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MODIFICATION OF FILM-FORMING MATERIALS FOR WATER-BASED PAINT AND VARNISH COMPOSITES

Abstract: *Waterborne paint and coating composites are finding increasingly broad application in construction, industry, and everyday use. This shift is largely motivated by environmental goals – lowering organic solvent emissions – and by cost advantages, since water is both less expensive and more widely available than organic solvents.At the same time, the key task remains to increase the barrier and mechanical characteristics of water-based coatings while maintaining the processability of application and rapid curing.Two main approaches are employed to modify water-dispersible systems: chemical modification of polymer binders and polymer blending. It has been shown that targeted tailoring of the polyurethane soft/hard segment structure, as well as the incorporation of an acrylate component and functional additives (plasticizers, nanofillers), enables control over the degree of crosslinking and phase distribution, thereby improving coating adhesion, abrasion resistance, and barrier properties. Among modified waterborne systems, polyurethane and acrylic-polyurethane coatings are of particular interest, as discussed in this article, owing to their unique combination of properties. These systems provide high coating durability and a wide range of applications, including protective and decorative coatings for various substrates. Special attention is given to methods for their modification. The promise of polyurethane and acrylic-polyurethane waterborne coatings for anticorrosion protection is highlighted, along with the need to tailor formulations to specific service conditions.*

Key words: *waterborne paint, composites, modified waterborne systems, polyurethane, acrylic-polyurethane, polymer blending.*

1 Introduction

Delivering reliable corrosion protection for metal structures under aggressive conditions remains a critical scientific and engineering task, as it directly affects service-life extension and more efficient use of materials and resources. [1]. Corrosion-induced degradation of steel and other structural metals leads not only to direct economic losses associated with repair, replacement, and downtime, but also to broader technological and environmental consequences, including reduced operational reliability and increased material consumption over the entire life cycle of engineering systems [2, 3]. For this reason, the development of durable protective coatings is increasingly regarded not merely as a maintenance measure, but as a strategic approach to improving infrastructure sustainability and reducing the total cost of ownership of metallic assets [4]. The application of protective paint and coating systems continues to be the most widely used approach to anticorrosion protection of metals, exceeding in prevalence and versatility many alternative surface-protection methods (e.g., thermal spraying, electroplating, passivation) [1, 5]. This widespread use is explained by the relative processability of coating technologies**,** the possibility of applying coatings to structures of complex geometry, and the flexibility of tailoring coating formulations for specific service environments. In addition, paint and coating systems can simultaneously perform protective, decorative, and, in some cases, functional roles, which further increases their industrial relevance in construction, transport, machinery, and infrastructure sectors

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[1, 6]. Such coatings primarily perform a barrier function by limiting contact between the metallic substrate and the corrosive medium [1, 5]. The effectiveness of this barrier depends on the continuity, density, adhesion, and physicochemical stability of the coating film, as even minor structural defects such as pores, microcracks, or interfacial heterogeneities may accelerate the ingress of water, oxygen, and aggressive ions to the metal surface. Accordingly, modern research in protective coatings is focused not only on the nominal chemical composition of the binder, but also on the mechanisms of film formation and the resulting microstructure of the cured coating [4, 6].

Current technology trends in metal protection are focused on upgrading these coating systems by shifting from solvent-borne composites to environmentally benign water-reducible (waterborne) coatings, driven by the need to reduce volatile organic compound (VOC) emissions and improve occupational and environmental safety [7, 8, 9]. This transition is also aligned with increasingly stringent environmental regulations and with the broader industrial agenda of developing safer and more sustainable materials technologies. Compared with conventional solvent-borne systems, waterborne coatings offer important practical advantages, including lower fire hazard, reduced toxicity during application, easier handling, and lower emissions of hazardous organic vapors into the workplace atmosphere. These features make waterborne technologies particularly attractive for large-scale industrial use, especially in contexts where environmental compliance and worker safety have become decisive criteria in material selection [10, 11, 12].

However, despite their undeniable environmental advantages, state-of-the-art waterborne paint and coating systems still underperform compared with solvent-borne counterparts in terms of anticorrosion efficiency, surface hardness, mechanical strength (tensile and impact), and coating drying time. This gap is commonly attributed to the comparatively limited film-forming ability of waterborne binders, which promotes defect-prone film microstructures and, consequently, weaker barrier (isolating) performance. [13, 14, 15]. The presence of residual hydrophilic groups, insufficient particle coalescence, and enhanced sensitivity of the forming film to drying conditions often result in coatings with higher permeability to moisture and corrosive species. As a result, the key challenge in the design of advanced waterborne anticorrosion materials is to reconcile environmental compatibility with the dense, defect-minimized film structure required for long-term protective performance [4, 16, 17].

Recent studies therefore place considerable emphasis on the modification of film-forming binders as a rational route to improving the performance of waterborne coating systems. Such modification may be achieved either by chemical approaches, involving the incorporation of reactive functional groups or the synthesis of hybrid macromolecular architectures, or by physical blending with other polymers and oligomers capable of altering intermolecular interactions, phase morphology, and film-packing density [18, 19, 20]. In both cases, the ultimate objective is to enhance the barrier properties, mechanical integrity, adhesion strength, and resistance of the coating to water and aggressive media without compromising the ecological advantages of waterborne formulations. Among the different classes of modified waterborne binders, polyurethane and acrylic–polyurethane systems are of particular interest because they combine good mechanical performance, elasticity, abrasion resistance, and the possibility of targeted structural tuning. At the same time, these systems remain highly relevant for corrosion-protection applications, since their properties can be adjusted through variation of segment composition, crosslink density, particle morphology, and interfacial interactions within the coating matrix [21, 22].

In this context, special attention has been given to acrylic–polyurethane hybrid materials and blends, which are capable of integrating the favorable attributes of both components: the hardness, weather resistance, and pigment compatibility of acrylics, together with the toughness, flexibility, and adhesion of polyurethanes. Such hybridization may contribute to the formation of more compact and structurally balanced coatings with improved resistance to crack formation, mechanical damage, and diffusion transport of corrosive agents. Therefore, the study of modified waterborne polyurethane and acrylic–polyurethane film-forming systems is an important and promising direction for the development of next-generation anticorrosion coatings for metal substrates operating under aggressive service conditions.

2 Approaches to modification of film-forming agents and focus on PU/acrylic-PU systems

Recent studies [13, 20, 23, 24] indicate that film-former modification is generally implemented either via chemical routes or by blending with other polymers (oligomers). Numerous investigations

[25-30] have reported the use of key functional agents – carboxyl and acetoacetyl groups, activated amines, acetals, polyalkoxysilanes and their derivatives, as well as isocyanate-containing compounds – for chemical modification of binders, resulting in enhanced film-forming capability.

In contrast to chemical modification, blending does not proceed through chemical pathways but rather through transformations governed at the level of intermolecular interactions; it leads to the formation of a new stable system that differs from the original constituents in spatial organization, rheological behavior, and structural-mechanical properties. The use of polymers to modify aqueous film formers is associated with the presence of heteroatom-containing polar moieties within their chains – urethane (–NH–C(O)–O–), ether (–O–), ester (–C(O)–O–), urea (–NH–C(O)–), and amide (–NH–C(O)–) groups-capable of associating into stable intermolecular structures through physical interactions (predominantly hydrogen bonding) [13, 27, 28-35].

Among the established development routes for water-dilutable (waterborne) coating materials is the modification of aqueous dispersions of polymers and copolymers to create multicomponent systems, including styrene-acrylate, acrylic, vinyl-acrylic, styrene-butadiene, vinyl acetate-ethylene (VAE), acrylic-polyurethane, methacrylate and styrene-acrylonitrile compositions [13, 36].

In recent years, polyurethane and acrylic–polyurethane (PU/acrylic) systems have become the most widely adopted within this family, largely because they combine high mechanical strength and elasticity with improved abrasion and chemical resistance, while enabling stable aqueous dispersions with low volatile organic compound (VOC) content [25, 35, 36]. In addition, their performance can be purposefully tuned by adjusting formulation variables and, critically, by engineering polymer-particle composition and morphology (e.g., core-shell vs. semi-IPN architectures) [2, 37, 38]. Nevertheless, due to the presence of hydrophilic carboxyl/carboxylate groups used for dispersion stabilization and the generally high surface energy of these binders, the materials remain prone to water uptake. Consequently, coatings based on (meth)acrylic resins may exhibit limited water and corrosion resistance, insufficient mechanical robustness and wear resistance, and a comparatively high minimum film-formation temperature (MFFT), among other shortcomings [39, 40].

In summary, the enhancement of the service performance of waterborne polyurethane and acrylic-polyurethane coatings is achieved through the incorporation of functional groups, the formation of hybrid networks, or the use of active nanoscale fillers. These modifications make it possible to purposefully tailor the adhesion strength and corrosion resistance of the resulting films. A summary of modification approaches and their effects on coating properties is presented below in Table 1.

Table 1 – Summary of modification methods for waterborne polyurethane and acrylic-polyurethane coatings and their impact on anticorrosion behavior and physicochemical characteristics

Modification type	Modification method	Effect on anticorrosion and physicochemical properties
Chemical (intrachain)	Incorporation of functional organosilicon compounds (silanes)	Increases coating hydrophobicity and enhances adhesion to the metallic substrate through the formation of Si-O-Metal bonds
Chemical (crosslinking)	External crosslinking with blocked isocyanates or carbodiimides	Promotes the formation of a dense three-dimensional network, thereby reducing the diffusion coefficient of water and aggressive ions (Cl^-, SO_4^{2-})
Hybrid synthesis	Formation of acrylic–polyurethane interpenetrating polymer networks (IPN)	Produces a synergistic effect by combining the chemical resistance of polyurethane with the weather resistance of acrylics, while suppressing microphase separation of the components
Nanocomposite	Modification with layered silicates (nanoclays) or graphene	Creates a “tortuous path” for water molecules, significantly improving the barrier properties of the coating
Active (pigment-based)	Incorporation of nanosized zinc phosphates or modified tripolyphosphates	Provides electrochemical protection and promotes passivation of the metal surface at coating defects
Inhibitor-based	Encapsulation of organic corrosion inhibitors within the polymer matrix	Enables controlled release of active species upon film damage, resulting in «self-healing» coating behavior

The analysis of the data presented in Table 1 confirms that achieving high service performance in waterborne polyurethane and acrylic–polyurethane systems is not possible without profound chemical or compositional modification. Of particular importance is the formation of hybrid acrylic-polyurethane structures, which exhibit a synergistic effect by combining the mechanical strength of polyurethane with the high hydrophobicity of acrylic polymers [41]. Chemical cross-linking remains one of the most effective tools for reducing the free volume of the polymer matrix, which is critical for blocking the diffusion of corrosion-active agents [42]. The incorporation of organosilicon fragments (silanes) makes it possible not only to strengthen the adhesive contact with the metallic substrate, but also to ensure the long-term stability of the phase boundary under high-humidity conditions [43]. The use of nanoscale fillers, such as graphene or modified silicates, creates a tortuous-path effect, significantly enhancing the barrier resistance of the coatings [44]. Modern studies also indicate the promise of corrosion-inhibitor encapsulation, which enables the implementation of the concept of “smart” self-healing coatings [45]. It should be noted that the effectiveness of active pigments in waterborne systems directly depends on their surface modification, which prevents premature coagulation of the dispersion [46]. The combination of physical and chemical modification methods makes it possible to obtain waterborne coating materials whose protective properties are comparable to those of conventional solvent-based systems [47]. At the same time, a critical factor remains the control of core-shell particle morphology, which determines the uniformity of film formation [48]. Further development of this field is associated with the design of biomimetic and environmentally safe modifiers capable of minimizing the content of volatile organic compounds [49, 50]. Thus, an integrated approach to the modification of polyurethane dispersions opens broad opportunities for the development of next-generation anticorrosion coatings with a targeted set of properties.

3 Design of anticorrosive coatings via polyurethanes, urethane acrylates, IPN networks, and blends

Polyurethanes are not a single “specific” polymer but a whole family of materials obtained by reacting isocyanate compounds (di- or polyisocyanates) with polyol components. Owing to the flexibility in selecting starting reagents and formulations, the term “polyurethanes” covers a wide variety of polymers with different structures and properties. What unites them is a common structural feature: the presence of urethane linkages (–NHCOO–) in the macromolecular chain, and, in the case of polyurethane-ureas, additional urea fragments (–NHCONH–). To obtain polyurethanes, a three-component set of precursors is typically employed: an isocyanate component (aromatic, aliphatic, or cycloaliphatic diisocyanates), a “soft” polyol block based on long-chain diols (polyether or polyester), and a low-molecular-weight chain extender – either a short-chain diol or a diamine. (Fig. 1) [51, 52].

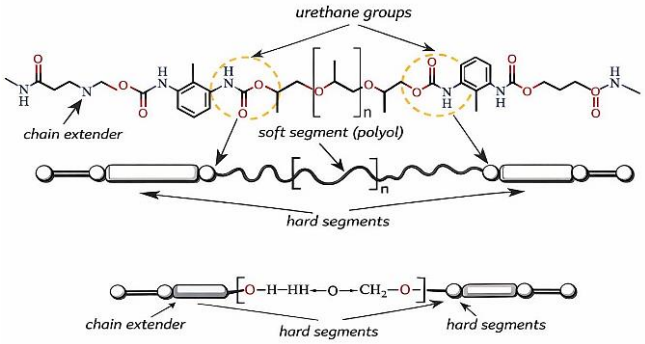

Figure 1 – Schematic of the chemical structure of polyurethane

Polyurethanes can be conveniently described as segmented copolymers: their macromolecular chains consist of alternating fragments, where the polyol component imparts elasticity, while the segments formed by the diisocyanate and chain extender provide rigidity. Polyol-rich regions typically exhibit a glass transition temperature below room temperature and are therefore referred to as «soft segments», whereas the urethane/urea domains based on the diisocyanate and chain extender form more ordered and rigid «hard segments». Polyurethane dispersions are stable colloidal systems in which water serves as the dispersion medium and polyurethane-urea particles

constitute the dispersed phase. The stability of these systems is ensured by hydrophilic moieties incorporated into the prepolymer structure during synthesis; these may include ionogenic groups (anionic or cationic) and/or nonionic hydrophilic blocks. [36, 51, 52].

Publications generally distinguish two main approaches to producing polyurethane dispersions: the prepolymer mixing route [53] and the acetone route [54]. In both cases, the process is essentially two-step. First, a polyurethane prepolymer is prepared by reacting polyisocyanates with polyols. Next, this prepolymer is dispersed in water and then chain-extended in the aqueous phase, typically using polyamines. A key limitation shared by both routes is the need to add a substantial amount of solvent during prepolymer preparation to lower viscosity and ensure processability. In the prepolymer method, high-boiling solvents such as N-methylpyrrolidone (NMP) [36] – sometimes up to 30 wt.% – are used and can remain in the finished dispersion. By contrast, the acetone method relies on low-boiling solvents, e.g., acetone [55] or methyl ethyl ketone [56], that are later stripped off by vacuum distillation. Although this enables dispersions with minimal residual organic solvent, the extra, energy-demanding distillation step and the requirements for solvent recovery make the acetone route noticeably more expensive.

The environmental profile of polyurethane dispersions can be improved by adjusting the formulation and the functional chemistry of the starting materials. If the components are selected so that the prepolymer viscosity is reduced already at the synthesis stage, dispersions can be produced via the simpler prepolymer route without adding organic solvents. Patent sources most often cite two solutions to this problem: replacing the isocyanate component with m-tetramethylxylylene diisocyanate (TMXDI) [57] or partially/fully using polyoxypropylene glycols (PPG) as the polyol component [58]. TMXDI is generally considered an option for specialized formulations where improved adhesion to plastic substrates is a key requirement [59]. At the same time, incorporating more affordable PPG into PUD formulations can also reduce overall material costs and partially offset high production expenses.

The elevated cost of polyurethane coatings, stemming from their complex synthesis and the utilization of expensive raw materials, has necessitated the development of modified polyurethane systems. These systems are designed to optimize economic performance without significantly compromising the service characteristics of the coatings. Polyurethane coatings are modified using various techniques, including: chemical modification via graft copolymerization with functional monomers [60]; incorporation of acrylate components into polyurethane systems [61]; development of hybrid latexes through emulsion polymerization [62].

One of the most promising research areas is the synthesis of acrylic-polyurethane hybrids, where a polyurethane matrix is integrated with acrylic components. These hybrids are produced through two primary methods: either by blending polyacrylate and polyurethane latexes or via a synthetic route involving the polymerization of acrylate comonomers within polyurethane latex particles or the emulsion copolymerization of a urethane prepolymer with acrylic comonomers [63]. Acrylate-urethane film-formers are defined as acrylate oligomeric compounds containing urethane-type ester groups within their oligomeric blocks (Fig. 2) [64].

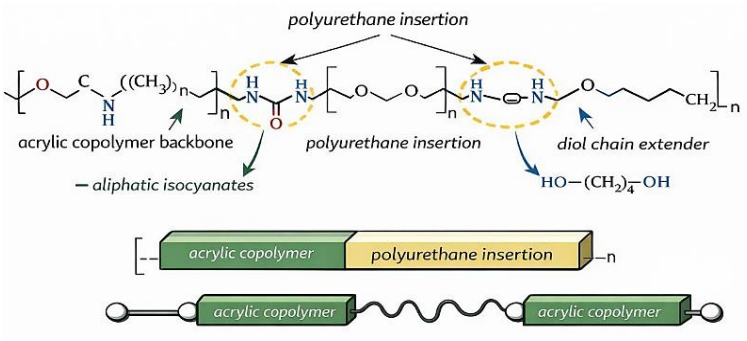

Figure 2 – Schematic of the chemical structure of acrylic-polyurethane

Acrylate-urethane oligomers are typically prepared from diisocyanates of either aliphatic or aromatic nature (for example, hexamethylene diisocyanate or 2,4-toluene diisocyanate) in combination with hydroxyl-containing reagents such as glycols, oligomeric diols, or multifunctional alcohols [65]. Recently, a widely adopted strategy has been the free-radical curing/polymerization of

oligomeric species that simultaneously carry urethane linkages and vinyl unsaturation within the same molecule. This approach has opened a practical route to crosslinked network polymers with tunable property profiles and has broadened polyurethane modification options via copolymerization with vinyl monomers and oligomers [66].

Unsaturated urethane-containing oligoesters with terminal acrylic-type double bonds can be obtained through two key synthetic schemes. The first relies on reacting diisocyanates with oligomeric diols followed by end-capping with hydroxyalkyl acrylates. The second involves oligocondensation routes based on glycol or bisphenol bischloroformates reacted with diamines and (alkyl/alkylaryl) acrylates bearing terminal chloroformate or amino functionalities [67].

From a structure-property standpoint, acrylate-urethane film formers are often associated with interpenetrating polymer network (IPN) architectures. In an IPN, two crosslinked polymer networks coexist in the same material volume while remaining largely ungrafted-i.e., without substantial covalent linking between the networks. Typically, one network is formed and crosslinked in the presence of the other; subsequently, the second component is polymerized and crosslinked via a different mechanism to achieve an optimized morphology [68]. Such mutual interpenetration suppresses macroscopic phase separation and provides synergistic performance effects, including improved adhesion, toughness/strain resistance, and barrier characteristics. Related variants include semi- or pseudo-IPNs, where a crosslinked network is combined with a linear polymer and the extent of interpenetration can vary [69].

IPN architectures provide a versatile platform for engineering polymer morphology, enabling targeted adjustment of coating properties through controlled network design. Moreover, interpenetrating systems can be built using hybrid synthesis strategies -combining, for example, grafting reactions with stepwise (sequential) polymerization to create multi-network structures with optimized performance. An example of this is the production of acrylate-modified urethane (via grafting) and urethane-modified acrylate (via sequential polymerization). The primary advantage of such networks lies in the enhancement of phase interaction between polymer chains [68, 69]. Currently, urethane acrylate is produced based on ethylene glycol monomethacrylate, 2,4-toluene diisocyanate and oligoxypropylene glycol [70].

Across the methods discussed, urethane linkages are commonly generated via isocyanate chemistry. Yet, isocyanate-driven urethane formation rarely proceeds “cleanly”: competing side reactions can introduce additional structures and functional groups (e.g., biuret and acylurea motifs) that show limited resistance to heat, thermo-oxidative aging, and mechanical stress, ultimately diminishing polyurethane performance. Moreover, diisocyanates are expensive and hazardous, and their high reactivity toward atmospheric moisture imposes strict processing requirements, which complicates manufacturing of polyurethane-based materials.

For these reasons, there is strong interest in non-isocyanate routes to polyurethane-type networks, where urethane bonds form during coating cure without involving isocyanates. A representative example is epoxy-polyurethane systems derived from cyclic carbonates and polyamines.

The resulting oligomers are typically clear (or only slightly tinted) liquids that dissolve well in most organic media and show a narrow molecular-weight distribution close to monodisperse behavior [51]. When the urethane fragment remains N–H (i.e., contains a mobile hydrogen capable of forming hydrogen bonds), the material tends to be noticeably more viscous than analogous systems in which the urethane nitrogen is substituted [71]. Acrylate-urethane oligomers may also be obtained by interfacial oligocondensation carried out in alkaline, two-phase water/organic solvent mixtures. Subsequent curing can be initiated either thermally with 2,2′-azobisisobutyronitrile (AIBN) or by applying radiation, including UV exposure [71].

Crosslinked acrylate-urethane networks that incorporate substituted urethane groups demonstrate enhanced resistance to hydrolysis, which is commonly attributed to phenyl-ring shielding of the urethane site that is otherwise most prone to hydrolytic attack [72]. Owing to the combined advantages of acrylates and urethanes, acrylate-urethane hybrids serve effectively as film-forming binders in coatings, offering strong pigment compatibility, favorable cost-to-performance, reduced reliance on organic solvents while maintaining fast cure, and good thermal stability, outstanding abrasion and impact resistance, improved chemical and solvent resistance, enhanced elasticity at low temperatures, and improved adhesion [73].

Acrylate-urethane hybrids combine the advantages of both polymer classes: those of acrylates (weather resistance, hardness, and good pigmentability) and those of urethanes (mechanical strength, abrasion resistance, and flexibility). They can be used either as standalone materials or in combination with urethane- or acrylate-based systems [64]. Acrylate-urethane hybrid materials are applied across many sectors: they are formulated as protective and decorative coatings for timber flooring, as finishes for mineral substrates such as concrete and brick, and as primers in automotive coating stacks. They are also used for plastic surfaces, serve as film-forming binders in printing-ink systems, and function as topcoats for textiles and leather. In addition, these hybrids underpin a variety of UV-curable coating technologies and find use in electronics-related coatings as well as in materials designed for optical signal transmission [64].

Blending (physical modification) involves the incorporation and homogeneous distribution of different polymers (oligomers) within the film-forming polymer matrix, thereby enabling an improvement in the material's processing and performance characteristics [52]. Blending of acrylic-polyurethane systems combines soft polyurethane segments with rigid acrylic domains, leading to the formation of a structured polymer matrix with enhanced chemical and mechanical resistance [74, 75]. By adjusting the ratio of urethane and acrylic segments, it is possible to optimize the crosslinking degree, phase distribution, and film density, which directly govern the coating's barrier and anticorrosion performance. Additional chemical modification of such blends using functional monomers, plasticizers, or nanofillers further improves metal adhesion, coating strength, and resistance to aggressive environments [76, 77]. Overall, acrylic-polyurethane blends enable the design of coatings with targeted, optimized chemical and service properties for effective corrosion protection of metallic substrates.

The combination of acrylic and polyurethane components determines the specific properties of acrylic-polyurethane systems. A comparative characterization of the main performance parameters of polyurethane and acrylic-polyurethane film-forming materials is presented in Table 2.

Table 2 – Comparison of the key performance characteristics of polyurethane and acrylic-polyurethane film-forming systems

Parameter	**Polyurethane film-forming materials**	**Acrylic-polyurethane film-forming materials**
Chemical structure	Polymers formed by the reaction of polyols with isocyanates	Acrylic copolymers modified with polyurethane fragments
UV resistance	Moderate	High due to the acrylic component
Weather resistance	High	Very high
Color and gloss retention	May decrease during prolonged service	Good color and gloss retention
Decorative properties of the coating	Limited; more commonly used as protective coatings	High decorative performance
Typical application areas	Industrial coatings, protective varnishes, floor coatings	Automotive, architectural, and decorative coatings

The analysis of the data presented in the table shows that the differences between polyurethane and acrylic–polyurethane film-forming materials are primarily determined by the features of their chemical structure [78-83]. Polyurethane systems are formed through the reaction of polyols with di- or polyisocyanates, resulting in macromolecules containing urethane groups, which account for the high strength and chemical resistance of the resulting coatings. Acrylic–polyurethane film-forming materials are modified systems in which the polyurethane matrix is combined with acrylic copolymers, making it possible to integrate the mechanical strength of polyurethanes with the high weather resistance of acrylic resins [19, 84].

Significant differences between these materials are also observed in their resistance to ultraviolet radiation. Polyurethane coatings, especially those based on aromatic isocyanates, generally exhibit comparatively lower light stability, which may lead to photochemical degradation of the polymer structure during prolonged UV exposure [85-87]. In contrast, acrylic–polyurethane systems show higher resistance to ultraviolet radiation owing to the presence of the acrylic component, which provides improved photostability of the coating [20,8]. These features are also reflected in the tendency of the coatings to yellow. In polyurethane materials, color changes may occur during prolonged service under the action of light and atmospheric oxygen [85, 86, 88].

Acrylic-polyurethane film-forming materials are characterized by a significantly lower tendency toward this phenomenon, which contributes to longer retention of the initial decorative properties of the coating [89-93].

In addition, acrylic-polyurethane systems demonstrate higher weather resistance and better color and gloss stability during outdoor service. Polyurethane coatings, in turn, are traditionally used in cases where high mechanical strength and protective performance are required [94-100]. Thus, the choice of film-forming material is determined by the required balance between the performance and decorative characteristics of the coating system.

Conclusion

Waterborne coating materials based on various polymer binders demonstrate substantial potential for the development of environmentally friendly and functional coatings. Their growing scientific and industrial relevance is associated not only with the reduction of volatile organic compound emissions, but also with the possibility of designing coating systems with a controlled balance of protective, mechanical, and technological properties. Among these, polyurethane and acrylic-polyurethane systems are of particular interest due to their enhanced service performance. These materials represent one of the most promising classes of modern film-forming systems for anticorrosion applications, since they allow the combination of ecological acceptability with high adaptability of formulation design.

Polyurethane and acrylic–polyurethane coatings exhibit distinct physicomechanical, chemical, and service-property profiles, which ultimately define their preferred roles in metal corrosion protection. Polyurethane systems are generally the better choice for harsh conditions that combine chemical attack with mechanical stresses, where maximum protective performance is critical. This is primarily due to their high adhesion strength, abrasion resistance, toughness, and resistance to chemically aggressive environments. Acrylic-polyurethane coating systems are applicable for the protection of metal surfaces operated under atmospheric exposure and solar radiation. The presence of an acrylic component influences film-formation processes and resistance to photochemical aging, as well as technological parameters related to coating application and curing. In addition, acrylic-containing systems generally provide improved color and gloss retention, enhanced weather resistance, and better long-term decorative stability under outdoor service conditions.

The analysis presented in this review also indicates that the performance limitations of waterborne coating systems can be effectively mitigated by directed chemical and compositional modification. The introduction of functional groups, the formation of hybrid or interpenetrating polymer networks, the use of crosslinking agents, and the incorporation of nanoscale functional fillers or corrosion inhibitors make it possible to regulate barrier properties, hydrophobicity, adhesion, resistance to aggressive media, and durability of the resulting films. Therefore, the development of high-performance waterborne anticorrosion coatings should be considered not only in terms of binder type, but also in terms of the relationship between chemical structure, dispersed-particle morphology, film-formation behavior, and final coating architecture.

The selection of a coating system should be based on service conditions, required protective and decorative properties, and the technological parameters of application and curing. The considerations outlined herein may be used to support the design and justification of coating systems for anticorrosion protection of metallic structures. In this regard, a rational choice between polyurethane and acrylic-polyurethane systems should be made on the basis of a comprehensive assessment of the operating environment, expected degradation factors, and the target lifetime of the protected structure. Future research should focus on formulation optimization, improving environmental safety, and extending coating service life under aggressive industrial exposure conditions. Particular attention should be paid to the development of multifunctional waterborne coatings capable of combining barrier protection with active anticorrosion action, self-healing ability, improved UV resistance, and reduced environmental impact. Such an approach will contribute to the creation of next-generation coating materials that satisfy both performance requirements and modern sustainability criteria.

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МОДИФИЦИРОВАНИЕ ПЛЕНКООБРАЗУЮЩИХ ДЛЯ ЛАКОКРАСОЧНЫХ КОМПОЗИТОВ НА ВОДНОЙ ОСНОВЕ

Лакокрасочные композиты на водной основе находят все большее применение в строительстве, промышленности и быту. Это обусловлено прежде всего экологическими (снижение эмиссии органических растворителей) и экономическими (вода дешевле и доступнее, чем органические растворители) причинами. Вместе с тем ключевой задачей остаётся повышение барьерных и механических характеристик водных покрытий при сохранении технологичности нанесения и быстрого отверждения. Применяются два основных подхода к модификации водоразбавляемых систем – химическая модификация полимерных связующих и блендирование полимеров. Показано, что целенаправленное варьирование структуры мягких/жёстких сегментов полиуретана, а также введение акрилатной компоненты и функциональных добавок (пластификаторов, нанонаполнителей) позволяет управлять степенью сшивки и фазовым распределением, тем самым повышая адгезию, износостойкость и барьерные свойства покрытий. Среди модифицированных водоразбавляемых систем особый интерес представляют полиуретановые и акрил-полиуретановые покрытия, которые были рассмотрены в статье благодаря уникальному сочетанию их свойств. Эти системы обеспечивают высокую долговечность покрытий и широкую сферу применения, включая защитные и декоративные покрытия для различных материалов. Особое внимание уделено способам их модификации. Отмечена перспективность полиуретановых и акрил-полиуретановых водоразбавляемых покрытий для антикоррозионной защиты и необходимость подбора составов с учётом условий эксплуатации.

***Ключевые слова**: водорастворимые лакокрасочные материалы, композиты, модифицированные водорастворимые системы, полиуретан, акрил-полиуретан, блендирование полимеров.*

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СУ НЕГІЗІНДЕГІ ЛАК-БОЯУ КОМПОЗИТТЕРІ ҮШІН ПЛЕНКА ТҮЗЕТІН МОДИФИКАЦИЯ

Су негізіндегі лак-бояу композиттері құрылыста, өнеркәсіпте және тұрмыста кеңінен қолданылып келеді. Бұл, ең алдымен, экологиялық (органикалық еріткіштердің эмиссиясын төмендету) және экономикалық (судың органикалық еріткіштерге қарағанда арзандығы әрі қолжетімділігі) факторларымен түсіндіріледі. Сонымен қатар, жағу технологиялылығын және тез

қатаюын сақтай отырып, су негізіндегі жабындардың тосқауылдық және механикалық қасиеттерін арттыру негізгі міндет болып қала береді. Сумен сұйылтылатын жүйелерді модификациялаудың екі негізгі тәсілі қолданылады: полимерлі байланыстырғыштарды химиялық модификациялау және полимерлерді блендтеу. Полиуретанның жұмсақ/қатты сегменттерінің құрылымын мақсатты түрде түрлендіру, сондай-ақ акрилат компонентін және функционалдық қоспаларды (пластификаторлар, нанотолтырғыштар) енгізу айқас байланысу дәрежесі мен фазалардың таралуын басқаруға мүмкіндік беріп, соның нәтижесінде жабындардың адгезиясын, тозуға төзімділігін және тосқауылдық қасиеттерін арттыратыны көрсетілді.Модификацияланған су негізіндегі жүйелердің ішінде полиуретанды және акрил-полиуретанды жабындар қасиеттерінің бірегей үйлесімі арқасында ерекше қызығушылық тудырады және мақалада осы жүйелерге басым назар аударылған. Аталған жүйелер әртүрлі материалдарға арналған қорғаныш және сәндік жабындарды қоса алғанда, жабындардың жоғары беріктігін және қолданылу аясының кеңдігін қамтамасыз етеді. Оларды модификациялау тәсілдеріне ерекше назар аударылады. Коррозияға қарсы қорғауда полиуретанды және акрил-полиуретанды су негізіндегі жабындардың перспективалылығы, сондай-ақ пайдалану жағдайларын ескере отырып, құрамдарды мақсатты түрде таңдаудың қажеттілігі атап өтіледі.

Түйін сөздер: *су негізіндегі лак-бояу материалдары, композиттер, модификацияланған су негізіндегі жүйелер, полиуретан, акрил-полиуретан, полимерлерді араластыру.*

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