

TECHNOLOGY FOR OBTAINING ANTICORROSIVE COATINGS BASED ON INORGANIC-MINERAL RAW MATERIALS

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Abstract

The development of anticorrosive coating technologies based on inorganic-mineral raw materials is becoming increasingly important for protecting metal structures used in construction, chemical production, agriculture, transport, water supply systems and industrial equipment. Conventional coating systems often depend on expensive synthetic pigments, imported additives and environmentally problematic components. Therefore, the use of locally available mineral raw materials such as kaolin, bentonite, wollastonite, zeolite, silica, calcium carbonate, talc, mica and phosphate-based inorganic inhibitors can reduce cost, improve technological accessibility and increase the ecological safety of coating production. This article analyzes the technological principles of obtaining anticorrosive coatings from inorganic-mineral raw materials. The study is structured according to the IMRAD format and focuses on raw material selection, formulation design, dispersion technology, film formation, adhesion, barrier properties and corrosion resistance. The proposed technology combines three main mechanisms: physical barrier protection, chemical passivation and adsorption-inhibition effects. The article presents comparative analytical tables describing mineral components, their functional roles, formulation variants, expected technological parameters and anticorrosive performance indicators. The analysis shows that the most promising coating system is a hybrid formulation containing epoxy or alkyd binder, micronized silica, wollastonite, zeolite and zinc phosphate. Such a system may provide improved adhesion, reduced water permeability, enhanced resistance to salt media and longer service life under atmospheric corrosion conditions. The article concludes that inorganic-mineral raw materials can serve not only as low-cost fillers but also as functional anticorrosive components when their particle size, surface activity, dispersion quality and compatibility with the polymer matrix are properly controlled.

Keywords: anticorrosive coating, inorganic-mineral raw materials, corrosion protection, kaolin, zeolite, wollastonite, zinc phosphate, silica, coating technology, metal protection.

Introduction

Corrosion is one of the most serious degradation processes affecting metallic structures in industrial and natural environments. Steel, cast iron, aluminum alloys and other engineering metals are exposed to oxygen, moisture, chloride ions, industrial gases, acidic precipitation and temperature fluctuations. As a result, electrochemical reactions occur on the metal surface, leading to rust formation, loss of mechanical strength, surface cracking, reduced service life and increased maintenance costs. In many sectors, corrosion is not only a technical problem but also an economic and safety issue. Pipelines, agricultural machinery, storage tanks, bridges, industrial frames, pumps, metal roofing, transport equipment and technological installations require reliable surface protection.

Among the available protection methods, anticorrosive coatings remain one of the most widely used because they are technologically simple, economically acceptable and suitable for large surfaces. A coating system performs several functions at the same time: it isolates the metal from corrosive agents, reduces diffusion of water and oxygen, improves surface durability, provides decorative appearance and, in some formulations, releases inhibiting ions that slow corrosion reactions. However, the effectiveness of a coating depends strongly on its composition, surface preparation, binder type, pigment-volume concentration, filler morphology, adhesion and curing conditions.

In recent years, attention has increased toward coatings based on inorganic-mineral raw materials. This trend is connected with several factors. First, many countries have natural reserves of clay minerals, silicates, carbonates, phosphates and aluminosilicates that can be used in coating technology. Second, mineral components are usually cheaper and more stable than many synthetic additives. Third, the environmental requirements for coatings are becoming stricter, especially regarding toxic chromate-based corrosion inhibitors. Fourth, mineral fillers can improve not only cost efficiency but also mechanical strength, barrier properties, heat resistance and rheology of coatings.

Inorganic-mineral raw materials can be divided into two functional groups. The first group includes passive barrier fillers such as mica, talc, kaolin, silica and calcium carbonate. These materials increase the tortuosity of diffusion pathways inside the coating film, making it harder for water, oxygen and chloride ions to reach the metal surface. The second group includes active or semi-active anticorrosive components such as zinc phosphate, modified zeolite, wollastonite and calcium silicate. These materials may participate in passivation reactions, ion exchange or surface adsorption, thereby reducing corrosion activity.

The relevance of this topic is especially high for regions where mineral resources are available but advanced coating technologies are insufficiently developed. Instead of

importing ready-made anticorrosive additives, local mineral raw materials can be mechanically activated, purified, micronized, surface-modified and incorporated into polymer binders. This creates a technological basis for producing competitive anticorrosive coatings for industrial and agricultural applications.

The aim of this article is to analyze the technology for obtaining anticorrosive coatings based on inorganic-mineral raw materials and to propose a scientifically grounded formulation model. The objectives are: to classify suitable mineral raw materials; to determine their functional role in anticorrosive protection; to describe the technological stages of coating preparation; to propose formulation variants; to compare expected performance indicators; and to identify the main risks and optimization directions.

Materials and Methods

The methodological basis of the article is a technological and analytical approach to the design of anticorrosive coatings. Since no specific laboratory dataset was provided, the results are presented as a model formulation analysis and should be verified by experimental testing before industrial use. The proposed coating technology is designed for carbon steel surfaces exposed to atmospheric corrosion, moderate humidity and chloride-containing environments.

The main inorganic-mineral raw materials considered in this study are kaolin, bentonite, wollastonite, zeolite, silica, mica, talc, calcium carbonate and zinc phosphate. These materials were selected because of their availability, chemical stability, particle morphology and potential anticorrosive contribution. The polymer binder may be epoxy, alkyd, acrylic or polyurethane depending on the application environment. For stronger industrial protection, epoxy-based formulations are preferable because of their high adhesion, chemical resistance and low permeability. Alkyd systems are cheaper and easier to apply but usually provide lower chemical resistance in aggressive media.

The technological process consists of the following stages: raw material preparation, drying, grinding, classification, surface activation, binder preparation, pigment-filler dispersion, viscosity adjustment, coating application, curing and performance testing. Mineral raw materials must be dried to reduce moisture content because absorbed water can cause poor dispersion, blistering and reduced adhesion. Grinding and micronization are necessary to obtain a uniform particle size distribution. For anticorrosive coatings, particles in the range of approximately 2–25 μm are usually desirable, depending on coating thickness and binder viscosity. Too large particles reduce smoothness and may create defects; too fine particles may increase viscosity and agglomeration.

Surface modification is an important technological stage. Minerals such as silica, kaolin and zeolite have hydrophilic surfaces, which may not be fully compatible with organic binders. Therefore, silane coupling agents, phosphate treatment or mechanical activation can be used to improve interfacial bonding between mineral particles and the polymer matrix. Improved interfacial adhesion reduces microvoids, lowers water penetration and increases coating durability.

The formulation design is based on the principle of balanced pigment-volume concentration. If the filler content is too low, the barrier effect is weak. If it is too high, the coating becomes porous, brittle and poorly adhesive. Therefore, the optimal mineral content must remain below the critical pigment volume concentration. The proposed model formulations include four variants: a control coating without functional mineral additive; a kaolin-silica barrier coating; a zeolite-wollastonite active mineral coating; and a hybrid coating containing silica, zeolite, wollastonite and zinc phosphate.

The following standard performance indicators are recommended for experimental validation: dry film thickness, adhesion by cross-cut test, pull-off adhesion strength, water absorption, salt spray resistance, corrosion creep from scribe, hardness, flexibility and electrochemical impedance. In practical conditions, at least three parallel samples should be tested for each formulation to ensure statistical reliability.

Table 1. Functional classification of inorganic-mineral raw materials for anticorrosive coatings

Mineral component	Main chemical nature	Functional role in coating	Expected anticorrosive contribution	Main technological risk
Kaolin	Hydrated aluminosilicate	Barrier filler, rheology modifier	Reduces permeability when well dispersed	High water absorption if poorly treated
Bentonite	Layered aluminosilicate	Thixotropy and suspension stability	Improves anti-settling and film uniformity	Excess content increases viscosity
Wollastonite	Calcium silicate	Reinforcing filler, semi-active pigment	Improves mechanical strength and passivation tendency	Requires good dispersion

Mineral component	Main chemical nature	Functional role in coating	Expected anticorrosive contribution	Main technological risk
Zeolite	Porous aluminosilicate	Ion-exchange mineral pigment	Can adsorb aggressive ions and carry inhibitors	May absorb moisture
Silica	Silicon dioxide	Dense barrier-forming filler	Reduces diffusion of oxygen and water	Agglomeration at nanoscale
Mica	Layered silicate	Lamellar barrier filler	Increases tortuous diffusion path	Poor wetting if untreated
Talc	Magnesium silicate	Hydrophobic filler, smoothness improver	Improves water resistance and film compactness	Weak active inhibition
Calcium carbonate	Carbonate mineral	Cost-reducing extender	Improves body and coverage	Low resistance in acidic media
Zinc phosphate	Inorganic phosphate inhibitor	Active anticorrosive pigment	Forms protective phosphate complexes	Cost and dispersion sensitivity

The experimental coating samples may be prepared on steel panels measuring 100 × 150 × 2 mm. The metal surface should be degreased, mechanically cleaned and sanded or blast-cleaned before coating. Surface preparation is critical because even the best coating formulation fails when applied over oil, rust, dust or weak oxide layers. After application, coatings should be cured according to binder requirements. Epoxy systems usually require controlled mixing of resin and hardener, while alkyd systems cure by oxidative drying.

Table 2. Proposed formulation matrix for experimental coating development

Component	F0 Control, wt. %	F1 Barrier mineral, wt. %	F2 Active mineral, wt. %	F3 Hybrid optimized, wt. %
Polymer binder	45	42	40	40
Solvent or water phase	18	17	16	15
Kaolin	0	12	4	5
Silica	0	8	4	6

Component	F0 Control, wt. %	F1 Barrier mineral, wt. %	F2 Active mineral, wt. %	F3 Hybrid optimized, wt. %
Zeolite	0	0	8	6
Wollastonite	0	0	10	8
Zinc phosphate	0	0	4	6
Talc or mica	5	6	5	5
Calcium carbonate	20	8	6	4
Dispersant/additives	2	2	2	2
Pigment/colorant	10	5	5	3
Total	100	100	100	100

The technological scheme of coating production can be expressed as follows:

Mineral raw material selection → drying → grinding → particle classification → surface modification → binder preparation → high-speed dispersion → viscosity adjustment → filtration → application on steel → curing → anticorrosive testing → formulation optimization.

Results

The analytical comparison of the proposed formulations shows that the anticorrosive performance of mineral-based coatings depends on the balance between barrier density, active inhibition and mechanical integrity. The control formulation F0 has limited protection because its filler system is mainly cost-oriented and does not contain sufficient barrier or inhibitor components. F1 improves the barrier effect due to kaolin and silica. However, if kaolin is not surface-treated, its hydrophilic nature may increase water uptake. F2 provides stronger active protection because zeolite, wollastonite and zinc phosphate contribute to ion exchange, passivation and reinforcing effects. F3 is the most balanced formulation because it combines dense silica, moderate kaolin, zeolite, wollastonite and zinc phosphate in one system.

Table 3. Model technological indicators of proposed coating formulations

Indicator	F0 Control	F1 Barrier mineral	F2 Active mineral	F3 Hybrid optimized
Dry film thickness, μm	80–100	90–110	100–120	110–130
Viscosity stability	Medium	Good	Medium	Good

Indicator	F0 Control	F1 Barrier mineral	F2 Active mineral	F3 Hybrid optimized
Sedimentation tendency	High	Medium	Medium	Low
Surface smoothness	Good	Good	Medium	Good
Expected adhesion level	Medium	Good	Good	Very good
Expected water resistance	Low-medium	Medium-good	Good	Very good
Expected salt resistance	Low	Medium	Good	Very good
Technological complexity	Low	Medium	Medium-high	High

The data in Table 3 indicate that the hybrid optimized formulation requires more careful technological control but may provide the best final performance. This is a typical tradeoff in coating technology: simple formulations are cheaper and easier to produce, but they rarely provide high corrosion resistance. More complex formulations can provide stronger protection, but they require better dispersion equipment, correct additive selection and stricter quality control.

Table 4. Comparative anticorrosive mechanism analysis

Protection mechanism	Mineral component responsible	Mechanism description	Importance level
Barrier protection	Silica, mica, kaolin, talc	Blocks diffusion of water, oxygen and chloride ions	Very high
Tortuous pathway effect	Mica, kaolin, wollastonite	Increases pathway length for corrosive species	High
Surface passivation	Zinc phosphate, wollastonite	Promotes formation of protective insoluble compounds	Very high
Ion adsorption	Zeolite	Adsorbs aggressive ions and may retain inhibitors	High

Protection mechanism	Mineral component responsible	Mechanism description	Importance level
Mechanical reinforcement	Wollastonite, silica	Improves hardness, cohesion and crack resistance	Medium-high
Rheology control	Bentonite, kaolin	Prevents sedimentation and improves application behavior	Medium
Cost reduction	Calcium carbonate, kaolin	Reduces formulation cost	Medium
Moisture sensitivity reduction	Talc, surface-treated silica	Improves hydrophobicity of the coating film	High

The expected improvement in corrosion resistance can be explained by the microstructural organization of mineral particles inside the binder. Lamellar and acicular particles create a more complex diffusion route, preventing direct movement of electrolyte through the coating. Porous zeolite particles may adsorb ions and reduce local concentration of aggressive species near the metal surface. Zinc phosphate can participate in passivation reactions and reduce electrochemical activity at anodic sites. Wollastonite can improve mechanical reinforcement and support protective film formation because of its calcium silicate structure.

Table 5. Model performance assessment after accelerated corrosion exposure

Performance criterion	F0 Control	F1 Barrier mineral	F2 Active mineral	F3 Hybrid optimized
Blistering tendency	High	Medium	Low-medium	Low
Rusting near scribe	High	Medium	Low	Very low
Adhesion loss after exposure	High	Medium	Low-medium	Low
Water absorption	High	Medium	Medium-low	Low
Coating cracking	Medium	Low-medium	Low	Very low

Performance criterion	F0 Control	F1 Barrier mineral	F2 Active mineral	F3 Hybrid optimized
Overall protection class	Low	Medium	Good	Very good

The model assessment suggests that F3 is the most rational formulation for further experimental development. Nevertheless, the formulation should not be considered final without laboratory testing. The real performance may change depending on mineral purity, particle size distribution, binder chemistry, substrate preparation, curing regime and environmental exposure.

Discussion

The obtained analytical results confirm that inorganic-mineral raw materials should not be treated as ordinary cheap fillers only. Their role in anticorrosive coatings is more complex. When selected and processed correctly, mineral components become functional elements of the protective system. The key factor is compatibility between mineral particles and the binder. Poor compatibility causes agglomeration, microvoids and channels through which water and ions can penetrate. Therefore, dispersion technology is as important as chemical composition.

One of the strongest advantages of mineral-based coatings is their potential localization. Many mineral raw materials are available in natural deposits and can be processed using relatively accessible technologies: crushing, drying, milling, classification and surface treatment. This makes the technology attractive for regional industrial production. For Uzbekistan and other mineral-rich regions, this direction may reduce dependence on imported anticorrosive pigments and create value-added products from local raw materials.

However, the technology also has serious limitations. The first risk is unstable raw material quality. Natural minerals may contain impurities such as iron oxides, soluble salts, organic residues or excessive moisture. These impurities can reduce coating stability and even accelerate corrosion. Therefore, raw material characterization is mandatory. Chemical composition, moisture content, oil absorption, pH, particle size, whiteness and soluble salt content must be controlled before formulation.

The second risk is poor dispersion. Mineral particles tend to agglomerate, especially silica, zeolite and clay minerals. Agglomerates create weak zones in the coating film. They reduce smoothness, increase porosity and lower adhesion. High-speed dispersion, bead milling or ultrasonic treatment may be required for high-performance coatings. Dispersants must be selected according to the binder system; otherwise, they may cause foaming, poor curing or phase separation.

The third risk is excessive pigment-volume concentration. Increasing mineral content reduces cost but may destroy film integrity. A coating with too much filler becomes brittle and porous. This is a common mistake in low-cost coating production. A scientifically designed anticorrosive coating must balance economy and performance. The goal is not to add as much mineral filler as possible but to add the right mineral in the right particle size and concentration.

The fourth risk is insufficient surface preparation of steel. Corrosion protection is a system problem, not only a formulation problem. If the metal surface is contaminated, wet, rusty or poorly roughened, even an optimized coating may fail. Surface cleaning, degreasing, abrasive preparation and correct drying conditions are essential.

From a technological point of view, the best strategy is to develop a multilayer coating system. The primer should contain active anticorrosive pigments such as zinc phosphate, zeolite or modified wollastonite. The intermediate layer should provide barrier thickness using silica, mica or kaolin. The topcoat should provide UV resistance, hydrophobicity, hardness and decorative stability. Such a system is more reliable than a single-layer coating, especially for aggressive environments.

Table 6. Practical risk analysis for industrial implementation

Risk factor	Possible consequence	Prevention measure
High mineral moisture	Blistering, poor adhesion	Drying at controlled temperature before dispersion
Large particle size	Rough film, weak barrier effect	Micronization and classification
Poor dispersion	Agglomerates and microvoids	High-speed dispersion and proper dispersant
Excess filler content	Brittle and porous coating	Control pigment-volume concentration
Hydrophilic mineral surface	Water absorption	Surface modification with silane or phosphate treatment
Poor steel preparation	Early coating failure	Degreasing, sanding or abrasive blasting
Wrong binder selection	Low chemical resistance	Match binder to exposure environment
Insufficient curing	Soft film and weak adhesion	Follow curing time, temperature and mixing ratio

The analysis shows that the most realistic direction for future research is the development of hybrid mineral-inhibitor systems. For example, zeolite can be modified with phosphate or rare-earth inhibitors; wollastonite can be combined with zinc phosphate; silica can be surface-treated to improve hydrophobicity; mica can be used to increase the diffusion path. Such combinations may provide synergistic effects. The coating then protects the metal not by one mechanism but by several mechanisms acting together.

Conclusion

The technology for obtaining anticorrosive coatings based on inorganic-mineral raw materials is a promising direction for developing cost-effective, environmentally safer and locally producible protective systems. Mineral components such as kaolin, silica, mica, talc, zeolite, wollastonite and zinc phosphate can perform different functions in coating formulations. Some of them act as barrier fillers, some improve mechanical properties, some regulate rheology, and others provide active inhibition or passivation.

The proposed technological model includes raw material preparation, drying, grinding, classification, surface modification, binder preparation, dispersion, application, curing and testing. Among the analyzed formulations, the hybrid system containing silica, zeolite, wollastonite and zinc phosphate appears to be the most promising because it combines physical barrier protection with active anticorrosive mechanisms. However, this formulation also requires stricter technological control.

The main scientific conclusion is that the effectiveness of mineral-based anticorrosive coatings depends not only on the chemical nature of the raw materials but also on particle morphology, particle size distribution, surface treatment, binder compatibility, dispersion quality and coating thickness. Poorly processed minerals can weaken the coating, while properly modified minerals can significantly improve corrosion resistance.

For future experimental research, it is recommended to test the proposed formulations using standard methods such as salt spray exposure, adhesion testing, water absorption measurement, electrochemical impedance spectroscopy and microscopic analysis of coating morphology. The final industrial formulation should be selected only after real laboratory validation under the intended service environment.

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