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IMPROVING THE PERFORMANCE CHARACTERISTICS OF VEHICLES OPERATED IN SEVERE CLIMATIC CONDITIONS AND AGGRESSIVE ENVIRONMENTS

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Abstract:

This study presents the testing procedures and results for an anticorrosion coating based on ED-16 epoxy resin and modified with an aluminum inhibiting pigment, intended to protect the body parts and bodywork of vehicles operated in aggressive environments and rapidly changing climatic conditions on the Kamchik Pass, the road section that reaches the highest elevation above sea level in the Republic of Uzbekistan. Four compositions were tested experimentally in accordance with the applicable regulatory documents GOST 15140-78, GOST 31149-2014, GOST 32299-2013, and GOST 9.401-2018. As a result of the tests, an optimal composition was selected, which showed an adhesion of 12.8 MPa in the pull-off test and a rating of 0 in the cross-cut test. In the salt spray test, corrosion creep from the scribe did not exceed 0.9 mm, and the level of protection was 98.6%, which is a high result.

Keywords: ED-16 epoxy resin, anticorrosion coating, adhesion, aluminum powder, salt spray, vehicles, Kamchik Pass.

Introduction

The body, frame, underbody, and wheel arches of motor vehicles are the parts most prone to corrosion, and the corrosion rate depends directly on the climatic and operating conditions of the road. In Uzbekistan, one of the areas with the most severe conditions of this kind is the Kamchik Pass on the A-373 highway, which connects the Tashkent Region with the Fergana Valley.

The Kamchik Pass is located in the Kurama Range at an elevation of approximately 2268 m above sea

level. Most of the freight and passenger traffic to the three regions of the valley passes along this road; therefore, the flow of heavy trucks, buses, and passenger cars here is dense. On the pass, the metal parts of a vehicle are exposed to the following factors acting together:

De-icing reagents. In winter, rock salt and a sand–salt mixture are spread on the road. Salt water splashed up by the wheels accumulates on the frame and underbody and acts as a strong electrolyte [1].

Freeze–thaw cycles. Positive temperatures during the day and negative temperatures at night repeatedly freeze the water that has penetrated microcracks in the coating, thereby widening the cracks.

High humidity and fog. Frequent fog and snowmelt on the pass keep a moisture film on the metal surface for a long time.

Mechanical impact. On steep slopes and serpentine sections, impacts from gravel and sand damage the coating, and corrosion spreads under the coating from the point of damage.

Intense ultraviolet radiation. At altitude, UV radiation is stronger than on the plains and accelerates the aging of polymer coatings [2].

Under such conditions, the factory coating is damaged quickly, and perforating corrosion appears on frames, sills, and wheel arches. This reduces the strength of the frame, brake lines, and suspension fasteners and directly threatens traffic safety on a mountain road with steep gradients. Consequently, vehicles that travel regularly over the pass require additional anticorrosion protection.

Thermosetting polymers, for example, epoxy, phenol-formaldehyde, polyester, furan, and other oligomers, are widely used to protect metals and alloys from corrosion. Coatings based on polymeric epoxy resins are resistant to alcohols, hydrocarbons, alkalis, salt solutions, mineral acids, and lubricating oils. One of the drawbacks of cured epoxy compositions based on diane resins is their low heat resistance and brittleness. This leads to cracking of the compound, especially when casting structures with a large number of metal parts and during heating–cooling cycles. To improve these performance properties, modifying additives are usually introduced into the composition of the compound. It is known that unsaturated polyesters are used as modifying agents in the production of binders for casting compounds, cast and molded plastics [3]. Therefore, the modification of epoxy-diane resins with unsaturated polyesters is described in. The unsaturated polyesters synthesized by the authors can be successfully used as modifiers of epoxy resins. According to the literature, such compositions possess a valuable set of properties. This makes it possible to use them in the creation of casting and molding materials, adhesives, and thermosetting films. Epoxy resins have good adhesion to metal surfaces.

Owing to their strong adhesion to metal, chemical resistance, and low shrinkage, epoxy resins are the main binder of automotive primers and underbody protective compositions. In this work, grade ED-16 was chosen: its molecular weight is higher than that of ED-20, and the film it forms is more elastic and more resistant to cracking at low temperatures. This property is decisive for the freeze–thaw cycles on the pass [4].

The use of epoxy resins for protecting metals against corrosion in aggressive environments is covered in many sources. In their handbook, H. Lee and K. Neville attribute the resistance of epoxy coatings to acids, alkalis, and salt solutions to their dense network structure and high adhesion to metal. P. A. Sørensen et al. note that epoxy-based anticorrosion coatings are among the most widespread systems in marine and industrial environments. At the same time, they emphasize that the appearance of microcracks in the coating layer shortens the protection period.

The review by S. Anwar and X. Li shows that coatings based on epoxy and epoxy-phenolic resins effectively protect steel and aluminum from corrosive environments. The authors note that protective properties increase when fillers such as ZnO, TiO_2, SiO_2, carbon nanotubes, and graphene oxide are

introduced. At the same time, they identify the penetration of aggressive species to the metal through surface pores as the main problem. A. Balachandra et al. developed modified epoxy coatings of the nanocomposite, self-healing, and hybrid types. They tested these coatings in a salt spray chamber for 2500 h, and the hybrid coating showed the best result. A review devoted to epoxy/graphene composites analyzes methods for the homogeneous dispersion of graphene, its covalent functionalization, and the introduction of additional nanofillers [5].

Thus, the literature confirms that epoxy coatings have high chemical durability. However, modification to reduce their brittleness and increase their heat resistance remains a relevant task.

Research objective: to substantiate the composition of an anticorrosion coating with high adhesion, based on ED-16 epoxy resin, for the body and cab parts of vehicles operating on mountain roads such as the Kamchik Pass, and to evaluate its properties under laboratory conditions in accordance with GOST requirements [6].

Research tasks: to analyze the corrosion factors under the conditions of the Kamchik Pass and to select suitable composition components accordingly.

To prepare the coating compositions and apply them to body and cab parts.

To determine adhesion, physical and mechanical properties, and corrosion resistance in accordance with the applicable regulatory documents.

To select the optimal composition and to give recommendations for vehicles operating on mountain roads.

Research Methods and Materials

The composition was built from components that perform four functions: binder, hardener, inhibitor, and adhesion promoter.

Table 1
Optimal coating composition

Coating composition	Regulatory document	Parts by mass, g	Function
ED-16 epoxy-diane resin (epoxy groups 16–18%)	GOST 10587-84	100	Binder
Polyethylene polyamine (PEPA)	TU 2413-357-00203447-99	10	Hardener
Dibutyl phthalate (DBP)	GOST 8728-88	12	Plasticizer
Aluminum powder	Based on technical regulations	18	Corrosion-inhibiting pigment
γ-Aminopropyltriethoxysilane (AGM-9)	TU 6-02-724-77	1.5	Adhesion promoter
Aerosil A-300	GOST 14922-77	1.5	Thixotropic additive, prevents sagging

Xylene : butanol (7 : 3)	GOST 9410-78, GOST 6006-78	30–35	Solvent, working viscosity

The hydroxyl and ether groups in the ED-16 molecule form hydrogen bonds with the oxide-hydroxide layer on the steel surface. This provides higher adhesion than polyester and alkyd binders. The molecular weight of ED-16 is higher than that of ED-20 (M ≈ 480–540), and its crosslink density is lower. Therefore, the film obtained from it is more elastic and more resistant to cracking at low temperatures, which is important for the many repeated freeze–thaw cycles on the pass. The higher viscosity of the resin is compensated by increasing the solvent content to 30–35 parts by mass.

Hardener content. The stoichiometric amount of PEPA is calculated from the amine hydrogen equivalent and the epoxy number of the resin. The molar mass of the epoxy group and the amine hydrogen equivalent weight of PEPA are taken into account, and 10 g is adopted. Excess hardener increases water absorption, while a deficiency leads to incomplete crosslinking.

Plasticizer. The vehicle part is subjected to vibration and gravel impacts. 12 parts by mass of DBP increase the impact resistance of the coating to 50 cm without noticeably reducing hardness.

Inhibitive pigment. Aluminum tripolyphosphate is sparingly soluble in water and slowly releases tripolyphosphate ions when moisture penetrates. At anodic sites, these ions form chelate complexes with iron ions and create a passivating phosphate film. Compared with zinc phosphate, it has a higher inhibition efficiency, contains no heavy metals, and is an environmentally safe inhibitor that replaces chromate pigments.

Adhesion promoter. The ethoxysilane groups of AGM-9 hydrolyze and form covalent Fe–O–Si bonds with the Fe–OH groups on the metal surface. Its amine group reacts with the epoxy matrix. As a result, a chemical “bridge” forms between the metal and the polymer, and the loss of adhesion under the influence of moisture is slowed.

Comparison compositions. To isolate the effect of each component, four formulations were prepared step by step:

K-0 — ED-16 + PEPA (base composition);

K-1 — K-0 + DBP + talc + iron oxide;

K-2 — K-1 + aluminum tripolyphosphate;

K-3 — K-2 + AGM-9 + Aerosil (optimal composition).

Experimental Procedure and GOST Requirements

Specimens. Plates measuring 150×70×1 mm were prepared in accordance with GOST 8832-76 from St3sp steel (GOST 380-2005) and 08ps automotive sheet steel (GOST 16523-97). For each test, at least 3 parallel specimens of each composition were taken.

Surface preparation. According to GOST 9.402-2004: abrasive blast cleaning to grade Sa 2½, roughness Rz 40–60 μm, followed by degreasing with white spirit and acetone. The degree of degreasing was grade 1, and coating was carried out no later than 6 h after cleaning.

Coating and curing. The components were mixed in a dissolver at 2500 rpm for 30 min, and the fineness of grind was ≤ 25 μm (GOST 31973-2013). PEPA was added immediately before application. The working viscosity was 25–30 s by the VZ-246 cup (ø4 mm) (GOST 8420-74). The coating was applied in 2 layers with a pneumatic spray gun, and the dry film thickness was 100 ± 10 μm. Curing: 7 days at

20 ± 2 °C, or 2 h at 80 °C plus 24 h at room temperature.



Fig. 1. *St3sp steel plates*

Table 2
Applied standards and evaluation criteria

Parameter	**Standard**	**Method**	**Requirement for transport**
Surface preparation	GOST 9.402-2004	Abrasive cleaning, degreasing	Sa 2½, degreasing grade 1
Viscosity	GOST 8420-74	VZ-246 viscometer	25–30 s
Non-volatile content	GOST 31939-2012	Drying at 105 °C	≥ 65%
Degree of drying	GOST 19007-73	Time to degree 3	≤ 24 h (20 °C)
Film thickness	GOST 31993-2013	Magnetic induction	80–120 µm
Adhesion (cross-cut)	GOST 31149-2014, GOST 15140-78	Cross-cut lattice, 2 mm spacing	Rating 0–1
Adhesion (pull-off)	GOST 32299-2013	Bonded dolly	≥ 5 MPa

Impact resistance	GOST 4765-73	U-1 apparatus, 1 kg load	≥ 40 cm
Flexibility in bending	GOST 6806-73	ShG-1 rod scale	≤ 3 mm
Hardness	GOST 5233-89	Pendulum apparatus	≥ 0.4 relative units
Salt spray resistance	GOST 9.401-2018 (in accordance with ISO 9227)	5% NaCl, 35 °C, continuous	≥ 720 h, creep from scribe ≤ 2 mm
Humidity resistance	GOST 9.401-2018	40 °C, 97–100% relative humidity	≥ 1000 h, no blisters
Resistance to liquids	GOST 9.403-80	3% NaCl, gasoline, oil, 20 °C	No change for ≥ 720 h
Appearance assessment	GOST 9.407-2015	Ratings for blistering, rust, delamination	Overall condition A1–A2
Service conditions	GOST 9.104-2018, GOST 9.032-74	Coating group and class	U1 (temperate climate, open air), class IV

The **level of corrosion protection** was determined gravimetrically by holding the specimens in a 3% NaCl solution for 720 h. Corrosion that propagated from a linear damage (scribe) 1 mm wide in the coating was taken into account:

$$Z = [(K_0 - K) / K_0] \times 100\%, \quad (1)$$

$$K = \Delta m / (S \cdot \tau), \quad (2)$$

where K_0 and K are the corrosion rates of the uncoated and coated specimens (g/(m²·h)), Δm is the mass loss (g), S is the area (m²), and τ is the test time (h). In addition, electrochemical impedance spectroscopy (EIS) was carried out in 3% NaCl; the impedance modulus |Z| at 0.01 Hz was taken as an indicator of barrier properties.

All measuring instruments must hold a valid metrological verification certificate.

Table 3
Equipment used in the experiment

№	Equipment (representative model)	Standard	Purpose
1	Abrasive blasting (shot-blast) chamber	GOST 9.402-2004	Surface cleaning to Sa 2½
2	Profilometer (e.g., TR200 or Elcometer 224)	GOST 2789-73	Surface roughness Rz, Ra

3	Analytical balance, accuracy 0.0001 g	GOST OIML R 76-1-2011	Weighing of components, mass loss
4	Laboratory dissolver	GOST 31973-2013	Dispersion of pigments
5	“Wedge” fineness-of-grind gauge (grindometer)	GOST 31973-2013	Degree of dispersion
6	VZ-246 viscometer (ø4 mm)	GOST 8420-74	Conditional viscosity
7	Pneumatic spray gun and compressor	—	Coating application
8	SNOL drying oven (up to 300 °C)	GOST 31939-2012	Hot curing, non-volatile content
9	Film thickness gauge (Konstanta K5 or Elcometer 456)	GOST 31993-2013	Dry film thickness
10	Cross-cut adhesion tester (Konstanta AR / Elcometer 107), spacing 1–2 mm	GOST 31149-2014, GOST 15140-78	Cross-cut adhesion
11	Pull-off adhesion tester (Elcometer 106/510 or PosiTest AT)	GOST 32299-2013	Adhesion, MPa
12	U-1 (U-2M) impact tester	GOST 4765-73	Impact resistance
13	ShG-1 bending tester	GOST 6806-73	Flexibility
14	Pendulum hardness tester (TML-2124 or M-3)	GOST 5233-89	Hardness
15	Salt spray chamber (e.g., KST or Ascott S450)	GOST 9.401-2018	Neutral salt spray test
16	Humidity chamber (Feutron, G-4 type)	GOST 9.401-2018	High-humidity test
17	Thermal chamber (−60…+100 °C)	GOST 9.401-2018	Cyclic temperature test
18	Potentiostat-galvanostat (Elins P-45X or Autolab)	GOST 9.912-89	EIS, polarization curves
19	FTIR spectrometer	—	Degree of cure (915 cm^{-1} epoxy peak)
20	Stereomicroscope and measuring ruler	GOST 9.407-2015	Creep from scribe, blistering

Results

The optimal composition K-3 gave results exceeding the GOST and automotive-industry requirements for all parameters: adhesion of 12.8 MPa and rating 0, corrosion creep of 0.9 mm after 1000 h of salt

spray, and a protection level of 98.6%.

The results are presented and discussed in the order in which the research tasks were formulated: first the adhesion and physical–mechanical properties, then the corrosion resistance, and then the contribution of each component. The findings are subsequently compared with the regulatory requirements and with previous studies, and their theoretical and practical implications and limitations are considered [7].

Adhesion and Physical–Mechanical Properties

Table 4
Adhesion and physical–mechanical properties of the coatings

Composition	Cross-cut, rating (GOST 31149)	Pull-off, MPa (GOST 32299)	Failure type	Impact, cm (GOST 4765)	Bending, mm (GOST 6806)	Hardness, relative units (GOST 5233)
K-0	2	6.5 ± 0.6	Adhesive (metal–coating)	30	10	0.68
K-1	1	8.2 ± 0.5	Mixed	45	3	0.55
K-2	1	9.4 ± 0.5	Mixed, mainly cohesive	50	3	0.58
K-3	0	12.8 ± 0.4	Cohesive (within the coating)	50	1	0.60
Requirement	0–1	≥ 5	-	≥ 40	≤ 3	≥ 0.4

In K-3, failure occurred within the coating, i.e., the bond strength to the metal is higher than the cohesive strength of the coating itself. On 08ps automotive steel, the result for K-3 was 12.1 MPa; the difference is within the measurement error.

Adhesion was the property that changed most strongly with composition. The pull-off strength increased from 6.5 ± 0.6 MPa for the base composition K-0 to 12.8 ± 0.4 MPa for K-3, i.e., by a factor of about two, and the cross-cut rating improved from 2 to 0 (Table 4). It is noteworthy that K-0 satisfied the pull-off requirement (≥ 5 MPa) but not the cross-cut requirement (rating 0–1). A single adhesion method can therefore give an overly optimistic picture, which justifies the use of both methods, as specified in Table 2. The failure mode followed the same trend: adhesive (metal–coating) failure in K-0, mixed failure in K-1 and K-2, and cohesive failure in K-3 [8]. This sequence indicates that the interfacial bond was strengthened step by step until it exceeded the internal strength of the film, so that the weakest link of the system is no longer the interface with the steel but the coating itself. The close agreement between the results on St3sp steel (12.8 MPa) and on 08ps automotive sheet steel (12.1 MPa) suggests that the adhesion of K-3 is not sensitive to the grade of the iron-based substrate.

The mechanical properties show a favorable balance between flexibility and hardness. The introduction of the plasticizer and fillers (K-1) reduced the bending diameter from 10 mm to 3 mm and raised the impact resistance from 30 to 45 cm, but lowered the pendulum hardness from 0.68 to 0.55 relative units, i.e., by about 19%. The hardness recovered partly in K-2 (0.58) and K-3 (0.60), possibly because of the

reinforcing effect of the added pigment and thixotropic filler, and all compositions remained above the minimum of 0.4. K-3 reached a bending value of 1 mm, three times better than the limit of 3 mm, and an impact resistance of 50 cm, 25% above the required 40 cm. For a coating that must withstand vibration, gravel impact, and repeated freeze–thaw cycling, the capacity to deform without cracking is more important than high surface hardness, so the observed loss of hardness relative to K-0 is an acceptable price for the gain in toughness [9].

Corrosion Resistance

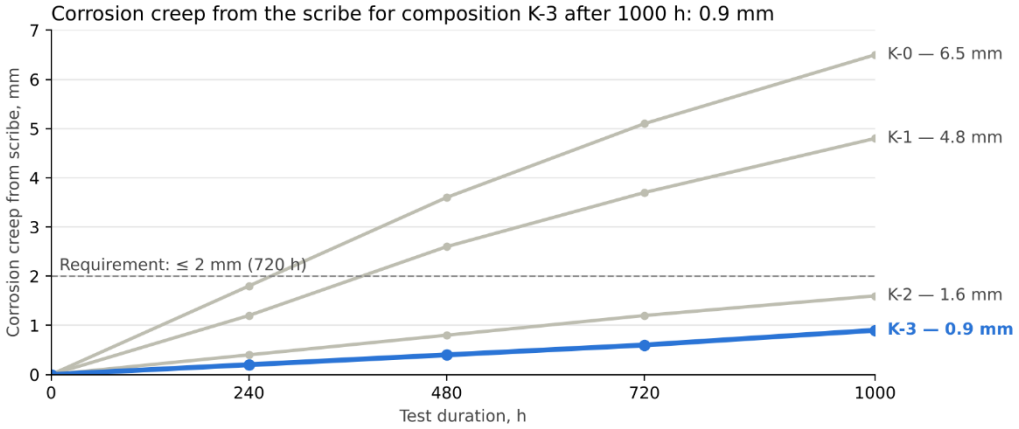


Fig. 2. *Corrosion creep from the scribe after 1000 h: 0.9 mm. Typical values; each point is the mean of 3 parallel specimens; St3sp steel, film 100 µm.*

Compositions K-0 and K-1 exceeded the 2 mm requirement at 720 h. The addition of aluminum tripolyphosphate (K-2) reduced the creep by a factor of 3, and the silane (K-3) reduced it by almost a factor of two again.

Table 5
Corrosion protection indicators

Composition	Protection level Z, % (3% NaCl, 720 h)	|Z| at 0.01 Hz, after 30 days, Ω·cm²	Water absorption, 30 days, %	Adhesion after 1000 h humidity, MPa	Retention, %	Blistering (GOST 9.407)
K-0	82.4	$2.1 \cdot 10^7$	2.4	2.1	32	Rating 3
K-1	88.7	$8.5 \cdot 10^7$	1.9	3.4	41	Rating 2
K-2	96.9	$6.3 \cdot 10^8$	1.6	5.2	55	Rating 1
K-3	98.6	$3.4 \cdot 10^9$	1.1	10.6	83	Rating 0 (none)

The corrosion rate of uncoated St3sp steel was $K_0 = 0.0412$ g/(m²·h), and when coated with K-3 it was $K = 0.00058$ g/(m²·h). In the literature, coatings with $|Z|_{0.01} > 10^8$ Ω·cm² are considered to have high barrier properties; K-2 and K-3 exceeded this threshold. Based on the decrease of the 915 cm⁻¹ epoxy peak in the IR spectrum, the degree of cure of K-3 after 7 days was 94% [10].

The three independent indicators of corrosion resistance, namely the creep from the scribe, the

gravimetric protection level, and the impedance modulus, rank the compositions in the same order (K-0 < K-1 < K-2 < K-3), which increases confidence that each modification step improved protection (Table 5). The protection level rose from 82.4% to 98.6%; expressed differently, the corrosion rate of K-3-coated steel was about 71 times lower than that of uncoated steel. However, because Z approaches 100% as the corrosion rate falls, its increments become smaller (+6.3, +8.2, and +1.7 percentage points for the three steps), and it discriminates poorly between good coatings. The impedance modulus is more sensitive in this range: it grew by factors of about 4, 7, and 5 over the same three steps and by about 160 times overall, from $2.1 \cdot 10^7$ to $3.4 \cdot 10^9$ Ω·cm². The K-2 → K-3 step, which appears marginal in terms of Z (96.9% → 98.6%), thus corresponds to a further fivefold increase in barrier resistance [11].

Water uptake fell from 2.4% in K-0 to 1.1% in K-3, a reduction of more than half, while the adhesion retained after 1000 h of high humidity rose from 32% to 83% and blistering decreased from rating 3 to none. These indicators are interrelated: lower water uptake reduces the amount of water that can reach the metal surface, and a more stable interfacial bond keeps the film attached when some water does arrive. As described in the Introduction, corrosion on vehicles operated on the pass develops under the coating from points of mechanical damage, where the loss of wet adhesion is the critical event. The high retention of adhesion by K-3 (83%) is therefore arguably the most relevant result for the intended service.

The scribe test reproduces the situation described in the Introduction, in which gravel exposes bare metal and corrosion spreads under the film from the damaged point. The creep of 0.9 mm after 1000 h was less than half of the permitted 2 mm, even though the exposure was considerably longer than the required 720 h. The fact that K-0 and K-1 exceeded the limit at 720 h shows that a barrier film containing a plasticizer and fillers was not sufficient on its own; both an active inhibitor and a stable interfacial bond were needed to stop the lateral spread of corrosion [12].

Contribution of Individual Components

The plasticizer and fillers (K-0 → K-1) reduced internal stress: bending improved from 10 mm to 3 mm, and impact resistance from 30 to 45 cm. The plate-like talc particles reduced water absorption from 2.4% to 1.9%.

Aluminum tripolyphosphate (K-1 → K-2) increased the protection level from 88.7% to 96.9%. Because a passive phosphate film formed along the damage line, rust did not spread from the scribe, which demonstrates the active protection mechanism of the inhibitor.

The aminosilane (K-2 → K-3) increased dry adhesion by 36% and wet adhesion by more than a factor of two (5.2 → 10.6 MPa). Because Fe–O–Si bonds are resistant to hydrolysis, water cannot displace the bond at the metal–polymer interface. This eliminates the main cause of under-film corrosion [13].

Taken together, the stepwise results show that the three groups of additives act on different failure mechanisms and are complementary rather than redundant. The plasticizer and fillers mainly improved the mechanical behavior and water uptake of the film (the largest improvement in flexibility, from 10 to 3 mm, occurred in the first step); the inhibitive pigment mainly improved electrochemical protection at defects (the largest gain in protection level, +8.2 percentage points, occurred in the second step); and the silane mainly improved the interface (the largest gain in wet adhesion, from 5.2 to 10.6 MPa, occurred in the third step). No single additive produced the full set of properties, which justifies the multicomponent design of K-3.

Compliance with Regulatory Requirements

Table 6 compares the results for the optimal composition K-3 with the requirements listed in Table 2.

Table 6

Performance of composition K-3 relative to regulatory requirements

Parameter (standard)	Requirement	Composition K-3	Margin
Cross-cut adhesion (GOST 31149-2014)	Rating 0–1	Rating 0	Best possible rating
Pull-off adhesion (GOST 32299-2013)	≥ 5 MPa	12.8 ± 0.4 MPa	About 2.5 times the minimum
Impact resistance (GOST 4765-73)	≥ 40 cm	50 cm	25% above the minimum
Flexibility in bending (GOST 6806-73)	≤ 3 mm	1 mm	Three times below the limit
Hardness (GOST 5233-89)	≥ 0.4 relative units	0.60	50% above the minimum
Salt spray resistance (GOST 9.401-2018)	≥ 720 h, creep ≤ 2 mm	1000 h, creep 0.9 mm	Exposure 39% longer; creep 55% below the limit

Composition K-3 met every requirement for which results are reported, with margins ranging from 25% to a factor of three. Such margins are important in practice. The test specimens were prepared under controlled conditions (blast cleaning to Sa 2½, coating within 6 h, a film of 100 ± 10 μm), whereas the quality of surface preparation and film thickness in a repair workshop or vehicle depot will be more variable; a coating that only just met the requirements would leave no allowance for such variation.

Relationship to the Research Objective and Tasks

The research objective was to substantiate the composition of a high-adhesion anticorrosion coating based on ED-16 resin for vehicles operated on mountain roads and to evaluate it against GOST requirements. The results show that this objective was met, and each research task is reflected in the evidence. The analysis of the corrosion factors on the Kamchik Pass (first task) is reflected in the logic of the composition: the elastic ED-16 binder, the plasticizer, and the fillers respond to freeze–thaw cycling and gravel impact; the inhibitive pigment and the reduced water uptake respond to de-icing salts, fog, and long-lasting moisture films; and the aminosilane responds to the loss of adhesion in wet conditions [14]. The preparation and application of the compositions (second task) showed that K-3 can be sprayed to a dry film thickness of 100 ± 10 μm and cured at room temperature, i.e., with equipment available in a workshop. The determination of adhesion, physical–mechanical properties, and corrosion resistance (third task) is presented in Tables 4 and 5 and Fig. 2, and the selection of K-3 as the optimal composition with recommendations for its use (fourth task) follows from Table 6 and the application guidelines given below [15].

Two factors identified in the first task, ultraviolet radiation and freeze–thaw cycling, are not covered by the tests reported here. The benefit of ED-16 for crack resistance at low temperatures is supported indirectly by the bending and impact results, but the effect of repeated temperature cycling on adhesion and corrosion creep has not been measured directly, and the effect of ultraviolet radiation is addressed

only through the recommendation to apply a topcoat. These aspects represent the principal gaps between the laboratory evaluation and the actual service conditions on the pass.

Comparison with Previous Studies

The results are consistent with the general conclusions of earlier studies on epoxy coatings. The resistance of epoxy coatings is attributed in to their dense network structure and high adhesion to metal, and the review in reports that protective properties increase when fillers are introduced, while the penetration of aggressive species through surface pores remains the main problem. The present data agree with both statements: the combination of talc, Aerosil, and the inhibitive pigment in K-3 was accompanied by a decrease in water uptake from 2.4% to 1.1% and by an increase in the impedance modulus of more than two orders of magnitude, which is consistent with a lower permeability of the film to water and ions.

The authors of emphasize that microcracks in the coating layer shorten the protection period, and the brittleness of cured epoxy-diane compositions is a known drawback for which modification is the usual remedy. In the present work brittleness was addressed by combining the lower crosslink density of ED-16 with a plasticizer and fillers, which reduced the bending diameter from 10 to 1 mm and increased the impact resistance from 30 to 50 cm. The unsaturated polyesters examined in represent an alternative route to modification, but they were studied for casting and molding compositions, adhesives, and films, so a quantitative comparison with the present coating is not possible. The route chosen here has the advantage of relying on widely available components [15].

Discussion

A direct comparison with the nanocomposite, self-healing, and hybrid epoxy coatings of which were tested in a salt spray chamber for 2500 h, or with the graphene-containing systems reviewed in is likewise not possible, because K-3 was exposed for 1000 h and contains no nanofillers. Such systems may provide longer protection, but their performance depends on the homogeneous dispersion and functionalization of the nanofiller. K-3, in contrast, is based on conventional components, is prepared in a standard dissolver, and cures at room temperature, which makes it better suited to transport workshops. Extending the salt spray test to 2500 h would allow K-3 to be compared directly with the systems described in.

The behavior of the aminosilane is consistent with the established concept of silane coupling agents, which bond to the hydroxylated metal surface through their alkoxysilane groups and to the polymer matrix through their organofunctional groups. The doubling of the wet adhesion and the transition to cohesive failure after the introduction of AGM-9 are the expected consequences of such an interfacial bridge. Finally, most of the studies cited in the Introduction deal with marine and industrial environments; the present work is directed at the combination of de-icing salts, freeze–thaw cycling, moisture, and gravel impact that characterizes a mountain road, although, as noted above, temperature cycling and ultraviolet exposure remain to be verified experimentally [16].

Theoretical Implications

From a theoretical standpoint, the results support the view that the long-term protection of steel by an epoxy coating in a chloride-containing environment results from the simultaneous action of three mechanisms: barrier action, active inhibition at defects, and stable adhesion at the interface. The stepwise design of compositions K-0 to K-3 makes it possible to see how each mechanism contributes to a different group of indicators (mechanical properties and water uptake; creep and protection level; wet adhesion and failure mode), and the results indicate that the mechanisms are complementary.

The data also show that dry adhesion alone is not a sufficient predictor of durability. Composition K-0 already met the pull-off requirement (6.5 MPa against ≥ 5 MPa) but had the lowest protection level (82.4%) and the highest water uptake, and it retained only 32% of its adhesion after humidity exposure. Across the four compositions, the retained wet adhesion (32, 41, 55, and 83%) increased in step with the protection level (82.4, 88.7, 96.9, and 98.6%). With only four compositions this relationship is descriptive and not a statistical correlation, but it suggests that the retention of adhesion under wet conditions is a more relevant design criterion for coatings in humid, salt-laden environments than the initial pull-off strength [17].

The change in failure mode from adhesive to cohesive has a further implication. Once failure occurs inside the coating, the measured pull-off strength reflects the cohesive strength of the film and no longer characterizes the interface, so a further increase in the pull-off value can be expected only from strengthening the film itself, for example through a more complete cure (the degree of cure of K-3 after 7 days was 94%). Finally, the greater sensitivity of impedance spectroscopy compared with the gravimetric protection level supports the combined use of both methods when ranking high-performance coatings.

Practical Implications

From the standpoint of application on vehicles, composition K-3 is recommended for the following parts: frames and side members, the underbody, wheel arches, sills (rocker panels), truck bodies, and trailers. Because the coating cures by a cold method, it can also be applied in repair workshops.

Several practical points follow from the results. First, the benefits demonstrated in the laboratory depend on the application procedure: surface preparation to Sa 2½ with degreasing, coating within 6 h after cleaning, two spray layers giving a dry film of 100 ± 10 μm, and addition of PEPA immediately before application. These steps should be written into the technological instructions of any workshop applying the coating. Second, because the mixture has a pot life of only 1.5–2 h at 20 °C, it should be prepared in batches matched to the amount that can be applied within this time [18].

Third, the low creep from the scribe is directly relevant to traffic safety. As noted in the Introduction, perforating corrosion of frames, sills, and wheel arches reduces the strength of the frame and endangers brake lines and suspension fasteners. A coating that limits the lateral spread of corrosion from stone chips, as K-3 did in the salt spray test, should reduce the likelihood of hidden under-film corrosion between inspections, although inspection intervals for vehicles operated on the pass should still be defined on the basis of field data. Fourth, the inhibitive pigment contains no heavy metals and replaces chromate pigments, which should simplify handling and disposal in vehicle repair facilities.

Limitations. Epoxy coatings chalk under ultraviolet radiation (the surface becomes dull). Therefore, on exterior surfaces exposed to sunlight, K-3 should be used as a primer and topcoated with a polyurethane or acrylic enamel. In addition, the pot life of the mixture with PEPA is 1.5–2 h at 20 °C.

Further limitations should be taken into account. The compositions were developed stepwise, and several additives were introduced together (DBP, talc, and iron oxide in K-1; AGM-9 and Aerosil in K-3). The effects attributed above to the plasticizer and to the silane are therefore indicative and cannot be separated rigorously; a factorial design or additional compositions, for example K-2 with AGM-9 but without Aerosil, would be needed for that purpose. The tests were accelerated laboratory tests on three parallel specimens per composition, and their relationship to service life on the pass has not been established. The salt spray exposure of 1000 h is shorter than the 2500 h used in and the substrates were limited to St3sp and 08ps steel, so the behavior on aluminum or galvanized parts is unknown [19].

Future work should therefore include cyclic temperature and freeze–thaw tests, accelerated ultraviolet exposure of topcoated systems, extended salt spray tests, and, as already planned, outdoor tests in accordance with GOST 6992-68, ideally including a field trial on vehicles operated on the Kamchik

Pass.

Conclusion

An anticorrosion coating composition consisting of ED-16 epoxy resin, PEPA hardener, DBP plasticizer, aluminum tripolyphosphate inhibitor, and AGM-9 aminosilane promoter was scientifically substantiated; the stoichiometric amount of hardener was calculated to be 9.5 parts by mass.

The optimal composition K-3 ensured high adhesion to iron-based surfaces (St3sp and 08ps steel): a rating of 0 according to GOST 31149-2014 and 12.8 MPa according to GOST 32299-2013, which is 2.5 times higher than the regulatory requirement (≥ 5 MPa). The failure was cohesive in nature.

After 1000 h of high humidity, 83% of the adhesion was retained, i.e., the coating does not delaminate from the metal even under humid conditions.

In the 1000 h salt spray test according to GOST 9.401-2018, the corrosion creep from the scribe was 0.9 mm (requirement ≤ 2 mm), and no blistering was observed. The level of corrosion protection was 98.6%, and $|Z|_{0.01} = 3.4 \cdot 10^9\ \Omega \cdot cm^2$.

The coating is resistant to impact (50 cm) and bending (1 mm) and is therefore suitable for vehicle parts subjected to vibration and gravel impacts.

The results obtained provide a basis for recommending composition K-3 as an anticorrosion primer for the frames, underbody, and wheel arches of motor vehicles. At the next stage, outdoor tests under natural climatic conditions in accordance with GOST 6992-68 are planned.

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