and consumer goods industries continue to drive the demand for composite materials. Moreover, nanotechnology advancements have further expanded their applications. According to industry statistics, the global market for composite materials has experienced consistent growth, with a compound annual growth rate (CAGR) of 7.04% from 2016 to 2021, increasing from USD 69.50

billion in 2015 to USD 105.26 billion in 2021 (Godara et al. 2021).

Looking to the future, governments, businesses, and academic institutions are expected to increase investments in polymer composite research, fostering the development of new fibers and resins. This could lead to broader applications across both existing and emerging industries. Additionally, the focus on environmentally friendly composite materials, such as bio-based polymers and recycled plastics, is expected to grow as sustainability concerns continue to shape industrial practices.

In Table 3, this structured timeline highlights the continuous improvements in polymer concrete reflecting both technological advancements and evolving industry demands. As polymer composites continue to evolve, their integration with emerging technologies, such as nanomaterials and artificial intelligence-driven material design, will further enhance their role in next-generation construction materials.

Table 3. Categorized polymer concrete evaluation process.

Properties	Unit	Polyester resin
Early development	1920s–1950s	<ul style="list-style-type: none"> Initial research and experimentation with polymer-modified mortars. Patent filing by Cresson and Lefebure (1923) for polymer-modified construction materials.
Emergence of polymer-modified concrete	1960s–1970s	<ul style="list-style-type: none"> Increased commercial applications of fiberglass-reinforced polymers (FRP). Use of polymer additives to improve concrete properties.
The advancements	1980s	<ul style="list-style-type: none"> Integration of advanced fibre reinforcements such as carbon fibres and aramid (Kevlar). Adoption of polymer concrete in high-performance infrastructure applications.
Eco-friendly developments	1990s–2000s	<ul style="list-style-type: none"> Increased research into sustainable and recycled polymer composites. Shift towards low-carbon and environmentally friendly polymer concrete formulations.
Modern innovations and trends	2010s–Present	<ul style="list-style-type: none"> 3D printing technology enabling the fabrication of complex polymer concrete structures. Development of bio-based and recyclable polymer binders for sustainable construction. Expansion of polymer concrete applications in smart cities and green building practices.

2.1. Early development (1920s–1950s)

The early use of polymers in concrete can be traced back to the 1920s and 1930s, a period marked by significant advancements in the polymer chemical industry. During this time, natural rubber latexes were chemically modified to create synthetic rubber latexes and resin emulsions, which were subsequently used as polymeric modifiers in construction materials. These early innovations laid the foundation for further exploration in polymer-enhanced concrete (Nodehi 2022).

Although polymer-modified concrete gained traction in the 20th century, the origins of synthetic polymers date back even earlier. The first plastic material, derived from nitrocellulose, was developed by Parkes in 1862 and later refined by Hyatt in 1866 (Feldman 2008). However, a major breakthrough in polymer science occurred in 1907, when Belgian-American chemist Leo Baekeland invented Bakelite, the first fully synthetic plastic (Suyambulingam et al. 2025). This thermosetting polymer revolutionized materials science, leading to the rapid growth of plastics, rubbers, coatings, adhesives,

and sealants as widely used materials in modern industries (Feldman 2008).

The advancement of polymer chemistry in the early 20th century led to the development of unsaturated polyester resin in 1930. Carleton Ellis discovered that the reaction between glycols and maleic anhydride could produce a polymer resin that, when catalyzed, hardened into an insoluble solid, paving the way for polymer-based composites (Ali and Ansari 2013). Around the same time, Baekeland's work on phenol-formaldehyde (PF) resins led to the synthesis of the first thermosetting polymer through a polycondensation process, which combined phenol and formaldehyde. Another early synthetic polymer, celluloid, was discovered by John Wesley Hyatt in 1869, marking the first commercially successful plastic made from cellulose, a natural polymer derived from plant fibers (Suyambulingam et al. 2025).

The success of phenol-formaldehyde resins prompted further research into other polycondensation-based polymers, leading to the development of urea-formaldehyde (UF) and melamine-formaldehyde (MF) resins. These amino resins, first identified by Tollens in 1884 and later

patented by John in 1918, became widely used in various industrial applications (Feldman 2008). Unlike phenoplasts, aminoplasts offer the advantage of being translucent or light-colored, making them suitable for diverse engineering applications. These early advancements in synthetic polymers paved the way for the creation of polymer composites, which later became integral to polymer-modified concrete (Suyambulingam et al. 2025).

The development of polymer-modified concrete was further facilitated by research into polyvinyl acetate (PVA) as a polymer modifier (Nodehi 2022). However, the discovery of vinyl chloride (VC) dates back even earlier, to 1835, when Liebig and Regnault first identified the compound (Feldman 2008). Its potential for polymerization was not fully understood until Baumann's 1878 study, which revealed that sunlight exposure could trigger VC polymerization, forming a white solid residue. This discovery laid the groundwork for polyvinyl chloride (PVC) production. Further advancements in the early 20th century led to the patenting of flexible PVC films by Ostramislenski in 1926 (Feldman 2008). Subsequent research showed that heating PVC with high-boiling-point liquids transformed it into a rubber-like material, leading to the development of phthalate-based plasticizers. By the 1930s, these materials were widely used in elastomeric applications, and large-scale commercial production of PVC began in 1935 (Feldman 2008).

World War II significantly accelerated the development and application of polymer composites, particularly due to material shortages and the urgent need for high-performance alternatives to rubber and metals (Suyambulingam et al. 2025). The war effort prompted innovations in synthetic rubber, electrical insulation, and high-strength composites, which later translated into civilian applications (Feldman 2008). One of the most crucial polymer advancements during the war was the development of epoxy resins (EP). Schlack, the inventor of nylon 6, synthesized the first epoxy resins in 1934 (Feldman 2008). These thermosetting polymers, derived from petroleum, exhibited outstanding mechanical, chemical, and adhesive properties. When reinforced with fibers, epoxy-based composites display remarkable strength, durability, and resistance to harsh environments, making them ideal for aerospace, automotive, and infrastructure applications (Suyambulingam et al. 2025).

By the end of World War II, polymer-based products had begun transitioning into civilian industries, marking the expansion of polymer composites into mainstream manufacturing. Developments in material science and production techniques enabled composites to be produced at lower costs and on larger scales, leading to their widespread use in consumer goods, transportation, and construction. The construction industry, in particular, recognized the potential of polymer-based materials, incorporating them into concrete formulations to improve performance, durability, and environmental resistance (Ali and Ansari 2013). By 1955, the building and construction sector had become the largest consumer of plastics, according to the Association of Plastics Manufacturers in Europe (APME). Today, the construction industry remains one of the top three global consumers of polymer-based materials, underscoring the growing re-

liance on polymer composites in structural applications (Ali and Ansari 2013).

2.2. Polymer-modified concrete (1960s–1970s)

Around The 1960s and 1970s marked a transformative period in the development of polymer-modified concrete (PMC), characterized by advancements in carbon fiber technology, thermosetting resins, and industry recognition. These innovations significantly improved the mechanical properties, durability, and performance of polymer concrete, leading to its widespread adoption in various engineering applications. The modern development of carbon fibers can be traced back to 1942, although their origins date as far back as 1879, when they were initially used as light bulb filaments (Feldman 2008). Derived from cellulosic precursors, the first commercially produced carbon filament was designed for incandescent lamp filaments. However, further research in 1959 and 1961 led to the development of high-strength and high-modulus carbon fibers from rayon and polyacrylonitrile (PAN), marking a breakthrough in high-performance reinforcement materials (Feldman 2008). Carbon fibers exhibit tensile strengths ranging from 3000 to 7000 MPa, significantly outperforming traditional reinforcement materials such as glass fibers and steel (Godara et al. 2021). Due to their remarkable strength-to-weight ratio, stiffness, and thermal stability, carbon fiber-reinforced composites became widely used in aircraft structures, including doors, wings, fuselage sections, and tail surfaces.

The introduction of thermosetting resins, such as epoxy, polyester, and phenolic resins, further enhanced the performance of polymer concrete. These resins improve adhesion between reinforcing fibers, allowing for the development of high-performance composite materials tailored for specialized applications (Suyambulingam et al. 2025). Glass fibers, another commonly used reinforcement material, typically exhibit tensile strengths between 2000 and 3500 MPa, making them suitable for lightweight yet durable structural components. The combination of carbon and glass fiber reinforcements with thermosetting resins enabled the production of advanced polymer composites with superior mechanical, chemical, and thermal resistance.

A significant milestone in polymer concrete research was the formal recognition of its importance by the American Concrete Institute (ACI) in 1971, with the establishment of ACI Committee 548 dedicated to polymer-modified concrete (Bedi et al. 2013). This institutional recognition accelerated research efforts, leading to the systematic study, standardization, and application of polymer-based concrete formulations. During this period, polymer concrete composites gained traction due to their versatile properties and ability to meet the increasing demand for high-strength, high-performance construction materials. Recent advancements have expanded the scope of polymer concrete composites, particularly through the use of industrial and agricultural waste in formulations, aligning with sustainability goals and environmentally friendly construction practices (Alhazmi et al. 2021).

2.3. Advancement in the 1980s

The 1980s marked a significant period of innovation in polymer composites, driven by the development of advanced fiber reinforcements such as aramid (Kevlar) and high-performance carbon fibers (Suyambulingam et al. 2025). These fibers offer exceptional strength-to-weight ratios, making them highly suitable for use in polymer-reinforced composites. Their lightweight nature, durability, and superior corrosion resistance enabled their application in civil engineering projects, including buildings, bridges, and infrastructure (Suyambulingam et al. 2025). The incorporation of advanced fiber reinforcements significantly enhanced the mechanical properties of polymer composites, making them adaptable for various applications. Several types of fibers were used during this period, including natural fibers (such as hemp and flax), glass fibers, carbon fibers, and aramid fibers. While synthetic fibers such as carbon and aramid fibers provided superior strength, stiffness, and fatigue resistance, natural fibers emerged as a cost-effective and environmentally friendly alternative in certain applications. The ability of these advanced fibers to withstand extreme conditions makes them suitable for high-performance applications in industries such as aerospace, automotive, and sporting goods.

The use of polymer concrete can be traced back to 1958 in the United States, where it was first utilized for building cladding applications (Fowler 1999). Unlike conventional concrete, polymer concrete eliminates the need for Portland cement and water, relying instead on aggregates bound by a polymer binder. As urbanization and large-scale infrastructure projects accelerated worldwide, the demand for cement-based materials surged, creating economic and environmental challenges, as illustrated in Fig. 3.

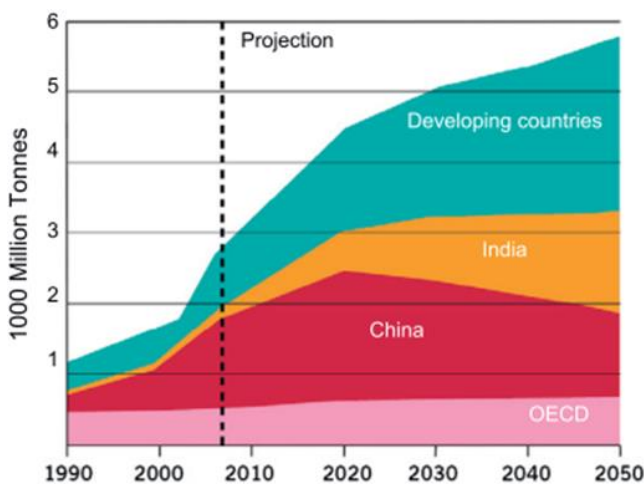


Fig. 3. The demand for cement varies by region and country (Fowler 1999).

The rising global cement demand from 1990 to 2050 underscores the urgent need for sustainable alternatives. Traditional cement production is associated with high energy consumption and CO₂ emissions, driving researchers to explore polymer concrete as a potentially

eco-friendly substitute. Compared to Ordinary Portland Cement (OPC)-based materials, polymer-based mortar and concrete offer enhanced durability, reduced permeability, and resistance to environmental degradation (Nodehi 2022).

Following 1980, the development of high-performance polymers led to new polymer formulations capable of competing with traditional materials. Notable advancements included Metallocene polyolefins, Polyamide 4-6 (1987), Syndiotactic polystyrene (PS) (1989), Polyphthalamide (1991), Styrene-ethylene copolymer and Syndiotactic polypropylene (PP) (1992) (Feldman 2008). These innovations contributed to enhanced material properties, broadening the applications of polymer composites in construction, transportation, and high-performance engineering fields. The continued evolution of polymer concrete in the 1980s demonstrated its potential as a durable and sustainable alternative to traditional cement-based materials, paving the way for further advancements in the 1990s and beyond.

2.4. Eco-friendly developments (present)

Since the 2010s, advancements in polymer research and development have progressed significantly, with a strong emphasis on enhancing polymer properties, expanding their applications, and improving sustainability. Researchers and industries worldwide are working to overcome the limitations of conventional polymers, particularly in composite materials, while simultaneously minimizing their environmental impact (Oladele et al. 2023). These efforts aim to tackle contemporary challenges such as environmental sustainability, material performance, and resource efficiency. With continued progress in technology and research, new opportunities have emerged to improve the durability, recyclability, and overall eco-friendliness of polymer composites (Suyambulingam et al. 2025). However, despite these advancements, the limited understanding of these materials and their associated technologies has hindered their widespread adoption in many industries (Oladele et al. 2023).

In recent years, research and technological improvements have positioned polymer-based materials as a viable alternative to traditional construction materials, progressively replacing conventional concrete and cement-based composites. A key area of research focuses on waste management strategies for reducing plastic waste and its environmental impact. As illustrated in Fig. 4, a typical plastic waste dump highlights the growing environmental concerns caused by improper disposal of non-biodegradable materials. The image illustrates how plastic waste accumulates in the natural environment, leading to soil and water pollution, endangering wildlife and contributing to visual pollution. This type of unmanaged plastic pollution highlights the need to develop sustainable waste management strategies, such as recycling plastics into value-added building materials such as polymer concrete. Salami et al. (2024) had highlighted the feasibility of using waste plastic in concrete production, citing benefits such as localized material use, reduced greenhouse gas (GHG) emissions, and improved durabil-

ity. One of the primary concerns in traditional concrete production is the high carbon footprint of cement, which contributes significantly to global CO₂ emissions. As cement demand continues to rise, the addition of polymers to concrete presents both challenges and opportunities. While the incorporation of polymer materials can reduce dependence on cement, thus lowering emissions, certain polymer production processes may still contribute to GHG emissions (Salami et al. 2024).

To address these challenges, geopolymer concrete has emerged as a sustainable alternative, offering enhanced strength characteristics while maintaining a low carbon footprint and reduced consumption of natural resources (Alhazmi et al. 2021). Unlike traditional concrete, polymer concrete replaces cement hydrate binders with liquid resins or polymer binders, making it a more environmentally friendly construction material (Rochman et al. 2024).



Fig. 4. Plastic waste dumping site (Koirala et al. 2025).

The introduction of polymer composites into 3D printing has revolutionized manufacturing and construction processes, providing key benefits such as increased design flexibility, reduced material waste and production of lightweight yet high-strength components. Advancements in additive manufacturing (AM), commonly known as 3D printing, have played a pivotal role in expanding the applications of polymer composites. This technology enables the fabrication of complex composite structures with customized geometries and mechanical properties, offering unprecedented precision and material efficiency (Suyambulingam et al. 2025). The use of polymer composites in 3D printing gained momentum in the early 2010s, evolving from traditional polymer-based methods such as fused deposition modeling (FDM) and stereolithography (SLA) to more advanced techniques. A major breakthrough occurred in 2014 with the launch of the Mark One 3D printer by Markforged, which introduced continuous fiber reinforcement technology. Unlike conventional polymer-based 3D-printed materials, this innovation enabled the production of structural components with strength and durability comparable to conventional composites. Fur-

thermore, the advantages of 3D printing go beyond its influence on the global market, offering substantial potential for environmental protection and supporting the growth of a globally sustainable economy (Alami et al. 2023).

3. Applications of Thermosetting Resins in Polymer Concrete

Polymer concrete (PC) is a high-performance construction material that has been in commercial use since the early 1960s (Rebeiz 1996). It is produced by adding small amounts of initiators and promoters to the resin, which triggers the curing or hardening process as shown in Fig. 5. The production process of polymer concrete using recycled PET. This process involves mixing a liquid component (unsaturated polyester resin), initiator, promoter, and solid aggregates, followed by curing to form the final material. This method highlights how recycled plastics can be used in sustainable construction. Polymer concrete was driven by the need to address the inherent limitations of traditional Portland cement concrete, which often suffered from issues such as cracking, high permeability, and low resistance to chemical exposure. Unlike conventional concrete, polymer concrete incorporates polymeric resins as a binder, which significantly enhances its mechanical strength, durability, and resistance to environmental degradation. The uses of polymer concrete largely depend on the physical and chemical properties of both the aggregates and the resin, with the resin's effectiveness also being influenced by how long it has been stored after production (Martínez-López et al. 2022).

3.1. Polyester resin

Polyester is a widely used class of polymers containing ester functional groups in their main chain, commonly found in coatings, textiles, and packaging. Due to its superior mechanical and chemical properties, affordability compared to epoxy resin, and widespread commercial availability, polyester resin is often the preferred choice for polymer concrete construction (Bulut and Şahin 2017). Polyester resins are synthesized through polycondensation reactions involving dicarboxylic acids and dihydroxy alcohols, forming durable thermosetting polymers (Tabatabaeian et al. 2019).

A study by Aravecchia et al. (2023) examined the use of recycled polyester (PE) resin powder as shown in Fig. 6(a), specifically identified as "PE/P/M BLACK RAL 9005," a waste product from the coating industry supplied by INVER S.p.A. PE resin is widely used for its excellent resistance to weathering and UV radiation. It has a density of 1380 kg/m³, a fine particle size of about 3.5 µm and is hydrophilic, as shown by its contact angle of approximately 74.4°, shown in Fig. 6(b). Additionally, the chemical composition of PE resin was analyzed using X-ray Photoelectron Spectroscopy (XPS) and Energy-Dispersive X-Ray Spectroscopy (EDS), revealing that carbon, oxygen, and calcium are its primary constituents. These findings suggest that PE resin could chemically in-

teract with Ordinary Portland Cement (OPC) rather than merely acting as an inert aggregate, indicating its poten-

tial as a reactive component in polymer concrete formulations (Aravecchia et al. 2023).

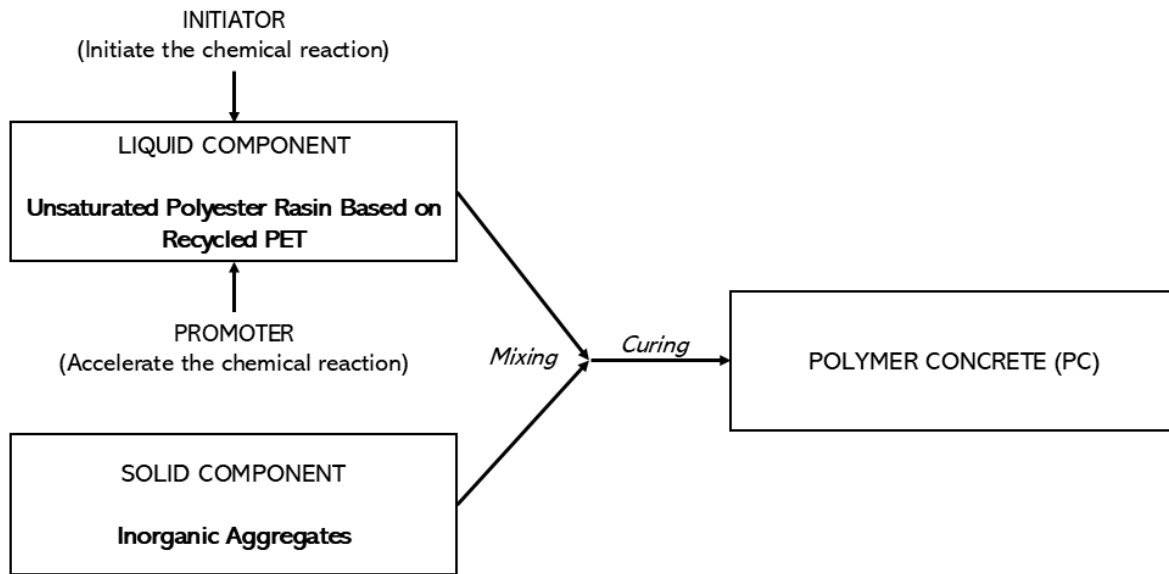


Fig. 5. The production of polymer concrete (Rebeiz 1996).

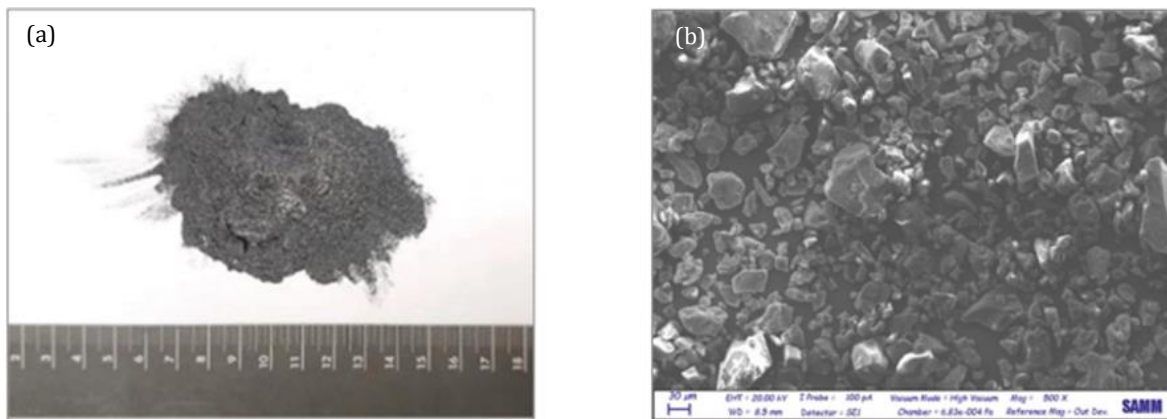


Fig. 6. (a) Polyester resin and (b) SEM image (Aravecchia et al. 2023).

Polyester resins are extensively used in gelcoat applications, with more than 85% of gelcoats incorporating unsaturated polyester (UP) resins. Research by (Akarken et al. 2025) explored formulations containing at least 42% unsaturated polyester resin, significantly exceeding conventional levels. While this higher resin content enhanced certain properties, it also complicated the modification process, potentially affecting durability, performance, and compatibility with other materials in gelcoat applications.

Advances in bio-based unsaturated polyester (UP) resins have also demonstrated promising results. A study by (Rubeš et al. 2024) found that bio-based UP resins exhibit mechanical properties comparable to traditional styrene-based formulations, including high flexural strength and compressive yield points. These findings highlight the potential of bio-based polyester resins as sustainable alternatives for applications requiring high durability and performance. Unsaturated polyester resins offer several notable advantages, including high chemical and me-

chanical resistance, robust weather resistance, cost-effectiveness and ease of handling and processing.

Additionally, unsaturated polyester resins can be easily reinforced with fibers, allowing for the development of lightweight and high-strength composite materials (Batista et al. 2021). Khallouqi et al. (2024) emphasized that polyester resins possess unique characteristics, such as insolubility, water resistance, optical transparency, and a density similar to human soft tissue (1.10–1.19 g/cm³). These attributes, along with their moldability and wide availability, make polyester resins highly adaptable for various industrial applications.

Despite their widespread use, unsaturated polyester (UP) resins pose significant environmental challenges. At the end of their life cycle, these resins contribute to substantial resource waste and environmental degradation (An et al. 2024). One of the major environmental concerns is the high volatile organic compound (VOC) content in polyester-based insulating coatings, which typically contain 50–70% VOCs derived from organic

solvents (Choe et al. 2023). These emissions contribute to air pollution and ecological harm, necessitating the development of low-VOC or VOC-free alternatives.

Additionally, polymer derivatives of polyester such as polyethylene terephthalate (PET) offer strong mechanical properties and economic advantages but lack biodegradability. The accumulation of PET waste has become a pressing environmental issue, underscoring the urgent need for more sustainable material alternatives. Researchers are now exploring bio-based polyesters and recycling strategies to minimize environmental impact and promote circular economy principles in polymer resin applications.

3.2. Epoxy resin

Epoxy resin is a widely used thermosetting polymer, recognized for its exceptional mechanical properties and versatility in industries such as transportation, aerospace, construction, and packaging (Zhang et al. 2024). Its key advantages include high corrosion resistance, superior electrical insulation, excellent chemical stability,

and strong adhesion, making it a preferred material for structural reinforcement and protective coatings.

Epoxy resins are synthesized through a coupling reaction between epichlorohydrin and compounds containing at least two active hydrogen atoms (Kumar 2016). During synthesis, dehydrohalogenation occurs in an intermediate stage, resulting in the formation of epoxy groups that define the resin's properties (Fig. 7). Compared to other thermosetting polymers, epoxy resins exhibit superior strength, resilience, and low shrinkage, making them ideal for offshore, coastal, and high-performance construction applications (Verma et al. 2020). Their resistance to harsh environments enhances the longevity of structures, particularly in marine and industrial settings (Fame et al. 2024).

Additionally, epoxy systems are extensively used in protective coatings due to their strong adhesion to various surfaces, along with excellent thermal, mechanical, and anti-corrosive properties. One of the major advantages of epoxy resins is their recyclability, making them a more sustainable option compared to conventional thermosetting materials (Tsyklinskaya et al. 2024).

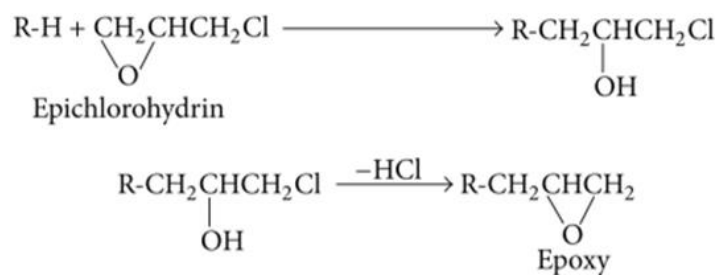


Fig. 7. Epoxy preparation (Kumar 2016).

The combination of epoxy and concrete significantly enhances the mechanical and chemical performance of the material. When used as a binder, sealer, or coating, epoxy improves concrete durability, impermeability, and structural integrity. Compared to polyester concrete, epoxy-modified concrete demonstrates superior performance; however, the addition of microfillers can elevate polyester concrete's properties to a comparable level (Kumar 2016).

A study by Fei et al. (2024) examined the mechanical properties of epoxy polymer concrete, using specialized equipment such as the YAW 4206 compression tester and Instron 3365 universal testing machine. The research assessed compressive, flexural, interfacial flexural, and tensile strength at curing intervals of 3, 7, and 28 days. Results demonstrated that epoxy-based concrete exhibited superior mechanical strength and enhanced corrosion resistance compared to traditional epoxy concrete formulations. However, to improve process efficiency and industrial applicability, reducing the curing time of epoxy resins remains a critical area of research (Kumar 2016).

As summarized in Verma et al. (2020), the studies by Wang et al. (1999) and Wang et al. (2011) reported the mechanical and physical properties of polyester and epoxy resins, highlighting their respective strengths and limitations, as shown in Table 4. Epoxy resins generally

offer higher tensile and flexural strength, lower shrinkage, and improved heat resistance, making it ideal for high-performance applications. These qualities make it well-suited for high-performance and demanding applications. On the other hand, polyester resin provides higher compressive strength and greater surface hardness, making it more suitable for structural applications that involve compressive forces. Both resins have their own strengths depending on how and where they are used.

3.3. Polyethylene terephthalate (PET)

Polyethylene terephthalate (PET) is one of the most widely used plastics globally in production (Fig. 8) of beverage containers and synthetic fibers. In fact, PET accounts for over 80% of all chemical fiber production worldwide (Waysal et al. 2023). As summarized in Table 5 by Aravecchia et al. (2023), primary studies by Azhdarpour et al. (2016), and Silva et al. (2005) highlight that the extensive use of PET has made it the most common form of plastic waste. This widespread disposal underscores the urgency of developing sustainable strategies to repurpose PET waste, particularly in the construction sector. An innovative approach is to incorporate PET into concrete mixtures, which not only helps reduce environmental pollution but also enhances the performance of the material.

Table 4. Typical thermosetting resins and their mechanical and physical characteristics (Verma et al. 2020).

Properties	Unit	Polyester resin	Epoxy resin
Elongation at break	%	5	5
Heat distortion temperature	°C	60–100	120
Tensile strength	MPa	42–71	~85
Density.	g/cm ³	1.10–1.46	1.11–1.23
Compressive strength	MPa	92–190	~11
Tensile elastic modulus	GPa	2.1–4.5	~3.2
Flexural strength	MPa	60–120	~130
Linear expansion coefficient	10 ⁻⁶ /°C	80–100	60
Water absorption (24h)	%	0.15–0.60	0.14
Rockwell hardness (6.35 mm, 100 kg)	–	115	100
Shrinkage rate	%	4–6	1–2

Table 5. Properties, primary production and waste generation of the most widespread polymers (Aravecchia et al. 2023)

Polymer	Id	Recycled	Category	ρ (kg/m ³)	f_t (MPa)	E (GPa)	Production (million tons)	Generated waste (million tons)
Polyvinyl chloride	PVC	Occasionally	Thermoplastic	1300–1580	50–60	2.7–3.0	38	15
Polyurethane	PUR	No	Thermosetting	–	–	–	27	16
Polystyrene	PS	No	Thermoplastic	1040–1050	30–55	3.1–3.3	25	17
Polypropylene	PP	Occasionally	Thermoplastic	900–910	25–40	1.3–1.8	68	55
Polyethylene terephthalate	PET	Yes	Thermoplastic	1270–1390	55–80	2.1–3.1	33	32
Low density polyethylene	LDPE	No	Thermoplastic	910–930	8–31	0.2	64	57
High density polyethylene	HDPE	Yes	Thermoplastic	950–960	22–31	1.08	52	40
Polyphthalamide	PP&A	Occasionally	Thermoplastic	–	–	–	59	42

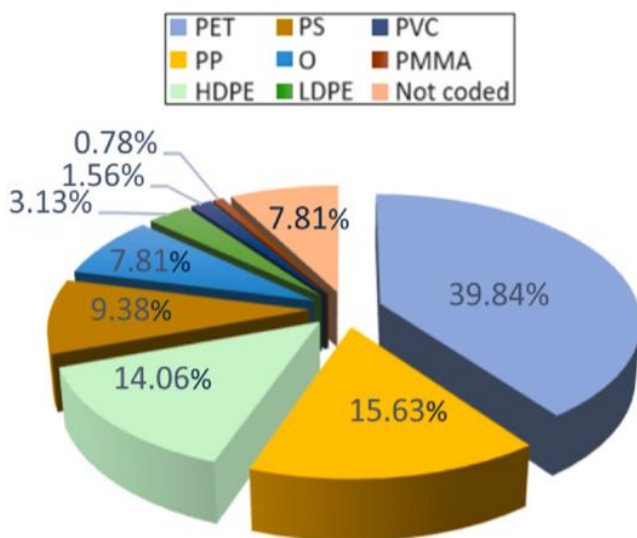


Fig. 8. Common usage of plastic packing materials (Mehdar 2024).

PET is a unique chemical structure were synthesized from terephthalic acid (H₂BDC) and ethylene glycol (EG) which results in a durable and chemically stable polymer, as shown in Fig. 9 (Wang et al. 2024). Its molecular formula, (C₁₀H₈O₄)_n, indicates a repeating ester unit that contributes to its strong physical and chemical properties (Fig. 10).

These characteristics include excellent thermal stability, high flexibility, strong corrosion resistance, wear resistance, and chemical inertness. Additionally, PET is lightweight, retains gases effectively, and can withstand high temperatures, making it not only ideal for packaging applications but also suitable for use in construction materials (Waysal et al. 2023). The integration of PET into concrete has demonstrated encouraging results. For instance, (Wattanavichien and Iwanami 2024) observed that replacing 20% of coarse aggregate with PET improved drying shrinkage and abrasion resistance. Remarkably, the PET-modified concrete recorded a compressive strength of 80 MPa, highlighting its potential for

high-performance structural applications. PET-enhanced concrete also shows high resistance to aggressive chemicals such as sodium chloride and sodium hydroxide, contributing to its long-term durability (Wattanavichien and Iwanami 2024).

Beyond mechanical improvements, PET offers environmental advantages to the world. Research by Pacheco-Torgal et al. (2012) revealed that using PET waste as a partial aggregate substitute not only enhances concrete workability but also reduces reliance on natural aggregates and mitigates landfill use. Furthermore,

PET waste can be converted into carbon nanomaterials, presenting an innovative route for both plastic waste reduction and carbon sequestration (Soni et al. 2024). In broader terms, other commonly used plastics in construction and packaging include Polyvinyl Chloride (PVC), High-Density Polyethylene (HDPE), Polypropylene (PP), Low-Density Polyethylene (LDPE), Polystyrene (PS), and Polymethyl Methacrylate (PMMA) (Mehdar 2024). However, PET stands out due to its balance of sustainability, mechanical strength, and chemical stability.

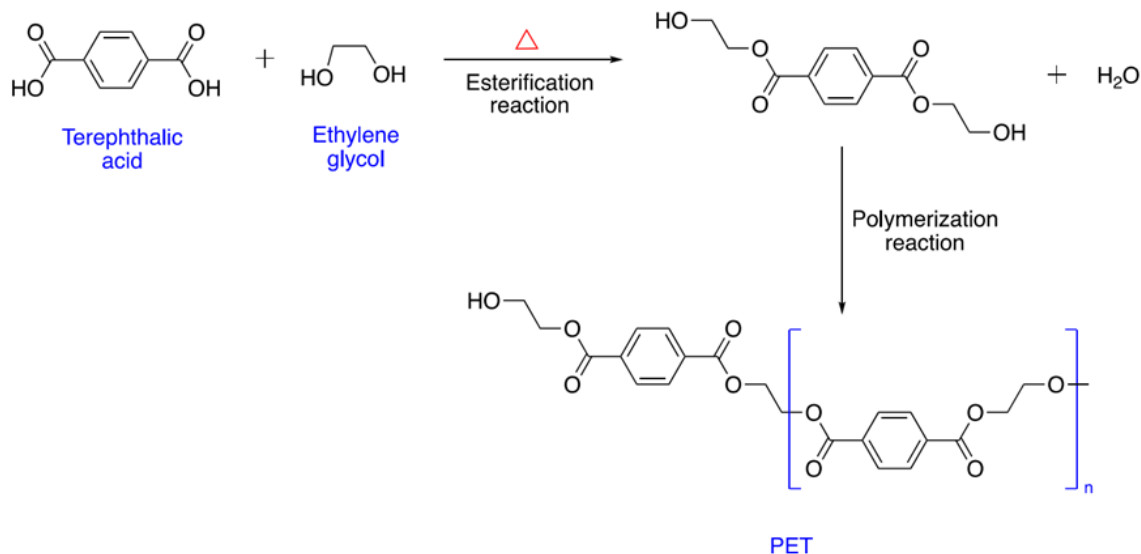


Fig. 9. Result of polymerization of terephthalic acid (H_2BDC) and ethylene glycol (EG) in the formation of the polymer PET plastic (Surucu 2025).

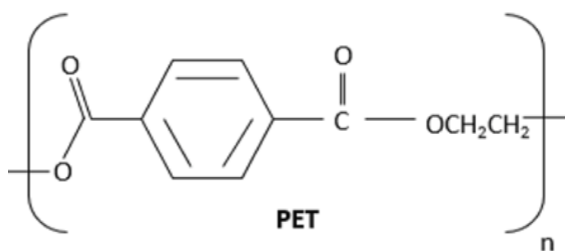


Fig. 10. Molecular structure of polyethylene terephthalate chemical formula: $(C_{10}H_8O_4)_n$ (Surucu 2025).

With global cement demand on the rise, researchers are increasingly turning to plastic waste as an eco-friendly, cost-effective, and sustainable alternative to traditional concrete materials (Z. Wang et al. 2024). One promising approach involves converting PET waste into composite materials for use in construction and road infrastructure projects (Heidari-Rarani et al. 2023). According to (Pacheco-Torgal et al. 2012), using PET waste as aggregate not only lessens dependence on natural resources and reduces landfill usage but also improves concrete workability, making it easier to mix and apply on-site. Additionally, concrete enhanced with PET demonstrates strong resistance to environmental chemicals like sodium chloride and sodium hydroxide by increasing its durability and lifespan in harsh conditions (Wattanavichien and Iwanami 2024). Together, these in-

sights highlight PET's potential as a versatile additive that addresses plastic waste while promoting more resilient and sustainable construction practices.

However, in recent years PET is one of the widely used polymers in 3D printing (Alami et al. 2023). It is particularly valued for its dimensional stability and durability, making it suitable for functional parts and prototypes. PET, along with its modified form polyethylene terephthalate glycol (PETG) is commonly used in sectors such as automotive, electronics, and healthcare, where strength and reliability are essential. Its widespread availability and cost-effectiveness also contribute to its popularity in additive manufacturing.

3.4. Vinyl ester

Among thermosetting polymers, certain materials stand out due to their exceptional performance characteristics. Epoxy and vinyl ester (VE) resins are particularly notable for their excellent adhesion, mechanical strength, chemical resistance, and thermal stability (Fame et al. 2024). Once catalyzed, these resins undergo an irreversible curing process, meaning they cannot return to their original state, unlike thermoplastic materials that rely on temperature-based curing (Rochman et al. 2024).

Compared to epoxy resins, vinyl ester resins are advanced thermosetting polymers that exhibit superior

chemical resistance, mechanical strength, and durability, making them a promising choice for composite materials (Rayati et al. 2025). Vinyl ester is synthesized by combining styrene and a condensation product of methacrylic acid with epoxy resin, and its curing process is facilitated through the addition of catalysts (Thomason and Xypolias 2024). One of the key advantages of vinyl ester resins is their low viscosity, which enhances workability in polymer concrete applications, making them easier to handle and process (Rochman et al. 2024).

To improve performance, cost efficiency, and sustainability, researchers have developed modified vinyl ester formulations. A study by Fei et al. (2024) explored modifications such as the incorporation of soybean oil-based resins and carbon sphere (CS) fillers, leading to improved mechanical properties and environmental benefits. Additionally, Venu et al. (2024) demonstrated that adding cenosphere particles of varying sizes further enhanced the mechanical strength and thermal stability of vinyl ester resins.

Vinyl ester resins are composed of bisphenol-A diglycidyl dimethacrylate epoxy and styrene. The general

chemical structure of vinyl ester methacrylate and the atomistic models for $n = 1$ (VE1) and $n = 2$ (VE2) are shown in Fig. 11 (a)-(b)-(c)-(d)-(e), along with the molecular structure of styrene. These structural properties contribute to the high-performance characteristics of vinyl ester resins, particularly in composite applications.

The physical and mechanical properties of vinyl ester resin have been widely studied, particularly in its application for glass fiber-reinforced polymer (GFRP) bars. Benmokrane et al. (2017) conducted an evaluation comparing vinyl ester, isophthalic polyester, and epoxy resins, assessing their flexibility, mechanical strength, and durability. Table 6 summarizes the typical properties of these thermosetting resin systems. When compared to other resins, vinyl ester resin used in GFRP bars demonstrates moderate resistance to temperature-induced flexibility. However, it is not as strong as epoxy resin, which offers superior mechanical performance and rigidity. Despite this, vinyl ester's chemical resistance and cost-effectiveness make it a viable alternative in specific applications where corrosion resistance and durability are critical.

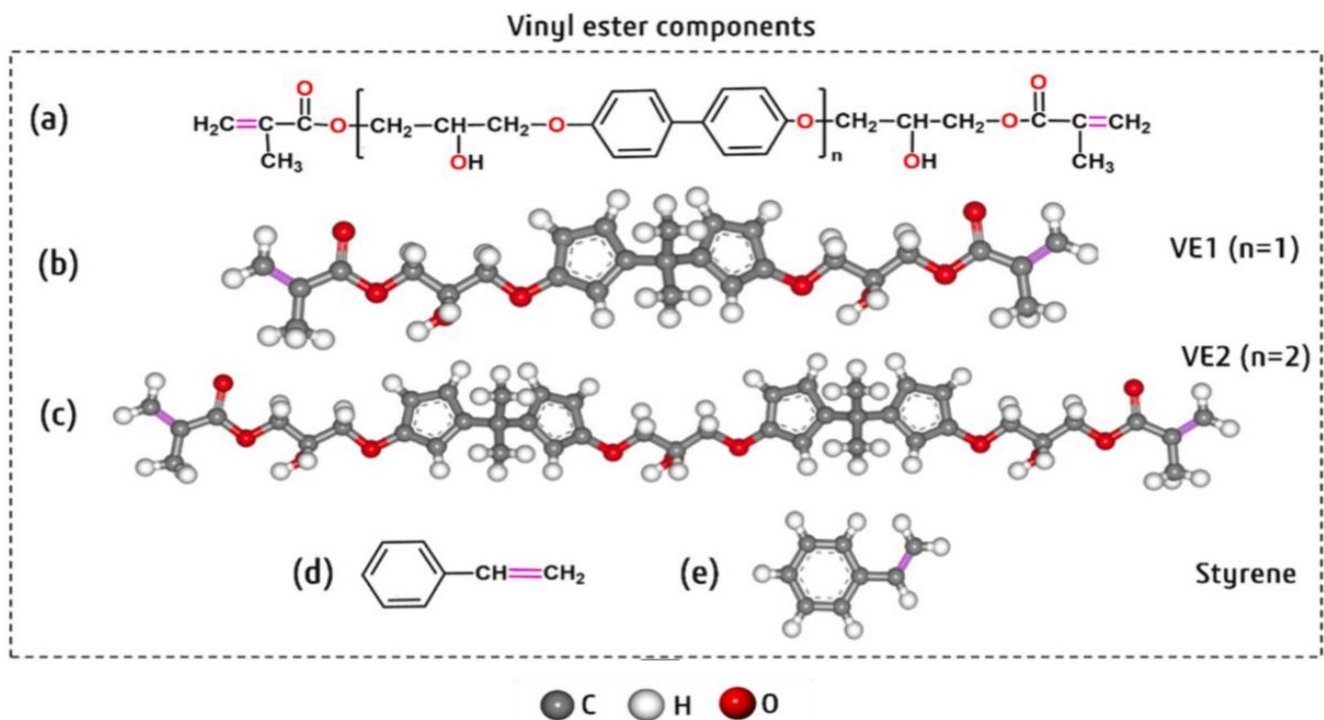


Fig. 11. Vinyl ester crosslinking steps: (a) Bisphenol-A diglycidyl dimethacrylate (VE) general chemical formula; (b) VE1 atomistic model; (c) VE2 atomistic model; (d) Styrene chemical formula; (e) Styrene atomistic mode (Fame et al. 2024).

Table 6. Typical characteristics of thermosetting resins (Benmokrane et al. 2017).

Properties	Unit	Polyester	Vinyl ester	Epoxy
Glass transition temperature (Tg)	°C	100	110	120
Tensile modulus	GPa	4.0	3.5	3.0
Tensile strength	MPa	65	82	90
Elongation	%	2/5	6.0	8.0
Property	Unit	Polyester	Vinyl ester	Epoxy

4. Comparison of Mechanical Properties of Polymers

The mechanical properties of polymer concrete vary significantly based on its preparation conditions. There were several factors influence the data including binder content, aggregate size distribution, micro-filler type and amount, and curing conditions, play a crucial role in determining overall performance (Bedi et al. 2013). These factors directly impact key mechanical properties

such as compressive strength, flexural strength, and tensile strength, as summarized in. Table 7 presents a comparative analysis of four key polymer materials polyester resin, epoxy, polyethylene terephthalate (PET), and vinyl ester by evaluating their compressive strength, flexural strength, and tensile strength based on data from multiple studies. The variations in these properties highlight the differences in mechanical performance, durability, and suitability for specific construction applications.

Table 7. Compressive strength, flexural strength and tensile strength comparison of polymer materials.

Polymer	Compressive strength (MPa)	Flexural strength (MPa)	Tensile strength (MPa)	Publication
Polyester resin	–	–	40–70	(Nodehi 2022)
	–	–	65	(Benmokrane et al. 2017)
	–	–	55	(Bulut and Şahin 2017)
	120	–	70	(Tabatabaeian et al. 2019)
	92–190	60–120	42–71	(Verma et al. 2020)
	89	110	68	(Kumar 2016)
	–	120	64	(van Zyl and Kruger 2025)
Epoxy	–	–	60–125	(Nodehi 2022)
	–	–	90	(Benmokrane et al. 2017)
	70	–	36	(Tabatabaeian et al. 2019)
	11	130	85	(Verma et al. 2020)
	22–95	–	–	(Gulabbhai et al. 2025)
	51–66	22.5	7.67–12.1	(Kumar 2016)
	–	40–80	–	(Luo et al. 2024)
Polyethylene terephthalate (PET)	–	–	47	(Nodehi 2022)
	80	–	–	(Wattanavichien and Iwanami 2024)
	26	–	–	(Safinia and Alkalbani 2016)
	40–50	6–10	–	(Grigoriadis et al. 2023)
	30.3	3.44	–	(Umasabor and Daniel 2020)
	–	–	140	(Sarwar et al. 2024)
	29–42	5.25–6.6	98.8	(Yılmaz and Nayır 2024)
Vinyl ester	–	–	70–84	(Nodehi 2022)
	–	–	82	(Benmokrane et al. 2017)
	89	–	–	(Gulabbhai et al. 2025)
	70	64.62	80	(Venu et al. 2024)
	–	115	15–95	(van Zyl and Kruger 2025)
	41–104	144	82	(Rochman et al. 2024)

Note: '–' indicates that data were not provided in the publication.

Polyester resin exhibits a wide range of compressive strength values, with studies reporting values between 92 MPa and 190 MPa (Verma et al. 2020). This range suggests that different formulations and modifications can significantly impact polyester resin's compressive performance. However, it generally has moderate tensile strength, ranging from 40 MPa to 70 MPa (Nodehi 2022). Polyester resin's flexural strength varies significantly, with reports of 60 MPa to 120 MPa (Verma et al. 2020).

Tensile strength has received more research attention in polyester resin likely because it is critical for understanding how well polymer composites resist cracking and stretching. In contrast, there is relatively less research on compressive and flexural strength. This imbalance suggests that while polyester resins generally offer a well-rounded mechanical performance for structural use, the variation in reported values may be due to differences in mix design, curing methods, and material composition.

Epoxy resin consistently demonstrates high mechanical properties, particularly in tensile and flexural strength. The tensile strength of epoxy resin varies between 60 MPa and 125 MPa, making it one of the strongest polymer resins in this comparison (Nodehi 2022). Its flexural strength is also impressive, reaching up to 130 MPa (Verma et al. 2020). However, compressive strength values vary widely, from as low as 11 MPa to as high as 95 MPa, depending on the formulation and testing conditions (Gulabbhai et al. 2025). It's well known for its strong bonding ability and resistance to chemicals, which helps explain why it often shows higher flexural strength. This high variability suggests that epoxy resin can be modified to optimize performance for different applications. When it comes to tensile strength, epoxy composites have received a lot of attention because they hold up well under pulling forces and help prevent cracking. This makes them especially useful in areas where the material needs to stay intact under tension like in bridges, aircraft parts or protective layers.

PET is notable for its high tensile strength, reaching up to 140 MPa (Sarwar et al. 2024). However, its compressive strength is relatively moderate, ranging from 26 MPa to 80 MPa (Wattanavichien and Iwanami 2024). Similarly, PET's flexural strength values are lower, varying between 3 MPa and 10 MPa, which limits its use in applications requiring high bending resistance (Grigoriadis et al. 2023). The limited research on the tensile strength of PET-modified concrete is likely due to its common use in compression-focused applications. Compared to other polymers, PET tends to have lower tensile performance, and tensile testing in concrete research is generally more complex. However, this presents an opportunity for future studies to explore PET potential in tension-dominated structural applications. Despite these limitations, PET remains attractive for sustainable construction applications due to its lightweight nature, recyclability, and chemical resistance. Studies have demonstrated that incorporating PET as a replacement for traditional aggregates can enhance drying shrinkage resistance, abrasion resistance, and durability, making it a viable alternative in eco-friendly concrete formulations.

Vinyl ester resin provides a good balance between tensile and flexural strength, with tensile strength values ranging from 70 MPa to 84 MPa (Nodehi 2022) and flexural strength reaching up to 144 MPa (Rochman et al. 2024). It offers moderate compressive strength, typically ranging from 41 MPa to 104 MPa (Rochman et al. 2024). Vinyl ester resins are widely used in chemically aggressive environments, such as marine, industrial, and infrastructure applications, due to their superior resistance to chemical degradation and moisture absorption. However, they exhibit lower temperature resistance and mechanical stiffness compared to epoxy resins, which may limit their applicability in high-heat or high-load environments. Its high strength-to-weight ratio and excellent thermal stability, it is widely used in industries such as marine, aerospace, and construction. These qualities help materials last longer and perform better, even when exposed to heavy mechanical stress and harsh chemicals.

The selection of polymer material for construction and composite applications depends on its specific mechanical properties and environmental resistance requirements. Epoxy resin is the best choice for applications requiring high mechanical performance, particularly in high-strength structural components. Vinyl ester resin provides a balance between strength and chemical resistance, making it suitable for corrosive environments. Polyester resin is a cost-effective solution with moderate mechanical properties, making it suitable for general-purpose applications. PET-based polymer concrete presents a sustainable alternative, particularly for lightweight and eco-friendly applications, although its lower flexural and compressive strengths must be considered.

To better understand the performance differences between polyester resin, epoxy, polyethylene terephthalate (PET), and vinyl ester in polymer concrete applications, mechanical strength values from various studies are compared. In addition, Fig. 12 illustrates experimental setups for compressive strength, tensile strength, and flexural strength testing, which are commonly conducted to evaluate the structural performance of these materials

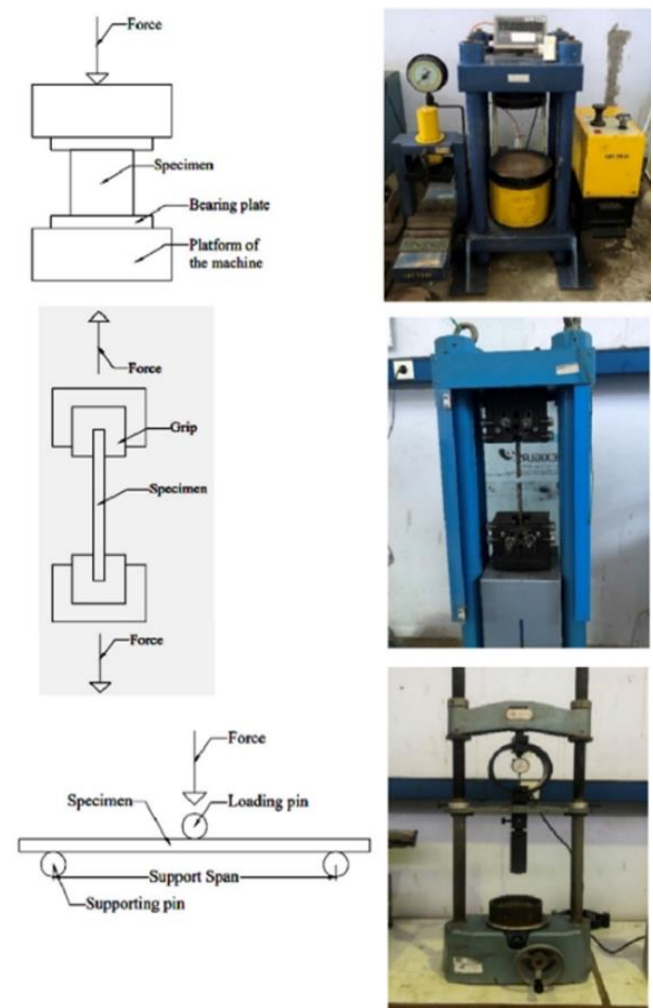


Fig. 12. Testing equipment for polymer concrete (Rochman et al. 2024).

5. Conclusions

Polymer concrete has evolved significantly since its initial development in the 1920s, with major advancements seen during its widespread adoption in the 1980s. Innovations in polymer resin formulations, fiber reinforcement technologies, and composite manufacturing have transformed polymer concrete into a high-performance material with improved mechanical strength, corrosion resistance, and long-term durability. The integration of thermosetting resins such as polyester, epoxy, vinyl ester and advanced fibers like aramid, carbon, and glass has expanded its use across infrastructure, aerospace, and industrial sectors.

This review has provided a comprehensive overview of the evolution, classification, and mechanical performance of these key polymer materials. Among them, epoxy demonstrates superior tensile and flexural strength, while polyester and polyethylene terephthalate (PET) offer notable benefits in compressive strength and sustainability. PET, in particular, shows great promise due to its potential for plastic waste reutilization, supporting both environmental and economic goals. However, research gaps persist, especially regarding the tensile behavior and long-term durability of PET in load-bearing applications.

Emerging technologies such as 3D printing have further enhanced the potential for precision-engineered polymer concrete, while the use of recycled materials and bio-based resins promotes resource efficiency and circular economy principles. Despite these advances, challenges remain, including the need for optimized curing methods, improved binder–aggregate compatibility, better workability, and standardized testing procedures. Addressing these limitations will require coordinated efforts among researchers, industry professionals, and policymakers. By overcoming current barriers, polymer concrete can achieve broader adoption and contribute meaningfully to next-generation, sustainable construction and infrastructure solutions.

Despite the comprehensive review of polymer concrete advancements, several research gaps remain, presenting opportunities for future exploration. The following recommendations outline key areas of focus to enhance the performance, sustainability, and applicability of polymer concrete in modern construction:

- The further research is needed to determine the ideal polymer-to-aggregate ratio for different types of polymer concrete. Achieving the optimal balance can help minimize material waste, enhance mechanical strength, improve workability, and increase cost-effectiveness.
- Studies should also consider the influence of microfillers and fiber reinforcements on polymer concrete formulations.

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Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

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