Contemporary Debates and Interdisciplinary Approaches in Engineering

Editor: Assist. Prof. Dr. Olcay PALTA

DUJAR

CONTEMPORARY DEBATES AND INTERDISCIPLINARY APPROACHES IN ENGINEERING

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Chapter 1

Current Status and Future Vision of Geopolymer Concrete Technology as a Special Type of Concrete

Nusret BOZKURT[1], Saffet SOYUGÜZEL[2]

Abstract

Geopolymer concrete technology has become one of the most important sustainable building material alternatives developed to counter the high carbon emissions and energy-intensive consumption caused by traditional Portland cement. These binder systems, obtained through alkali activation of aluminosilicate-rich industrial by-products, have attracted significant attention in the field of building materials in recent years due to their properties such as low carbon footprint, high chemical resistance, and superior thermal stability. In particular, the utilization of fly ash, blast furnace slag, metakaolin, and various agricultural wastes in geopolymer matrices contributes to industrial waste management and supports the circular economy approach.

This section comprehensively discusses the historical development, reaction mechanism, microstructural properties, and macro-scale engineering performance of geopolymer concrete. It has been observed that the N-A-S-H (Sodium Aluminosilicate Hydrate) and C-A-S-H (Calcium Aluminosilicate Hydrate) based binder gels formed during the geopolimerization process play a decisive role in the strength, impermeability, and long-term durability performance of the material. Geopolimer matrices, which form a denser and more homogeneous microstructure compared to traditional cement-based systems, exhibit high resistance to sulfate, chloride, and acidic environments. Furthermore, their ability to maintain structural integrity at high temperatures reveals that geopolymer concrete has significant potential, particularly in applications requiring fire resistance.

When evaluated in terms of structural performance, it is understood that the bending, shear, and axial load behavior of geopolymer reinforced concrete elements is largely compatible with conventional reinforced concrete systems. However, the brittle behaviour and low fracture toughness of the material are

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among the significant structural limitations. To overcome this problem, hybrid composite systems developed with steel, basalt, polypropylene, and various synthetic fibers have been found to have positive effects on ductility, energy absorption capacity, and impact resistance. In addition, self-compacting geopolymer concretes and hybrid mixtures that can set at ambient temperature stand out as important developments that increase the field applicability of the technology.

Within the scope of this chapter, sustainability discussions are also addressed from a life cycle assessment perspective. While it is known that geopolimer concretes can significantly reduce the global warming potential, the high energy requirements of alkali activator production and negative consequences in some environmental impact categories are noteworthy. Therefore, it is understood that in order for geopolimer technology to truly become an environmentally friendly building material, the development of low-energy activator systems, the widespread use of recycled aggregates, and the reduction of thermal curing requirements are necessary.

In recent years, the integration of geopolimer concretes with smart building systems has also become an important research area. New generation geopolimer composites developed with carbon fiber, piezoelectric sensors, and artificial intelligence-supported prediction models enable advanced engineering applications such as structural health monitoring and performance prediction. In addition, thanks to waste-based hybrid systems, recycled aggregates, and biomass-based additives, geopolimer technology has ceased to be merely an alternative binder; it has transformed into a sustainable, multifunctional, and high-performance building material platform.

Keywords: Special concretes, geopolymer concrete, alkali activation, sustainable building materials.

1. Introduction

Traditional Portland cement (OPC), a cornerstone of global infrastructure projects and rapid urbanization, requires high energy and calcination reactions during its production phase. As a result, it releases large amounts of greenhouse gases into the atmosphere, constituting one of the most critical environmental problems faced by modern engineering. Current life cycle assessment data shows that approximately one ton of carbon dioxide is released into the atmosphere for every ton of cement produced. These data clearly reveal that the cement industry alone is responsible for 5% to 9% of global anthropogenic CO_2 emissions (Chen et al., 2010; Turner and Collins, 2013). This high carbon footprint and natural resource consumption created by the sector has led materials scientists to search for alternative binders that recover industrial waste for the circular economy, have low emissions, and offer much higher performance (Malhotra, 2002). The concept of geopolymers, a pioneering outcome of these explorations, was first introduced in 1978 by the French scientist Joseph Davidovits (Davidovits, 1991). In these early studies, geopolymers were introduced into the scientific literature to define three-dimensional polymeric networks based on inorganic aluminosilicate (Davidovits, 1991; Duxson et al., 2007). Geopolymer concrete, produced by activating silicon and aluminum-rich waste materials such as fly ash from thermal power plants, blast furnace slag (a byproduct of iron and steel production), calcined clays (metakaolin), and rice husk ash with strong alkaline solutions based on sodium or potassium, is considered a third-generation cement in the construction sector, following lime and conventional cement (Provis et al., 2015; Pradhan et al., 2022). The aluminosilicate-based precursor materials, alkali activator solutions, and mix design process used in the production of geopolymer concrete are schematically illustrated in Figure 1 (Amran et al., 2020).

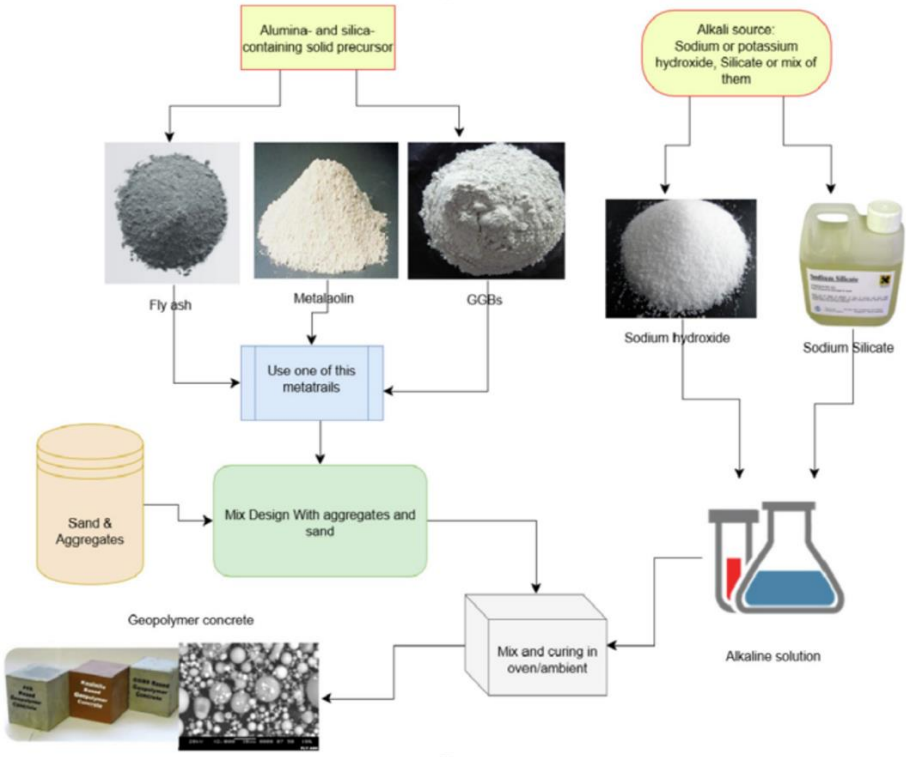

Figure 1. Geopolymer Concrete Production Components and General Mixing Process Flowchart. (Amran et al., 2020)

The remarkable physical and mechanical properties exhibited by geopolymer concrete are fundamentally due to the intense reaction kinetics occurring within the matrix. This reaction results in the formation of a highly homogeneous microstructure that crystallizes. This process, defined as geopolymerization, consists of successive stages such as the dissolution of aluminosilicate sources in a highly alkaline environment, the coagulation of the released monomers, and subsequently the formation of three-dimensional, zeolite-like polycondensation networks (Yip et al., 2005). Of course, the phase structure of the matrix can vary depending on the nature of the raw material used. For example, in low-calcium fly ash-based systems, a highly stable and dense N-A-S-H (sodium aluminosilicate hydrate) gel acts as the main binder. By adding calcium-rich components such as blast furnace slag to the system, C-A-S-H (calcium aluminosilicate hydrate) gel is also integrated into the structure, significantly increasing the early age strength of the material (Pradhan et al., 2022; Yip et al., 2005). This unique inorganic polymer network provides geopolimer concrete with a significant chemical passivation capability against chloride penetration,

sulfate attacks, and aggressive acidic environments compared to conventional OPC-based concretes (Bakharev, 2005; Li et al., 2024). Furthermore, unlike conventional C-S-H gels, this cross-linked network, which is not dependent on hydration water, offers high thermal stability by not disintegrating even under extreme thermal shocks reaching 800 °C to 1000 °C and maintaining its structural integrity (Kong and Sanjayan, 2010).

When the structural performance of the material at the macro scale is examined, it is seen that the promising data obtained at the laboratory level can be successfully adapted to large-sized structural elements (Sarker, 2009). Design studies on geopolymer reinforced concrete columns, beams, and slabs show that this innovative material can compete with OPC elements in axial load, bending, and shear stresses. Furthermore, it has been shown to offer a load-carrying capacity that can surpass them and exhibit superior adhesion force to steel reinforcement (Mo et al., 2016; Sarker, 2011). However, the microscopic rigidity of the inorganic polymer network reduces the structural fracture toughness of the material, causing it to exhibit a more brittle failure behavior compared to Portland cement concrete (Pan et al., 2011). Furthermore, the fact that mixtures using only low-calcium fly ash require furnace curing to gain strength, while somewhat surmountable in the prefabrication industry, creates a significant practical challenge in field casting applications (Hardjito et al., 2004).

To overcome these structural challenges and transform geopolymer from a purely static load-bearing material into a smart, ductile, and functional composite, modern materials science has turned to hybrid reinforcement systems. Integrating steel, basalt, polypropylene (PP), or glass fiber reinforced polymer wastes into the geopolymer matrix in specific volumetric ratios has significantly increased the dynamic flexural toughness, energy absorption capacity, impact resistance, and freeze-thaw resistance of the system, enabling the design of Ultra High Performance Geopolymer Concrete (UHP-GPC) technology (Qaidi et al., 2022; Wu et al., 2024). Simultaneously with these modifications, ambient temperature setting mixtures have been developed by adding blast furnace slag to the system to eliminate the disadvantage of traditional heat curing, and even Self-Compacting Geopolymer Concrete (SCGC) concepts capable of self-compacting between complex reinforcement networks have been successfully formulated (Patel and Shah, 2018; Pradhan et al., 2022).

The contribution of geopolimer concrete to environmental sustainability necessitates a more critical approach when examined from a Comprehensive Life Cycle Assessment (LCA) perspective. While numerous studies have shown that fly ash and slag-based geopolimer systems reduce global warming potential by 45% to 80% compared to Portland cement, the material's eco-friendly nature also

carries several disadvantages (Habert et al., 2011; Turner and Collins, 2013). It is known that the industrial production stages of commercial alkaline activators such as sodium silicate and sodium hydroxide, necessary to trigger the reaction, require very high energy input (Habert et al., 2011). This situation can cause geopolimer concrete to generate higher negative bills than OPC concrete in other environmental impact categories such as inanimate resource depletion, marine ecotoxicity, and acidification (Habert et al., 2011). Therefore, for this technology to be considered truly environmentally friendly, it is necessary to optimize reliance on chemical activators and develop alternative low-energy activators. At the same time, in addition to replacing cement, it is essential to increase overall resource efficiency.

At the most advanced stage, in accordance with circular economy principles, zero-waste architectures using recycled concrete aggregates obtained from construction and demolition waste instead of natural aggregates in geopolimer matrices are attracting significant attention (Thomas et al., 2022). Today, geopolimer concrete has evolved from a simple industrial waste repurposing tool into a sustainable, durable, and multifunctional building material serving advanced engineering applications such as ocean structures, corrosion barriers, and heavy-duty smart composites, acquiring a multi-dimensional perspective.

2. Development and Current Status of Geopolymer Concrete

Traditional Portland cement (OPC), the primary binder material for meeting global infrastructure demands, releases approximately one ton of carbon dioxide (CO_2) into the atmosphere for every ton produced, making it responsible for 5% to 9% of global anthropogenic greenhouse gas emissions (Gartner, 2004; Meyer, 2009). This severe environmental crisis has made the development of low-carbon footprint and sustainable binders that can be an alternative to OPC, which depletes natural resources and requires high energy, imperative for the scientific community (Singh et al. 2015). The most critical turning point in this search for alternatives, which revolutionized the chemistry of construction materials, began with the French researcher Joseph Davidovits' definition of inorganic polymeric structures formed by alkali activation of aluminosilicate minerals as geopolymers in the scientific literature in 1978-1979 (Davidovits, 1991; Ghafoor et al., 2021).

Following lime and Portland cement, geopolymers, categorized in the literature as third-generation cements, are produced by activating silicon and aluminum-rich by-products such as fly ash, blast furnace slag, and metakaolin with strong alkaline solutions like sodium hydroxide or sodium silicate (Duxson et al., 2007; Pradhan et al., 2022). This synthesis process, called geopolymerization, involves the dissolution, coagulation, and polycondensation

of Al and Si components in an alkaline environment, resulting in a three-dimensional, amorphous inorganic polymeric network (N-A-S-H or C-A-S-H gels) woven with covalent bonds (Davidovits, 1999; Yip et al., 2005). Initially developed through metakaolin-based calcium-free systems, this innovative technology was taken to a new commercial and environmental dimension in the early 1990s by Wastiels et al. using low-calcium fly ash as a binder (Wastiels et al., 1993; Wastiels et al., 1994).

When the current technological status of geopolimer concrete is evaluated, it is seen that the material is not only a passive industrial waste utilization method, but has also transformed into a superior structural element that can directly compete with conventional concrete in terms of macro-mechanical and durability parameters (Ma et al., 2018). Current and comprehensive studies indicate that geopolimer concretes show significant chemical corrosion resistance to sulfate and acid attacks compared to conventional cement matrices. Furthermore, current research reveals that it has very low creep values and can maintain its structural integrity even at high temperatures exceeding 1000°C (Bakharev, 2005; Kong and Sanjayan, 2010; Wallah, 2010). When examined in the context of environmental impact and sustainability goals, it has been determined that geopolymer concrete production, depending on the optimization of the activator and raw materials used, can reduce global warming potential and greenhouse gas emissions by 26% to 80% compared to OPC concrete (Habert et al., 2011; Turner and Collins, 2013).

One of the most strategic advancements in this new generation of concrete technology is the evolution of curing regimes to increase the practical applicability of the material on-site (Nath and Sarker, 2014). In the past, pure geopolimer mixtures using low-calcium fly ash required oven curing at high temperatures of 60°C to 80°C to achieve sufficient load-bearing strength at an early age, significantly limiting the in-situ casting practice (Hardjito et al., 2004; Nath and Sarker, 2014). However, with modern design approaches in recent years, hybrid geopolimer systems have been developed that blend calcium-rich blast furnace slag (BFS) with fly ash in specific ratios. This allows the material to set and harden completely in the environment without the need for any artificial heat treatment (Nath and Sarker, 2015; Pradhan et al., 2022).

In addition, the development of single-component solid activator powder geopolymer technologies that self-activate by simply adding water, just like traditional cement, to eliminate occupational safety risks associated with transporting high-viscosity and corrosive liquid alkaline solutions (sodium silicate, etc.) to the construction site, represents the most advanced point in current research and the closest to commercialization (Adesanya et al., 2018;

Qaidi et al., 2022). Consequently, geopolymer concrete, having moved beyond its conceptual origins at the laboratory level and successfully integrated into the production of full-scale structural elements such as columns, beams, and slabs, is a candidate to become the sustainable, high-performance, and functional main building material of the future if it overcomes industrial obstacles such as the lack of standard design codes and activator production costs (Ma et al., 2018; Yost et al., 2013). A comparison of traditional Portland cement concretes and geopolymer concretes (GeoPC) in terms of fundamental engineering properties such as durability, setting times, chemical resistance, and thermal stability is given in Figure 2 (Amran et al., 2020).

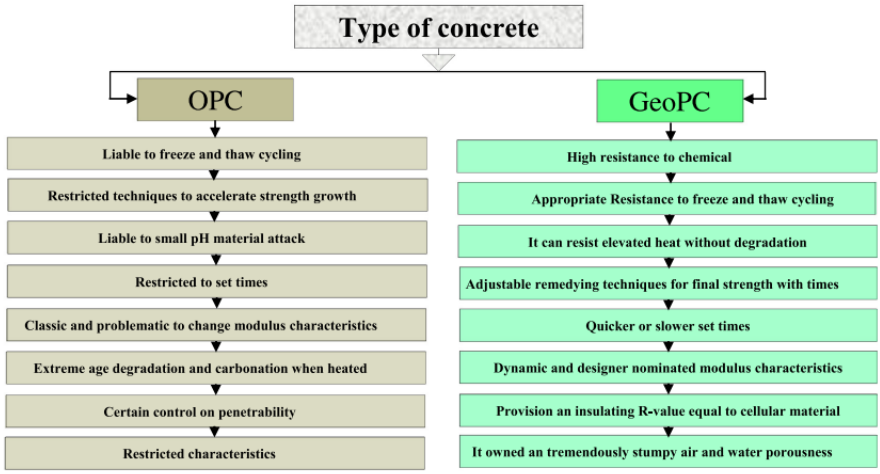

Figure 2. Comparison of Technical Properties of Traditional Portland Cement Concrete (OPC) and Geopolymer Concrete (GeoPC) (Amran et al., 2020).

3. Sustainability Discussions

It has been previously stated that the global cement industry alone is responsible for approximately 5% to 9% of anthropogenic carbon dioxide emissions in the atmosphere. In addition, each ton of Traditional Portland Cement production leads to the release of an average of one ton of CO_2 into the atmosphere due to the calcination process and fossil fuel consumption (Patel and Shah, 2018; Xie et al., 2020). Besides this enormous environmental damage, OPC production is a highly energy-intensive process as it requires raising the temperature in the kilns to 1450°C to 1500°C (Patel and Shah, 2018; Wong, 2022). In the face of this scorching situation, geopolymer concretes, obtained through alkali activation of inorganic industrial wastes such as fly ash, blast furnace slag, and metakaolin, are being promoted as sustainable green concrete

because they not only offer solutions to waste disposal problems but also have the potential to significantly reduce CO_2 emissions (Amran et al., 2020; Thomas et al., 2022). Traditional approaches in the literature widely accept that geopolymers reduce the global warming potential by 45% to 80% compared to OPC concrete, depending on specific mix designs (Habert et al., 2011; Turner and Collins, 2013). However, when the true environmental sustainability of geopolymer concretes is examined more critically through the lens of Comprehensive Life Cycle Assessment methodology, it is seen that they are not as effective as claimed (Habert et al., 2011). The industrial production stages of commercial alkaline activators such as sodium silicate and sodium hydroxide, which initiate the polymerization of the geopolymer matrix and build its structural framework, require a considerable amount of energy (Habert et al., 2011; Wong, 2022). The energy sources and emission pathways in the geopolymer concrete production and activator synthesis processes are schematically illustrated in Figures 3-4 (Habert et al., 2011).

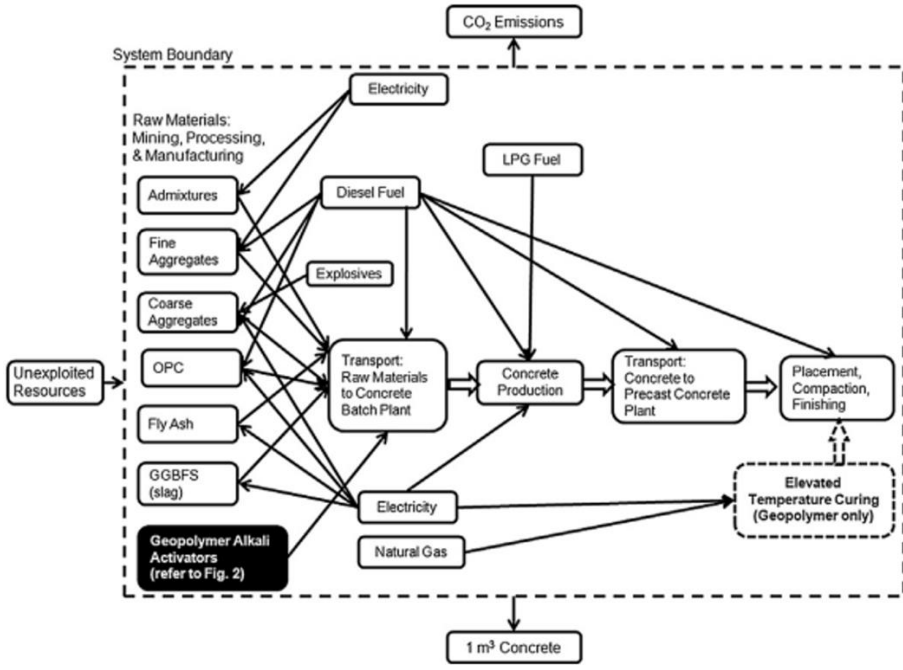

Figure 3. CO_2 emission system diagrams for the production of 1 m^3 of concrete (Habert et al., 2011).

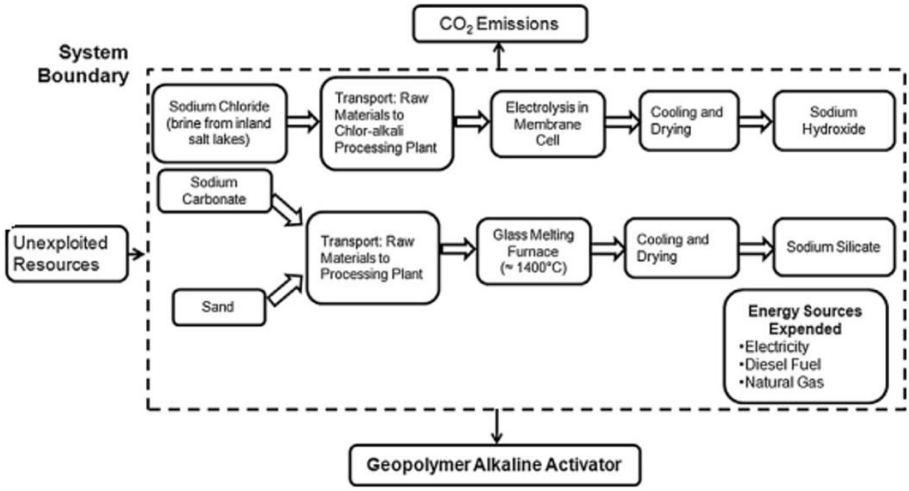

Figure 4. CO_2 emission system diagrams for the synthesis of 1 m^3 of alkaline activator (Habert et al., 2011).

Detailed LCA analyses conducted by Habert et al. (2011) confirm that geopolimer concrete is more advantageous than standard cementitious concrete in terms of its global warming potential. However, it clearly demonstrates that it has a much higher negative environmental cost than OPC concrete in other key impact categories such as depletion of inanimate natural raw material resources, marine ecotoxicity, and environmental acidification (Habert et al., 2011). In other words, replacing cement with geopolimer with high-concentration liquid activator solves the atmospheric carbon problem while carrying the risk of creating a dangerous pollution transfer in other pollution parameters (Habert et al., 2011). The performance of geopolimer concrete in environmental impact categories according to different raw material sources (fly ash, slag, metakaolin, etc.) and allocation models is detailed in Figure 5 (Habert et al., 2011).

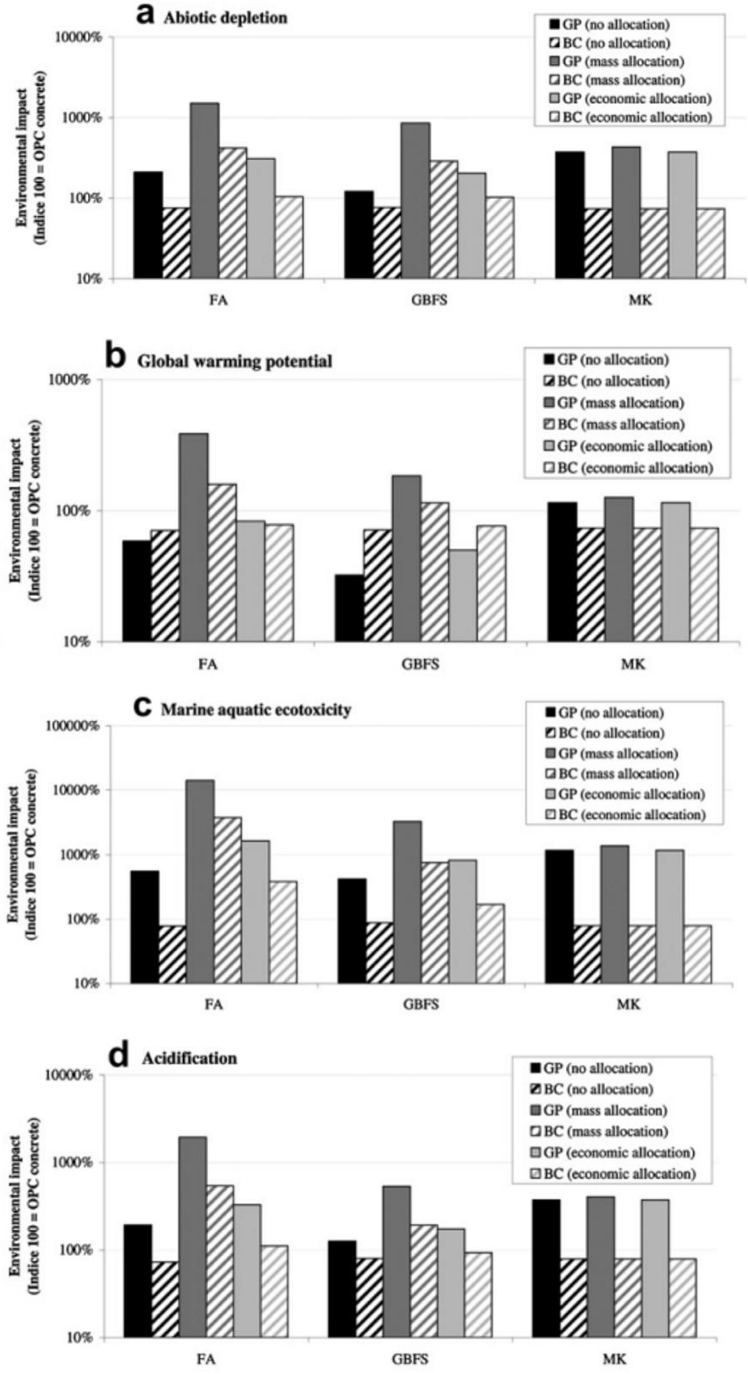

Figure 5. Comparison of Geopolymer and Portland Cement Concrete According to (a) Abiotic Resource Depletion, (b) Global Warming Potential, (c) Marine Aquatic Ecotoxicity and (d) Acidification Categories (Habert et al., 2011).

Another critical breaking point in the scientific basis of sustainability discussions is whether industrial by-products (fly ash or slag) are classified as waste or as a secondary product with economic value in LCA calculations (Habert et al., 2011). If these raw material sources are considered only as waste and their environmental production loads are entered into the system as zero, geopolimer concretes have remarkably low emissions (Habert et al., 2011). However, when these materials are subjected to an economic or mass allocation model according to the rules of the modern circular economy, it has been found that the global warming advantage offered by geopolimer concretes is largely lost, and they fall to similar environmental impact levels as concretes using traditional blended cement (e.g., OPC with 30% slag) (Habert et al., 2011). This situation reveals that standard-designed geopolimer concrete alone is not a sufficient or miraculous technology to achieve the goals of reducing emissions in the cement industry by a quarter (factor 4) (Habert et al., 2011). Strategic optimizations are inevitable to overcome these critical barriers and minimize the environmental footprint of geopolimer technology. To break the dependence on sodium silicate solutions, which lead to high acidification and toxicity, it is strongly recommended to design hybrid raw materials with ideal Silicon/Aluminum (Si/Al) molar ratios in reaction kinetics (e.g., integrated use of metakaolin with slag) (Habert et al., 2011). In parallel, the commissioning of systems using only single-component activators (e.g., only low molarity NaOH) instead of costly chemical solutions with high environmental impact holds great potential. Indeed, it has been successfully demonstrated that optimized geopolimer mixtures, produced from slag (GGBS) and setting entirely at ambient temperature without requiring heat curing, reduce carbon emissions by more than 60% (Zannerni et al., 2020).

In the zero-waste and ecological vision of the future, it is essential that geopolimer binders not only eliminate cement use but also integrate aggregate consumption into the circular economy. The inclusion of recycled concrete aggregates purified from construction and demolition waste into the geopolimer matrix, replacing traditional quarry aggregates, enables the material to reduce carbon emissions. In addition, it ensures the protection of rapidly depleting natural underground resources, thus bringing the material into a holistic sustainability concept (Thomas et al., 2022). In conclusion, for geopolimer concretes to be a truly green building material, they must eliminate the hidden environmental impacts arising from alkali activator production, be combined with recycled aggregates, and eliminate the need for thermal curing.

4. Microstructure and Performance Relationship

The high mechanical strength and resistance to environmental effects exhibited by geopolymer concretes at the macro scale are fundamentally based on the complex chemical networks and phase distributions in the microstructure of the material. Unlike calcium silicate hydrate (C-S-H) gels, which are the primary binder in traditional Portland cement (OPC) systems, the microstructure of the geopolymer matrix is shaped according to the nature of the precursor material used (Pradhan et al., 2022). Systems dominated by low-calcium components such as fly ash or metakaolin produce a highly cross-linked and three-dimensional pseudo-zeolitic N-A-S-H (sodium aluminosilicate hydrate) gel; while the addition of calcium-rich materials such as blast furnace slag (BBS) to the matrix simultaneously forms a denser C-A-S-H (calcium aluminosilicate hydrate) phase (Farhan et al., 2019; Pradhan et al., 2022). The density and homogeneity of this inorganic polymeric network are the most critical microstructural elements that directly determine the ultimate compressive and flexural strength of the material. The distribution of Si, Ca, and Al elements within the geopolymer matrix and the phase densities formed by these elements are clearly visible in the EDS (Energy Dispersive Spectroscopy) mapping images in Figure 6 (Provis and van Deventer, 2014).

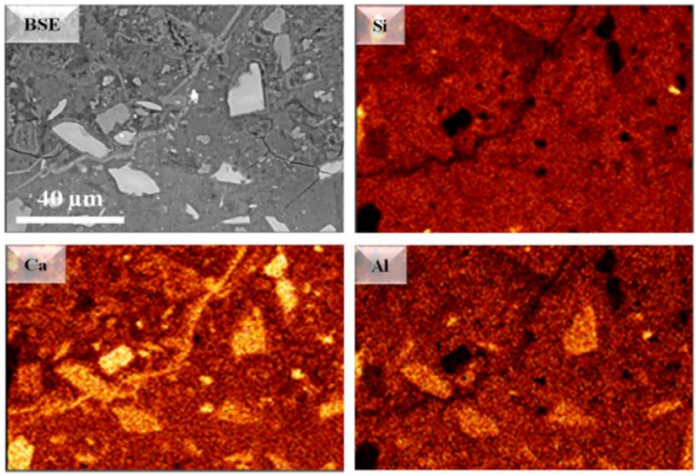

Figure 6. Microscopic Element Mapping of Geopolymer Concrete: Distribution of Silicon (Si), Calcium (Ca), and Aluminum (Al) by Backscattered Electron (BSE) Image (Provis and van Deventer, 2014).

The most significant microstructural difference between geopolimer concrete and conventional concrete lies in the characteristic Interfacial Transition Zone (ITZ) formed between the aggregate and the binder paste (Beygi et al., 2014). In OPC concretes, the ITZ is considered the weakest link due to its high porosity

and weak structure, allowing external chemicals such as chlorides or sulfates to penetrate the structure and being the first point where microcracks begin under mechanical load (Singh et al., 2015). In contrast, the ITZ of geopolimer concretes is much denser, more homogeneous, and so robust that it is indistinguishable from the bulk binder matrix (Singh et al., 2015). The dissolved silicates in the activation solution form an aluminum-rich aluminosilicate layer on the aggregate surface, effectively bonding the aggregate physically and chemically to the matrix (Singh et al., 2015). Scanning Electron Microscopy (FESEM) analyses show that spongy amorphous geopolimer gels directly overlap with the aggregate surface, creating a high adhesion force (Singh et al., 2016). This strong ITZ also alters the fracture mechanics of the material; in geopolimer concrete, cracks, instead of traversing the weak interface, pass directly through the aggregates, forming the fracture plane, which significantly increases the splitting tensile strength and fracture energy of the material (Beygi et al., 2014).

Another important microstructural parameter affecting performance is the porosity profile and pore size distribution of the material. This pore system, formed as a result of the voids left by the water expelled from the matrix during the geopolymerization reaction, directly affects the long-term durability of the material (Ryu et al., 2013). Detailed analyses using Mercury Intrusion Porosimetry (MIP) have shown that the pores in the geopolimer matrix are divided into two main categories. These are meso-pores with a diameter smaller than 50 nanometers and macro-pores with a diameter larger than 1000 nanometers (1 micron) (Gunasekara et al., 2016). Meso-pores essentially represent the voids within the aluminosilicate gel phase and manage the capillary water absorption capacity of the material; macro-pores, on the other hand, are large voids between unreacted particles and directly determine the water and gas permeability of the concrete (Gunasekara et al., 2016). In particular, the use of high-concentration (high molarity) alkali activators maximizes the degree of geopolymerization, reduces the volume of macro-pores, compacts the matrix, and thus creates an excellent barrier against external chemical attacks (Ryu et al., 2013).

The thermodynamics and kinetics of geopolymerization never occur with 100% efficiency. Therefore, the microstructure always contains unreacted or partially dissolved fly ash or slag particles. Microscopic examinations reveal that these fully unreacted spherical fly ash particles function as micro-filling materials, physically filling the voids in the amorphous matrix and imparting additional stiffness to the matrix (Ghafoor et al., 2021; Singh et al., 2016). Optimizing the molarity of sodium hydroxide (NaOH) increases the dissolution rate of these particles, accelerating the formation of the N-A-S-H gel and

reducing non-reactive weak points in the structure (Ghafoor et al., 2021). However, if the activator ratio exceeds the ideal level (e.g., 0.5% activator/fly ash ratio) or if very high alkali concentrations are used, dissolved silicon and aluminum monomers precipitate suddenly before completing the geopolymerization process. This leads to the formation of microscopic cracks and large voids in the microstructure, severely weakening both the compressive and flexural performance of the concrete (Ghafoor et al., 2021; Singh et al., 2016). Consequently, achieving the targeted service life of geopolymer concretes on an industrial scale depends on precisely calibrating the chemistry of the precursor materials, the activator concentration, and the curing regime to obtain the densest, non-porous, and homogeneous microstructure.

5. Structural Design and Application Challenges

The superior physical and chemical properties of geopolymer concrete at the micro level are directly reflected in the performance of load-bearing structural elements at the macro scale. Extensive structural tests conducted in the literature show that the behavior of geopolymer reinforced concrete columns, beams, and slabs under axial load, shear, and bending is quite similar to, and in most cases structurally superior to, elements produced with conventional Portland cement (OPC) (Sarker, 2009). The load-carrying capacities, energy absorption properties, and crack widths of geopolymer reinforced concrete beams under bending effects are comparable to those of OPC beams. However, in some design scenarios, it has been determined that they can deflection slightly more under service loads due to the material having a lower modulus of elasticity compared to conventional concrete (Dattatreya et al., 2011). When the elements under the influence of shear force were examined, it was proven that the diagonal crack formation and failure modes of geopolimer concrete adhered to the same mechanical principles as classical concrete (Yacob et al., 2019).

Geopolimer systems offer a significant performance advantage compared to conventional concretes in terms of reinforcement-concrete adhesion (bond strength), which is one of the most fundamental elements of safety in structural design. Thanks to its high splitting tensile strength and the dense interfacial transition zone (ITZ) it forms with aggregates, the bond strength of geopolimer concrete with reinforcing steel is much higher than that of OPC concrete (Sarker, 2011). This situation has led researchers to question the applicability of existing structural design regulations (ACI 318, Eurocode 2, AS 3600) to geopolimer concrete. Extensive analyses have shown that the analytical equations developed for OPC concrete can be used conservatively and safely in calculating the bearing capacity and reinforcement anchorage length of geopolimer reinforced concrete

elements (Chang et al., 2009; Sofi et al., 2007). However, the fact that the material's modulus of elasticity is estimated to be higher than that by these standards makes the creation of customized new design codes essential for reliable structural modeling (Xie et al., 2020).

Despite these promising structural capacities, the integration of the material into the construction site and large-scale industrial use faces major application challenges. Chief among these handicaps is the high brittleness resulting from the extremely dense and three-dimensional cross-linked network structure of the geopolimer matrix. Geopolimer concretes have significantly lower fracture toughness and limited crack growth resistance compared to OPC concrete; The characteristic length of the material is only about one-third that of classical concrete (Pan et al., 2011; Yang et al., 2023). This structure, which tends to fail suddenly and with extreme brittleness under load, limits the performance of the material under dynamic and impact loads, making external reinforcement of the matrix with steel, basalt, or polypropylene fibers virtually a necessity (Yang et al., 2023).

Another critical practical challenge in construction site operations is the difficulty in controlling the rheological properties and setting times of fresh concrete. The high viscosity and stickiness of alkali activator solutions, such as sodium silicate and sodium hydroxide, which initiate the reaction, significantly reduce the workability of the material and make it difficult to place in the formwork (Ma et al., 2018). The inability of standard polycarboxylate or naphthalene-based superplasticizers used in the classical concrete industry to maintain their chemical stability and lose their effectiveness in a high-alkali environment prevents overcoming the rheological bottleneck (Xie et al., 2020). In addition, adding extra water to the fresh mix to improve workability destroys both the mechanical and durability properties of the material. Finally, occupational health and safety and the pouring conditions on site pose serious obstacles. The necessity for workers to store, transport, and mix extremely corrosive and dangerous alkaline liquids on site poses significant risks to the environment and occupational safety (Shahedan et al., 2024). Furthermore, geopolymer systems using only low-calcium fly ash require high-temperature oven curing to achieve sufficient load-bearing strength at an early age in the field. However, the fact that the material is much more sensitive to curing conditions such as moisture and temperature than traditional concrete means that the technology is currently limited to the precast industry rather than in-situ casting projects (Azarsa and Gupta, 2020; Singh et al., 2015). Overcoming these specific structural code deficiencies and eliminating temperature/activation challenges is

the greatest expectation of the construction industry for the adoption of a universal material.

6. Integration with Smart Concrete Systems

One of the most remarkable academic research areas in recent years is the transformation of geopolymer concretes from passive load-bearing materials into smart systems that can monitor their own condition, have high damage tolerance, and are optimized with computational algorithms, overcoming the structural limitations of traditional construction materials (Han, Yu, and Ou, 2014). Unlike traditional concrete matrices, geopolymers with an inorganic polymeric structure gain the capacity to monitor structural health simultaneously when combined with special conductive materials and modern sensors integrated into them. For example, the ability of carbon fiber reinforced geopolymer composites to detect external mechanical stresses through changes in electrical resistance (piezoresistive behavior) has given these materials self-sensing capabilities (Vaidya and Allouche, 2011). In addition, by non-destructively embedding piezoelectric sensors into fly ash-based geopolymer systems, the strength development, damage status, and internal structural integrity of the concrete can be continuously monitored externally (Talakokula et al., 2016). Another dimension of intelligent integration at the mechanical level is to achieve an extremely ductile, deformation-hardening structure by manipulating the inorganic and brittle nature of the material. The integration of advanced microfibers such as polyvinyl alcohol (PVA), steel, or polyethylene into the geopolimer matrix in optimum ratios (hybrid) has given rise to the Ultra High Performance Geopolimer Concrete (UHPGC) concept. These systems exhibit exceptional ductility and multiple micro-crack mechanisms, intelligently absorbing destructive earthquake or impact energy (Lao et al., 2022). In-depth studies on fracture mechanics confirm that such ultra-high performance fiber-reinforced geopolimer concretes (UHPFRGC) surpass conventional composites in terms of damage tolerance and dynamic load absorption capacity (Ghasemzadeh et al., 2022). Analytical research aimed at testing and theoretically modeling the impact resistance of these hybrid fiber systems has clearly demonstrated how the material proactively maintains its structural integrity against dynamic external influences (Asrani et al., 2019).

Beyond physical and mechanical intelligence, geopolimer concrete technology is currently undergoing a digital revolution, synchronized with Artificial Intelligence (AI) and Machine Learning algorithms. Artificial Neural Networks (ANN), an advanced computational data model, offer a high degree of accuracy in predicting the structural performance of self-compacting geopolimer

concretes and their adhesion strength with basalt fiber reinforced polymer (BFRP) reinforcements (Rahman and Al-Ameri, 2023). Thanks to this AI-based computational modeling, the service life, fracture mechanism, and structural behavior of the material can be predicted with high precision during the design phase without the need for destructive laboratory tests (Rahman and Al-Ameri, 2021). In conclusion, advancements in technology, such as sensor equipment, high-performance fiber architectures, and AI-powered predictive models, indicate that geopolymer concrete can be used more widely in smart infrastructure systems. To transform these smart buildings into fully autonomous and zero-carbon structures, energy automation systems must also be integrated. In this context, utilizing intelligent tracking mechanisms optimized by algorithms such as fuzzy logic to maximize energy harvesting in renewable systems will elevate the eco-friendly vision of the material into a holistic sustainability model (Palta, 2020).

7. Waste-Based and Hybrid Geopolymer Systems

While geopolymer concrete technology initially relied on individual aluminosilicate sources such as metakaolin or pure fly ash in its early laboratory-level development stages, it has undergone a structural evolution towards highly complex hybrid and waste-based matrices in line with today's zero-waste philosophy and interdisciplinary sustainability goals. The blending and use of industrial and agricultural by-products with different characteristics in the same reaction medium has not only minimized the environmental footprint of the material but has also eliminated the weaknesses of individual precursors through a synergistic approach. For example, the problem of geopolymers using only low-calcium fly ash requiring oven curing to react has been solved by integrating blast furnace slag (BFS) into the matrix. This allows the material to set quickly even at ambient temperature, maintain its workability, and achieve high strength early (Deb et al., 2014). Similarly, hybrid alkaline activation systems in which metakaolin is blended with slag have been found to significantly improve long-term mechanical performance and overall resistance to aggressive environments (Bernal et al., 2012).

Expanding the binder material pool beyond pure ash and slag is a significant milestone in incorporating agro-industrial residues into engineering structures. Structural geopolymer composites produced by integrating palm oil fuel ash (POFA) into fly ash and slag networks significantly reduce thermal carbon emissions while exhibiting satisfactory lightness and stable microstructural integrity thanks to their cellular structure (Islam et al., 2015; Liu et al., 2016). The polymerization of lead smelting slag, known for its toxicity and whose

disposal is a global crisis, together with fly ash has enabled the material to safely immobilize heavy metals by trapping them within its rigid zeolitic structure and forming a load-bearing matrix (Albitar et al., 2015). On the other hand, the hybrid interaction of red mud, a byproduct of bauxite processing, with high-silica rice husk ash (RHA) in an alkaline environment constructs a superior sodium aluminosilicate network that alleviates pollution pressure in landfills (He et al., 2013). In order to maximize the micro-mechanical potential of these developed hybrid matrices, advanced composites are designed in which the pore network is refined at the nanometric level by adding extremely low proportions of conventional Portland cement (OPC) and nano-SiO_2 particles to high-calcium fly ash mixtures (Nuaklong et al., 2018). The system's ability to fit into a fully closed-loop model was made possible by substituting the aggregates, which constitute 70% to 80% of the matrix, from waste sources. The inclusion of recycled concrete aggregates (RCA) purified from construction and demolition waste (CDW) in geopolimer production, instead of aggregates obtained from traditional natural quarries, is one of the most pragmatic steps taken in recent years. Electron microscopy (SEM) analyses clearly demonstrated that the Interface Transition Zone (ITZ) formed between the geopolimer matrix and the surface of the recycled aggregate provides a much denser, more homogeneous, and microscopically crack-free interlocking than in classical cementitious systems (Nuaklong et al., 2016; Shi et al., 2012).

Aggregate-based hybrid innovations have not been limited to recycled old concrete. The integration of bottom ash granules from thermal power plant furnace bottoms into the system as structural lightweight aggregate provides the material with significant thermal insulation capability without compromising high compressive strength (Wongsa et al., 2016). Permeable geopolymer concretes designed from these waste aggregates to support urban flood management in infrastructure engineering offer an effective modular solution for sustainable urbanization with their high void ratios and hydraulic capacities (Sata et al., 2013). In more extreme bio-hybrid studies pushing the boundaries of industry, unwanted wild giant reed biomass has been modified and used in place of aggregate in concrete. Thus, by embedding a completely organic waste into a mechanical carrier matrix, the environmental sustainability level of the material has been taken to a unique point (Ismail and Jaeel, 2014).

8. Future Vision and Research Gaps

Geopolymer concrete technology has made significant progress, from fundamental reaction kinetics at the laboratory scale to full-scale structural element testing. However, critical research gaps remain between academia and

industry before the material can become a universal standard in the global construction market. The first and most fundamental step in the future vision is eliminating factors that limit the material's field applicability. Most current production models require the on-site processing of corrosive alkaline liquids with high pH values (sodium silicate, etc.) and, in some cases, high-temperature firing of the matrix. In this context, optimizing and commercializing single-component geopolymer systems with solid activators that can harden at ambient temperature like conventional cement with only the addition of water is one of the most important research goals (Ahmed et al., 2022).

From the perspective of durability and micro-mechanical investigations, long-term (decades-long) service life data of geopolymer concretes under real-world field conditions are still insufficient. Comprehensive modeling is needed to predict the slow-motion disruptive effects of chloride-induced corrosion, freeze-thaw cycles, and sulfate attacks on the inorganic polymer network (Gunasekara et al., 2019). At this point, going beyond traditional porosimetry methods, precise mapping of the convolution and liquid/gas permeability pathways in the internal pore structure of geopolymer binders using advanced non-destructive three-dimensional imaging techniques such as X-ray microtomography holds significant research potential (Provis et al., 2012). Furthermore, the integration of advanced deep learning architectures and texture feature fusion approaches, which have demonstrated high accuracy in complex microscopic image classifications, can be adapted to analyze these microtomography images to autonomously detect micro-cracks and structural anomalies in geopolymer matrices (Palta et al., 2026).

From an environmental and economic sustainability perspective, there is still no clear consensus in the literature. The use of industrial wastes (e.g., slag, fly ash, mining waste) that may contain toxic heavy metals in geopolymer production carries the risk of these hazardous trace metals leaching into groundwater or soil after decades. Therefore, environmental toxicity tests that will prove long-term leaching behavior and the reliability of the matrix in trapping heavy metals should be increased (Azarsa and Gupta, 2020). At the same time, advanced nanotechnology and fiber-reinforced systems such as Ultra High Performance Geopolymer Concrete (UHP-GPC) need to be clearly evaluated against traditional concretes using Integral Life Cycle Analyses (LCA) that encompass the social, environmental, and economic three pillars, including cost efficiency, thermal resistance, and carbon/energy footprint, before being used in large-scale infrastructure projects in the construction sector (Ahmed et al., 2022; Qaidi et al., 2022). Furthermore, the high industrial costs of chemical activators used in these innovative mixtures necessitate finding alternative natural alkali sources that will

reduce the production costs per cubic meter of the material (Zannerni et al., 2020).

The most significant research gap in structural design and codification is the lack of standards suitable for the fracture mechanics of the material. A very large portion of the research has been carried out on laboratory-scale simple-support beams or compression cylinders; The data pool on the behavior of elements such as real-size column-beam connection zones, slab floors, and load-bearing shear walls is limited (Ahmed et al., 2022). Therefore, under multiaxial stress conditions, the focus should be on the stiffness loss, fatigue, creep, shrinkage, and fracture propagation under dynamic seismic loads of geopolymer reinforced concrete systems. Existing design specifications such as ACI or Eurocode should be scientifically revised with analytical parameters specific to this binder (Ahmed et al., 2022).

Finally, extending geopolymer technology to marine applications by taking advantage of its superior chemical passivation and corrosion resistance is a strategic future vision. In projects for the repair and structural strengthening of existing marine infrastructures exposed to severe wave erosion and chloride attack, field testing of geopolymeric repair mortars with optimized chloride migration coefficient and concrete cover thickness will ensure that the technology becomes a sought-after innovative protective layer in the construction market (Shahedan et al., 2024).

9. Conclusion

Geopolymer concrete technology is considered one of the strongest candidates for sustainability-focused transformation in the field of building materials. Considering the high carbon emissions and energy-intensive consumption of traditional Portland cement, geopolymer systems produced by alkali activation of industrial by-products offer significant environmental advantages. In particular, the reintegration of waste resources such as fly ash, blast furnace slag, and metakaolin into the construction sector both reduces the consumption of natural resources and constitutes an important solution in terms of waste management.

The dense and homogeneous binder network formed in the microstructure of geopolymer concretes provides the material with high compressive strength, low permeability, and superior chemical resistance. Its high resistance to sulfate, chloride, and acidic environments, and its stability at high temperatures, make this material a strong alternative, especially for engineering structures exposed to aggressive environmental conditions. However, the brittle structure of the geopolymer matrix, difficulties in rheological control, the cost of alkali activators, and the inadequacy of standard design codes are among the main

problems limiting the widespread adoption of the technology. In recent years, fiber-reinforced hybrid systems, ambient temperature curable mixtures, self-compacting geopolimer concretes, and single-component activator technologies have made significant progress in overcoming these limitations. Furthermore, with the use of smart sensor systems, AI-powered modeling, and recycled aggregates, geopolimer concrete technology is transforming from a classic binder system into a multifunctional engineering platform. It holds significant future potential, particularly in areas such as sustainable infrastructure, marine structures, high-temperature resistant applications, and smart building systems. However, for geopolimer concrete to become a full-fledged industrial standard, more comprehensive research into its long-term field performance is needed. Advanced studies on durability behavior, environmental toxicity effects, economic feasibility, and standard design criteria will determine the future of the technology. Based on current scientific data, geopolimer concrete stands out as an innovative system of strategic importance among future building materials, combining environmental sustainability, high performance, and circular economy goals.

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Chapter 2

Attendance System with Face Recognition and Spoof Detection

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Introduction

Attendance monitoring is an essential administrative task in educational institutions, directly influencing academic evaluation, course management, and student engagement. Traditional attendance methods such as manual roll calls and paper-based sign-in sheets are time-consuming and prone to human error. Moreover, these approaches are highly vulnerable to proxy attendance, where one individual records attendance on behalf of another, undermining the reliability of attendance records.

To overcome these limitations, automated attendance systems based on biometric technologies have been widely investigated. Among various biometric modalities, facial recognition has gained significant attention due to its non-intrusive nature, low deployment cost, and compatibility with standard camera devices. Unlike fingerprint or iris-based systems, face recognition does not require physical contact or specialized hardware, making it suitable for classroom and remote learning environments (Jain et al., 2004).

Early face-based attendance systems relied on classical computer vision techniques such as Haar Cascade classifiers and Histogram of Oriented Gradients (HOG). While these methods offer low computational complexity, their performance deteriorates under variations in illumination, pose, and facial expressions, which are common in real-world scenarios (Viola & Jones, 2001; Dalal & Triggs, 2005). Recent advances in deep learning have led to the development of convolutional neural network (CNN)–based face detection and recognition models that significantly improve robustness and accuracy. Methods such as MTCNN and RetinaFace enable reliable face detection in unconstrained environments, while deep embedding-based recognition models such as FaceNet and ArcFace provide highly discriminative facial representations (Zhang et al., 2016; Deng et al., 2019a; Schroff et al., 2015; Deng et al., 2019b).

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Despite these advancements, face recognition systems remain vulnerable to presentation attacks, where adversaries attempt to deceive the system using printed images, videos, or digital displays. Several studies have shown that neglecting liveness detection can lead to high false acceptance rates, particularly in web-based biometric systems (Shao et al., 2019; Chingovska et al., 2012). Therefore, integrating face anti-spoofing mechanisms has become a critical requirement for secure biometric attendance systems.

In the light of the literature studies reviewed, it becomes apparent that in such systems, the face, which is a personal biometric data, can be used more easily without requiring any special hardware, Besides, various mechanisms are also needed for detecting faces from video images captured by cameras, then recognizing faces correctly and, preventing spoofing accesses.

In this paper, we propose a secure web-based biometric attendance system that combines face detection, liveness detection, and face recognition within a modular and scalable architecture. The system separates application logic from biometric inference by employing an independent AI inference service, improving scalability and maintainability. Additionally, a token-based session mechanism is introduced to allow verified users to rejoin sessions without repeated biometric verification, enhancing usability while maintaining security. Unlike many existing systems, the proposed approach records granular session-level attendance information, including join, disconnect, and rejoin events.

The remainder of this paper is organized as follows. Section II reviews related work on face-based attendance and biometric verification systems. Section III presents the proposed system architecture and biometric verification pipeline. Section IV describes the system methodology and implementation details. Section V reports experimental results and performance evaluation. Section VI discusses the findings and limitations of the system, and Section VII concludes the paper with directions for future work.

Literature Review

Automated attendance systems have been extensively studied as a solution to the inefficiencies and security issues of traditional attendance methods. Early digital approaches relied on RFID cards, QR codes, or fingerprint-based systems. Although these methods reduced manual effort, they introduced new challenges such as card sharing, hygiene concerns, and the need for specialized hardware (Jain et al., 2004).

Facial recognition has emerged as a promising alternative due to its non-intrusive nature and ease of deployment. Initial face-based attendance systems employed classical computer vision techniques, including Haar Cascade

classifiers (Viola & Jones, 2001) and Histogram of Oriented Gradients (HOG) (Dalal & Triggs, 2005). These methods use handcrafted features and sliding-window detection strategies, enabling fast processing on limited hardware. However, their sensitivity to environmental variations such as lighting conditions, head pose, and occlusions significantly limits their effectiveness in real-world classroom settings.

Recent advances in deep learning have substantially improved the robustness of face detection and recognition systems. Convolutional neural network (CNN)–based face detectors such as Multi-task Cascaded Convolutional Networks (MTCNN) (Zhang et al., 2016) and RetinaFace (Deng et al., 2019a) have demonstrated high detection accuracy under unconstrained conditions. MTCNN employs a cascaded architecture that jointly performs face detection and alignment, offering a favorable balance between accuracy and computational efficiency. RetinaFace further improves detection precision by leveraging dense feature representations, although at the cost of increased computational complexity.

For face recognition, embedding-based approaches have become the dominant paradigm. FaceNet (Schroff et al., 2015) introduced a metric learning framework based on triplet loss to generate highly discriminative facial embeddings. ArcFace (Deng et al., 2019b) enhanced this approach by incorporating an additive angular margin loss, resulting in improved inter-class separability and state-of-the-art performance on benchmark datasets. While these models achieve high accuracy, their computational requirements may limit real-time deployment in resource-constrained environments. Lightweight alternatives such as dlib's ResNet-based face recognition model provide a practical compromise between recognition performance and inference efficiency (King, 2009).

Despite the effectiveness of deep learning-based recognition models, face recognition systems remain vulnerable to presentation attacks. Attackers may exploit the system using printed photographs, video replays, or images displayed on digital devices. To address this vulnerability, face anti-spoofing techniques have been proposed as an essential security layer. MiniFASNet is a lightweight deep learning architecture designed for real-time face anti-spoofing, achieving competitive detection performance while maintaining low inference latency (Shao et al., 2019). Previous studies have shown that integrating liveness detection significantly reduces false acceptance rates in biometric systems (Chingovska et al., 2012).

Several recent studies have combined face detection and recognition for attendance management applications (Khan et al., 2017; Kale et al., 2024, Jha et al., 2023). However, many existing solutions either neglect liveness detection or

treat attendance as a binary event, failing to capture session-level participation details. Furthermore, few studies address system scalability and architectural design for web-based deployment. Motivated by these limitations, the proposed system integrates face detection, liveness verification, and recognition within a modular, service-oriented architecture while supporting granular attendance logging. This approach addresses both the security and functional gaps identified in previous research.

Proposed System

This section presents the design and workflow of the proposed facial recognition–based attendance system. The system is designed as a modular, service-oriented architecture to ensure scalability, security, and real-time performance.

System Architecture Overview

The proposed system includes a three-layer architecture composed of a presentation layer, an application layer, and an AI inference layer. This layered separation improves maintainability and allows each component to scale independently.

Figure 1 illustrates the high-level architecture of the system proposed in the paper, showing interactions between users, system components, and external services.

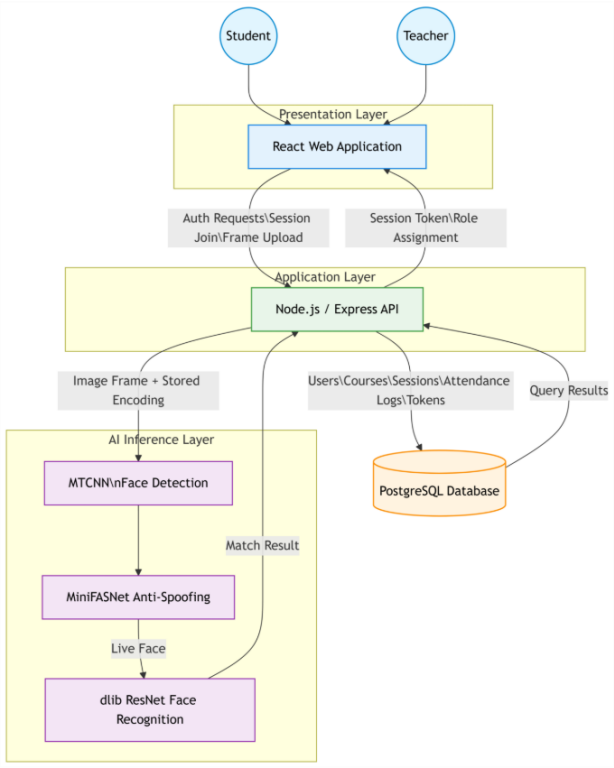

Figure 1. Architecture diagram of the proposed biometric attendance system

The presentation layer consists of a React-based web application that serves the users including both students and teachers. Users interact with the system through this interface to enroll face profiles, join live sessions, and view attendance records. The application layer is implemented using a Node.js and Express backend, which handles authentication, session management, role assignment, and communication with the database and AI inference services.

The AI inference layer is implemented using FastAPI and is responsible for all biometric processing tasks, including face detection, liveness verification, and face recognition. Attendance data, user profiles, session tokens, and logs are stored in a PostgreSQL relational database.

Biometric Verification Pipeline

The biometric verification process follows a sequential multi-stage pipeline to ensure both efficiency and security. As shown in Figure 2, biometric processing begins only after the backend validates the user request and authentication token.

During enrollment or session joining, the client captures image frames from the user's webcam and transmits them securely to the backend server. The

backend forwards validated frames to the AI inference server, where the biometric pipeline is executed.

The pipeline consists of three consecutive stages:

1. Face Detection:

On deciding the method to be used for face detection, performances of Haar, HOG, MTCNN and RetinaFace have been evaluated in terms of time latency and detection accuracy through experiments on 25 images.

While RetinaFace offers near-complete face detection, its high latency limits its suitability for real-time web-based systems. Conversely, Haar and HOG prioritize speed but fail to provide reliable detection in realistic classroom conditions.

MTCNN emerges as a practical compromise, delivering strong detection performance with manageable computational overhead. As a result, MTCNN is used to detect and align faces from the input frame, ensuring robustness under varying illumination and pose conditions.

2. Face Anti-Spoofing:

The MiniFASNet-based anti-spoofing module was evaluated by attempting several common presentation attacks. Static photographs and mobile phone displays were consistently rejected, yielding liveness scores below the acceptance threshold. Live face inputs, by contrast, reliably produced high liveness scores, enabling seamless progression to the recognition stage.

Although a quantitative benchmark against alternative anti-spoofing models was not performed, the observed behavior confirms the suitability of MiniFASNet as a lightweight and effective liveness detection solution for real-time attendance systems.

MiniFASNet performs liveness detection to distinguish real faces from spoofing attempts such as photographs or video replays. Frames failing this stage are immediately rejected.

3. Face Recognition:

The face recognition module was evaluated by comparing the performance characteristics of dlib (ResNet-based), FaceNet, and ArcFace models. The evaluation focused on recognition consistency, computational efficiency, and robustness to minor variations in pose and illumination.

The dlib model demonstrated highly consistent embedding generation, producing stable Euclidean distances for repeated captures of the same individual. FaceNet showed increased sensitivity to noise and lighting variation,

occasionally resulting in fluctuating distance scores. ArcFace achieved high recognition accuracy but required significantly greater computational resources, which limited its practicality for the intended deployment environment.

Based on these observations, the dlib ResNet-based model was selected as the recognition component due to its efficient inference time and reliable performance under controlled enrollment conditions. A ResNet-based face recognition model (dlib) extracts facial embeddings and compares them with preciously stored encodings to determine identity.

Only when all three stages succeed does the AI server return a positive verification result to the backend. On any fails of these steps, the client's attempt to join the systems is rejected.

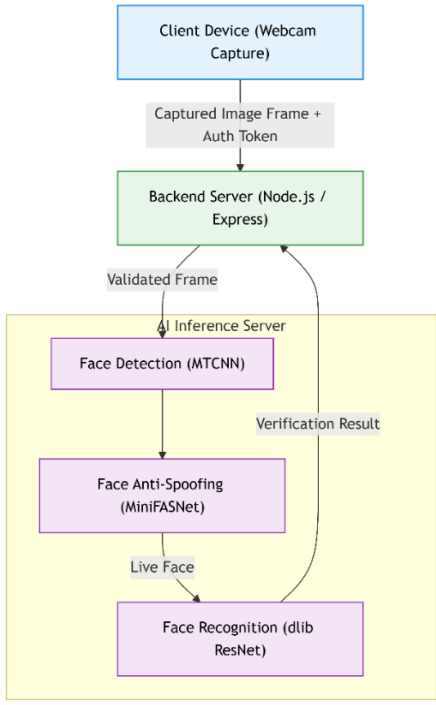

Figure 2. Biometric verification pipeline used during session enrollment and attendance logging

Session Management and Attendance Logging

Upon successful biometric verification, the backend issues a secure session token and assigns the appropriate role (student or teacher) to the client. This token allows verified users to rejoin the session without repeating biometric verification, improving usability while maintaining security.

Attendance is logged at a granular level, capturing join time, disconnection time, and total session duration, a student will be marked as present if the total participation time exceeds a duration specified by the teacher as shown in Figure 3. Teachers can later retrieve detailed attendance reports through the web interface. This design enables accurate tracking of student participation beyond simple presence verification. Attendance data of all students can be analyzed in relation to course performances at the end of the term.

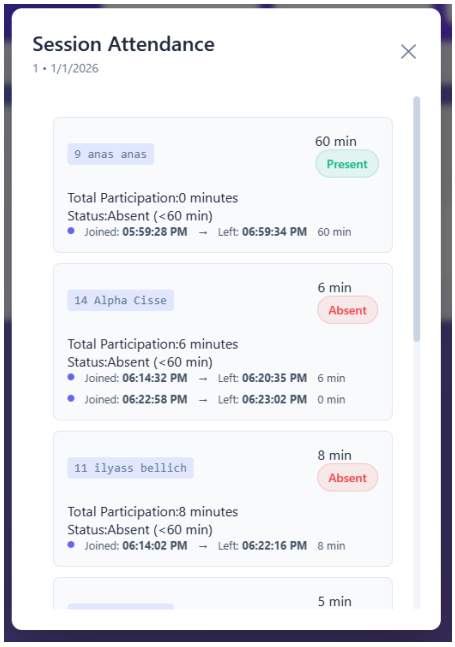

Figure 3. Example of an attendance list of a session

Experimental Setup And Results

This section presents the experimental setup used to evaluate the proposed biometric attendance system and discusses its performance in terms of accuracy, robustness, and real-time feasibility.

1. Experimental Environment

All experiments were conducted in a real-world usage scenario to reflect practical deployment conditions in educational environments. The system was tested using standard laptop webcams under varying lighting conditions and background settings.

The frontend application was executed in a modern web browser, while the backend server was deployed using Node.js and Express. The AI inference

service was implemented using FastAPI and executed on a machine equipped with GPU acceleration. Communication between components was performed over secure HTTP-based APIs.

Unlike traditional machine learning evaluation setups, the system does not rely on a fixed training, validation, or test split. This is because the proposed approach focuses on identity verification rather than classification, where each user enrolls their own facial data during registration. The system therefore evaluates real-time matching between live input and stored embeddings rather than predicting predefined class labels.

2. Evaluation Criteria

System performance was evaluated based on the following criteria:

- Face Detection Reliability: Ability to detect faces under different poses and lighting conditions.
- Liveness Detection Robustness: Resistance to spoofing attacks such as printed images or mobile phone replays.
- Recognition Accuracy: Correct matching of enrolled users during session joining.
- System Responsiveness: End-to-end latency during verification and session entry.

These criteria collectively assess both the security and usability of the system.

3. Experimental Observations

The MTCNN-based face detector demonstrated stable detection performance in most indoor environments, successfully handling moderate pose variations and partial occlusions. Liveness detection using MiniFASNet effectively rejected spoofing attempts in controlled tests, significantly reducing false acceptance rates.

The ResNet-based face recognition model achieved consistent identity matching for enrolled users, provided that enrollment images were captured under reasonable lighting conditions. In cases where liveness verification failed, the pipeline terminated early, preventing unnecessary computational overhead during recognition.

From a system-level perspective, the multi-stage pipeline ensured that computationally expensive face recognition was only executed after successful liveness verification. This design choice improved overall efficiency and reduced server load.

Discussion

The experimental results indicate that the proposed system provides a practical balance between security and performance. Token-based session reuse significantly reduced repeated biometric verification without compromising attendance integrity. This feature is particularly beneficial for long sessions or intermittent connectivity scenarios.

However, the system's performance is influenced by webcam quality and environmental lighting. Poor image quality may negatively impact detection and recognition accuracy. Despite this limitation, the modular architecture allows future improvements to individual components without affecting the entire system.

Conclusion

This paper presented a secure web-based biometric attendance system that integrates face recognition and liveness detection to prevent proxy attendance and identity spoofing. By adopting a modular, multi-layer architecture, the system separates user interaction, session management, and biometric inference, ensuring scalability and maintainability.

The proposed multi-stage biometric pipeline combines face detection, anti-spoofing, and recognition to enhance both security and efficiency. Experimental observations demonstrated that early liveness verification effectively reduces unnecessary computation while improving resistance to presentation attacks. The use of token-based session management further enhances usability by allowing verified users to rejoin sessions without repeated biometric verification.

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Chapter 3

Statics vs. Dynamics Biodegradation Regimes Comparative Behavior of PLA Scaffolds in Simulated Physiological Conditions

Elnaz ABEDINI[1]*, Daver ALI[2]

Abstract

Predictable degradation kinetics are essential to the success of the translation of tissue-engineered constructs out of the laboratory to clinical use. Polylactic acid (PLA) and its derivatives stand as the most popular synthetic polymers to be used in bone and cartilage regeneration because of their good biocompatibility and adjustable mechanical characteristics. Nevertheless, there remains a major "degradation paradox": a scaffold should offer short-term mechanical protection whilst degrading on equal measure to the new tissue growth. The conventional immersion assays that are controlled by ISO and ASTM standards do not represent the multifaceted mechanobiological context of the human body. This chapter compares the regimes of biodegradation of PLA scaffolds in a systematic way; comparison is made between the static and dynamic regimes. Section 1 serves to emphasize the shortcomings of existing standards and the need to include fluid dynamics and mechanical loading in in vitro models. Part 2 deals with the basic chemistry of PLA hydrolysis, including random chain scission and the autocatalytic influence of carboxylic acid end-groups. Later passages discuss the effect of scaffold geometry, material composition, and the combination of these factors with mechanical stimulation on mass transport, molecular weight development, and mechanical property maintenance. Finally, this chapter makes the case that dynamic testing standards should be adopted to enhance the safety and efficacy of biodegradable implants in regenerative medicine.

Keywords: polylactic acid (PLA), tissue engineering, biodegradation, dynamic bioreactors, mechanical loading, hydrolytic degradation, mass transport, bone scaffolds.

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1. INTRODUCTION

1.1. The Probability of Controlled Degradation in Tissue Engineering.

Tissue engineering (TE) is an area of biomedical research that seeks to regenerate or enhance the quality of the compromised tissues using biocompatible and biodegradable porous scaffolds [1]. Aliphatic polyesters, especially PLA, have become the standard of bone and cartilage replacement [2,3]. Although it has been widely used, the generation of a well-controlled degradation profile has remained a fundamental issue in biomaterial science. The rate of degradation is not a material property by itself, but a dynamic behavior of the local microenvironment, which is vastly different in vivo as compared to the lab environment.

1.1.1. The Ideal Scaffold: A Temporary Mechanical Support.

In musculoskeletal TE, a scaffold is an interim extracellular matrix (ECM) that brings about structural integrity but directs cellular attachment, proliferation, and differentiation [4,5]. A perfect scaffold should have mechanical properties -Young's modulus, ultimate tensile strength that is in line with native tissue to prevent stress shielding [3], and should have an interlocked porous architecture to support mass transport and vascular ingrowth [1,6]. At the same time, the scaffold is required to degrade and allow a new biological matrix to be produced. The scaffold must be too persistent to allow tissue integration, too fast to allow structural collapse before the neo-tissue can take mechanical load [5,7].

1.1.2. The Degradation Paradox: Strength Reduction vs. Tissue Ingrowth.

This is the balance that determines the degradation paradox. In the case of PLA, the loss in mechanical strength is common before mass loss can take place in a major manner, and this is based on hydrolytic chain cleavage [34,37]. A scaffold can lose up to 50% of its mechanical strength in a clinical setting and remain 90 percent of its original mass in the air, which gives a vulnerability window that can be used to cause fatigue failure [5]. This paradox may also be enhanced in vivo by mechanical stimuli, which promote the degradation of the polymer chain [39,40]. Therefore, the optimization of matching the degradation curve of the biomaterial to the healing curve of the patient is a multi-variable problem that needs profound knowledge of how the physiological conditions affect the polymer chemistry.

1.2. Restrictions of Static Degradation Assays.

The assessment of the longevity of PLA implants has been based on decades of immersion testing, which is not in motion. Although these give a material base, they are considered less sufficient in explaining actual behavior in vivo.

1.2.1. Standard ISO and ASTM Protocols: Immersion-Only Methods.

According to the ISO 10993-14 or ASTM guidelines, the protocol is performed by immersing the biomaterials in the simulated body fluid (SBF) or phosphate-buffered saline (PBS) at a fixed temperature of 37 °C [6,40]. These criteria put more emphasis on reproducibility but consider the degradation environment as a closed and non-moving system. Most of the time, the only controlled variable is the medium volume-to-scaffold medium volume-to-surface area ratio, without regard to the crucial importance of fluid turnover and convective mass transport [35,36].

1.2.2. The Diving Between In Vitro and In Vivo Reality.

The main flaw of the static assays is that degradation byproducts accumulate. The lactic acid oligomers reduce the local pH in the scaffold pores as PLA hydrolysates. These acidic species are not eliminated in a stagnant environment, so they create a localized autocatalytic effect and artificially enhance the rate of core degradation [34,37]. Blood flow and interstitial fluid in vivo are in a constant process of eliminating acidic byproducts, which probably reduces degradation of the internal environments as compared to predictions of a static environment [6,40]. This difference causes large-scale over- or underestimation of functional lifespan, and highlights the necessity of more physiologically realistic testing programs.

1.3. Active Physiological Conditions: The Lapsed Variable.

In an effort to narrow the in vitro-in vivo divide, scientists are resorting to dynamic biodegradation regimes that take into account the mechanical and fluidic signals found in native tissue.

1.3.1. Native Bone Tissue Loading using a Mechanical Method.

Bone is a mechanosensitive organ that is adapted as per Wolff's Law. When performing day-to-day activities, therefore, bone scaffolds are subjected to compressive and tensile loads on a cyclic basis. Mechanical strain raises internal polymer chain energy and induces micro-cracks, which enlarge the surface area to which hydrolysis can occur [7,39]. Successively determined research indicates that PLA scaffolds subjected to physiological strain (0.5-1.0

MPa) biodegrade much more quickly in comparison to unloaded controls, and molecular weight loss and stiffness decrease are more pronounced [39].

1.3.2. Fluid Dynamics and Mass Transfer In vivo.

The second important dynamic variable is fluid flow. Interstitial fluid exerts shear stress, which is a controller of the osteogenic genes expression, and regulates the transport of masses in vivo [36]. Computer fluid dynamics (CFD) simulation has also shown that velocity distributions inside scaffold pores have a significant impact on the degradation products concentration gradients [9,36]. This flow is simulated by perfusion bioreactors, where degradation profiles are more similar to surface-to-core erosion in animal models by avoiding the autocatalytic trap of immiscible phase assays [6,35].

1.4. Chapter Objectives and Scope.

The chapter gives a detailed comparison between the regimes of biodegradation of PLA scaffolds in the case of a static regime and in the case of a dynamic regime. Widely generalized by 2017 to 2025, we outline the effects of mechanical loading and fluid perfusion on the basis of hydrolysis, molecular weight development, mass loss dynamics, and mechanical property degradation under different simulated physiological conditions. We recommend the use of dynamic testing standards to enhance the safety and efficacy of biodegradable implants in the field of regenerative medicine.

2. FUNDAMENTAL MECHANISMS OF PLA DEGRADATION

2.1. Chemistry of Degradation by Hydrolysis.

The hydrolytic cleavage of ester bonds within the polymer backbone is the major mode of degradation of PLA. It happens in four stages, which are water absorption, reducing molecular weight, mechanical integrity, and loss of mass by solubilization of short-chain oligomers [34,37].

2.1.1. These are the random Chain Scission of Ester Bonds.

Hydrolysis occurs through a random chain scission: The water molecules approach the ester linkages randomly along the backbone, not only at the end of chains [34]. This generates a fast initial reduction in number-average and weight-average molecular weights (Mn) as well as (Mw) prior to any measurable reduction in mass. The concentration of the ester groups and the presence of water in the polymer matrix control kinetics [37]. PLA is relatively hydrophobic and, hence, the rate of hydrolysis is low but increases with rising hydroxyl and carboxyl end-group concentrations, increasing hydrophilicity.

2.1.2. Autocatalytic Action of Carboxylic Acid End-Groups.

The cleavage of every ester bond produces a new carboxylic acid molecule (−COOH), which decreases the local pH and encourages further hydrolysis - a self-amplifying autocatalytic cycle [37]. This is spatially heterogeneous in bulk scaffolds: the byproducts of degradation formed inside the scaffold have a longer diffusion path towards the external medium. As a result, the concentration of carboxylic acid and hence the rate of hydrolysis is greater at the core than at the surface [34,37], which creates the typical inside-out pattern of degradation that is strongly dependent on the conditions of fluid flow. Heljak et al. [9] showed that intraporous pH in stagnating incubated PLA scaffolds can be 0.3-0.6 units lower than bulk medium pH, which boosts autocatalytic kinetics approximately 1.8-fold compared to the first-order hydrolysis in theory.

2.1.3. Crystalline and Amorphous Region Degradation.

The semi-crystalline structure of PLA has a significant impact on hydrolytic behavior. Water is more likely to diffuse into amorphous areas, which are disordered; thus, hydrolysis starts almost exclusively at the disordered amorphous regions [38]. The degradation of amorphous domains leads to a rise in the overall scaffold crystal-like structure, which is also known as chemi-crystallization, as measured by the increase in melting enthalpies in DSC studies [41,50]. When the amorphous tie-chains that surround crystalline lamellae are ruptured, crystalline lamellae eventually succumb, eventually leading to a final stage of rapid structural collapse. Increase in D-lactide provides more amorphous polymers, which degrade more quickly [2,38].

2.2. Key Degradation Parameters

It is necessary to measure degradation accurately by simultaneously measuring the values of various stages of material degradation.

2.2.1. Molecular weight (Mw/Mn/PDI) and its determination.

The most sensitive of the early-stage indicators is molecular weight change. Gel Permeation Chromatography (GPC) is used to measure Mw, Mn, and Polydispersity Index (PDI); the extension or contraction of PDI indicates the aspect of degradation, either as uniform or chain-length-selective [5]. Bond cleavage with the assistance of mechanical strain in a dynamic environment is faster than Mw reduction [39]. PLA mechanical properties start to fail when Mw reduces to a critical value, which is usually 50 70 kDa [3, 5].

2.2.2. Mass Loss and Volume Loss: Different Phenomena.

When using polymers such as PLA that erode in large amounts, the scaffold can retain its initial external volume for weeks, and the internal density can be reduced significantly [34,37]. Mass loss becomes substantial when the fragments of the chain become large enough to leach into the medium (usually, less than 10 units of lactic acid) [6]. Volume loss, in its turn, may frequently be sudden as the surrounding structural framework fails to hold its weight or the loads exerted on the physiological processes and collapses with a sudden porous-architecture failure [5,7].

2.2.3. Mechanical Property Deterioration Profile.

The mechanical property degradation has non-linear behavior: a small increment in the elastic modulus can take place during the chemi-crystallization process, and then a slight decrease in its value, and then a final disastrous loss of strength can be observed [38]. In dynamic regimes, modulus of elasticity degrades much quicker; scaffolds in cyclic compression situations demonstrated to lose 80 percent of compressive strength five times faster than under static conditions [39]. It is hence important to assess "residual strength" as opposed to just initial strength when using load-bearing scaffolds [5,7].

2.3. Operating Factors Kinetics Degradation.

The rate of degradation is a representation of the intrinsic design of the material as well as the environment.

2.3.1. Intrinsic Factors: Molecular weight, Crystallinity, L D Ratio.

The most characteristic factor is the stereochemical composition. Poly(L-lactic acid) (PLLA) is semi-crystalline and degrades slowly (1224 months), and Poly(D, L-lactic acid) (PDLLA) is amorphous and degrades much faster (36 months) [2,38]. An increase in the initial Mw can slow down the loss of mass by increasing the number of ester bonds that have to be broken before the chains attain the solubility level [34,37]. The architecture of the scaffold, the surface-volume ratio, defines the percentage of the material that is directly exposed to the hydrolytic media [3,6].

2.3.2. Extrinsic Factors: PH, Temperature, Ionic Strength.

According to Arrhenius kinetics, temperature is a significant catalyst of hydrolysis; experiments typically employ 50-70 °C to squeeze degradation curves [34]. Ester bond cleavage is accelerated by both acidic and basic conditions, whereas at neutral pH, a relative stability is obtained [37]. Polymer

swelling and diffusion of water into the scaffold interior are influenced by ionic strength [6,40]. These extrinsic factors in dynamic bioreactors can be kept close to physiological levels by continuous medium replacement, and in static assays, they change gradually in response to scaffold degradation [35,36].

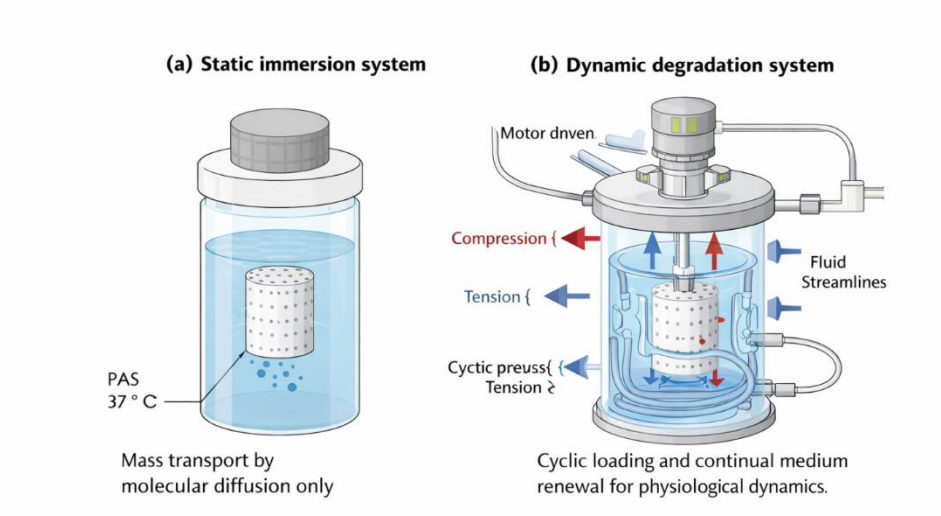

Figure 1: Comparison of a model of a static and dynamic degradation setup schematically. (a) Static immersion system. The figure depicts a PLA scaffold through a sealed vial of phosphate-buffered saline (PBS) at 37 °C, in which mass transport is due to molecular diffusion only. (b) Dynamic degradation system with a perfusion bioreactor with built-in mechanical actuators to provide cyclic loading (compression/tension). The bioreactor has a continual medium renewal, which recreates the physiological dynamics of fluid flow and mass transport in the body. There are arrows of fluid streamlines and vectors of mechanical forces.

3. STATIC DEGRADATION REGIME

3.1. Normal Static Degradation Policies.

3.1.1. PBS Immersion at 37°C: ISO 10993 and ASTM F1635.

Statistical degradation testing is most commonly done in PBS at 37 °C according to ISO 10993-13 and ASTM F1635, respectively, which regulate the determination of degradation products and in vitro hydrolytic testing of polymeric implants, respectively. These standards recommend the composition of solutions, pH (7.4 ± 0.2), temperature, and medium-to-scaffold volumetric ratio to allow inter-laboratory and regulatory submission. PBS is selected due to its ionic strength and buffering capacity, which are close to extracellular fluid,

whereas the absence of enzymatic activity, though convenient methodologically, is a basic weakness [8].

3.1.2. Sample Preparation and Environmental Control.

Scaffolds are dried to equal weight in the vacuum at 40 °C, and weighed to within 0.1 mg accuracy and put under pre-equilibrium PBS in a volume to mass ratio ⊳of 30 mL g 1 to avoid lactic acid saturation and pH diminution [42]. Temperature is held constant in incubation chambers to within ±0.1 °C, and medium renewal (after every 3-7 days) is specified a priori to avoid uncontrolled autocatalytic buildup [43]. In porous scaffold advancements, ethanol-gradient pre-wetting removes air in the internal pore networks, and this uniform bulk degradation occurs across the three-dimensional structure [41].

3.1.3. Sampling Timepoints and Endpoint Analysis.

Sampling is fixed-interval or logarithmic with 1-52 weeks of PLA formulation and clinical use. Retrieved scaffolds at each time point are washed in deionized water, lyophilized, and their mass is measured to ascertain the fraction of mass remaining (Wt /W0). The commonly used endpoint analyses are: gravimetric mass loss; MWD by GPC; compression or tensile mechanical tests; DSC thermal profiles; and SEM morphological analysis [8,42]. The uptake of the water is measured independently on the basis of wet weight and dry weight, which provides the ratio of swelling required to deconvolute the phenomenon of fluctuation as in Section 3.2.3.

3.2. Kinetics of Degradation at Static Conditions.

3.2.1. First Lag Phase: Low Mass Loss.

The degradation of Static PLA takes place in three typical stages. In the initial lag stage (usually 0-4 weeks at 37 °C in medical-grade PLA), the gravimetric loss of mass is less than 23%, although the Mn loss is measurable [8]. The process of hydrolytic chain scission produces oligomeric fragments, which are physically trapped within the matrix; macroscopic integrity of the scaffold is preserved, but the level of polymerization decreases. Diffusion of water into amorphous regions triggers cleavage of the chain randomly, but the products are not mobile enough to leach out of the medium in detectable amounts. GPC at this stage indicates the PDI is widened, and the elution curve is shifted to the left, which proves the presence of hydrolysis without any apparent loss of mass [41].

3.2.2. Phase of Acceleration: Autocatalytic Hydrolysis.

The chain scission and the decrease of Mn to less than about 1015 kDa trigger autocatalysis in the presence of terminal carboxylic acid groups that are accumulated [43]. In the static medium, molecular diffusion is the sole determinant of the scaffold surface renewal; lactic acid and oligomers remain in high concentration in the pore structure, keeping the local pH low and creating a positive feedback mechanism. The consequence is a mass-loss curve (which accelerates typically during weeks 616), and a medium pH can be formed, which is measurable when the buffer capacity is limited [8,43]. This internal acidification, in which intrapore pH may decrease 0.3-0.6 units below the bulk medium, is the mechanistic heart of the distinction between the static and dynamic degradation regimes.

3.2.3. The Phenomenon of Fluctuation: Poised Loss of weight.

One of the most commonly described phenomena of the degradation of the statically deformed PLA is the fluctuation phenomenon: non-monotonic mass-loss curves, in which the net experimental weight swings or temporarily increases and then again follows a descending pattern [9,50].

3.2.3.1. Weight Gain due to Swelling vs. Polymer Erosion.

This variation is due to the conflicting nature of water absorption (swelling) versus polymer erosion in the measured dry mass. The degradation products that are hydrophilic, such as the oligomers of lactic acid, the hydroxyl-terminated chain segments incorporated in the matrix, enhance the water affinity of the polymer. When drying and reweighing scaffolds, the net weight of the scaffold can be greater than the dry mass of the scaffold when the mass of oligomers that were not extracted is higher than that of those fragments that were leached. The maximum transient increments in weight of 4.7 percent of initial dry mass were observed by Alamán-Díez, P. et al. [50] during the 3 to 6 weeks and the periods of the highest water-uptake ratios. The erosion takes over, and the net weight decreases exponentially as the degree of degradation increases and oligomers are mobile enough to diffuse away. The profile of variation is then a combination process of two counteracting mass influxes: soluble product release (negative) and the retention of oligomers and water uptake (positive), the relative magnitudes of which change with the level of degradation.

3.2.3.2. Crystallinity modifications and Density variations.

Further change in bulk crystallinity helps in modifying the phenomenon of fluctuation. Since the hydrolysis rate selectively breaks ester bonds in the amorphous regions, the relative crystallinity (Xc) of the remaining polymer increases with the elimination of amorphous domains, which was confirmed by DSC results of increasing melting enthalpies during the degradation process [41,50]. This rise in crystallinity raises residual matrix density, partly counteracting the loss by volume of mass and adding to the effect of apparent weight stabilization or gain seen gravimetrically. Alamán-Diaz et al. [50] have found Xc increasing between 8 and 34% in 12 weeks of immersion in static PBS, which was accompanied by quantifiable densification of the pore-wall. The complex interaction between the rising crystallinity, changing porosity, and the dissimilar mass transport makes the kinetics of the static degradation unique, non-linear, and challenging to develop simple first-order degradation functions.

3.3. Structural and Morphological Evolution.

3.3.1. Surface Erosion and Bulk Degradation.

The degradation of PLA occurs mainly by bulk degradation due to the presence of relatively large water permeability of amorphous PLA matrix, and the slow rate of homogeneous hydrolysis at 37 °C. Water can infiltrate the entire thickness of struts in hours to days and develop a virtually smooth hydrolytic front [8]. This is unlike the surface-eroding polyanhydrides, which only decompose to a progressively expanding surface layer. Autocatalytic deposition of acid within the interior of PLA scaffolds (that cannot be removed by diffusion) leads to the core degrading at a faster rate than the surface, resulting in a typical hollow-core strut geometry at intermediate stages. This mechanism was confirmed in cross-sectional SEM [41] and micro-CT, at which point central strut cavitation preceded macroscopic structural collapse.

3.3.2. Pore Collapse and Dimensional Changes.

The gradual accumulation of bulk degradation leads to structural failure of the wall and strut of the pore, which results in pore collapse, anisotropic shrinkage, and decreasing dimension. Without mechanical loading, loss of material continuity is the cause of collapse because Mw drops below the entanglement threshold [42]. It is evident in the micro-CT that pore diameter reduces by 15- 30% before macroscopic fragmentation, and total scaffold volume diminishes by 8 20% depending on porosity and original architecture [50].

3.3.3. SEM Findings: Pitting and Cracking of the surface.

SEM gives direct morphological information about the process of degradation at rest. The lag phase is the period during which scaffold surfaces are smooth. Weeks 4-8 The surface pitting and micro-crack formation may be observed at defects, grain boundaries, and amorphous-rich surface areas [8]. During the acceleration phase, extensive surface fissuring, strut fractures, and inconsistently eroded pieces of debris are formed by the crack propagation and coalescence. Gu et al. [43] observed a gradual surface roughening (Ra between 0.3 μm and 4.1 μm) during the course of 16 weeks, and the end result was the fracture of particles into lenticular fragments typical of autocatalytic bulk degradation.

3.4. Shortcomings of Static Models.

3.4.1. The Real-World Degradation Rates should be underestimated.

In vivo rates are underestimated in a systematic way through static degradation procedures. The physiology surrounding implants exposes them to interstitial fluid flow, cellular activity, enzymatic activity, and cyclical mechanical loading, which are not seen in the case of a static environment in PBS [8]. The outcomes of degradation of the model in vivo may vary 1.5-3.0 times with respect to the site of implantation and scaffold geometry [41], which directly undermines the predictive validity of mechanical property and drug release in vivo.

3.4.2. Powerful Amassment of Acidic Byproducts.

In the absence of a convective fluid renewal, lactic acid and oligomeric products continuously build up in scaffold pores. There is no such thing as bulk medium renewal every 3-7 days, preventing equilibration of the pore interior with the bulk medium because the diffusion-limited transport does not allow equilibration of the pore interior with the bulk medium [43]. Contrastingly, the possibility of overestimating local tissue acidification hazards and underestimating bulk degradation rates is a simultaneous inherent indeterminism to translational fidelity, both in kinetic prediction and biocompatibility testing.

3.4.3. Absence of Mass Transport Simulation.

The fundamentally mechanistic shortcoming of the static models lies in their inability to model the mass transport processes in vivo of the degradation. The flow by convection across scaffold pore structure is favorable in the elimination of acidic byproducts, local pH homeostasis, and delivery of dissolved oxygen,

as well as exerts shear forces that may mechanically disturb partially degraded surfaces [50]. The process of static immersion eliminates all these transport effects and introduces artificial concentration gradients, which compose the artificial local hydrolytic kinetics and obscure the actual scaffold performance envelope. Such restrictions have inspired the design of active degradation regimes utilizing the bioreactor with a controlled flow field, the discussion of which will follow.

4. DYNAMIC DEGRADATION REGIME

4.1. Mechanical Stimulation (static load, cyclic load, fluid shear) types.

Different types of mechanical and fluidic stimulation are applied to scaffolds in a dynamic degradation regime. These are the types of loads that stay constant (as they are the representation of constant pressure), loads that are cyclical (they are the simulation of such physiological processes as walking or breathing), and fluid shear (the representation of blood flow or interstitial fluid movement) [32]. The kinetics of degradation of each of these stimulations are different. As an illustration, cyclic loading may encourage the development of microcracks, whereas fluid shear may promote the mass transfer of water and degradation byproducts [34, 35].

When the scaffold is subjected to a constant force over a long period of time, it is called creep or static loading. It may cause a gradual deformation of the polymer matrix and may affect the speed of diffusion of water into the material. Cyclic loading, on the other hand, deals with the repetitive introduction and removal of the force that is far more indicative of the dynamic body environment. Such a kind of stimulation may result in fatiguing the polymer network, which develops microcracks and subsequently degrades the structural integrity of the scaffold. The other important critical stimulus is fluid shear, which is especially important in scaffolds being deployed in vascular or bone tissue engineering. Shear stresses on the polymer surface caused by the flow of fluid through the scaffold pores have the potential to increase the elimination of degradation byproducts and determine the pace of hydrolysis.

These various classes of stimulation are also capable of interacting in a complex way. An example is that by cyclic loading, the permeability of the scaffold can be improved, which then boosts the impact of fluid shear. On the other hand, the fluid flow can also be used to give the cooling effect, which may reduce the thermal effects that come with the cyclic loading. These synergistic interactions are important to understand how one can create more accurate models in vitro and to make scaffolds that can resist the complex mechanical environment of the human body. Due to the further development of the field of

tissue engineering, dynamic degradation regimes will gain even greater significance in terms of the safety and effectiveness of biodegradable implants.

4.2. Experimental Bioreactor Systems.

The experiments used in dynamic degradation are normally carried out in a bioreactor system that is designed to mimic a certain physiological environment [36]. These systems may be divided into perfusion bioreactors, where the medium circulates in the scaffold pores, and mechanical loading bioreactors, where compressed or tensile forces are applied in a controlled manner [37, 38]. There are advanced bioreactors that are capable of combining the mechanical loading and perfusion to create a complex environment of bone or cartilage [39, 40]. Under physiologically relevant conditions, these systems permit degradation parameters to be monitored in real-time [41, 42].

4.3. Chain unfolding, Microcracking, Enhanced Mass Transport (Stress-Accelerated Degradation Mechanisms)

A number of stress-dependent mechanisms cause the enhancement of PLA degradation in the dynamic conditions. To begin with, the presence of mechanical stress may give rise to the unfolding of polymer chains, thereby exposing ester bonds to water molecules [43]. Second, cyclic loading may cause microcracks in the polymer matrix, which serve as a pathway to speedy water infiltration [44, 45]. Third, the load has been used to increase the mass movement of water into the scaffold and acidic byproducts into the scaffold [46]. This decreases the autocatalytic effect and enhances the total rate of hydrolysis by keeping a high concentration of water at the sites of reaction [47, 48].

4.4. Analogical Kinetics: Comparing Dynamic and Static.

In the dynamic and static regimes, a number of differences come into place. Dynamic degradation is a process where there is a constant, accelerated change of molecular weight and mass, without the significant "fluctuation" of the model in static conditions [49]. Loss or deterioration of mechanical strength is also much greater in dynamic conditions [50]. As an example, a PLA scaffold that has suffered 80 percent of its strength during 4 weeks in a static PBS might lose half of its strength during the same time under cyclic loading [51]. This is the crucial need to address mechanical stimulation when designing and testing scaffolds [52].

Table 1: Even comparison of the parameters of degradation in the state when it is static and in the state when it is dynamic.

Parameter	Static Regime (ISO/ASTM)	Dynamic Regime (Simulated Physiological)
Medium / Environment	PBS or SBF, stagnant immersion	Perfusion flow, continuous renewal
Temperature	Constant 37°C (or accelerated)	Physiological 37°C
Mechanical Load	None (Unloaded)	Cyclic compression/tension (0.5–2.0 MPa)
Mass Transport	Diffusion-limited	Convection-dominated (Pumping effect)
Degradation Kinetic	Non-linear fluctuations (Swelling vs. Erosion)	Predictable, steady decline
Byproduct Accumulation	High (Internal autocatalysis)	Low (Washed out via flow)
Mechanical Failure	Chemical dissolution-driven	Fatigue-hydrolysis interaction
Clinical Relevance	Baseline material characterization	High fidelity to in vivo conditions

Table Notes: PBS: Phosphate Buffered Saline; SBF: Simulated Body Fluid. Dynamic parameters based on the musculoskeletal bone tissue engineering range.

5. INFLUENCE OF SCAFFOLD GEOMETRY

Physical architecture has a dramatic effect on the kinetics of scaffold degradation. Geometry determines the smaller environmental environments, namely, transport of fluids, surface available area, and the concentration of byproducts, and thus serves as the sole point of contact between material and surrounding medium in comparison of both the static and dynamic regimes [5].

5.1. Pore Architecture and Porosity.

Porosity defines the total volume to be penetrated by fluids and hydrolytic chain scission, and its structure dictates whether the degradation will be evenly spread or accelerated at local locations [6].

5.1.1. High Porosity (>90%): Both Regime Accelerated Degradation.

High-porosity (>90) scaffolds have high surface-volume ratios, which ensure a high rate of hydration of the matrix and rapid decrease in molecular weight in both static and dynamic modes [6]. The high porosity also enhances the possibility of early mechanical breakdown under the dynamic mechanical loading; the thin structural members decay quickly due to the combined effect of hydrolysis and mechanical shear stress.

5.1.2. Interconnectivity of Pores and Permeability of Fluid.

The high level of interconnectivity guarantees the regular fresh-medium circulation in dynamic regimes, preserving gradients of concentration and effectively eliminating acidic byproducts. Poor interconnectivity leads to stagnant dead zones in the poorer regimes, where product accumulation results in autocatalytic processes, making the scaffold core degrade significantly faster than the periphery [5,59].

5.1.3. Effects of Ratio of Surfaces to Volume.

A major kinetic controller is the surface-to-volume (S/ V) ratio. Characteristic of fibrous or porous architectures in nature with a high S/V, degradation tends toward surface-erosion properties by maximizing contact area between polymers and the medium [20]. In the case of a specific PLA mass, geometric optimization can provide an increase in S/V ratio, which can be used to accelerate mass loss by up to 30 in dynamic systems because of enhanced mass transfer at the solid-liquid interface [20].

5.2. Pore Size and Geometry

Individual pore dimensions influence both biological integration and the local chemical environment during degradation.

5.2.1. Micropores (<100 μm): Limited Cell Infiltration, Faster Degradation

Microporous structures (<100 μm) restrict cell infiltration and vascularization but affect degradation kinetics via capillary action. These small voids trap acidic byproducts in static regimes, accelerating hydrolysis of

surrounding PLA walls through localized pH depression [11]. In dynamic conditions, high flow resistance of microporous structures prevents efficient flushing, rendering the internal microenvironment functionally static even under external flow.

5.2.2. Macropores (100–500 μm): Optimal for Tissue Ingrowth

Macropores (100–500 μm) promote bone and tissue ingrowth while enabling efficient nutrient and byproduct exchange [11]. In dynamic bioreactors, macroporous geometries facilitate laminar or transitional flow, maintaining physiologically appropriate shear stress and preventing the hollow-core "autocatalytic" degradation pattern seen in smaller-pore scaffolds.

5.2.3. Graded Porosity: Spatial Control of Degradation Rates

Functionally graded scaffolds transitioning in pore size or porosity from core to surface enable spatial control of degradation rates [68]. A dense outer shell with a highly porous core can deliver a "delayed-release" degradation profile: the shell maintains structural integrity while the core degrades early to accommodate tissue formation, effectively decoupling mechanical persistence from biological space-making.

5.3. Structural Design Parameters

Additive manufacturing enables precise control over unit cell geometry, dictating both mechanical response and degradation behavior under load.

5.3.1. Strut Thickness and Load-Bearing Capacity

Strut thickness is inversely related to degradation rate; thicker struts have lower S/V ratios and require longer to hydrate fully, yet are more susceptible to internal autocatalysis. In dynamic regimes, strut thickness must be balanced to maintain adequate load-bearing capacity as Mw decreases, preventing premature structural collapse before neo-tissue has matured [59].

5.3.2. Layer Height and Printing Orientation Effects

In FDM-printed PLA scaffolds, printing orientation and layer height create anisotropic degradation profiles. Inter-layer interfaces are typically the earliest sites of hydrolytic attack. Under dynamic flow, fluid shear can exacerbate inter-layer delamination, producing faster stiffness loss compared to static immersion, where degradation is more homogeneous across the surface.

5.3.3. Gyroid vs. Cubic vs. Hexagonal Unit Cells

Unit cell topology significantly impacts fluid dynamics and degradation uniformity. Triply Periodic Minimal Surface (TPMS) structures, such as the Gyroid, provide smooth, continuous surfaces eliminating sharp corners found in cubic or hexagonal cells [69]. These smooth curvatures reduce turbulence and stagnation points in dynamic regimes, yielding more uniform byproduct removal and more predictable, spatially homogeneous degradation compared to traditional lattice architectures [69].

5.4. Geometry-Mediated Byproduct Release

The spatial release of lactic acid the primary PLA hydrolysis byproduct is a critical determinant of long-term biocompatibility and degradation rate.

5.4.1. Acidic Product Trapping in Closed-Pore Structures

Closed-pore or poorly interconnected geometries act as lactic acid reservoirs. Rising carboxyl end-group concentration drives pH downward, catalyzing further hydrolysis in a cycle most pronounced under static conditions, often terminating in sudden, catastrophic structural failure when internal acidity reaches a critical threshold [67].

5.4.2. Channel Design for Enhanced Byproduct Removal

Advanced scaffold designs incorporate dedicated micro-channels that function as "exhaust systems" in dynamic regimes: external pressure gradients drive acidic molecules out, maintaining local pH near 7.4 and slowing degradation relative to static conditions where such channels provide no active transport benefit.

5.4.3. Local pH Changes and Their Biological Consequences

Geometry-mediated acid trapping can cause localized pH drops sufficient to trigger inflammation and fibrous encapsulation [67]. Dynamic regimes mitigate this risk by diluting acidic concentrations through convective flow. Consequently, a scaffold geometry deemed cytotoxic in a static laboratory assay may prove biocompatible in dynamic in vitro or in vivo environments, highlighting the fundamental risk of relying solely on static testing for biocompatibility assessment.

6. The effect of composition on degradation regimes.

The main degradation rate tuning of PLA is the chemical composition: isomer ratio, copolymerization, and addition of fillers. Hydrophilicity, crystallinity, and buffering capacity are compositional factors that react differently with both dynamic and static environments.

6.1. Pure PLA Grades

Stereochemistry of the lactic acid monomer causes significant changes in the physical structure of polymers and their degradation rate.

6.1.1. PLLA vs. PDLA: The Crystallinity and Degradation Rate Difference.

PLLA is semi-crystalline; crystalline domains of order limit diffusion of water, initially hydrolysis occurs in the amorphous region, leading to slow degradation that can last longer than 1224 months [29]. The resistance of shear-induced erosion is enhanced by the presence of crystalline areas in dynamic regimes. PDLLA, in its turn, is entirely amorphous because of the distribution of the isomers, is more vulnerable to water infiltration, decays much more quickly [30], and it is more likely to swell and deform when exposed to dynamically moving fluids.

6.1.2. PDLLA: A-Form and Better Degradation.

L- and D-lactide units carried randomly in PDLLA do not form crystalline lattices, and this makes it applicable in use cases where swift mass loss is required. Nevertheless, its increased tendency to swelling and dimensional change in the flow regime has to be taken into consideration in the dynamic bioreactor design and load-parameter optimization.

6.2. PLA Blends and Copolymers

In order to negate the inherent brittle nature and slow degradation of pure PLLA, blending and copolymerization are used.

6.2.1. PLA-PGA (PLGA): Degradation by Controlling Glycolide Content.

Lactide is copolymerized with the more hydrophilic, methyl-free glycolide to increase degradation; a reduced lactide to glycolide ratio (i.e., 50:50, 75:25) modulates degradation between weeks and months [60]. PLGA scaffolds have a less non-linear mass-loss profile in dynamic regimes as the glycolide units are more vulnerable to uninterrupted fluid exposure.

6.2.2. PLA-PHB Blends: Effect of Second Phase Dispersion.

PLA/PHB blends alter mechanical characteristics; degradation is highly affected by the dispersion of the PHB phase. PHB has been found to degrade more slowly than PLA, but phase interfaces can be used as water-entry conduits that can enhance scaffold fragmentation in dynamic regimes where fluid enters these boundaries [61].

6.2.3. Block Copolymers: Phase Separation under control.

Amphiphilic block copolymer PLA/PEG or other amphiphilic polymers exhibit rapid initial erosion and hydration of surfaces. The hydrophilic block preferential leaching in dynamic regimes forms a porous surface layer that further enhances the PLA backbone degradation, which provides a design approach to programmatically tune the early-late-stage degradation.

6.3. Composite Systems

The inorganic fillers have a dual use, which is to boost the mechanical performance and to control the chemical degradation environment.

6.3.1. Hydroxyapatite (HA) Reinforcement: Buffering Effects and Degradation Slows Down.

HA enhances osteoconductivity and is an alkaline buffer: PLA breaks down to lactic acid, which reacts with the neutralized particles of HA and neutralizes the local pH [62], preventing autocatalysis and effectively retarding degradation in steady-state conditions. Buffering is not as important in dynamic regimes since the fluid flushing eliminates it, but HA still teaches much-needed mechanical support to the polymer fabric as it becomes weaker [62].

6.3.2. Addition of Bioglass: Acceleration and Bioactivity of Degradation.

Na^+, Ca^{2+}, and PO_4^{3-} ions released during the process of bioactive glasses (e.g., 45S5) raise the local osmotic pressure and enhance the uptake of water in PLA [63]. They are highly reactive and thus enhance the formation of a carbonated hydroxyapatite layer on the scaffold surface, which could at first shield PLA from the degradation medium before the polymer and glass interface structure is broken to allow hydrolytic access [63].

6.3.3. Natural Additive Plant-Derived Accelerators.

Plant-based additives (e.g., cellulose, silk) or natural fibers enhance the hydrophilicity of composites, forming preferential water-diffusion pathways that circumvent the hydrophobic PLA surface and allow faster internal

hydrolysis - again, this effect is particularly strong in dynamic regimes where fluid perfusion constantly renews these pathways.

6.4. Surface Modifications

Surface treatments control the initial scaffold-medium interaction with no changes in bulk material properties.

6.4.1. Plasma Treatment: Increment of Hydrophilicity and Primary Degradation.

Polar functional groups (−OH, −COOH) are introduced on the PLA surface by oxygen or nitrogen plasma treatment, which has a great effect on enhancing the surface energy and the wettability [65]. Plasma-treated scaffolds in both static and dynamic regimes experience an increased rate of early surface mass loss due to instantaneous wetting of the entire architecture that removes the lag phase of untreated hydrophobic PLA [65].

6.4.2. Coating Techniques: Barrier Coating and Controlled Release.

Non-degradable polymer or ceramic coating could slow down the onset of degradation by serving as protective layers [66]. Drugs or growth factor coatings are also beneficial as therapeutic agents. The stability of the coating is the most important consideration in dynamic regimes: the high flow rates may lead to delamination or faster erosion of the coating surface, exposing the underlying PLA matrix too soon and nullifying the intended release profile [66].

7. SYNERGISTIC EFFECTS AND PREDICTIVE MODELING

The degradation of PLA scaffold in a physiological environment cannot be described as a linear process of hydrolysis, but it arises as the result of the complex interaction of architectural geometry, chemical composition, and external mechanical forces. Such factors engage with each other synergistically in the dynamic regimes, such that their results are significantly different from the results of the static predictions of immersion [1,64].

7.1. Interaction Effects

Interaction effects demonstrate the inherent response of one variable through the presence of another on the overall rate of degradation, with scaffold architecture being the major predictor of local chemical microenvironment.

7.1.1. The Stress-accelerated Degradation Enhanced by Porosity.

Porosity is a multiplier of stress-accelerated degradation under the conditions of dynamic mechanical loading. A high porosity (>80%) lowers the effective cross-sectional area of polymer struts, increasing local strain, accelerating the rate of diffusion of water, and chain scission in the amorphous section [64]. This mechanical force of pumping fluid into the polymer matrix and increasing chain vulnerability to hydrolysis happens concurrently during this process; the pumping effect is a phenomenon that is missing in the inert models that utilize porosity as a purely geometric parameter.

7.1.2. Composite Fillers as Stress-Shielding or Stress-Concentrating Elements.

HA, TCP, and bioactive fillers have a dual role in dynamic regimes. They will be able to stress-shield the polymer matrix by sharing a mechanical load, which can slow down degradation. Poor filler-PLA interfacial bonding, on the other hand, forms the micro voids, which develop stress-concentration and quick-water-infiltration locations throughout cyclic loading [4]. Dynamic testing, therefore, indicates that fillers can both counter autocatalytic degradation by buffering pH as well as promoting mechanical breakdown when composite integrity is lost [27].

7.1.3. Design of so-called Degradation Profiles based on Mechano-Active Degradation.

Scaffold architectures that are skewed purposefully on the basis of being scaffolds that actively respond to particular mechanical cues are moving towards research. Graded porosity provided by additive manufacturing allows more load-bearing areas to degrade proportionally to the formation of new tissue [1], a step towards more rigorous degradation over bulk degradation in a coordinated process of structural handover of scaffold to regenerating tissue.

7.2. Combined Effects Predictive Modeling.

The level of prediction of the lifespan also needs computational models that can ascertain the multi-physics nature of the dynamic degradation.

7.2.1. Multi-Physics Simulation Frameworks.

In current simulations, FEA is coupled with hydrolysis kinetics and CFD, and the scaffold is simulated to be an evolving geometry in which Young's modulus declines with the concentration of local water and scission of chains [64]. The SBF flow using pores to simulate flow allows prediction of the so-

called dead zones where acidic byproducts have been concentrated, even in dynamic environments- actionable design guidance before scaffold fabrication.

7.2.2. Prediction of Degradation with the help of Machine Learning.

Machine Learning (ML) is becoming a potent instrument for processing the large, dynamic degradation data. Mw loss, mass loss, and stiffness data trained algorithms can predict new scaffold-design behavior without the need to undertake exhaustive 6-month in vitro experiments, and in particular have the capability of finding non-linear correlations between polymer crystallinity and load-bearing capacity [68].

7.2.3. Consummation with Long-term In Vivo Tests.

Although dynamic models in vitro have been shown to be much better than the static tests, in vivo data validation is the top priority. Comparative experiments indicate significantly greater correlation between scaffolds subjected to fluid flow and cyclic compression versus stabilities in the in vivo degradation rate ($R^2 > 0.85$) [66].

7.3. Design Optimization Strategies.

Optimization is a trade-off between short-term mechanical demands of the surgical site and long-term biological objectives of tissue incorporation.

7.3.1. Degradation Rate Customized to Timeline of Tissue Healing.

PLA degradation should be coupled with the target tissue. The bone scaffolds should have an integrity of 3 to 6 months. This can often require high-molecular-weight PLLA or copolymer PLLA-co-PCL to lengthen the lifespan of functional devices in dynamic environments, in which the rate of degradation is increased [1,2].

7.3.2. Load-Bearing Capacity During Degradation Cycle.

One critical failure mode of PLA implants is the so-called sudden collapse, a structural integrity loss that occurs before enough tissue has matured. Optimization entails sub-structures which are sacrificial to give cell-infiltration space, though a core load-bearing architecture survives until the very last healing phases [64].

7.3.3. Case-Specific Designs: Bone vs. Cartilage vs. Skin.

Different tissues have different mechanical environments. Bone scaffolds need to be stiff and stress-cracking resistant under high-frequency cyclic loads;

cartilage scaffolds need to deal with high fluid pressure and shear, with dynamic facets of degradation considered to be crucial; skin scaffolds, which are mainly subjected to tension, need to be made of higher elasticity PLA to prevent premature mechanical rupture during degradation [1,3].

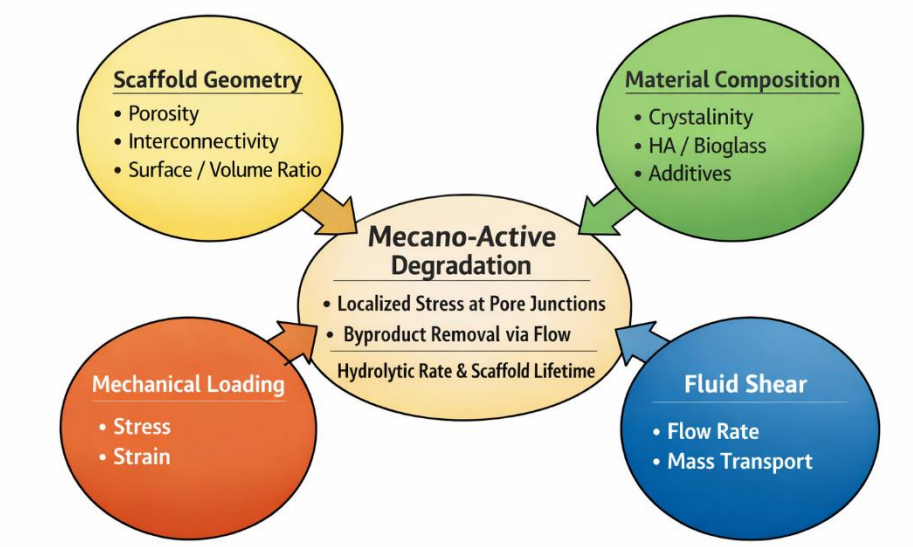

Figure 3: Synergistic interaction diagram of degradation variables of PLA. Such a diagram shows the dynamic interaction between the geometry of the scaffold (porosity, interconnectivity, surface to volume ratio) and material composition (crystallinity, added material, such as HA/Bioglass) with external mechanical load and fluid shear. The intersections characterize the profile of degradation that is Mechano-Active, in which the concentration of stress at pore junctions and the removal of byproducts mediated by the flow together define the local hydrolytic rate and scaffold lifetime.

8. CLINICAL TRANSLATION AND REGULATORY CONSIDERATIONS

Even though it is scientifically acknowledged that dynamic factors can significantly change the behavior of PLA scaffolds, the regulatory bodies still embrace the existence of static degradation protocols to a great extent. The gap must be bridged in order to exploit next-generation smart biodegradable scaffolds commercially.

8.1. Dynamic Degradation Testing Standardization.

The existing standards, like ISO 10993-13, are used to identify and quantify products of degradation of polymeric medical devices, although they fail to comply with the static immersion in buffered solutions [27].

8.1.1. New ISO/ASTM Standards Requirement.

Standardized protocols of dynamic biodegradation are badly needed. These must detail perfusion flow rates, cyclic loading rates, and demands of bio-mimetic media with proteins or enzymes as lubricants or catalysts during mechanical wear [66] - parameters which capture the conditions that determine clinical scaffold operation.

8.2. Implying Regulatory Pathways of Degradable Implants.

The FDA and the EMA consider degradable scaffolds as high-risk (Class III) devices since their characteristics change with time, and at the same time, their degradation products have to be safely metabolized.

8.2.1. FDA and EMA Requirements of PLA-Based Devices.

Worst-case data on degradation is extensive to meet the requirements of regulators. The traditional approach of considering a safe baseline as the result of static testing can be considered as the actual worst case because of stress-acceleration. The manufacturers need to ensure that the released lactic acid does not surpass the local metabolic clearance capacity, which avoids localized acidosis [27,64].

8.2.2. Providing Evidence of Equivalence of Static and Dynamic Tests.

Clearance of devices frequently requires manufacturers to furnish correlation factors among the static lab tests and anticipated dynamic operation. The main ways to achieve this equivalence are through strong mathematical modeling and past data of other similar formulations of the PLA in the market.

8.3. Examples of Commerce and Clinical Outcomes.

A number of PLA-based devices have been able to pass the bench-to-bedside test, but most have comparatively simple geometries.

8.3.1. Orthopedic Fixation Devices: Screws and Plates.

Screws made of PLLA interference and bone plates have been in clinical use for decades with no revision required. Nevertheless, 5 -10% of patients develop late-stage inflammatory reactions along with device fragmentation a

phenomenon that can be easily overlooked during in vitro assays but can be forecasted in dynamic fatigue-degradation simulations [64].

8.3.2. Tissue Engineering Scaffolds: Bedside to Benchside.

More complicated tracheal or alveolar bone scaffolds are now in clinical trials, with 3D-printed structures that are only optimized through dynamic simulation to preserve structural stability during constant movement of respiratory or masticatory systems [1] an example of how dynamic modeling is already affecting commercial device design.

9. Future Projections and Research Strengths.

The future of the research on PLA biodegradation is in combining the aspects of time management and real-time monitoring, a step towards truly personalized regenerative medicine.

9.1. Emerging Trends

The PLA scaffold design and assessment are redefining the possibilities presented by advances in manufacturing and sensor technology.

9.1.1. 4D 4D Printing: Time-Programmed Degradation.

Applications of 4D printing 4D printing entails 3D printing of (materials that evolve over time) in response to external stimuli (temperature, pH, moisture). In the case of PLA, it allows scaffolds to grow after implantation to fill defects or control porosity as they resorb to support increasing tissue [68]. This time-programmed behavior provides it with a fourth design dimension and unprecedented control over the dynamic degradation-tissue ingrowth interface.

9.1.2. Intelligent Self-Monitoring Scaffolds: Inbuilt Sensors.

Scaffolds containing built-in biodegradable sensors that can relay real-time information on the local pH, pressure, and scaffold thinning are under active development [68]. Locally measured monitoring of the scaffold-tissue transition would allow clinicians to tune patient loading or rehabilitation schedules to maximize the healing dynamics a paradigm-shifting use of regenerative engineering.

9.1.3. Individually Degrade with the aid of AI Design.

It is possible that through the combination of medical imaging (CT/MRI) and AI design algorithms, one can produce patient-specific PLA scaffolds with degradation behavior based on age, activities, and bone density of a specific

patient [1,68]. This kind of personalization is an obvious consequence of the dynamic degradation concept that emerged during the course of this chapter.

9.2. Scientific Questions that are still open.

In spite of the considerable advances, there are still several fundamental questions on the long-term biological effects of dynamic degradation.

9.2.1. Long-Term Byproduct Destiny within Dynamic Environments.

Although the metabolism of lactic acid is well-known, there is scant understanding of the systemic fate of micro- and nano-sized PLA fragments produced during dynamic mechanical wear. It is of great importance to determine whether these particles are eliminated through the lymphatic system or cause chronic inflammatory reactions in other distant organs [64].

9.2.2. Degradation Product Immune Response to Degradation Products Under Load.

There has been an emergence of evidence that the immune response towards a degrading polymer is mechanically regulated. Macrophage phenotype (M1 vs. M2) changes depending on the stiffness of substrates; the effect of changing the stiffness of a dynamically degradable PLA scaffold on this immunomodulatory activity is an essential open area of research [66].

9.2.3. Enhancing at the Scaffold Level to an Organ Level Construct.

The vast majority of studies on degradation involve small scaffolds (12 cm). Taking dynamic degradation models to organ-level structures, where distances of transport of nutrients and byproducts are many orders of magnitude bigger, poses significant engineering problems in ensuring uniform degradation conditions and forms the next step in the development of scaffold bioreactors [1].

10. CONCLUSION

The relative study of the dynamics and static biodegradation regimes highlights the radical change of paradigm in biomaterials science: no longer is the scaffold a passive temporary support, but a dynamic entity in the healing process. Static tests give the required base of chemical characterization but fail to show the important synergies between mechanical loading, fluid dynamics, and structural geometry that determine in vivo performance. In the case of PLA scaffolds, dynamic conditions increase the rate of degradation due to stress concentration and increased byproduct removal, and, at the same time, have the opportunity to introduce the so-called mechano-active designs of scaffolds that

respond to tissue regeneration in a comparable way. The fluctuation behavior at the static conditions, which is due to competing swelling, crystallinity, and erosion dynamics, is suppressed to a great extent in the presence of dynamic perfusion and loading, with more predictable, linear degradation profiles that are more useful in clinical predictions. The Stereochemistry of PLLA/PDLLA, composite fillers like HA or bioglass, and the geometry of the scaffold (porosity, pore size, unit cell topology) are interplaying to form the degradation envelope, and multi-physics FEA-CFD models verified on in vivo data are increasingly able to represent these interactions. With the field moving toward 4D printing, in-situ biosensors, and AI-based personalized design, incorporating dynamic testing procedures in both regulatory and design processes will be the key to successful clinical implantation of next-generation biodegradable surfaces.

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Chapter 4

A Current Literature Review on Polymer Concrete Technology as a Special Type of Concrete

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ABSTRACT

Polymer concretes are a type of high-performance, specialized concrete and composite structural material developed to reduce the mechanical and environmental limitations of traditional Portland cement concretes. Thanks to the polymers used in their design, they possess properties such as low permeability, high chemical resistance, rapid curing, and improved mechanical strength. Because of these properties, they have become a significant research topic in infrastructure, repair, and industrial production. This study examines the historical development, classification, production principles, and engineering performance of polymer concrete technology within the framework of a current literature review. The study explains the fundamental structural differences between polymer-modified concretes (PMC/PCC), polymer-impregnated concretes (PIC), and polymer concretes (PC). The effects of epoxy, polyester, and vinyl ester-based resin systems on mechanical behavior are evaluated. Furthermore, the role of temperature changes, chemical attacks, aging mechanisms, and environmental effects on the durability of polymer concretes is analyzed in line with current findings in the literature. The effects of modern optimization approaches such as fiber additives, nanomaterials, and hybrid systems on the ductility, crack control, and fatigue strength of the material are also addressed. The research revealed that polymer concretes are not only high-strength structural materials but also transforming into next-generation engineering materials integrated with sustainability, digital manufacturing, and smart infrastructure systems. In this context, innovative applications such as bio-based resins, self-healing systems, sensor-integrated smart concretes, and 3D printing technologies were evaluated. Furthermore, it was determined that artificial intelligence and machine learning-based mix design methods provide significant advantages in predicting and optimizing the performance of polymer

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concretes. Literature review results have shown that polymer concretes offer long service life and high performance under aggressive chemical environmental conditions, but suffer significant performance losses when exposed to high temperatures. Furthermore, high production costs, lack of standardization, limited long-term field data, and insufficient studies on aging behavior have been identified as major obstacles to the widespread use of these materials. Therefore, it is believed that future studies should focus on sustainable material development, field performance analysis, and the establishment of international standards.

Key words: Special concretes, Polymer concrete, Polymer-modified concrete, Construction and building materials technology.

1. INTRODUCTION TO POLYMER CONCRETES AND BASIC CONCEPTS

In contemporary civil engineering and building materials science, conventional Portland cement concrete (OPC) constitutes the undisputed backbone of modern infrastructure, particularly due to its low production cost, ease of shaping, and widespread availability (Ghassemi & Toufigh, 2020). However, this conventional material also has some fundamental limitations due to its high capillary porosity, low tensile/flexural strength, and long curing times (Mostofinejad et al., 2024). Due to this pore network, traditional concrete is susceptible to penetration by aggressive chemicals such as chlorides, acids, and sulfates, and experiences serious resistance problems against freeze-thaw cycles and chemical corrosion (Mostofinejad et al., 2024). These limitations, as well as the different performances expected from concrete and the specific goals involved, have given rise to the subject of special concretes. Researchers and engineers have made it possible to produce many types of specialized concrete by minimizing the limitations of current concrete while designing it to achieve specific goals. Within the context of these limitations and specific goals, researchers have found a solution to the increasing performance expectations of structures with polymer concrete (Bedi et al., 2013). This is because cement-based concrete cannot adequately meet the high-level demands such as high strength, absolute impermeability, and rapid setting required in bridge decks, industrial floors, marine structures, and repair-strengthening projects (Ferdous et al., 2020). It is precisely at this point that polymer concretes come into play, offering a solution to these limitations. Polymer concrete, as a specialized type of concrete that can achieve high strength values in just a few hours and provide protection against chemical attacks, offers a more robust engineering solution (Li et al., 2025; Özdemir & Çakır, 2025).

A chronological examination of past studies reveals that innovative steps in the use of polymers in the world of concrete date back to the 1920s (Wang et al., 2005). A review of the literature shows that the first attempts in this area began with the addition of natural rubber latexes to cement mortars. British patents obtained by Cresson in 1923 and Lefebure in 1924 are recorded as the first official documents in this field (Wang et al., 2005). By the 1950s, polymeric materials were being tested for the first time in the United States on bridge decks and architectural building surfaces (Fontana & Bartholomew, 1980). The late 1960s and 1970s marked a period of significant advancement for concrete-polymer composites. In particular, the establishment of Committee No. 548 on “Polymers in Concrete” within the American Concrete Institute (ACI) ensured the establishment of standards (ACI Committee 548, 2009). In the academic world,

the recognition of this subject area as an independent discipline occurred with the first “International Congress on Polymers in Concrete (ICPIC)” held in London in 1975 (Koblischek, 1975). More recently, since the 2000s, the construction industry has focused on circular economy principles, incorporating waste PET (polyethylene terephthalate) bottles, scrap tires, and electronic plastic waste into polymer concrete formulations, thus giving these materials sustainability and a green character (Alhazmi et al., 2021; Pacheco-Torgal et al., 2012).

After this brief chronological review of their emergence and general development process, the subject can be understood in terms of how these materials are used and what types exist when considered within the framework of current materials science literature. Looking at the literature from this perspective, it is possible to define concrete-polymer composites in three main classes according to the method of integrating polymeric materials into the system and the chemical structure of the resulting matrix (Czarnecki, 2018):

Polymer Modified Concrete (PMC) / Polymer Cement Concrete (PCC): Traditional Portland cement is a grade produced by adding latexes such as styrene-butadiene (SBR) or acrylic polymers in emulsion/dispersion form to a fresh mixture of water and aggregates (Zhang et al., 2021). In the main mechanism of this grade, while cement hydration (hardening) continues in the mixture, polymer particles simultaneously coalesce to form a thin film layer. This creates an interpenetrating composite polymer-cement matrix in the microstructure (Zhang et al., 2021). In this method, the addition of polymer material to the mixture along with cement in the matrix significantly improves the workability, adhesion, and water impermeability of the material (Zhang et al., 2021).

Polymer Impregnated Concrete (PIC): In this class, the method adopted is the impregnation of polymer material into pre-poured, set, and hardened conventional concrete. The production mechanism is based on the principle of removing moisture from the hardened concrete, prepared according to traditional mixing principles, by baking or vacuuming it, and then polymerizing it by injecting low-viscosity liquid monomers (e.g., methyl methacrylate) under pressure into the empty capillary voids (Mostofinejad et al., 2024). As a result of this process, the capillary pores are occluded with plastic, and the concrete acquires good corrosion and freeze-thaw resistance (Mostofinejad et al., 2024).

Polymer Concretes (PC): In this class of composite polymer concretes, unlike other methods, the cement and water components, considered essential in traditional concrete, are completely removed from the formula (Nodehi, 2021). Instead of these familiar materials of traditional concrete, in this class of polymer concretes, inorganic aggregates, quartz sand, and fine fillers are used as

aggregates, while thermoset (thermally curing) synthetic resins such as epoxy, unsaturated polyester, or vinyl ester are used as the binder phase to create the concrete structure (Gao et al., 2019; Nodehi, 2021). Thanks to cross-linking achieved through chemical polymerization, these materials have much higher compressive, tensile, and flexural strength values than traditional systems (Ozdemir & Cakir, 2025). In addition, the setting time and time to be put into use of polymer concretes created in this class are much shorter compared to traditional concrete. However, since polymer materials are used as binders instead of cement in the main structure, and due to the cost of the chemical materials used to adjust their setting time, the economic viability of the produced concrete should also be discussed. In conclusion, it would be incomplete to consider polymer concretes solely as a patch or repair/reinforcement material covering the defects of traditional concrete. Beyond these uses, it would be more accurate to consider them as an innovative type of special concrete that offers improved resistance and lifetime performance in situations involving aggressive chemical conditions and heavy mechanical loads. Many classifications of polymer use in concrete or polymer concretes can be found in various sources. Figure 1 presents a typical classification graph for polymer concretes.

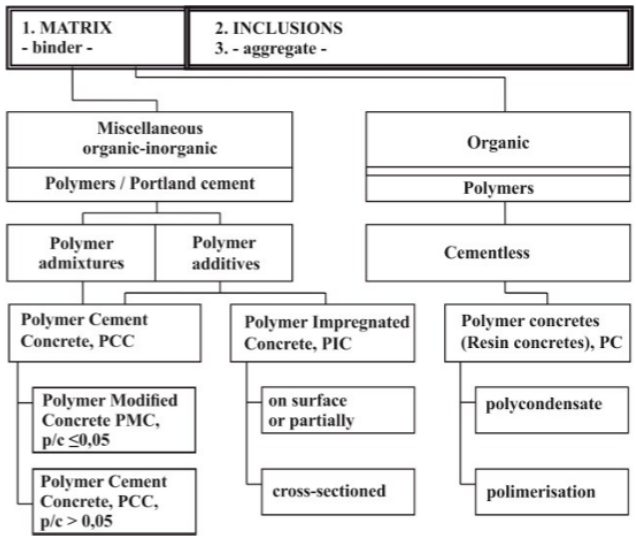

Figure 1. Classification of Concrete-Polymer Composites, C-PC (Czarnecki, 2018).

2. THE MATERIAL-FOCUSED DEVELOPMENT PERIOD (1970-2000)

The first studies and applications of polymer concretes in the USA, Japan, and Europe date back to the 1950s. The material's true recognition in the construction industry, particularly in thin coatings, structural repairs, and prefabricated component applications, occurred in the 1970s. The first International Polymer Concrete Congress (ICPIC), held in London in 1975, and subsequently Committee No. 548 established within the American Concrete Institute (ACI), laid the groundwork for the global academic and industrial standardization of these materials. Examining their geographical and chronological development, while polymer concretes gained a dominant market share in Japan and Europe in the 1970s, widespread acceptance in the United States only began in the 1980s. As Ohama (1997) also emphasizes in his work, these composites, which are preferred in Japan mostly for surface finishing and repair work, have been used extensively in the USA, particularly under the leadership of the Bureau of Reclamation and the Oregon and California Transportation Departments (ODOT and Caltrans), for abrasion-resistant coating and patching of bridge decks (Fowler 1999). The development-time graph of polymer concrete from the 1920s to the 2000s is presented in Figure 2.

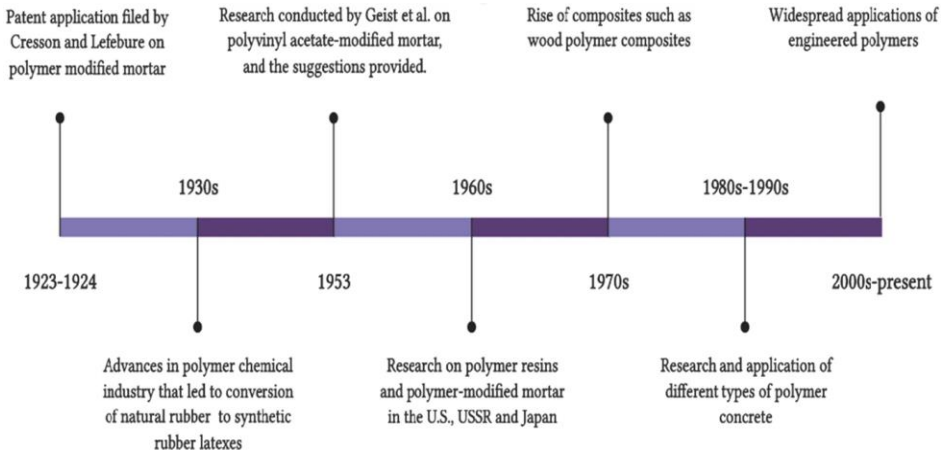

Figure 2. Developmental timeline of polymer concrete (Nodehi 2022).

The Development of Resin Technologies: In this material-focused development period, the inorganic cement binder used in traditional concrete production has been completely replaced by organic polymer binders, especially thermoset resins. Epoxy, unsaturated polyester, and vinyl ester resins have become the most preferred matrices on an industrial scale during this period. The basic hardening mechanism of polymer concretes begins with the polymerization

reaction of monomers and oligomers with the addition of a suitable hardener (catalyst or initiator). This is followed by a solidification process that transforms the liquid state into long, branched, three-dimensional, and cross-linked spatial networks. At this point, while the use of different materials in the design does not alter the internal mechanism, it can differentiate the resulting functionality. For example, orthophthalic polyester is the most commonly used type due to its low cost and ease of production, while isophthalic polyesters are preferred in cases where corrosion and temperature resistance are important. On the other hand, vinyl ester resins have been developed to combine the high thermal and mechanical properties of epoxy with the low cost of polyester and have become a very important alternative in infrastructure projects.

Early Strength and Chemical Resistance Advantages: The main reason for the rapid adoption of polymer concretes in the construction industry is their ability to offer 3 to 5 times higher mechanical strength compared to traditional Portland cement concretes. One of the most remarkable features of these materials is their rapid curing capability. This advantage allows for demolding prefabricated structures to be completed within a few hours, while enabling repaired roads or structures to be opened to traffic and use in a very short time. In fact, polymer concretes can reach 70-75% of their ultimate compressive strength with only one day of curing at ambient temperature. Compressive strengths of 70 to 120 MPa and splitting tensile strengths exceeding 15 MPa can be achieved. These composite materials can also have approximately four times higher vibration damping capacity than cast iron. In addition, their low permeability, water insulation properties, and superior resistance to aggressive chemicals such as acids and sulfates have made polymer concretes a better option for sewer pipes, acid tanks, and industrial floor coverings in harsh environmental conditions.

Limiting Factors: Despite all the extraordinary technical advantages and high expectations it offered in the early stages, the biggest and most difficult obstacle to overcome limiting the mass-scale use of polymer concretes has been production costs. The polymer resins, which are the main binder, are 10 to 100 times more expensive than conventional Portland cement on a volumetric basis. This cost difference has made it economically impossible to use these materials in large-scale projects (such as road pavements and foundation construction) and has limited their use to specific applications where high durability is essential. In addition to cost, physical incompatibilities and difficulties in the production area also pose significant obstacles. The thermal expansion coefficient of polymer concretes is 3-4 times higher than that of conventional cement-based concretes. This can create very high shear and tensile stresses at the interfaces, especially in

applications on old concrete surfaces such as bridge deck coatings, along with temperature changes. These types of stresses lead to premature delamination and cracking failures. In the production process, the requirement that the aggregates used must be completely dry and free of moisture, and the additional energy costs required for drying them if they are not dry, creates a different dimension of the problem. The very limited polymer mixing and workability time (typically around 3 minutes) and the fact that the weather conditions in the working environment directly affect the reaction rate make this material considerably more difficult and sensitive to work with compared to traditional concrete in field applications.

3. PERFORMANCE IMPROVEMENT APPROACH AND PERIOD

Polymer concretes (PCs), throughout their development from the past to the present, have evolved beyond being merely an alternative to traditional concrete. They have entered a period of performance enhancement through the use of resin formulations, multi-scale admixtures, and advanced application techniques in their design. This period represents a phase in which high-strength and long-lasting composites, capable of responding to specific industrial needs, are designed at the micro and macro levels.

Epoxy, Polyester, and Vinyl Ester Systems: In polymer concrete production, thermoset resins, including epoxy, unsaturated polyester, and vinyl ester, are commonly used as binder matrices (Nodehi, 2021). Although polyester resins offer a relatively low cost advantage and ease of processing, they are disadvantageous due to their relatively high shrinkage rates after curing (Nodehi, 2021). Vinyl ester systems, on the other hand, combine certain advantages of epoxy and polyester, exhibiting better chemical corrosion resistance and higher impact toughness compared to polyesters. However, their tendency to form weak bonds with other materials can lead to a risk of delamination (Nodehi, 2021). On the other hand, although epoxy resins stand out with their high resistance to moisture, negligible shrinkage rates, and mechanical and thermal properties, their production costs are quite high compared to other resins (Nodehi, 2021).

Mechanical and Durability Performance: Polymer concretes, optimized and developed with a performance focus, have a significant advantage in terms of compressive, tensile, and flexural strengths compared to ordinary cement-based concretes (Bedi, Chandra, and Singh, 2013). Thanks to their dense and impermeable microstructures, these materials exhibit greater resistance to chemical attacks such as acids and sulfates (Ghassemi and Toufigh, 2020). However, since the thermal performance of these composites depends on the glass transition temperature of the polymer forming the matrix, exposure to high

temperatures (e.g., 250 °C) results in significant losses in the physico-mechanical properties of the material and the formation of macrocracks (Elalaoui et al., 2012). At the same time, experimental studies have shown that optimized polymer concretes subjected to repeated thermal cycling lose their mechanical strength over time (Heidari-Rarani et al., 2014).

Fiber and Nano-Additives: Modifying the matrix at different scales to optimize the brittle fracture tendency of polymer concretes and increase their toughness is an important research area. Macro- and micro-addons such as glass, carbon, basalt, and natural fibers limit crack propagation by establishing bridging mechanisms within the matrix and improve the flexural and fracture energy of the material (Elalaoui 2023; Salamat Talab et al., 2024; Akzharkyn et al., 2024; Reis, 2006). However, as indicated in the studies conducted by Ulu et al. (2022), the addition of excessive amounts of fiber to the mixture leads to fiber agglomeration. Similarly, problems such as interfacial cracks and increased voids within the matrix occur, which significantly reduce the compressive and flexural strength of the material. Another dimension of the performance improvement period is the integration of addons such as nanocarbon tubes (CNTs) into polymer concrete. These types of additives strengthen the matrix at the microscopic level, significantly increasing the ductility and impact damping capacity of the material (Douba et al., 2019).

Industrial Applications (Prefabrication, Repair, Infrastructure): The improved and optimized versatile properties of polymer concretes have made the material preferable in specific industrial fields. In particular, thanks to their much higher vibration damping capacities than cast iron, they have become the main alternative in the production of precision CNC machines and machine foundations (Orak, 2000; Haddad and Al Kobaisi, 2012). Its ability to adhere to conventional cement-based concrete and its rapid curing make polymer concrete an ideal rapid repair material for airport runways and damaged bridge decks (Jung, Roh and Chang, 2014; Fowler 1999). In infrastructure systems, due to its high corrosion resistance, it is used in the production of prefabricated components such as precast wastewater pipes, drainage channels, and underground manholes, providing structures with a longer service life (Shrestha et al., 2024).

Despite these developments in polymer concrete technology, although it has become an advanced engineering material since its discovery, the obstacles to its large-scale use remain unchanged. Today, the most fundamental obstacle is the very high raw material and production costs of polymer resins (especially epoxy systems) compared to ordinary cement (Nodehi, 2021). On the other hand, as emphasized by Fowler (1999), another structural problem hindering the mass adoption of polymer concrete technology is the lack of globally unified design

codes and standard test guidelines. The absence of standard specifications causes engineers to hesitate in material selection. In addition, although laboratory tests prove the short-term performance of polymer concrete, there are not enough studies on the performance of the material in real field conditions. Field data and analyses explaining the fatigue behavior of polymer concrete, especially under dynamic traffic and usage loads, or its long-term response to changing environmental cycles, are still insufficient today (Shokrieh et al., 2011). Figures 3 and 4 present the compressive strength results obtained for polymer concretes in response to increasing temperature, utilizing the limited studies available. Figure 3 shows that while acceptable compressive strength loss occurs up to 200ºC, significant strength losses are observed, particularly at 250ºC. Similarly, Figure 4 compares the compressive strength of cement-based concrete and polymer concrete with increasing temperature. Figure 4 shows that while the strength of the conventional cement-based concrete mixture remains normal with increasing temperature, the compressive strength of the polymer concrete mixture exhibits a significant decrease. Figure 5 supports this, showing that the total porosity of a polymer-modified concrete type increases significantly with increasing temperature, reaching 200ºC. This evidence suggests that some types of polymer concrete will cause serious problems, especially at temperatures exceeding 200ºC.

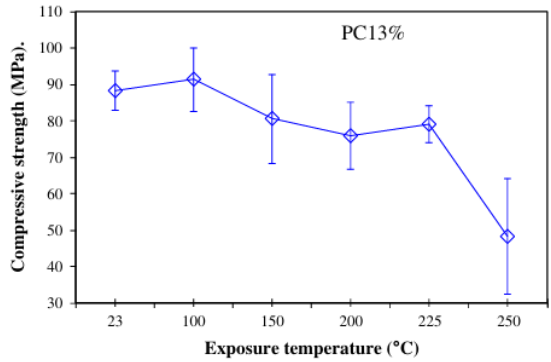

Figure 3. Effects of the temperature exposure on the residual compressive strength. (Elalaoui vd., 2012).

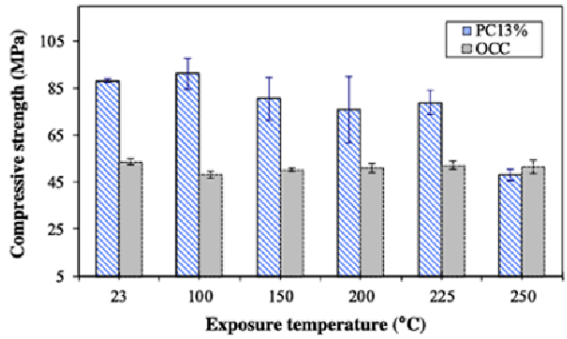

Figure 4. Effect of exposure temperature on the residual strengths of polymer concrete and cement based concrete. (Elalaoui vd., 2012).

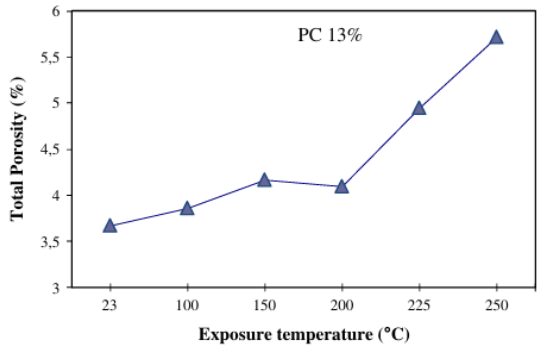

Figure 5. Effect of the exposure temperature on the total porosity of the PC designed with a polymer ratio of 13%. (Elalaoui vd., 2012).

4. KEY PROBLEMS IN THE LITERATURE

There are significant gaps in the literature that need to be closed in order for these materials to be used more widely and reliably at the structural and industrial levels. A review of current research in the field reveals a number of research needs, ranging from the service life of the material to deficiencies in standardization.

Service Life Uncertainty: Although polymer concretes exhibit very high strength and chemical resistance in the short term, the long-term behaviour of their structural safety and service life under harsh environmental conditions is still not clearly predictable (Ghassemi and Toufigh, 2020). Compared to conventional concretes, it is quite difficult to accurately predict the fatigue life and fatigue strength of polymer concretes under dynamic service loads or continuously changing cyclic loadings (Bondarev et al., 2022; Ghassemi et al.,

2020; Ren and Hu, 2022). Furthermore, the lack of sufficient quantitative long-term durability data leads to incomplete or inadequate life cycle assessments for these materials (Salami et al., 2024). In this context, long-term performance studies that more comprehensively examine the corrosive effects of time are needed to fully verify the service life of polymer cement repair and building materials (Yuan et al., 2023).

Aging and Degradation Mechanisms: The specific aging and degradation mechanisms of polymer matrix materials under high temperatures, ultraviolet radiation, and harmful chemical environments have not yet been fully elucidated. For example, when the exposure temperature exceeds 150°C, macro-level cracks form in polymer concretes, thermo-oxidative degradation mechanisms are triggered, and the material gradually exhibits brittle behavior (see Figures 3-4) with an increase in microstructural voids (see Figure 5) (Nodehi, 2021). In addition, binders such as unsaturated polyester resins are highly sensitive to excessive energy and acidic/basic chemical attacks. Hydrolysis of ester bonds can occur, severely breaking down polymer chains (Gao et al., 2019). While it is known that long-term exposure to ultraviolet radiation leads to surface flaking and cracking at the polymer-matrix interface, our understanding of how some polymer fillers compensate for or block these degradations is limited (Tran et al., 2022).

The aging tendencies exhibited by certain polymer types, such as butylbenzene, in the long term can compromise the stability of composite structures, therefore the degradation kinetics need to be addressed in much greater detail (Yuan et al., 2023).

Micro-Macro Relationship Lack: The structural and mechanical performance of polymer concretes largely depends on the quality of adhesion between its components (aggregate, cement, and polymer resin) and the microstructural formation of the matrix. Although how polymer particles affect cement hydration, fill voids, and form a film layer at the interface has been analyzed at the microscopic level, integrated and comprehensive theoretical models that directly relate these microstructural behaviors to macroscopic mechanical performance are still lacking (Beeldens et al., 2005). The organic-inorganic interaction process in polymer-modified cement systems is quite complex, and the structural mechanisms exhibited by different polymer types within the matrix can differ significantly (Zhang et al., 2021). The macroscopic predictability of the fracture behavior of various polymer types under complex stress states and shear/tensile loading remains limited (Salami et al., 2024). Figure 6 is a diagram that schematically summarizes the development process of polymer-based composite or polymer-modified structural materials. The main

purpose of this material design flowchart is to show which chemical components the polymer is made from, which auxiliary agents are used during production, and which performance criteria the resulting material is evaluated against. In short, Figure 6 illustrates the relationship between chemical composition, microstructure, and macro performance.

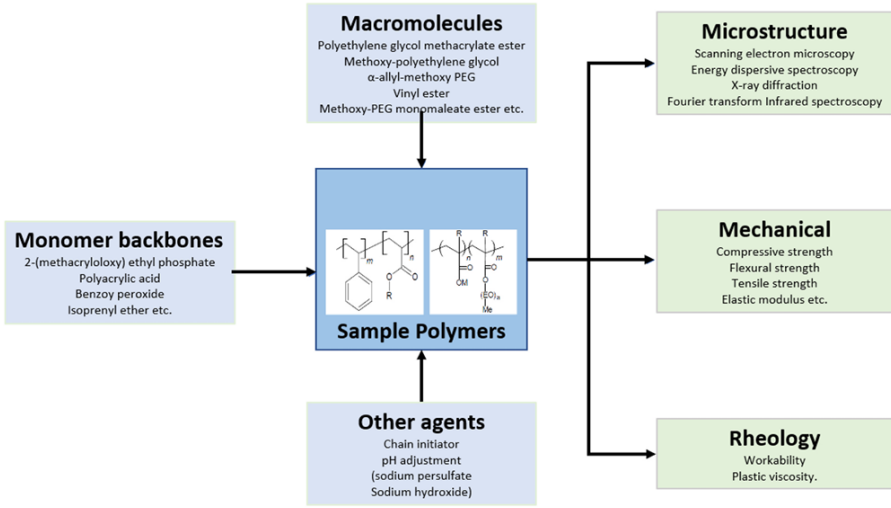

Figure 6. Schematics depict the components for polymer synthesis and the characterization techniques (Salami vd., 2024).

Lack of Design Standards: One of the main obstacles to the widespread adoption of polymer concrete and composite technology in the construction industry, similar to traditional concrete, is the absence of globally unified quality control and design standards (Wang et al., 2024). Unlike traditional concrete, there is no defined universal strength classification for polymer concrete, and the final properties of the material can vary drastically depending on the type of resin used (isophthalic, orthophthalic, epoxy, vinyl ester, etc.) and aggregate composition (San-José et al., 2007). This lack of standardization and methodology makes it impossible to predict the structural behavior of polymer concrete in projects with real-time accuracy. Similarly, the creation of design guidelines and testing standards to serve the industry has become essential (Salami et al., 2024; San-José et al., 2007).

Insufficient Field Application and Data: A review of the existing literature reveals that almost all research evaluating the durability and mechanical properties of polymer concretes has been conducted under controlled laboratory conditions (Ahmad et al., 2025). However, these laboratory tests cannot fully

simulate real-world conditions with varying soil types (soil variations, different environmental climate cycles, extreme humidity/temperature changes, seismic activity, aggressive chloride/sulfate attacks, etc.) (Ahmad et al., 2025). While these controlled environment tests in the laboratory provide important information about the nature of the material, they are insufficient for real-world structural operational applications (Ahmad et al., 2025). For all these reasons, it is crucial to validate micro-level laboratory findings and conduct real-time, comprehensive field research, field trials, and long-term field data monitoring studies (Ahmad et al., 2025).

5. CURRENT APPROACHES AND INNOVATIVE TECHNOLOGIES

The chronological and innovative development in polymer concrete technology has transformed the material from merely a high-strength structural element into an environmentally friendly, autonomously responsive, and fully integrated smart system capable of digital production technologies. Below, the developments in the current literature regarding sustainable and smart structures of polymer concretes are examined under subheadings.

Bio-Based and Low-Carbon Resins: The high carbon emissions caused by polymer binders traditionally produced from petrochemical sources have led researchers in the construction sector to explore renewable and bio-based alternatives (Salami et al., 2024). Bio-based polyurethane (PU) resins are synthesized from renewable sources such as plant-derived natural oils or agricultural waste. The use of these resins in the production of polymer concrete (BPC) offers an environmentally friendly alternative by reducing the carbon footprint by 50% compared to traditional Portland cement-based concretes (Murcia et al., 2023). Figure 7 highlights that bio-polymer concrete has a much lower carbon footprint compared to reference cementitious concrete. Furthermore, these bio-polymer concretes not only provide environmental benefits but also exhibit better resistance to acidic and harmful environmental conditions. Figure 8 shows the weight losses of conventional and bio-polymer concrete after acid exposure at different holding times. As can be seen from Figure 8, the weight losses of bio-polymer concrete are very low compared to conventional cementitious concrete. In addition, polymer concretes obtained in this way achieve structural compressive strengths ranging from 20 to 30 MPa and tensile strengths of around 4 MPa, demonstrating a highly competitive mechanical performance (Murcia et al., 2023).

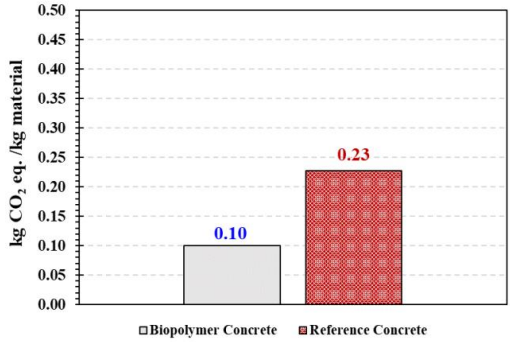

Figure 7. Carbon footprint analysis comparing BPC to reference cement concrete. (Murcia vd., 2023).

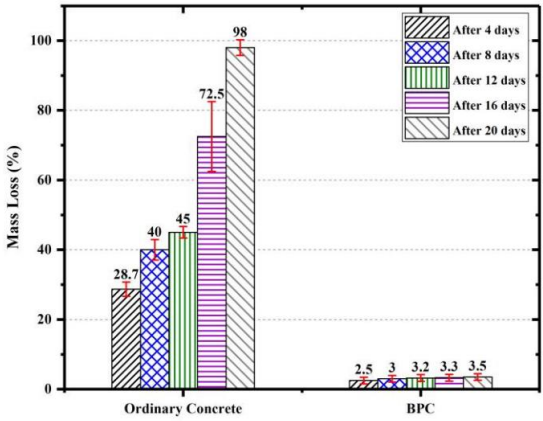

Figure 8. Weight loss of ordinary and BPC exposed to hydrochloric acid (HCL). Values shown above the bars represent the mean values. (Murcia vd., 2023).

Self-Healing Systems: To maximize the service life of polymer concrete and polymer-modified cementitious systems, self-healing mechanisms capable of autonomous repair upon microscopic damage have been developed (De Belie et al., 2018). For example, embedding polymeric healing agents such as epoxy resin into the matrix within microcapsules is a prominent exogenous mechanism. Capsules that rupture upon crack formation release polymeric adhesives, enabling mechanical restoration (Li et al., 2013). Another innovative method in the literature is the use of hollow vascular networks produced by 3D printing to accommodate maximum aggregate size (De Nardi et al., 2020). Alternatively, shape-memory polymer tendons that close cracks and restore structural integrity when triggered by electrical current are also a significant advancement in moving crack control in concrete from a passive to an active state (Teall et al., 2018).

Sensor-Integrated Smart Concrete: Continuous monitoring of structural health is vital in future infrastructure projects, and new generation polymer concretes are evolving into directly sensor-equipped smart materials (Sony et al., 2019). The addition of electrically conductive nano-fillers such as carbon black and carbon nanofiber hybrids to polymeric cementitious composites gives the material autonomous sensing capabilities (Li et al., 2024). In addition to these materials, smart polymer concretes produced by adding steel slag to the mixture can proportionally change their electrical resistance in response to applied pressure, thus enabling the material itself to function as a strain sensor without the need for an externally integrated device (Ding et al., 2019).

3D Printing and Digital Manufacturing: Three-dimensional concrete printing technology, which significantly reduces formwork costs and waste in industrial construction production, is revolutionizing design freedom when combined with polymer materials (Tay et al., 2017). However, to prevent structural micro-defects during the continuous extrusion process, ensuring the power quality of these automated 3D printing machineries by eliminating network harmonics via active power filters is a crucial industrial requirement (Palta & Guldemir, 2019).While weak interlayer mechanical bonding is considered one of the biggest challenges in extrusion-based 3D printed concrete, integrating polymer-modified mortars into the interfaces successfully overcomes this bond weakness (Wang et al., 2020). On the other hand, the use of polymeric admixtures, which replace traditional binders, together with industrial wastes such as fly ash, increases the extrusion capability in 3D printing processes and brings together material science and architectural digitalization in a sustainable way (Dvorkin et al., 2022).

AI-Assisted Mix Design: In predicting the complex mechanical behavior of polymer-containing concretes and optimizing mix ratios, artificial intelligence (AI) algorithms have begun to replace traditional long-term testing procedures (Moein et al., 2023). In polymer concretes with rubber waste additives or epoxy-based polymers, multivariate properties such as compressive strength can be successfully predicted with Artificial Neural Network (ANN) models (Diaconescu et al., 2013). Furthermore, Multilayer Perceptron (MLP) and Extreme Gradient Boosting (XGBoost) algorithms achieve high accuracy (R^2) rates in estimating dynamic parameters such as damping coefficient in hybrid polymer concrete systems (Dang et al., 2024). Additionally, advanced deep learning architectures and texture feature fusion approaches, which have proven highly effective in complex microscopic image classifications, can be integrated into this AI-driven framework to autonomously analyze scanning electron microscopy (SEM) images of polymer matrices for micro-crack detection (Palta

et al., 2026). Similarly, the integration of hybrid approaches such as Grey Wolf Optimization (GWO) and Imperial Competitive Algorithm (ICA) with LightGBM or MLP can model the structural performance of geopolymer and special polymer concretes with a higher level of accuracy. The use of these methods offers a data-driven quality control opportunity despite the shortcomings in design standards (Wang et al., 2023; Zhang et al., 2024; Zhong et al., 2024).

6. FUTURE APPROACHES AND STUDIES

Recent advancements in polymer concrete technology necessitate integrating the material not only into its intrinsic mechanical properties but also into a multifaceted system engineering and sustainability goals. The innovative vision in the sector should not only include performance-based designs and environmental impact analyses of these composites. Furthermore, it needs to encompass a broad perspective covering everything from standardization policies to multidisciplinary collaborations. Considering these aspects, the turning points in the transformation of this material into a versatile system can be discussed under the following brief headings:

A Performance-Based Design Approach Beyond the Traditional: Traditional concrete designs often utilize empirical ratios or trial-and-error methods. In such specialized concrete designs, it is necessary to go beyond this design logic and develop performance-based mix design strategies specifically for polymer concretes (Ferdous et al., 2020; Jafari et al., 2018). Some scientific research in the literature emphasizes the need to determine optimum polymer-aggregate ratios that simultaneously maximize the mechanical parameters of the material without compromising its workability (Ahmad et al., 2025; Ciminli and Bulut, 2025; Muthukumar and Mohan, 2004). Today, modern design algorithms directly integrate machine learning and artificial intelligence models such as Multilayer Perceptron (MLP), Deep Neural Networks (DNN), Extreme Gradient Enhancement (XGB), and Support Vector Regression (SVR) into the process to find the most ideal recipe outcome in polymer-modified systems (Laqsum et al., 2025; Palamarchuk et al., 2024). Thanks to these predictive smart algorithms that guide design, damping coefficients or specific responses under dynamic loads of complex composites can be estimated with high accuracy rates (R^2) (Dang et al., 2024), and at the same time, sectoral research hotspots can be identified through bibliometric analyses, allowing for more efficient use of resources (Wang et al., 2024).

Life Cycle Engineering: To address the environmental burden of polymer concrete and organic-inorganic cementitious composites within the context of

circular economy principles, the inclusion of Life Cycle Assessment (LCA) models in the system is an industrial necessity (Meshram and Kumar, 2022). Comprehensive LCA and ex-ante LCA studies should be conducted, examining the environmental scorecard of all steps in the production process, from raw material acquisition to final recycling. These studies aim to minimize emissions (NO2, SO2) and Global Warming Potential (GWP) values arising from chemical processes, and to improve sustainable 3D-printed composites through multi-criteria decision-making (MCDM) analyses (Almutairi et al., 2025; Yao et al., 2020; Yoris-Nobile et al., 2023). Moreover, compliance with ecological circular economy directives is largely achieved through the integration of industrial and household plastic waste (PET, rubber, etc.) into the concrete matrix (Alhazmi et al., 2021). On the other hand, when economic parameters are considered, despite the high initial investment costs caused by synthetic resins, Life Cycle Cost Analysis (LCCA) models present striking results. Considering the chemical attack resistance, low maintenance requirements, and very long service life of polymer concretes, it has been scientifically proven that these materials are far more economical and budget-friendly over time than traditional Portland cement infrastructures (e.g., wastewater manholes) (Shrestha et al., 2024a; Sakhakarmi & Shrestha, 2018; Shrestha et al., 2024b).

Figure 9. Circular economy cycle and linear economy model.
(Alhazmi vd., 2021).

To understand life cycle engineering, Figure 9 should be examined closely. As shown in the figure, the linear economy model is compared with the circular economy model. The linear economy approach, shown at the bottom, involves the extraction of natural resources, the production of products, and their disposal as waste after use. In this system, while resource consumption continuously increases, a large portion of the waste produced cannot be recovered and reintegrated into the economic cycle. On the other hand, the circular economy model aims to retain resources within the system as much as possible.

The Need for Standardization: Despite their mechanical performance, the biggest handicap slowing the mass adoption of polymer cementitious systems in the global construction industry is the lack of universally unified quality control, testing, and design standards (Salami et al., 2024; Wang et al., 2024). Unlike traditional Portland cement, the combination of various polymeric binder types such as epoxy, isophthalic/orthophthalic polyester, or vinyl ester with different aggregates creates extreme variations in concrete mechanics. This variability makes it difficult to establish a universal strength classification for polymer concretes (San-José et al., 2007). Although various guidelines from internationally reputable institutions such as the American Institute of Concrete (ACI), ASTM, and RILEM exist, or national specifications from different countries (e.g., China, Japan, USA), this set of rules has not been transformed into a uniform code set (unified standard) on the international stage (Fowler, 1999). The existing gap and deficiency in standardization restricts the selection of reliable materials in construction projects. Furthermore, it directly hinders commercial approval and certification procedures for next-generation automation processes such as structural 3D concrete printing (Alhazmi et al., 2021; Singh et al., 2023).

The Need for Multidisciplinary Research: To meet the infrastructure demands and safety standards of the future, polymer concrete technology must go beyond being a classic civil engineering subject. This particular type of concrete, incorporating polymer materials, necessitates a multidisciplinary approach, especially one that includes chemistry. The process is a fusion of multidimensional worlds where inorganic cement and organic polymers intertwine (Van Gemert et al., 2005). This innovative shift from materials science to multifaceted systems engineering requires the coordinated work of a wide range of disciplines, including polymer chemistry, advanced materials science, machine learning, 3D digital automation, and ecology (Palamarchuk et al., 2024; Wang et al., 2024). Of course, it is crucial not to overlook the fact that laboratory research alone is insufficient to address the industry's waste crisis and implement circular economy principles. Academic studies indicate a need for a transparent,

stable, and coordinated network of collaboration between major chemical raw material producers, policymakers, and construction industry professionals on the ground (Alhazmi et al., 2021; Salami et al., 2024).

7. CONCLUSION

In concrete technology, traditional concretes are insufficient to meet the expectations of current civil engineering. Therefore, special types of concrete have emerged to meet specific goals and engineering requirements. Polymer concrete technology is a significant approach to special concrete that offers alternative solutions to the fundamental problems of traditional concrete systems, such as permeability, low tensile strength, long curing time, and inadequate chemical resistance. Unlike cement-based systems, the use of polymer admixtures or binders in their design provides these materials with high mechanical strength, low void ratio, and improved chemical resistance. Polymer concretes are known to offer significant advantages, particularly in infrastructure systems operating in aggressive environmental conditions, rapid repair/strengthening applications, and industrial areas requiring high durability. While providing significant advantages in terms of mechanical behavior compared to traditional concretes, their low permeability structures allow for a longer service life against harmful chemical effects such as chlorides, sulfates, and acids. Modern polymer concrete systems, reinforced with fiber and nano-additives, reduce brittleness, increase energy absorption capacity, and bridge or limit crack propagation. Thus, polymer concretes are seen to be transformed into advanced composite materials that not only possess high strength but also exhibit more controlled behavior.

Alongside all these stated advantages, current literature reviews highlight that significant problems still persist that limit the widespread use of polymer concretes. In particular, high resin costs, sensitivities in the production process, and lack of standardization restrict application areas. In addition to these limitations, issues such as long-term field performance, fatigue behavior, thermal aging effects, and the microstructure-macroperformance relationship have not yet been fully clarified. Focusing on how the material will behave in real-world field conditions in the long term, especially after positive results are obtained in the laboratory, is critical for future research. Similarly, sustainability-focused approaches have significantly changed the direction of polymer concrete research. Recycling of waste plastics, low-carbon bio-based resins, and life cycle analyses offer new solutions to reduce environmental impacts.

Innovative applications such as sensor-integrated smart concretes, self-healing systems, and AI-assisted mix design are also transforming polymer

concretes into advanced infrastructure components capable of generating data and responding to environmental conditions.

Overall, the future of polymer concretes depends not only on material performance but also on sustainable production, digitalization, smart infrastructure systems, and interdisciplinary engineering approaches. Future research focusing on real-world field applications, long-term performance analyses, and the development of international standards will significantly contribute to the more widespread and reliable use of this technology in the construction industry.

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