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A COMPREHENSIVE REVIEW OF CONVENTIONAL AND NANO-MODIFIED POWDER COATINGS: MATERIALS, PERFORMANCE ENHANCEMENT, AND INDUSTRIAL APPLICATIONS

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Abstract

The solvent-free nature and high efficiency in coating have led to powder coatings becoming popular in industries as an alternative to traditional liquid coatings since they offer an environmentally friendly and efficient alternative to liquid coatings. This review includes a summary of the traditional and nano-modified powder coating with particular focus on the material composition, performance, and industrial applications. Traditional powder coatings, such as thermoset and thermoplastic finish types, are characterized by excellent resistance to corrosion, mechanical stability and aesthetic flexibility, but fail in severe service environments. Integration of nanomaterials has greatly enhanced the performance of coating through increase in mechanical strength, wear and corrosion resistance, thermal stability, and functional characteristics e.g. UV protection and antimicrobial activity. Such enhancements are mainly explained by fined microstructure, better interfacial bonding, and better barrier mechanisms. The major areas of application and the current challenges posed by nanoparticle dispersion and implementation on a large scale are also described in the review. Altogether, nano-modified powder coatings are an alternative solution to high-performance sustainable and high-protection surfacing requirements.

Keywords: Powder coatings; Nano-modified coatings; Nanomaterials; Corrosion resistance; Sustainable coatings.

1.Introduction

The powder coating technology has become important in industries because of being environmentally friendly, economically viable, and better performance of the coating process as compared to the traditional liquid coating system. In contrast to solvent-based coating, powder-based is applied in a dry and free flowing particulate composition and then subjected to thermal or ultra-violet energy to form a continuous and solid film. The lack of volatile organic compounds (VOCs), in addition to reducing the environmental pollution, also guarantees better working conditions and adherence to the ever-stricter environmental regulations. These merits have resulted into the use of powder coating that has become common in the automotive, architectural, appliance, furniture, and heavy engineering industries.

Table 1: Research Studies on Nanomaterials and Advanced Construction Materials

Author(s) & Year	Study Focus	Methodology / Data Source	Key Findings	Contribution to Sustainable Construction & Advanced Materials Research
Adhikary et al., 2024 [1]	Enhancement of microstructural integrity and mechanical strength of mortar using nanomaterial reinforcements	Experimental investigation using CNTs, graphene nanoplatelets, and nano-silica in incinerated ash-based mortar	Nanomaterial reinforcements significantly improved compressive strength, durability, and microstructural density	Demonstrated effective utilization of waste-derived materials reinforced with nanotechnology for high-performance and sustainable construction
Aljibori et al., 2023 [2]	Advances in corrosion protection coatings	Comprehensive review of recent experimental and industrial coating technologies	Advanced coatings enhance corrosion resistance,	Provided an integrated understanding of modern corrosion protection strategies critical for infrastructure longevity

			durability, and service life of metallic structures	
Allujami et al., 2022 [3]	Application of nanomaterials in recycled aggregate concrete	Systematic review of mechanical and durability performance studies	Nanomaterials improve strength, permeability resistance, and long-term durability of recycled concrete	Established nanotechnology as a key enabler for sustainable recycling practices in concrete production
Ayar et al., 2024 [4]	Application of nano-TiO_2 in asphalt pavement for sustainable roads	Critical review of laboratory and field studies	Nano-TiO_2 enhances pavement durability, self-cleaning properties, and environmental performance	Highlighted the potential of nanotechnology to improve sustainability and lifespan of road infrastructure
Chopra et al., 2024 [5]	Advanced characterization techniques for functional coatings	Review of modern structural, mechanical, and surface characterization tools	Sophisticated techniques enable accurate structure–property correlation in advanced coatings	

Traditional powder finishes are appreciated because they provide good corrosion protection, mechanical life and aesthetic flexibility, and a variety of surface finishes and color stability. The increased need of advanced surface protection, however, due to the severe service conditions and better performance demands has however shown that there are some weaknesses like scratch resistance, wear resistance, thermal stability as well as multifunctional performance in traditional formulations. In order to deal with these challenges, nanotechnology has come out as one of the promising techniques of improving performance of powder coating.

The introduction of fillers in the nanoscale into powder coating matrices allows a considerable improvement in the coating behavior through the enhancement of microstructure, enhancement of interfacial bonding, and the increasing barrier properties to moisture, and corrosive agents. The use of nano-modified powder coatings has shown better mechanical strength, better thermal and chemical resistance, and other functional characteristics than the conventional systems. This review will be focused on the development of the powder coating technology of the traditional formulations to the nano-modified ones, paying special attention to the material design, the actions of improving performance, and their increased industrial applicability.

2. Conventional Powder Coatings: Materials and Characteristics

Standard powder systems are generally categorized into thermoset and thermoplastic, according to the manner in which they cure as well as the molecular constitution [6]. These coating systems have been highly developed and optimized because of their environmental benefits, coating efficiency and balanced mechanical and protective properties that have made them applicable in a wide variety of industrial applications.

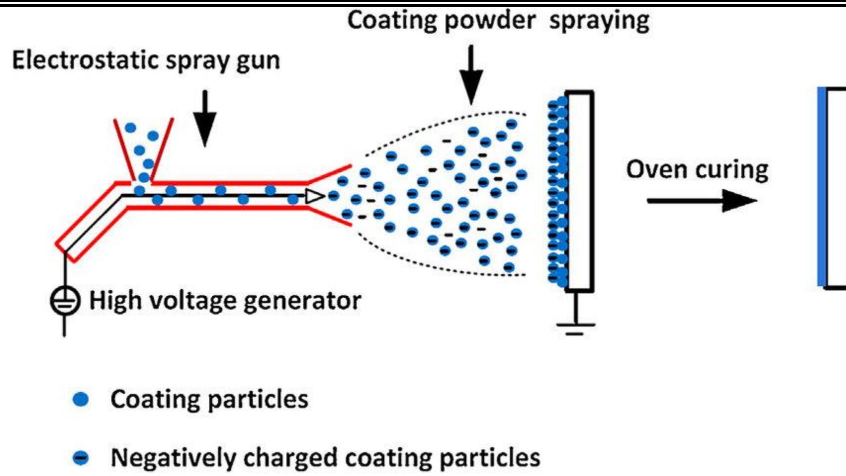

Figure 1: Schematic of the electrostatic powder coating process.[7]

The treats and your best friend in need meets her demise, and on the night the moon will shine, you will be by her side! 3D and cross-linked networks The thermoset powder coating create a cross-linked network during the coating process that is both irreversible and provides the coating film with a high degree of mechanical strength, chemical resistance and dimensional stability. Examples of common thermoset systems are epoxy, polyester, epoxy-polyester hybrids, polyurethane and acrylic-based coatings. The epoxy powder coatings have been extensively applied both in industrial and protective coating due to high adhesion, corrosion resistance and chemical durability. Nevertheless, they can be degraded easily by ultraviolet light hence cannot be used in the outdoor environment. Polyester and polyurethane powder coating on the other hand have a greater weather resistance, color wear, and aesthetic properties on surfaces hence is applied more in architectural and exterior work. Hybrid systems provide the good features of epoxy and polyester and are used in a combination to create better flexibility, durability, and economical people decorations.

Curing of thermoplastic powder coatings, including polyethylene, polypropylene, polyvinyl chloride and nylon does not require chemical cross-linking [8]. They instead become soft when heated and hard when cool so that they can have thicker coatings that are highly impact resistant and flexible. These finishes are especially appreciated in the uses needing of abrasion and toughness as in pipelines, wire coating, and industrial parts. But thermoplastic coatings can usually be processed at a higher temperature and may be less thermally stable and resistant to solvents than thermoset systems.

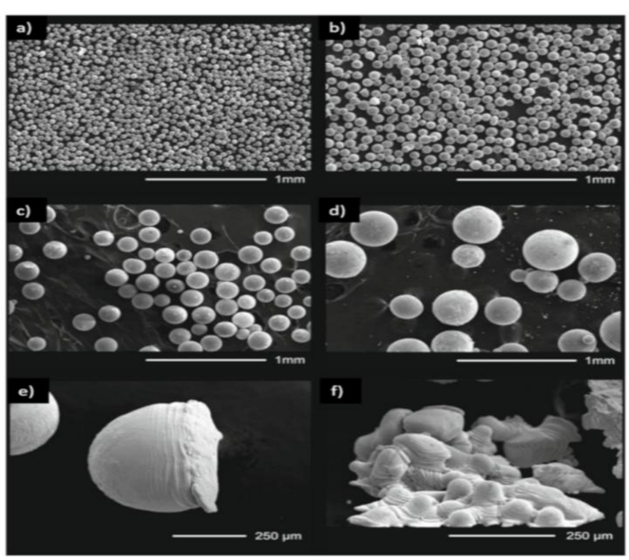

Figure 2: Schematic of the electrostatic powder coating process. [9]

Traditional powder coating solutions typically include polymer, curing, pigment, filler, flow modifier and other functional additives. These are melt mixed and extruded then cooled, ground, and the size of the pellets are sorted to obtain even powder properties [10]. Although they are quite widely successful, traditional powder coatings have certain limitations, such as average scratch resistance, poor barrier characteristics under harsh conditions, as well as limited multifunctionality. These difficulties have stimulated the production of improved coating systems with the change of materials and integration of nano technology.

Table 2: Comparison of Thermoset and Thermoplastic Conventional Powder Coatings

Parameter	Thermoset Powder Coatings	Thermoplastic Powder Coatings
Curing behavior	Chemical cross-linking (irreversible)	Physical melting and solidification
Common materials	Epoxy, polyester, polyurethane, acrylics	Polyethylene, polypropylene, nylon
Mechanical strength	High hardness and dimensional stability	High impact resistance and flexibility
Chemical resistance	Excellent	Moderate
UV resistance	Limited (epoxy) to good (polyester)	Generally moderate
Processing temperature	Moderate	High
Recyclability after curing	Not recyclable	Recyclable
Typical applications	Automotive parts, appliances, architectural coatings	Pipelines, wire coatings, industrial components

The summarized comparative features presented in Table 1 allow concluding that the choice of traditional powder coating systems is extremely application-specific. Coatings made by thermosets are usually used where high mechanical strength, chemical resistance and dimensional stability are needed over time especially in the automotive, appliance and building industry. Thermoplastic coatings on the other hand are better suited where coating layers are thicker, impact resistance is needed and high levels of flexibility are needed e.g. in pipeline protection and industrial components [11]. Although both thermoset and thermoplastic powder coating have proven itself as a reliable production method in the industrial context, the two types of coating materials have various intrinsic constraints regarding surface integrity, porous control and operational flexibility. Such limitations have led to further studies to make material changes and the use of new fillers, which will result in the creation of the nano-modified powder coating systems with new and improved performance properties.

3. Nano-Modified Powder Coatings: Materials and Performance Enhancement

Nano-modified powder coating is of a more advanced category of coating systems where the filler nano-particles are used to replace the particle fillers in standard polymer systems to improve the performance of the filler at low concentrations [12]. Due to their large surface area and interfacial interactions, nanomaterials play a major role in the coating microstructure, barrier performance, and functional activity with negligible effects in terms of coating thickness or processability.

3.1 Nanomaterials Used in Powder Coatings

Nanomaterials based on a variety of inorganic and carbon-based materials have been explored in powder coating. Nanosilica and nano-alumina are inorganic nanoparticles which are normally used to enhance hardness, wear resistance and thermal stability. Titanium oxide nanoparticles and zinc oxide nanoparticles offer protection against UV rays, longevity, and antimicrobial properties, which is specifically useful in the use of outdoor and hygienic purposes [13].

Nanomaterials based on carbon such as graphene and carbon nanotubes can provide outstanding mechanical reinforcement, electrical conductivity and barrier properties at very low loadings. These nanofillers may need surface modification in order to increase their compatibility with polymer matrices and to achieve homogenous dispersion when they are melting processed

Table 3: Common Nanomaterials Used in Powder Coatings and Their Performance Contributions

Nanomaterial	Primary Role	Key Performance Benefits
Nanosilica	Reinforcement	Improved hardness and scratch resistance

Nano-alumina	Mechanical stability	Enhanced wear and abrasion resistance
Titanium dioxide (TiO_2)	UV protection	Improved weather durability
Zinc oxide (ZnO)	Functional additive	Antimicrobial and corrosion resistance
Graphene	Barrier reinforcement	Superior corrosion resistance and conductivity
Carbon nanotubes	Multifunctional filler	Improved toughness and electrical properties

3.2 Performance Enhancement Mechanisms

The main ways of obtaining performance enhancement in nano-modified powder coating are through enhanced load transfer, limited polymer chain movement and creation of tortuous diffusion routes to prevent the entry of moisture and corrosive species. These processes result in harder, scratch-resistant, abrasion-resistant and corrosion-resistant [14]. Increased heat dissipation and char development also increases thermal stability and flame retardancy.

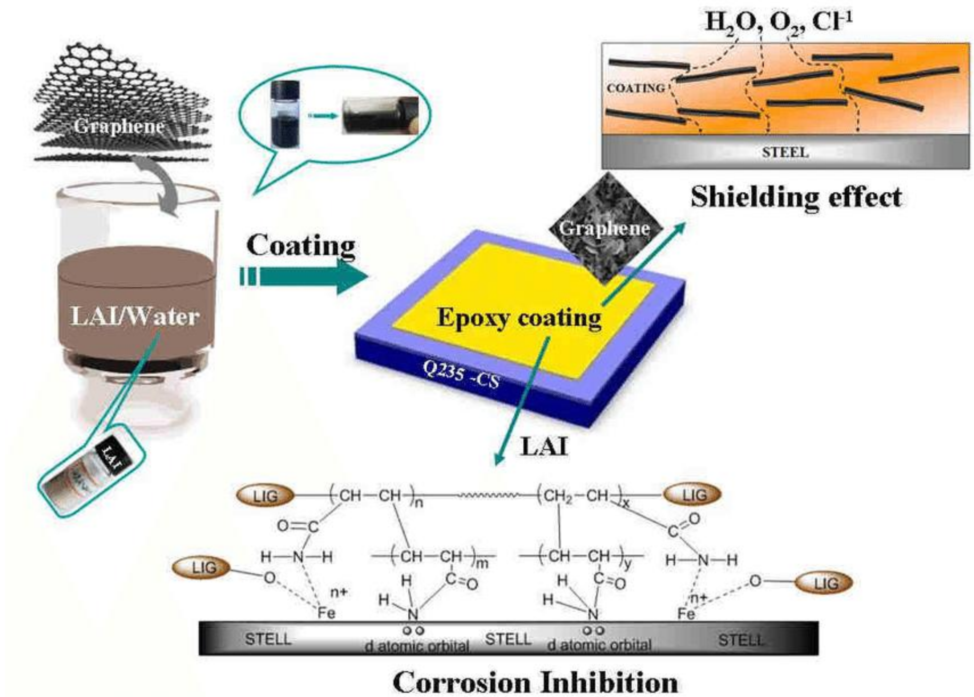

Figure 3: Schematic of corrosion and wear protection mechanisms in graphene-modified powder coatings [15]

Moreover, nano-modified coatings may have such functional properties as UV resistance, antimicrobial activity, electrical conductivity, and self-cleaning. Nonetheless, still, there are issues of nanoparticle agglomeration, dispersion control and scalability which require optimization of processing methods and surface-treated nanomaterials to obtain uniform performance.

4. Industrial Applications of Conventional and Nano-Modified Powder Coatings

Powder coatings have gained great acceptance in industry with their high degree of coating efficiency, excellent durability, and resistance to corrosion coupled with their environmentally benign property [16]. Performance requirements, service conditions and economical aspect are the main factors that determine the choice between conventional and nano-modified powder coatings [17].

4.1 Automotive and Transportation Applications

Underbody components, chassis parts, suspension system, and wheels are a few components of the automotive and transportation industries that use powder coating [18]. Traditional powder paints are sufficiently strong mechanically, corrosive, and aesthetics of the surface to meet standard applications [19]. Nevertheless, nano-modified powder coatings are finding their way into components with a high need, such as a high degree of abrasion resistance, thermal stability, and prolonged corrosion protection. The enhanced barrier performance of nanofillers is linked to the long life of components operating in hostile operating conditions [20].

4.2 Architectural and Consumer Product Applications

Powder coating finds an extensive use in the architectural styles such as aluminum profiles, window frames, facades, and railings because of their good weathering and color ability properties. Traditional powder coats are made out of conventional polyester, and they are usually applied to items in cases where the price factor and their appearance are the main concerns [21]. Nano-modified powder coatings are better in UV resistance, surface deterioration and self-cleanable and are specially applied in exterior architectural features [22]. Powder coating offers impact protection, chemical stability and finishes on the surfaces of conventions in consumer products and home appliances, with nano-modified forms offering additional options in scratch protection and functionality in relation to hygiene [23].

4.3 High-Performance and Specialized Industrial Applications

The nano-modified powder coatings are now finding more high performance and specialized uses in aerospace parts, marine structures, electrical enclosures, medical devices, and energy infrastructure. In these industry applications, improved mechanical strength, resistance to corrosion, electrical conductivity and antimicrobial behavior are important [24]. Powder coatings allow the use of nanomaterials to achieve high performance requirements without violating the standards of environmental and regulatory requirements. Subsequently, the nano-modified powder coating is stretching the functional and use limits of the traditional coating technologies.

5.Conclusion

The present review highlights how the power coating technology has been evolving to incorporate the use of nano-modified rather than the conventional formulations [25]. Traditional powder-based finishes remain very popular as they are environmentally friendly, cost-effective and provide good protective features, yet have drawbacks when subjected to harsh service environments. Introduction of nanomaterials has dramatically increased the coating performance by facilitating the mechanical strength, corrosion and wear resistance, thermal stability and functional aspects like UV protection and antimicrobial behaviour. These increases are due to perfect microstructure and improvement of barrier mechanisms in the nanoscale. Although several challenges still exist since issues to do with dispersion and large-scale processing, current studies are gradually overcoming the problems. In general, nano-modified powder coating is an impressive and effective high-performance and sustainable solution in the industrial and specialized coating processes of the next generation.

References

1. Adhikary, S. K., Patel, J., Antwi, M., Truong, T., Mishra, A., Yu, Y., & Perumal, P. (2024). Enhancing microstructural integrity and mechanical strength of mortar containing incinerated ash using carbon nanotube, graphene nanoplatelet and nano silica reinforcements. *Construction and Building Materials*, *446*, 138061.
2. Aljibori, H. S., Alamiery, A., & Kadhum, A. A. H. (2023). Advances in corrosion protection coatings: A comprehensive review. *Int. J. Corros. Scale Inhib*, *12*(4), 1476-1520.
3. Allujami, H. M., Abdulkareem, M., Jassam, T. M., Al-Mansob, R. A., Ng, J. L., & Ibrahim, A. (2022). Nanomaterials in recycled aggregates concrete applications: Mechanical properties and durability. A review. *Cogent Engineering*, *9*(1), 2122885.
4. Ayar, P., Ruhi, A., Baibordy, A., Asadi Azadgoleh, M., Mohammadi, M. M., & Abdipour, S. V. (2024). Toward sustainable roads: a critical review on nano-TiO2 application in asphalt pavement. *Innovative Infrastructure Solutions*, *9*(5), 148.
5. Chopra, S., Banshiwal, J. K., Singh, A., & Bag, D. S. (2024). Sophisticated Characterization Techniques for Structure–Property Evaluation of Functional Coatings. *Functional Coatings: Innovations and Challenges*, 522-583.
6. Gao, K., Zhang, Y., Yi, J., Dong, F., & Chen, P. (2024). Overview of Surface Modification Techniques for Titanium Alloys in Modern Material Science: A Comprehensive Analysis. Coatings. 2024; 14 (1): 148. *doi. org/10.3390/coatings14010148*.
7. Gu, Y., Xia, K., Wu, D., Mou, J., & Zheng, S. (2020). Technical characteristics and wear-resistant mechanism of nano coatings: a review. *Coatings*, *10*(3), 233.
8. Han, G., Dai, S., Zhang, J., Gao, Y., & Liu, Y. (2024). Study on the workability and early mechanical properties of carbon nanotube-coated fly ash modified cement-based grouting materials. *Construction and Building Materials*, *439*, 137327.
9. Huang, H., Wang, Y., Wu, X., Zhang, J., & Huang, X. (2024). Nanomaterials for modified asphalt and their effects on viscosity characteristics: a comprehensive review. *Nanomaterials*, *14*(18), 1503.
10. Huseien, G. F. (2023). A review on concrete composites modified with nanoparticles. *Journal of Composites Science*, *7*(2), 67.
11. Irfan, Hu, M., Meng, L., Zhao, H., & Wang, A. (2024). Microstructures and properties of nano-modified multimodal Cr3C2-NiCr coatings made through laser cladding. *Journal of Materials Science*, *59*(39), 18516-18532.

12. Jamwal, D., Sharma, A., Kanwar, R., & Mehta, S. K. (2021). The multifaceted dimensions of potent nanostructures: a comprehensive review. *Materials Chemistry Frontiers*, *5*(7), 2967-2995.
13. Jenima, J., Dharshini, M. P., Ajin, M. L., Moses, J. J., Retnam, K. P., Arunachalam, K. P., ... & Munoz, R. F. A. (2024). A comprehensive review of titanium dioxide nanoparticles in cementitious composites. *Heliyon*, *10*(20).
14. Liu, J., Liu, J., Attarilar, S., Wang, C., Tamaddon, M., Yang, C., ... & Tang, Y. (2020). Nano-modified titanium implant materials: a way toward improved antibacterial properties. *Frontiers in Bioengineering and Biotechnology*, *8*, 576969.
15. Olawore, A. S., Asafa, T. B., Oladosu, K. O., Lateef, A., & Durowoju, M. O. (2021). Enhancing functionalities of paints with nanoparticles: a review. *Nano Plus: Science and Technology of Nanomaterials*, *2*(1), 97-119.
16. Qu, H., Feng, M., Li, M., Tian, D., Zhang, Y., Chen, X., & Li, G. (2023). Enhancing the carbonation and chloride resistance of concrete by nano-modified eco-friendly water-based organic coatings. *Materials Today Communications*, *37*, 107284.
17. Ravindran, L., MS, S., Kumar S, A., & Thomas, S. (2022). A comprehensive review on phenol-formaldehyde resin-based composites and foams. *Polymer Composites*, *43*(12), 8602-8621.
18. Shah, A. H., Rasool, F., Mir, S. B., Alsaif, A., Bhat, H. F., Jan, I., ... & Najar, K. (2024). Enhancing concrete properties with graphene and graphene-based additives: A comprehensive analysis of their effect on microstructure and macrostructure of concrete. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, *48*(4), 1817-1836.
19. Sharma, D., Thakur, A., Sharma, A. K., Kherb, J., Kumar, A., & Om, H. (2024). Future Developments in Nano-Hybrid Smart Coatings. In *Nano-Hybrid Smart Coatings: Advancements in Industrial Efficiency and Corrosion Resistance* (pp. 385-415). American Chemical Society.
20. Sharma, H., & Ashish, D. K. (2023). Nano CaCO3 for enhancing properties of cement-based materials: A comprehensive review. *Journal of Sustainable Cement-Based Materials*, *12*(12), 1475-1494.
21. Shi, C., Liu, S., Irfan, Gong, Q., Wang, H., & Hu, M. (2022). Deposition mechanisms and characteristics of nano-modified multimodal Cr3C2–NiCr coatings sprayed by HVOF. *Reviews on Advanced Materials Science*, *61*(1), 526-538.
22. Tanimola, J. O., & Efe, S. (2024). Recent advances in nano-modified concrete: enhancing durability, strength, and sustainability through nano silica (nS) and nano titanium (nT) incorporation. *Applications in Engineering Science*, *19*, 100189.
23. Thakur, A., & Kumar, A. (2024). Chemical and Physical Properties of Nano-Hybrid Smart Coatings. In *Nano-Hybrid Smart Coatings: Advancements in Industrial Efficiency and Corrosion Resistance* (pp. 59-94). American Chemical Society.
24. Thakur, A., Kaya, S., & Kumar, A. (2023). Recent trends in the characterization and application progress of nano-modified coatings in corrosion mitigation of metals and alloys. *Applied Sciences*, *13*(2), 730.
25. Thissen, P., Bogner, A., & Dehn, F. (2024). Surface treatments on concrete: An overview on organic, inorganic and nano-based coatings and an outlook about surface modification by rare-earth oxides. *RSC Sustainability*, *2*(8), 2092-2124.

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