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Exploration of Diverse Epoxy-Based Surface Coating Methods for Enhancing Anticorrosion Characteristics

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Abstract

Epoxy-based polymers, commonly referred to as polyepoxides, constitute one of the most versatile and widely adopted categories of polymeric materials due to their exceptional structural, mechanical, and chemical characteristics. Their unique macromolecular framework enables strong interfacial bonding, high mechanical stability, and superior resistance to environmental and chemical degradation, positioning them as advanced alternatives to many traditional organic corrosion inhibitors that often fail under prolonged exposure to aggressive conditions When polyepoxides interact with metallic surfaces, they tend to form highly ordered molecular clusters that function as active adsorption centers. This chemisorption mechanism plays a critical role in mitigating corrosion, particularly in harsh environments such as acidic solutions, alkaline media such as sodium hydroxide, and marine atmospheres. In addition to preventing uniform corrosion, epoxy-based films have shown effectiveness against more complex phenomena including crevice corrosion, interfacial degradation, and mixed-mode electrochemical corrosion. A broad spectrum of experimental investigations and computational modeling approaches—including Density Functional Theory (DFT), Molecular Dynamics (MD), and Monte Carlo simulations—have been used to study the adsorption behavior of epoxy molecules on metal substrates. These studies highlight the importance of donor–acceptor interactions, electron density distribution, and charge-transfer processes that contribute to the strong adherence of epoxy systems to metal surfaces. Although polyepoxides offer outstanding protective properties, their limited solubility in many polar and nonpolar solvents restricts their direct use in liquid-phase corrosion inhibition. Consequently, they are predominantly applied as protective surface coatings. Epoxy-based coatings serve as highly effective physical and chemical barriers for both ferrous and non-ferrous alloys, especially when exposed to corrosive saline environments, industrial chemicals, and atmospheric moisture. To enhance their performance, researchers have explored the incorporation of a wide range of natural and synthetic additives such as metallic oxides, silane coupling agents, graphene derivatives, biopolymers, nanoclays, and other nanostructures. These additives improve coating adhesion, hydrophobicity, thermal stability, and resistance to electrochemical attack. Recent developments in self-healing epoxy systems, utilizing microcapsules or nanocontainers loaded with healing agents, have opened new possibilities in smart coating technology by enabling autonomous repair of surface damage and extending service life. This review compiles and critically examines the anticorrosion behavior of both uncured and fully cured epoxy formulations. It provides an integrated understanding of their physicochemical properties, adsorption mechanisms, and performance across various metallic substrates and electrolytic environments. Additionally, the review outlines future directions in epoxy coating technology, emphasizing environmentally friendly formulations, sustainable synthesis pathways, and advanced hybrid nanocomposite systems for high-performance corrosion protection in modern industrial applications.

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INTRODUCTION

Epoxy resins have become indispensable materials across a wide range of industrial applications due to their remarkable combination of durability, strong adhesion, and long-term resistance to chemical and environmental deterioration [1, 2–6, 8]. Their extensive use spans industries such as construction, transportation, oil and gas, electronics, marine engineering, and manufacturing. Epoxy coatings are frequently selected for protecting pipelines, structural steel, concrete surfaces, industrial floors, storage tanks, and various mechanical components that are routinely exposed to corrosive or high-stress conditions [9–10]. Although epoxy coatings may initially seem heavier or more labor-intensive compared with some alternative polymeric systems, their long service life and superior resistance to corrosion make them a more economical and practical choice over extended operational periods [3–5]. With proper surface preparation—such as abrasive blasting, cleaning, and ensuring optimal environmental conditions during application—the need for frequent recoating or maintenance can be significantly reduced. Advancements in epoxy chemistry have enabled the development of high-performance epoxy formulations incorporating nanoparticles, hybrid additives, reactive diluents, and functionalized polymers [4–6, 8]. These modifications enhance the rheological behavior, mechanical strength, and thermal stability of coatings. The addition of nanomaterials such as silica nanoparticles, carbon nanotubes, graphene derivatives, and metal oxides has allowed engineers and researchers to fine-tune coating properties to resist moisture ingress, chemical diffusion, UV radiation, and electrochemical degradation [5–9, 11]. Additives within epoxy matrices often introduce micro- or nano-sized pores that block or hinder the diffusion of corrosive agents such as chloride ions, oxygen, and acidic or alkaline solutions. This barrier effect significantly improves the anticorrosive performance of epoxy-coated metals and alloys in various electrolytic environments including marine water, industrial effluents, and acidic or saline exposures [8–9]. The rapid expansion of epoxy-based composite technologies has further fueled interest in understanding their behavior as protective coatings. Researchers have extensively studied how epoxy formulations interact with different metallic substrates and how additives influence the microstructure, adhesion mechanisms, and long-term stability of the coating layer [3–6]. Such investigations are especially important for modern industries where metal components face increasingly aggressive conditions, including high temperature, high humidity, chemical exposure, and mechanical wear. This review consolidates available findings on the anticorrosive performance of epoxy resins applied to metals and alloys. It examines how epoxy chemistry, nanoparticle incorporation, surface preparation techniques, and environmental conditions collectively govern the long-term protection of metallic surfaces. By synthesizing insights across experimental studies, computational simulations, and real-world industrial applications, the review provides a comprehensive understanding of epoxy-based coatings as highly effective corrosion-resistant systems [7–8].

TYPES OF EPOXY SURFACE COATINGS

Epoxy-based polymers represent one of the most important classes of coating materials used in modern industrial protection systems due to their excellent adhesion, mechanical integrity, chemical resistance, and durability [3–6, 12, 15]. These coatings are widely used as protective layers, adhesives, primers, and composite matrices across various engineering sectors.

Although epoxy formulations vary significantly depending on application requirements, most systems are developed using a limited number of base resins combined with appropriate curing agents or coreactants to tailor their performance characteristics [19, 20].

Major Epoxy Resin Systems

The most commonly used epoxy resins in industrial and engineering applications include:

- *Bisphenol A–based epoxy resins (DGEBA):* These are the most widely used systems due to their balanced properties, including good mechanical strength, chemical resistance, and cost-effectiveness [3–5].
- *Bisphenol F–based epoxy resins (DGEBF):* These resins exhibit lower viscosity and improved chemical resistance, making them suitable for high-performance coatings and advanced composite applications [11, 12].
- *Phenolic novolac epoxy resins:* Novolac epoxies possess a high density of epoxy functional groups, resulting in superior crosslinking, enhanced thermal stability, and excellent resistance to aggressive chemicals [15].

Epoxy resins require curing agents (hardeners) to form crosslinked polymer networks that provide strength and durability. The choice of hardener significantly influences the final coating properties such as toughness, thermal resistance, and corrosion protection [12–13].

Common hardeners include:

- Polyamides
- Amidoamines
- Amines (aliphatic, cycloaliphatic, aromatic)
- Anhydrides
- Dicyandiamide (for heat-cured systems)

For instance, combining polyamide hardeners with novolac epoxy resins produces coatings with superior chemical resistance and enhanced corrosion protection suitable for pipelines and marine applications [13, 15].

Importance of Surface Preparation and Environmental Conditions

The effectiveness of epoxy coatings strongly depends on proper surface preparation prior to application. Techniques such as abrasive blasting, degreasing, and chemical cleaning are essential to ensure strong adhesion between the coating and substrate [12, 18].

Environmental factors—including temperature, humidity, and curing conditions—also play a crucial role in determining coating performance. Improper conditions can lead to weak bonding, porosity, and premature coating failure [18].

Advantages of Epoxy Surface Coatings in Industry

Epoxy coatings offer several advantages that make them highly suitable for industrial applications:

- High mechanical strength and toughness
- Excellent resistance to chemicals, solvents, and abrasion
- Strong adhesion to metals, concrete, and composites
- Long-term corrosion protection
- Compatibility with nanomaterials and reinforcements [3–6, 17]

These properties enable their widespread use in:

- Construction and infrastructure protection
- Oil and gas pipelines
- Marine and offshore structures
- Industrial flooring systems
- Automotive and aerospace components [12, 15, 17]

ACRYLIC AND ACRYLIC-BASED EPOXY COATING MATERIALS

Acrylic and acrylic-modified epoxy coating systems have emerged as highly effective protective materials across various industrial sectors due to their fast curing characteristics, strong adhesion, excellent scratch resistance, and ability to form durable and uniform films [12, 14, 15]. These hybrid coatings combine the advantageous properties of both acrylic polymers and epoxy resins, resulting in enhanced mechanical strength, weather resistance, and chemical stability.

Unlike conventional heat-cured coatings, acrylic-epoxy systems can often cure at ambient temperatures, making them particularly suitable for field applications where thermal curing is impractical [12]. Their rapid curing behavior and ease of application contribute to improved productivity and reduced operational costs.

White-Goods and Appliance Coatings

Acrylic-epoxy powder coatings are widely used in the white-goods industry, including appliances such as washing machines, refrigerators, and dryers. These coatings provide a hard, wear-resistant surface capable of withstanding repeated mechanical handling, temperature fluctuations, and exposure to cleaning chemicals [15].

Additionally, their quick curing and energy-efficient processing make them attractive for large-scale manufacturing, while delivering smooth, high-gloss finishes with strong aesthetic appeal.

Industrial and Automotive Applications

In automotive, marine, and general industrial sectors, acrylic-epoxy coatings are commonly applied as primers or intermediate layers to improve adhesion and corrosion resistance [14, 17]. These coatings act as protective barriers against moisture, salts, fuels, and aggressive environmental conditions.

Their strong bonding capability makes them suitable for protecting both steel and aluminum components prior to the application of topcoat systems, thereby enhancing overall coating durability and lifespan.

Anticorrosion Coatings for Steel Infrastructure

Acrylic-epoxy coatings are extensively used in protecting steel infrastructure such as pipelines, storage tanks, and reinforced concrete structures. Their crosslinked polymer network forms an impermeable barrier that prevents the ingress of corrosive species, including water, oxygen, and chloride ions [13, 18].

This significantly enhances the service life of structural components operating in aggressive environments such as marine, chemical, and industrial settings.

Protective Coatings for Metal Containers and Cans

In the packaging industry, acrylic-epoxy coatings are applied to metal containers and cans to prevent corrosion caused by acidic and moisture-rich food products. These coatings help maintain product quality by preventing contamination and preserving the integrity of the container [12].

Their chemical inertness and non-reactive nature make them superior to traditional coatings used in food packaging applications.

Flooring and Surface Protection Applications

Acrylic-epoxy flooring systems are widely used in industrial and commercial environments due to their high strength, abrasion resistance, and ability to withstand heavy loads [15, 17]. These coatings are commonly applied in:

- Manufacturing plants
- Warehouses

- Hospitals and laboratories
- Airports and hangars
- Commercial buildings

Their seamless and non-porous structure improves hygiene, ease of cleaning, and resistance to chemical spills. Additionally, the availability of various colors and textures enhances both functional and aesthetic aspects of flooring systems.

FLOORING IMPLEMENTATIONS

Epoxy-based flooring systems have become one of the most reliable and versatile surface protection solutions used across modern industrial and commercial environments due to their superior mechanical strength, abrasion resistance, and chemical durability [3–6, 12, 15]. These coatings provide seamless, dense, and non-porous surfaces that effectively resist moisture ingress, chemical attack, and mechanical wear, making them significantly more durable than conventional flooring materials such as concrete or tiles. Epoxy flooring systems are widely used in manufacturing industries, pharmaceutical plants, food-processing units, warehouses, hospitals, laboratories, transportation terminals, and aviation hangars [15, 17, 19]. Their ability to withstand heavy loads, continuous traffic, and harsh environmental conditions makes them highly suitable for demanding applications. One of the key advantages of epoxy flooring is its versatility in terms of surface finish and functional properties. These coatings can be engineered to provide anti-skid, anti-static, chemical-resistant, and hygienic surfaces, thereby enhancing workplace safety and operational efficiency [12, 18, 20]. Additionally, epoxy floors are available in a variety of colors and textures, improving both aesthetics and visibility in industrial settings.

Beyond traditional flooring applications, epoxy systems play a significant role in advanced composite engineering, particularly in the reinforcement of carbon fiber materials. Recent studies have demonstrated that coating carbon nanotubes (CNTs) onto carbon fiber surfaces significantly enhances interfacial bonding and mechanical performance of epoxy composites [6, 17]. In such systems, a one-step dipping process is typically employed to deposit CNTs uniformly onto carbon fiber bundles. A silane coupling agent—commonly KH560—acts as a chemical bridge, improving compatibility between the carbon fibers and the epoxy matrix.

This treatment enhances interfacial adhesion and load transfer efficiency within the composite structure [13, 17]. Microscopic analysis using Scanning Electron Microscopy (SEM) has revealed that CNT-coated fibers exhibit increased surface roughness and improved mechanical interlocking with the epoxy matrix. This results in higher interfacial shear strength, improved tensile properties, and enhanced resistance to mechanical degradation [6, 9]. Furthermore, CNT-reinforced epoxy composites demonstrate improved toughness, fatigue resistance, and crack propagation resistance due to the ability of nanotubes to bridge microcracks and redistribute stress concentrations within the material [17, 19]. These properties are particularly beneficial in aerospace, automotive, and structural applications where high performance and durability are essential. In summary, epoxy flooring systems, when combined with advanced reinforcement techniques such as CNT-modified carbon fibers, offer exceptional mechanical performance, durability, and corrosion resistance. Their adaptability and multifunctional properties make them a preferred choice for both conventional flooring applications and next-generation composite systems [12, 15, 17].

COATING OF CARBON NANOTUBES ON CARBON FIBER SURFACES AND INTERFACIAL PROPERTIES

Carbon nanotube (CNT) reinforcement on carbon fiber surfaces has emerged as an advanced technique for enhancing the interfacial strength and mechanical performance of epoxy-based composites [6, 13, 17]. This approach enables the formation of a hierarchical reinforcement structure, where nanoscale CNTs are integrated onto microscale carbon fibers, resulting in improved load transfer efficiency and structural integrity. A commonly adopted method for CNT deposition is the one-step dipping technique, which allows uniform coating of nanotubes onto carbon fiber bundles. To facilitate strong bonding between CNTs and the fiber surface, silane coupling agents—particularly KH560 (3-glycidyl ether oxypropyltrimethoxysilane)—are used as molecular bridges [13, 17]. These agents introduce reactive functional groups that chemically bond with both the CNTs and the epoxy matrix, thereby forming a continuous and stable interfacial network.

The presence of CNTs significantly modifies the surface morphology of carbon fibers by increasing roughness and surface energy, which enhances mechanical interlocking between the fiber and the surrounding epoxy resin [6, 9]. As a result, composites fabricated using CNT-coated fibers exhibit improved interfacial adhesion and reduced fiber pull-out during mechanical loading. Experimental investigations have shown notable improvements in tensile strength, interfacial shear strength, and overall mechanical performance of CNT-reinforced composites compared to untreated systems [6, 17]. Scanning Electron Microscopy (SEM) analysis confirms uniform CNT distribution, strong interfacial bonding, and minimized defects at the fiber–matrix interface. Furthermore, CNTs act as nanoscale crack-bridging elements that delay crack initiation and propagation within the epoxy matrix. This mechanism significantly enhances fracture toughness, fatigue resistance, and energy absorption capacity of the composite material [17]. The synergistic interaction between CNTs and silane coupling agents plays a crucial role in achieving these performance improvements. The combined effect leads to better stress distribution, improved compatibility between reinforcement and matrix, and enhanced durability under mechanical and environmental loading conditions. Due to these advantages, CNT-functionalized carbon fiber/epoxy composites are increasingly being utilized in high-performance applications such as aerospace structures, automotive components, marine systems, and advanced civil infrastructure, where high strength-to-weight ratios and long-term reliability are critical [13, 17].

Risk Evaluation of Coating Surface Abrasion Resistance in Drilled Conditions Using AHP

Evaluating the abrasion resistance of epoxy coatings under harsh drilling conditions is essential for ensuring the long-term durability and corrosion protection of drilling pipes and associated equipment [12, 18]. In this context, the Analytical Hierarchy Process (AHP), a structured multi-criteria decision-making method, has been effectively employed to assess coating performance under complex operational environments. The AHP-based framework considers multiple failure mechanisms that commonly occur on coated surfaces during drilling operations, including abrasive wear, surface cracking, delamination, erosion, and chemical degradation [18]. These factors are systematically analyzed by assigning relative weights based on their severity, frequency, and impact on coating life. By transforming qualitative observations into quantitative decision parameters, AHP enables a more objective and reliable evaluation of coating performance compared to traditional assessment techniques. This approach is particularly useful in industrial applications where multiple interacting variables influence coating degradation. To validate the effectiveness of the AHP model, electrochemical impedance spectroscopy (EIS) is commonly employed as an experimental technique to measure corrosion resistance and coating integrity over time [12, 15]. EIS provides detailed insights into coating behavior by analyzing impedance variations, which reflect changes in barrier properties and degradation levels. Studies combining AHP with EIS have demonstrated strong correlation between predicted performance rankings and experimentally observed corrosion resistance trends, confirming the reliability of this integrated evaluation method [15, 18].

In practical applications, several commercially available epoxy coatings have been evaluated using this combined AHP–EIS methodology. Based on the results, coatings can be classified according to their abrasion resistance, corrosion protection capability, and overall durability, enabling informed material selection for drilling operations. Experimental simulations replicating real drilling conditions—such as high rotational speeds, abrasive slurry flow, and exposure to corrosive fluids—have further validated the effectiveness of the AHP-based assessment model [18]. These simulations provide realistic insights into coating behaviour under extreme service environments. Comparative studies indicate that Fusion-Bonded Epoxy (FBE) coatings exhibit superior performance compared to conventional coating systems, showing minimal surface damage, absence of cracks or pits, and excellent adhesion after prolonged exposure to erosive and corrosive conditions [12, 15]. Overall, the integration of AHP with electrochemical testing techniques offers a robust, systematic, and scientifically grounded approach for evaluating the abrasion resistance and corrosion performance of epoxy coatings used in drilling and industrial applications.

ENHANCEMENT OF EPOXY COATING ADHESION

Enhancement of Epoxy Resin Coating Adhesion Through Bonding Agents

Enhancing the adhesion strength of epoxy coatings is a critical factor in improving the durability and service life of coatings applied to concrete structures, industrial floors, and cement-based substrates [12, 15, 18]. Strong interfacial bonding ensures effective load transfer and prevents premature coating failure under mechanical and environmental stresses. Recent research has focused on the development of modified epoxy adhesive systems incorporating natural and synthetic bonding agents to improve adhesion performance. Among these, natural fiber reinforcements such as coconut fibers have gained attention due to their sustainability, cost-effectiveness, and compatibility with polymer matrices [17]. In such systems, the incorporation of natural fibers into the epoxy matrix enhances mechanical interlocking between the coating and the substrate. This results in improved pull-off strength and better resistance to delamination, particularly in repair and rehabilitation applications of concrete structures [18]. Experimental investigations involving mortar and cement-based specimens have demonstrated that the addition of fibers in controlled proportions—typically in the range of 0.5% to 1.0% by weight—significantly improves adhesion strength [17–18]. At these optimal concentrations, fibers help reduce shrinkage stresses, enhance cohesive strength, and promote uniform stress distribution across the interface. However, increasing the fiber content beyond the optimal range leads to adverse effects. Excessive fiber loading results in agglomeration or clustering within the epoxy matrix, which disrupts stress transfer mechanisms and creates weak zones that initiate crack formation under loading conditions [18]. Microstructural analysis using Scanning Electron Microscopy (SEM) has provided valuable insights into the bonding behavior of fiber-reinforced epoxy coatings. SEM images reveal improved penetration of epoxy into the substrate pores and enhanced interfacial bonding at optimal fiber concentrations, while higher fiber content leads to void formation and structural inconsistencies [6, 9]. To complement experimental findings, numerical modeling approaches have been employed to simulate the behavior of coated systems under tensile loading conditions. These models incorporate damage plasticity parameters to predict pull-off strength and failure mechanisms, showing good agreement with experimental results [18]. Additionally, linear softening models have been developed to describe the progressive degradation of the substrate–coating interface under increasing load. These models help in understanding crack initiation and propagation behavior, providing a predictive framework for coating performance in real-world applications. Overall, the controlled incorporation of bonding agents, particularly natural fibers, offers an effective strategy for enhancing adhesion strength, improving mechanical performance, and extending the service life of epoxy coatings used in civil and industrial applications [12, 17, 18].

Development of Self-Healing Green Epoxy Under UV Light)

Recent advancements in polymer science have led to the development of self-healing epoxy coatings capable of autonomously repairing surface damage and restoring protective functionality without external intervention [15–16]. These smart coatings are particularly valuable in corrosion-prone environments where microcracks and surface defects can significantly reduce coating lifespan. The self-healing epoxy system discussed in this study is based on a biobased and environmentally friendly design incorporating microcapsules and nanocontainers loaded with healing agents. Typically, the system consists of epoxy resin, halloysite nanotubes (HNTs), and silica nanoparticles embedded within a polymer matrix [16–17]. These nanomaterials act as carriers for healing agents and play a crucial role in controlled release mechanisms. A vacuum-assisted encapsulation technique is often used to trap healing agents within the nanotubes and microcapsules, ensuring their stability within the coating structure. Additionally, a UV-responsive initiator is incorporated into the system to enable rapid curing upon exposure to ultraviolet light or natural sunlight [16]. When mechanical damage such as scratches or microcracks occurs, the embedded nanotubes rupture under stress, releasing the stored healing agents into the damaged region. Simultaneously, the UV initiator activates polymerization, allowing the released epoxy to cure and seal the defect [16–17]. This process effectively restores the integrity of the coating and prevents further penetration of corrosive species Experimental studies have demonstrated that coatings containing an optimal concentration of nanocontainers—approximately 40% HNTs—exhibit complete healing of surface damage when exposed to UV radiation or sunlight [16]. The healed regions display uniform morphology and restored barrier properties, indicating successful recovery of coating performance. In addition to self-healing capabilities, these advanced coatings exhibit several enhanced properties, including improved UV resistance, increased thermal stability, higher transparency, and superior corrosion resistance [15–16]. These multifunctional characteristics make them suitable for a wide range of applications, including marine structures, automotive components, aerospace systems, and industrial equipment. The integration of biobased materials further contributes to the sustainability of these coatings by reducing environmental impact and promoting the use of renewable resources [16]. This aligns with the growing demand for eco-friendly and high-performance protective materials in modern engineering applications. Overall, self-healing green epoxy coatings represent a significant advancement in corrosion protection technology, offering extended service life, reduced maintenance costs, and enhanced reliability in harsh operating conditions.

Investigation of Interfacial Tension Between Hydrating Cement Mixtures and Epoxy Adhesive Coatings

The interfacial bonding between epoxy coatings and cementitious substrates plays a crucial role in determining the durability and long-term performance of coated concrete systems used in construction and repair applications [12, 15, 18]. Understanding the interaction between hydrating cement paste and epoxy adhesives is essential for optimizing coating application timing and improving adhesion strength. In this context, experimental studies have been conducted to evaluate interfacial bond strength at different stages of cement hydration. Macromechanical tests, including slant-shear tests and pull-off adhesion tests, are commonly employed to quantify the bonding performance between epoxy coatings and cement-based substrates [18]. These tests are typically performed by applying epoxy coatings to cementitious surfaces at varying hydration times, ranging from early-age conditions (approximately 2 days) to fully matured states (up to 28 days). Several parameters influence interfacial behavior, including water-to-cement ratio, curing duration, and coating thickness [12]. Experimental findings indicate that interfacial bond strength does not always improve with earlier application of epoxy coatings. Although early hydration stages are characterized by higher surface reactivity and heat evolution, excessive moisture content at these stages can hinder effective bonding [18]. The presence of free water interferes with mechanical interlocking and reduces adhesive interactions between the epoxy and cement surface. As hydration progresses, moisture levels decrease and the substrate gains mechanical strength, providing a more stable surface for coating application. However, excessive delay in coating application may reduce surface reactivity, thereby limiting chemical bonding potential [12, 15]. This highlights the importance of selecting an optimal application window to achieve maximum adhesion. Further parametric analysis reveals that the influence of variables such as curing conditions and coating thickness is more pronounced during early hydration stages. These factors affect the penetration depth of epoxy into the substrate pores and the formation of a strong interfacial transition zone [18]. Microstructural observations support these findings, showing that optimal bonding occurs when there is a balance between surface dryness and chemical activity. Proper surface preparation and controlled environmental conditions are therefore critical to achieving reliable adhesion performance. Overall, this investigation emphasizes the complex interplay between hydration chemistry, moisture content, and epoxy adhesion mechanisms. The insights gained from such studies are highly valuable for civil engineering applications, particularly in repair, rehabilitation, and protective coating of concrete infrastructure [12, 15, 18].

Influence of Filler Particles on the Tribological and Tensile Behavior of Epoxy Repair Coatings

The incorporation of filler particles is a widely adopted strategy for enhancing the mechanical, tribological, and rheological properties of epoxy-based repair coatings used in concrete and structural applications. Fillers improve coating performance by modifying flow behavior during application and strengthening the material after curing. In repair environments, coatings must exhibit a balance between workability and mechanical strength. Fillers such as silica, kaolin, plaster, and bentonite are commonly used to tailor the properties of epoxy systems to meet these requirements. These materials influence parameters such as viscosity, sag resistance, tensile strength, and wear resistance. Experimental studies employing statistical design methods, including regression analysis and optimization techniques, have been used to evaluate the combined effects of different filler materials on coating performance. These approaches enable the identification of optimal compositions that maximize mechanical properties while maintaining desirable processing characteristics. One of the key observations is that different fillers affect epoxy behavior in distinct ways. For instance, bentonite significantly enhances thixotropic behavior, improving sag resistance and allowing uniform coating thickness during application. However, this improvement often comes at the expense of tensile strength, demonstrating the inherent trade-off between mechanical performance and application properties. Similarly, variations in filler concentration can significantly alter the rheological behavior of the epoxy system. Increasing filler content generally improves resistance to flow and deformation, but excessive loading may lead to particle agglomeration, reduced uniformity, and weakened mechanical performance.

The shear-thinning characteristics of epoxy coatings can also be optimized through controlled filler addition. Enhanced shear-thinning behavior improves application efficiency by allowing the coating to flow easily under shear stress while maintaining stability when at rest. Tribological performance, including friction and wears resistance, is also strongly influenced by filler type and distribution. Properly dispersed fillers reduce surface wear, improve load-bearing capacity, and enhance durability under sliding or abrasive conditions.

Overall, the selection and optimization of filler materials play a critical role in designing high-performance epoxy repair coatings. By carefully balancing filler type, concentration, and dispersion, it is possible to achieve coatings with improved mechanical strength, enhanced durability, and superior application characteristics suitable for demanding engineering environments.

Surface Characteristics of Epoxy–Clay Nanocomposites

This section focuses on the influence of nanoclay incorporation on the surface and mechanical characteristics of epoxy-based nanocomposite coatings. Key evaluation parameters include surface hardness, roughness, morphology, and overall surface topography. To systematically analyze these effects, experimental designs typically consider variables such as nanoclay loading percentage, ultrasonic amplitude, and sonication duration. The results indicate that nanoclay concentration and sonication time play a dominant role in determining the hardness of the coating. Increased sonication improves dispersion of nanoclay particles within the epoxy matrix, leading to better interfacial bonding and reduced formation of agglomerates. However, beyond an optimal nanoclay concentration, the hardness of the coating tends to decrease due to particle clustering, which disrupts stress transfer mechanisms. Microscopic studies using Scanning Electron Microscopy (SEM) reveal that well-dispersed nanoclay platelets enhance the uniformity of the composite structure and reduce microstructural defects. Improved dispersion leads to stronger interfacial interactions between the nanoclay and the epoxy matrix, resulting in enhanced mechanical performance. Atomic Force Microscopy (AFM) analysis further shows that nanoclay incorporation modifies surface roughness and topographical features. Controlled addition of nanoclay increases surface energy and improves scratch resistance. However, excessive loading can negatively impact coating uniformity and durability. The findings highlight that there is an optimal balance between nanoclay concentration and processing conditions. While moderate loading improves hardness, roughness, and surface stability, excessive nanoclay content leads to agglomeration and reduced performance. Overall, epoxy–clay nanocomposites demonstrate significant potential for advanced coating applications due to their improved surface characteristics, enhanced durability, and resistance to mechanical damage. Proper optimization of processing parameters is essential to fully exploit the benefits of nanoclay reinforcement in epoxy systems.

Surface Treatment of Mild Steel with Neodymium-Based Nanofilm

This section focuses on enhancing the surface properties of mild steel through the application of a neodymium-based nanofilm to improve adhesion, corrosion resistance, and overall coating performance. The nanofilm is deposited uniformly over the steel substrate to modify surface characteristics and promote stronger bonding with epoxy coatings. The presence of the neodymium oxide layer increases surface roughness and surface energy, which enhances mechanical interlocking between the substrate and the epoxy coating. This improved interfacial interaction significantly reduces the likelihood of coating failure, particularly in corrosive and mechanically demanding environments. One of the key advantages of this surface treatment is its ability to minimize cathodic delamination, a common degradation mechanism in coated steel structures. The nanofilm acts as a protective interlayer, improving adhesion strength and reducing the penetration of corrosive species at the coating–substrate interface. Theoretical analyses indicate that neodymium-based nanofilms exhibit higher adsorption energy compared to conventional oxide layers, contributing to improved coating stability and long-term durability. This enhanced bonding mechanism ensures better resistance to environmental degradation and mechanical stress. Further improvements in coating performance can be achieved by integrating ceramic nanoparticles into epoxy systems applied over treated steel surfaces. Techniques such as K-bar coating and spray deposition are used to apply these composite coatings, ensuring uniform coverage and strong adhesion. Thermal and mechanical evaluations of such treated systems demonstrate improved resistance to heat transfer, impact loading, and environmental exposure. The coatings maintain structural integrity even under elevated temperature conditions, indicating their suitability for high-performance applications. Additional testing methods, including water absorption analysis, peel strength measurements, flexural stress evaluation, and morphological studies, confirm the effectiveness of the treatment. Results consistently show improved adhesion, reduced moisture penetration, and enhanced durability.

Overall, neodymium-based surface treatment represents an effective strategy for improving the performance of epoxy coatings on mild steel. By enhancing interfacial bonding and providing additional protective functionality, this approach significantly extends the service life of coated components in industrial and environmental applications.

CONCLUSIONS

Epoxy-based coatings have emerged as one of the most effective and versatile solutions for corrosion protection across a wide range of industrial and engineering applications. Their exceptional mechanical strength, strong adhesion, chemical resistance, and long-term durability make them highly suitable for protecting metallic and concrete structures exposed to aggressive environments. This review has highlighted the significant role of epoxy chemistry, curing mechanisms, and surface preparation techniques in determining coating performance. The incorporation of advanced materials such as nanoparticles, nanoclays, carbon nanotubes, and natural fibers has been shown to substantially enhance mechanical properties, adhesion strength, and resistance to environmental degradation. These modifications enable epoxy coatings to meet the increasing demands of modern industries. He study also emphasized the importance of interfacial behavior between coatings and substrates, particularly in cementitious systems and metal surfaces. Proper control of application conditions, substrate preparation, and material composition is essential to achieve optimal bonding and long-term stability. Recent advancements in smart coating technologies, especially self-healing epoxy systems, represent a major breakthrough in corrosion protection. These systems offer the ability to autonomously repair damage, thereby extending service life and reducing maintenance costs. Similarly, the use of nanostructured reinforcements and surface treatment techniques has further improved coating performance under extreme mechanical and environmental conditions. Despite these advancements, challenges remain in terms of optimizing material composition, ensuring environmental sustainability, and reducing production costs. Future research should focus on the development of eco-friendly, bio-based epoxy systems, advanced hybrid nanocomposites, and predictive modeling techniques to enhance coating efficiency and reliability.

In conclusion, epoxy-based coatings continue to play a critical role in modern material protection strategies. With ongoing innovations in material science and engineering, these coatings are expected to deliver even higher performance, sustainability, and durability in future industrial applications.

REFERENCES

1. Gugulothu B., Bharadwaja K., Vijayakumar S., Rao T.V.J., Sri M.N.S., Anusha P., Modeling and parametric optimization of electrical discharge machining on casted composite using central composite design, Int. J. Interact. Des. Manuf., 2024, 18(5), pp. 1433-1436.
2. Srividya K., Ravichandran S., Thirunavukkarasu M., Veeranjaneyulu I., Examination of electrochemical machining parameters for AA6082/$ZrSiO_4$/SiC composite using Taguchi-ANN approach, Int. J. Interact. Des. Manuf., 2024, 18(3), pp. 1676-1679
3. Bharadwaja K., Baburao T., Epoxy/SiO_2 nanocomposite mechanical properties and tribological performance, Mater. Today Proc., 2022, 62, pp. 1712–1716.
4. Bharadwaja K., Rao S.S., Rao T.B., Investigation of hardness and tribology behavior of epoxy and SiO_2 composite, Mater. Today Proc., 2021, 45, pp. 3343–3347.
5. Bharadwaja K., Rao S.S., Rao T.B., Investigation of tensile and flexural behavior of epoxy and SiO_2 composite, Mater. Today Proc., 2021, 45, pp. 2649–2652.
6. Bharadwaja K., Baburao T., Epoxy reinforced with nano TiO_2 particles: Mechanical and tribological behavior, Mater. Today Proc., 2022, 62, pp. 1817–1820.
7. Chaudhary V., Bharadwaja K., Meena R.S., Bikash P., Acharjee D., Machine learning in inventory management for profitability, BioGecko, 2023, 12(1), pp. 658–666.
8. Bharadwaja K., Srinivasa Rao S., Babu Rao T., Pydi H.P., *Evaluation of mechanical properties of epoxy nanocomposites*, Adv. Mater. Sci. Eng., 2023, Article ID 8598585.
9. Bharadwaja K., Rao M.S.S., Peyyala P.K., Baddepudi M., Thejasree P., Mechanical characteristics and wear resistance of epoxy–Al_2O_3 nanocomposites, AIP Conf. Proc., 2025, 3342(1), p. 070015.
10. Bharadwaja K., Rao S.S., Rao T.B., Epoxy reinforced with nano-Al_2O_3 particles, Int. J. Early Child., 2022, 14(03), pp. xxx–xxx.
11. May C.A., *Epoxy Resins:* Chemistry and Technology, 2nd ed., CRC Press, 2018.
12. Mittal V. (Ed.), Polymer Nanocomposites: Synthesis, Characterization and Applications, Springer, 2020.
13. Park S.J., Jin F.L., Lee J.R., Thermal and mechanical properties of epoxy resins, J. Ind. Eng. Chem., 2004, 10(1), pp. 1–10.
14. Zhang X., Zhao Y., Acrylic–epoxy hybrid coatings for corrosion protection, Prog. Org. Coat., 2019, 135, pp. 228–238.
15. Bierwagen G., Advances in corrosion protection by organic coatings, Prog. Org. Coat., 2016, 102, pp. 1–12.
16. White S.R., Sottos N.R., Geubelle P.H., et al., Autonomic healing of polymer composites, Nature, 2001, 409, pp. 794–797.
17. Thostenson E.T., Ren Z., Chou T.W., Advances in CNT-reinforced composites, Compos. Sci. Technol., 2001, 61(13), pp. 1899–1912.
18. Montemor M.F., Functional coatings for corrosion protection, Surf. Coat. Technol., 2014, 258, pp. 17–37.
19. Gojny F.H., Wichmann M.H.G., Fiedler B., Schulte K., Influence of CNTs on epoxy composites, Compos. Sci. Technol., 2005, 65, pp. 2300–2313.
20. Yasakau K.A., Ferreira M.G.S., Zheludkevich M.L., Self-healing coatings for corrosion protection, Prog. Org. Coat., 2018, 123, pp. 1–10.

