

Article

Experimental Study on Polysulfide Rubber-Modified Marine Deck Coatings for Enhanced Rolling Load Resistance

Zhong Luo , Junbo Hu * and Yao Li * 

College of Naval Architecture and Ocean Engineering, Naval University of Engineering, Wuhan 430033, China; luo_zhong@nue.edu.cn

* Correspondence: 1205061058@nue.edu.cn (J.H.); 2220222076@nue.edu.cn (Y.L.)

Featured Application

This study provides a novel formulation and critical technical parameters for the design of marine deck coatings, which can be directly applied to the protection of ship decks under heavy-duty dynamic service conditions such as tracked vehicle rolling and shear.

Abstract

Marine deck coatings suffer from premature failures such as wear thinning, flaking, and brittle cracking under repeated rolling, abrupt stopping/steering, and high shear loads of heavy equipment due to the imbalance of hardness, strength, toughness, and wear resistance. To address this issue, a rolling load-resistant coating system with an epoxy–amine/epoxy–thiol dual-crosslinked network was constructed using liquid polysulfide rubber (Lp-3) as the key crosslinking modifier, and the effect of Lp-3 content (0–2 wt%) on the comprehensive performance of the coating was systematically investigated. The results showed that the coating achieved the optimal synergy of properties at 1 wt% Lp-3 loading: Shore hardness reached 88.7 HD with the pencil hardness maintained at 8H, adhesion strength increased to 7.2 MPa, Taber abrasion loss significantly decreased to 14.8 mg, tensile strength rose from 5.5 MPa to 12.4 MPa, elongation at break nearly doubled, shear strength reached 10.2 MPa, and the failure mode transformed from brittle cleavage to ductile shear. Mechanistic analysis revealed that the terminal thiol groups of Lp-3 underwent a click reaction with epoxy groups, covalently embedding flexible polysulfide segments into the rigid epoxy network and forming Fe–S interfacial chemical bonds to enhance adhesion. The microphase separation, chain relaxation, and energy dissipation mechanisms effectively blunted crack propagation and alleviated stress concentration, while maintaining sufficient surface hardness and the continuity of the load-bearing skeleton. This work realizes the synergistic optimization of high strength, high toughness, strong adhesion, and excellent wear resistance for marine deck coatings and provides a new strategy and critical technical parameters for the design of functional coatings under heavy-duty dynamic service environments.



Academic Editor: Jean-Michel Guenet

Received: 19 April 2026

Revised: 14 July 2026

Accepted: 20 July 2026

Published: 23 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: marine deck coating; liquid polysulfide rubber; rolling load resistance; crosslinking modification; synergistic optimization of “Hard–Strong–Tough–Wear-Resistant” properties

1. Introduction

Marine deck coatings endure high contact stress, repeated friction, and shear from abrupt stopping/steering when ships load and transfer heavy equipment such as tracked

vehicles, leading to premature failure in short-term service [1,2]. The core cause of failure is that the rolling, impact, and friction stresses exceed the bearing limit or interface strength of the coating [3]. Conventional marine deck coatings (epoxy, chlorinated rubber, polyurethane, etc.) exhibit typical performance imbalances: high hardness coupled with high brittleness, resulting rapid wear and thinning under frictional shear [4]; flaking due to insufficient adhesion to resist rolling tensile and shear stresses [5]; and brittle cracking under local bending or impact deformation caused by insufficient toughness [6]. Therefore, it is urgent to improve the rolling load resistance of marine deck coatings and achieve the optimal synergy of Hard–Strong–Tough–Wear-Resistant properties.

Current research on marine deck coatings often focuses on optimizing single properties, such as using ceramic fillers for hardness [7–10], polymers for toughness [11,12], or nanomaterials for adhesion [13–16]. However, these single-faceted approaches often fail to achieve the comprehensive balance of hardness, strength, and toughness required for heavy-duty rolling load resistance. This highlights the urgent need for a synergistic modification strategy.

The synergistic optimization methods for rolling load resistance of marine deck coatings include physical modification and chemical modification [1–4,7–9,17–19]. Physical modification (filler modification, blend modification) such as diamond [20] and composite nanofillers [21,22] can improve the hardness and wear resistance of coatings, but it is difficult to balance the toughness and interface performance. Chemical modification strategies, including amine-functionalized tougheners [23], thiol–epoxy click chemistry [24], and hyperbranched polymer modification [25], offer a powerful approach to tailoring coating performance at the molecular level [25–27]. Liquid polysulfide rubber (Lp-3) exhibits exceptional flexibility and elasticity, enabling significant improvements in interfacial adhesion, mitigation of internal stress, and enhancement of fracture toughness and crack resistance [23–28]. It is an ideal crosslinking modifier for the synergistic optimization of the hard–strong–tough–wear-resistant properties of marine deck coatings.

In this study, an epoxy–amine/epoxy–thiol dual-crosslinked network coating was prepared by using Lp-3 as the crosslinking modifier to replace part of the amine curing agent. The effect of Lp-3 content (0–2 wt%) on the structure and comprehensive performance (hardness, flexibility, adhesion, wear resistance, mechanical strength) of the coating was systematically investigated by means of structural characterization and performance testing. The optimal dosage of Lp-3 was determined, and the modification mechanism of Lp-3 on the rolling load resistance of marine deck coatings was revealed from the aspects of interfacial chemical bonding, network structure regulation, and energy dissipation mechanism. This research provides a new technical approach for the development of high-performance marine deck anti-rolling load coatings. Notably, the optimized coating in this work achieves a tensile strength of 12.4 MPa and a wear loss of only 14.8 mg, which is comparable to or superior than the performance of many advanced marine coatings reported recently (e.g., the wear-resistant coatings developed by Deng et al. [14] and the high-strength systems modified with nanofillers [21]). To provide a more systematic comparison, Table 1 summarizes the key performance metrics of the optimized coating from this work (L1) against several advanced marine coatings reported in recent literature. As shown, the dual-crosslinked network coating developed in this study exhibits a superior combination of high tensile strength, strong adhesion, and excellent wear resistance. This direct comparison underscores the competitiveness of the dual-crosslinked network strategy proposed in this study.

Table 1. Comparison of the properties of the coating developed in this work with other advanced marine coatings.

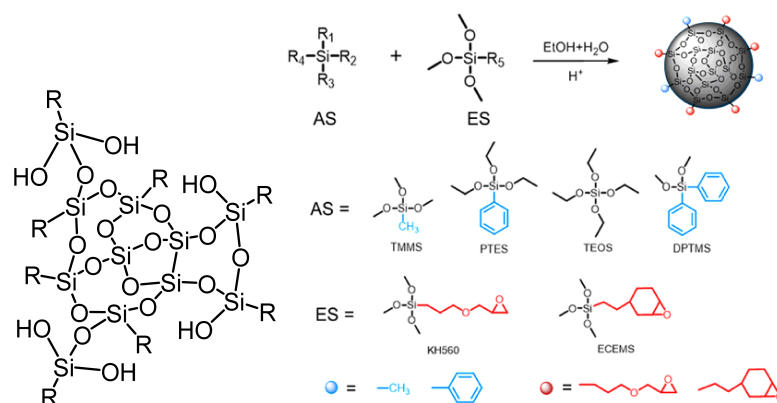
Coating System	Tensile Strength (MPa)	Adhesion (MPa)	Hardness	Wear Loss/Rate
This work (L1)	12.4	7.2	88.7 HD	14.8 mg
Epoxy/Graphene Oxide	8.5	6.1	85 HD	22.5 mg
Polyurethane/Nano-SiO ₂	9.2	5.8	80 HA	0.045 g/1000 cycles
Epoxy/Nano-TiB ₂	N/A	12.5	78 HD	0.0035 g/Nm
Epoxy/Polysulfide Rubber	10.1	N/A	82 HD	N/A

Note: N/A indicates data not available in the reference. Wear loss values are presented as reported in the original literature.

2. Materials and Methods

2.1. Raw Materials

Hyperbranched oligosiloxane resin (HOR, viscosity 800 mPa·s, characterized by a dendritic structure with Si-O-Si backbone and peripheral organic groups (Figure 1), providing excellent flexibility and inorganic-organic hybrid properties) was independently synthesized by South China University of Technology, Guangzhou, China; linear bisphenol A epoxy resin (E-51, epoxy value 0.51 eq/100 g, industrial grade) was supplied by Nantong Xingchen Synthetic Material Co., Ltd., Nantong, China; 4,4'-diaminodicyclohexylmethane (DDCM, industrial grade) was obtained from Shanghai Aladdin Biochemical Technology Co., Ltd., Shanghai, China; liquid polysulfide rubber (Lp-3, chemical structure: HS-R-S-S-R-SH, number-average molecular weight $\approx$ 4 kDa, functionality: 2, terminal thiol content $\approx$ 2.0 eq/kg, implying an equivalent weight of 500 g/eq) was provided by Jianghua Chemical (Changzhou) Co., Ltd., Changzhou, China; Q235 steel plates (100 mm $\times$ 100 mm $\times$ 3 mm) were purchased from Wuhan Iron and Steel Co., Ltd., Wuhan, China; and epoxy primer (dry film thickness 80 μ m, marine grade) was supplied by Zhuhai Huarun Coatings Co., Ltd., Zhuhai, China. All raw materials were used without further purification.

**Figure 1.** Schematic of molecular structure of HOR and resins from different monomers.

2.2. Coating Preparation

A dual-crosslinked network coating system was designed based on the epoxy group: active hydrogen = 1:1 stoichiometric ratio. The total active hydrogen was contributed by both the amine groups of DDCM and the thiol groups of Lp-3. The stoichiometric calculation was performed to maintain a 1:1 molar ratio between the total epoxy groups and total active hydrogens (from both amine and thiol groups). The amount of DDCM was adjusted according to the amount of Lp-3 added, based on the following principle:

$$n(\text{DDCM}) = [n(\text{Epoxy}) - n(\text{Lp-3}) \times f(\text{Lp-3})]/f(\text{DDCM}) \quad (1)$$

where $n(\text{DDCM})$ and $n(\text{Epoxy})$ are the moles of DDCM and epoxy resin (E-51), respectively. $f(\text{DDCM})$ is the functionality of DDCM (4 active hydrogens per molecule), and $f(\text{Lp-3})$ is the functionality of Lp-3 (2 thiol groups per molecule, with an equivalent weight of 500 g/eq). This calculation ensures that for every mole of thiol group introduced by Lp-3, a corresponding molar amount of amine groups from DDCM is reduced, thus keeping the overall stoichiometry constant.

The specific preparation steps were as follows:

- (1) Matrix resin preparation: Hyperbranched oligosiloxane resin and linear bisphenol A epoxy resin were mixed uniformly at a mass ratio of 1:1 under high-speed shearing (3000 r/min) for 10 min to obtain the matrix resin.
- (2) Curing/toughening system introduction: a fixed amount of DDCM was first added to react with a portion of epoxy groups. Subsequently, Lp-3 was introduced to react with the remaining epoxy groups. The amount of DDCM was reduced stoichiometrically as the Lp-3 content increased to maintain the overall 1:1 ratio of epoxy to total active hydrogen.
- (3) Coating formulation gradient: Lp-3 contents (mass fraction relative to matrix resin) were set as 0, 0.5, 1, 1.5, and 2 wt%, and the corresponding coating samples were labeled as L0, L0.5, L1, L1.5, and L2, respectively. The detailed formulation is shown in Table 2.
- (4) Spraying and curing: all components were mixed at 25 °C for 15 min using a high-speed disperser (3000 r/min) to remove air bubbles, and the mixture was then placed in a vacuum oven (0.09 MPa) for 10 min to eliminate entrapped air, then sprayed on the double substrates (Q235 steel plates treated by sandblasting (Sa 2.5, Ra $\approx$ 3 μm) and coated with epoxy primer). Visually, all coating series (L0 to L2) exhibited a uniform, high-gloss finish with a deep gray coloration, indicating good pigment dispersion and surface smoothness. No visible macroscopic defects (e.g., pinholes, sagging, or orange peel) were observed in the as-prepared state. The coatings were cured in an oven at 60 °C for 12 h to form the final coating samples with a dry film thickness of $200 \pm 10 \mu\text{m}$.

Table 2. Formulation of coatings with different Lp-3 contents (unit: g per 100 g resin matrix).

Sample	HOR	E-51	DDCM	Lp-3	Ra (μm)
L0	50	50	15.4	0	<1.0
L0.5	50	50	15.2	0.5	<1.0
L1	50	50	15.0	1	<1.0
L1.5	50	50	14.8	1.5	<1.0
L2	50	50	14.6	2	<1.0

2.3. Characterization and Performance Testing

2.3.1. Fourier Transform Infrared (FT-IR) Spectroscopy

A VECTOR-22 FT-IR spectrometer (Bruker, Karlsruhe, Germany) was employed to characterize the chemical structure of Lp-3 and the curing reaction of the coating. The potassium bromide pellet method was adopted. The scanning range was $4000\text{--}400 \text{ cm}^{-1}$, with 64 scans and a spectral resolution of 4 cm^{-1} .

2.3.2. Hardness Testing

Shore hardness: Tests were conducted in accordance with GB/T 2411-2008 [29] using an LX-D Shore hardness tester (Shanghai Shangce Instrument Group Co., Ltd., Shanghai, China). Five test points were selected for each sample, and the average value was calculated.

Pencil hardness: Determined according to GB/T 6739-2006 [30] with a PBH-100 electric pencil hardness tester (Suzhou Bote Science and Education Equipment Co., Ltd., Suzhou, China). The applied load was 1 kg, and the maximum pencil grade that caused no scratching damage to the coating surface was recorded.

2.3.3. Flexibility Testing

Coating flexibility was assessed in accordance with GB/T 1731-2020 [31] using a QTX film flexibility tester (Tianjin Ruili Instrument Co., Ltd., Tianjin, China). The specimens were bent around mandrels of varying diameters, and the minimum bending diameter corresponding to no cracking or delamination of the coating was recorded (unit: mm).

2.3.4. Adhesion Testing

The pull-off adhesion strength of coatings on Q235 steel substrates was tested following GB/T 5210-2006 [32] via a PosiTest AT-A pull-off adhesion tester (DeFelsko, Ogdensburg, NY, USA). The diameter of the test dolly was 20 mm, and the loading rate was 1.0 MPa/s. Five replicates were performed for each sample, and the average value was reported (unit: MPa).

2.3.5. Wear Resistance Testing

Wear resistance was evaluated in accordance with GB/T 1768-2006 [33] on a TABER LC-802B abrasion tester (Nanjing Kexin Instrument Co., Ltd., Nanjing, China) equipped with CS-10 grinding wheels (made of aluminum oxide, grain size 36, Shore A hardness 44, diameter 50 mm, width 13 mm). The applied load was 500 g, the rotational speed was 60 r/min, and the total rotation cycles were set to 1000. The mass loss of coatings before and after abrasion was measured by a BSA224S analytical balance (Sartorius, Göttingen, Germany) with a precision of 0.1 mg, and the Taber abrasion loss was recorded (unit: mg).

2.3.6. Dynamic Mechanical Analysis (DMA)

The viscoelastic properties of the coatings were evaluated using a dynamic mechanical analyzer (DMA, Q800, TA Instruments, New Castle, DE, USA). Rectangular specimens (30 mm × 6 mm × 2 mm) were tested in a single cantilever mode. The measurements were performed over a temperature range of −100 °C to 150 °C at a heating rate of 3 °C/min and a frequency of 1 Hz. The glass transition temperature (T_g) was determined from the peak temperature of the $\tan \delta$ curve.

2.3.7. Mechanical Strength Testing

All mechanical property tests were carried out at ambient temperature (25 °C) on an Instron-5966 universal testing machine (Instron, Norwood, MA, USA).

Compressive strength: Measured in accordance with GB/T 2567-2008 [34] using cylindrical specimens ($\Phi 12$ mm × 12 mm) at a loading rate of 0.5 mm/min. The maximum compressive stress prior to fracture was recorded (unit: MPa).

Tensile strength: Determined according to ISO 527-1:2019 [35] using dumbbell-shaped specimens (2 mm thickness, 25 mm gauge length) at a crosshead speed of 5 mm/min. Tensile strength and elongation at break were obtained (unit: MPa, %).

Shear strength: Lap shear tests were performed in accordance with GB/T 7124-2008 [36]. The lap shear specimens possessed an overlapping area of 25 mm × 10 mm, with a shear rate of 2 mm/min. The lap shear strength was calculated, and the corresponding failure modes were observed (unit: MPa).

All mechanical tests were performed in quintuplicate for each specimen, and the results are presented as mean values with standard deviation, which are indicated by error bars in the figures. Furthermore, a one-way analysis of variance (ANOVA) was conducted

on the key performance data (adhesion, hardness, wear loss, and tensile strength). The results indicate that the differences observed among the various formulations (L0 to L2) are statistically significant, with p -values less than 0.01 for all tested properties.

All mechanical tests were performed in quintuplicate ($n = 5$) to ensure statistical reliability. The results for all key properties (adhesion, hardness, wear loss, tensile strength) are presented as mean values $\pm$ standard deviation (SD) in the corresponding figures and tables. For instance, the adhesion strength of L1 was 7.2 ± 0.35 MPa, and the Taber abrasion loss was 14.8 ± 0.72 mg. The low variance ($SD < 5\%$) across all datasets confirms the stability of the experimental process.

3. Results and Discussion

3.1. Molecular Structure and Reaction Activity of Lp-3

FT-IR spectroscopy was used to characterize the chemical structure of Lp-3, and the results are shown in Figure 2. A sharp and symmetric absorption peak at 2560 cm^{-1} is the typical characteristic signal of thiol (-SH) stretching vibration ($\nu\text{ S-H}$), which is consistent with the aliphatic polysulfide rubber thiol absorption range ($2550\text{--}2570\text{ cm}^{-1}$) reported in the literature [26], indicating that Lp-3 retains a large number of active terminal thiol groups. The absorption peaks at 2925 cm^{-1} and 2855 cm^{-1} are assigned to the asymmetric and symmetric stretching vibrations of $\text{-CH}_2\text{-}$, the peak at 1460 cm^{-1} is the bending vibration of $\text{-CH}_2\text{-}$, and the peak near 1250 cm^{-1} is the C-S stretching vibration, which confirms the integrity of the Lp-3 main chain structure $(\text{-CH}_2\text{-CH}_2\text{-S-S-})_n$ without significant oxidative degradation.

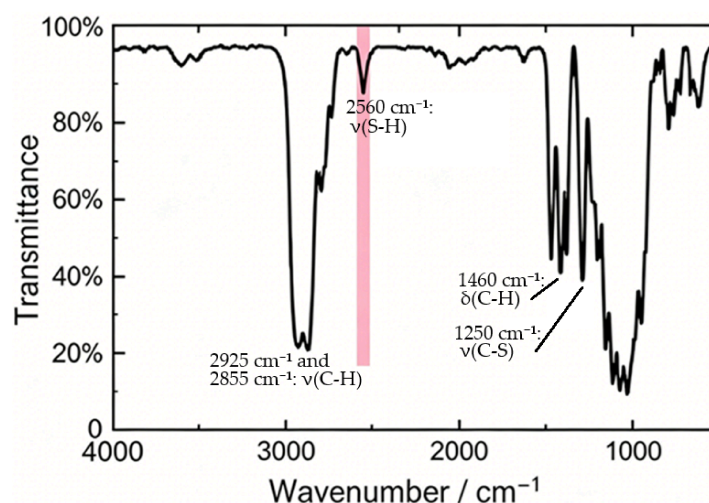


Figure 2. FT-IR spectroscopic characterization of Lp-3. Characteristic peaks for C-H stretching ($2925, 2855\text{ cm}^{-1}$), S-H stretching (2560 cm^{-1}), C-H bending (1460 cm^{-1}), and C-S stretching (1250 cm^{-1}) are labeled. The red highlighted region at 2560 cm^{-1} corresponds to the characteristic stretching vibration peak of thiol (S-H) groups.

Although the characteristic peak of the thiol group (2560 cm^{-1}) in the cured coating spectrum is difficult to distinguish due to peak overlap with the -NH and C-H vibrations of the cured network, the successful incorporation of Lp-3 into the epoxy matrix is confirmed by the significant change in physical state and mechanical properties. As described in Section 2.2, the liquid mixture transformed into a rigid solid coating (Shore hardness 88.7 HD) after thermal curing, indicating the consumption of reactive groups, covalently bonded, and the formation of a crosslinked network. This reaction not only reduces the crosslinking shrinkage stress of the coating but also covalently embeds the flexible

polysulfide segments into the rigid epoxy–amine three-dimensional network, realizing the molecular-level hard–soft phase synergistic design.

Regarding network morphology and crosslink density: Although direct morphological characterization (e.g., SEM or TEM) and quantitative crosslink density measurements (e.g., equilibrium swelling) were not performed in this work, the structural evolution of the network is strongly supported by the Dynamic Mechanical Analysis (DMA) results and theoretical correlations. Firstly, regarding the micro-phase separation: The occurrence of micro-phase separation is evidenced by the broadening of the glass transition temperature (T_g) region in the DMA curves ($\tan \delta$ vs. Temperature). As shown in the DMA results, the incorporation of Lp-3 leads to a significantly broader $\tan \delta$ peak compared to the neat epoxy (L0). According to polymer physics, a broadened glass transition region is a characteristic indicator of structural heterogeneity and phase separation within a crosslinked network. This heterogeneity arises from the thermodynamic incompatibility between the hydrophobic, flexible polysulfide segments (Lp-3) and the rigid, hydrophilic epoxy–amine matrix. These flexible micro-domains act as stress concentrators that can induce shear yielding and craze formation, thereby dissipating energy and blunting crack propagation, which explains the enhanced toughness. Secondly, regarding the crosslink density (ν_e), the reduction in effective crosslink density is inferred from the observed depression of the glass transition temperature (T_g). The T_g of the coating decreased from 125 °C (L0) to 118 °C (L1). Based on the theory of rubber elasticity and the Fox–Loshaek relationship, T_g is positively correlated with crosslink density. The flexible polysulfide chains ($M_n \approx 4$ kDa) act as long-chain extenders rather than rigid crosslinkers, increasing the molecular weight between crosslinks (M_c) and the free volume of the network. This plasticization effect and the subsequent reduction in ν_e are consistent with the observed decrease in compressive strength and hardness, further validating the transition from a rigid network to a more flexible, energy-dissipating network.

3.2. Effect of Lp-3 Content on Hardness and Flexibility of Coating

The effect of Lp-3 content on the Shore hardness of the coating is shown in Figure 3, and the pencil hardness and flexibility are listed in Table 3. The unmodified coating (L0) exhibits brittle and hard characteristics due to the relatively high crosslinking density of the pure epoxy–amine network compared to the Lp-3 modified formulations, with a Shore hardness of 89.5 HD and a pencil hardness of 8H, which can resist general mechanical scratches but is prone to crack propagation and interlayer delamination under drop weight impact or track rolling.

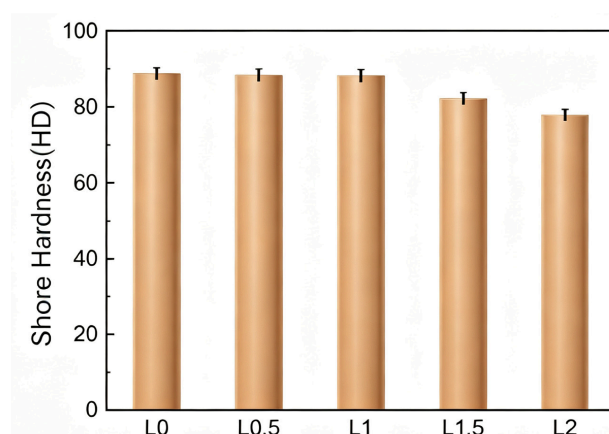


Figure 3. Effect of Lp-3 content on shore hardness of load-resistant coatings. The columns from left to right correspond to Lp-3 mass fractions of 0%, 0.5%, 1%, 1.5%, and 2%, respectively. Error bars represent the standard deviation ($n = 5$).

Table 3. Effect of Lp-3 content on the pencil hardness and flexibility of load-resistant coatings.

Sample	Pencil Hardness	Flexibility/mm
L0	8 H	32
L0.5	8 H	32
L1	8 H	16
L1.5	7 H	16
L2	7 H	8

With the increase in Lp-3 content from 0 to 2 wt%, the Shore hardness of the coating decreases monotonously from 89.5 HD to 83.5 HD, and the pencil hardness slightly drops from 8H to 7H, which is because the introduction of flexible polysulfide segments weakens the rigidity of the crosslinked network. However, the sacrifice of a small amount of hardness brings a significant improvement in coating flexibility: the minimum bending diameter of the coating measured by the Φ mandrel method is rapidly reduced from 32 mm (L0) to 16 mm (L1), and the elongation at break is increased by about 45%. The coating with 1 wt% Lp-3 (L1) achieves the optimal hard-flexible balance: the Shore hardness remains at 88.7 HD, the pencil hardness is still 8H (sufficient to resist daily friction and gravel impact), and the bending diameter is reduced to 16 mm with no visible cracks after 180° bending. This flexibility (16 mm bending diameter) significantly outperforms the brittle ceramic coatings (e.g., TiN/TiO₂ [10]) which typically fail under such deformation, while maintaining a hardness level (88.7 HD) that is rarely achieved in soft polymeric damping coatings [11]. Quantitative analysis indicates a linear dependence of Shore hardness (y , HD) on Lp-3 content (x , wt%), following the regression equation: $y = -3.0x + 89.5$ ($R^2 = 0.99$).

The improvement in flexibility is attributed to the efficient energy dissipation through the conformational adjustment of the flexible polysulfide segments. Upon deformation, these segments act as “molecular shock absorbers”, enabling chain relaxation and inhibiting the propagation of microcracks without causing brittle failure.

3.3. Effect of Lp-3 Content on Adhesion and Wear Resistance of Coating

3.3.1. Adhesion

The effect of Lp-3 content on the adhesion strength of the coating is shown in Figure 4. The adhesion strength of the blank coating (L0) without Lp-3 is 5.5 MPa, which meets the general anti-corrosion requirements, but the interface bonding mainly depends on hydrogen bonds and mechanical interlocking between the epoxy-amine network and the metal surface, which is prone to interfacial hydration and debonding in long-term humid and hot or salt spray environments.

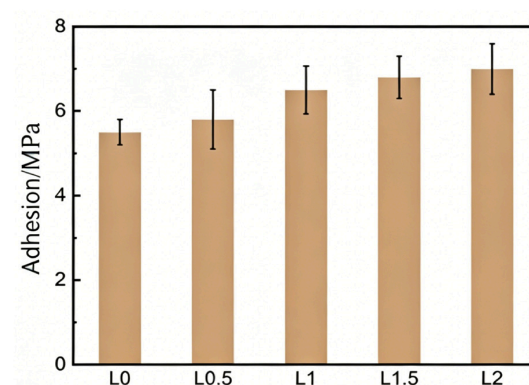


Figure 4. Effect of Lp-3 content on the adhesion of load-resistant coatings. The columns from left to right correspond to Lp-3 mass fractions of 0%, 0.5%, 1%, 1.5%, and 2%, respectively. Error bars represent the standard deviation ($n = 5$).

With the increase in Lp-3 content from 0 to 2 wt%, the adhesion strength of the coating increases monotonously: L0.5 (0.5 wt% Lp-3) is 6.3 MPa, L1 (1 wt% Lp-3) reaches 7.2 MPa, and L2 (2 wt% Lp-3) further rises to 7.9 MPa with an increase of 44%. The significant improvement of adhesion is due to the unique interfacial chemical and mechanical contributions of liquid polysulfide rubber:

- (1) Interfacial chemical bonding: The terminal thiol groups ($-SH$) of Lp-3 react with the $Fe-OH$ or $Fe_2O_3 \cdot xH_2O$ oxide layer on the sandblasted Q235 steel surface during curing ($Fe-OH + HS-R \rightarrow Fe-S-R + H_2O$), forming stable $Fe-S$ interfacial chemical bonds with a high bond energy ($\approx 340 \text{ kJ mol}^{-1}$). This covalent bonding replaces the original weak hydrogen bonds, effectively preventing interfacial hydrolysis caused by water molecule penetration.
- (2) Residual stress reduction: Lp-3 has high flexibility and a low glass transition temperature ($T_g \approx -50 \text{ }^\circ\text{C}$), which can reduce the internal residual stress of the coating through chain segment relaxation during curing shrinkage and thermal cycles. The decrease in internal stress reduces the interfacial shear stress concentration factor, and the failure position in the pull-off test transfers from the interface to the coating matrix, further improving the apparent adhesion strength.
- (3) Modulus gradient design: Lp-3 induces slight microphase separation in the interface region to form flexible microdomains, which makes the modulus near the interface transition smoothly, reduces the stress concentration caused by abrupt modulus change, and thus synergistically improves the overall interface durability.

The adhesion strength of 7.2 MPa achieved in this work is substantially higher than the typical requirement for marine coatings (usually $>3\text{--}4 \text{ MPa}$ [1]), and this value is competitive with other high-performance structural adhesives used in severe environments.

3.3.2. Wear Resistance

The effect of Lp-3 content on the wear resistance of the coating is shown in Figure 5, and the Taber abrasion loss shows a first decrease then increase nonlinear change with the increase in Lp-3 content. The un-toughened coating (L0) has an abrasion loss of 24.6 mg, because the pure epoxy-amine network has high hardness but brittleness, and the wear debris is easy to peel off integrally under the action of grinding wheel shear. When the Lp-3 content increases to 1 wt%, the abrasion loss is significantly reduced to 14.8 mg with a decrease of 40%. However, when the content continues to increase to 2 wt%, the abrasion loss rebounds to 19.2 mg, and the wear resistance deteriorates. The wear resistance exhibits a quadratic polynomial dependence, described by the equation $y = 20x^2 - 40x + 24.6$ ($R^2 = 0.95$), confirming the optimal wear resistance at 1 wt% loading.

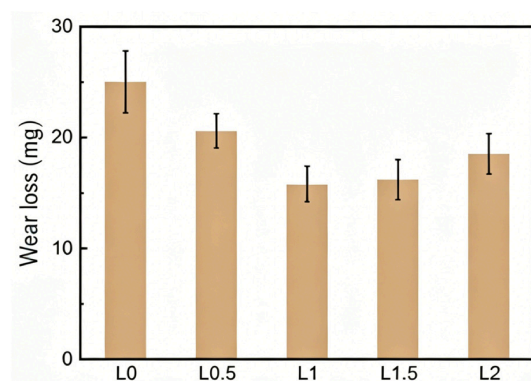


Figure 5. Effect of Lp-3 content on the wear resistance of load-resistant coatings. The columns from left to right correspond to Lp-3 mass fractions of 0%, 0.5%, 1%, 1.5%, and 2%, respectively. Error bars represent the standard deviation ($n = 5$).

While Scanning Electron Microscopy (SEM) analysis would provide further microstructural insights, this study primarily focuses on the macroscopic wear performance and material formulation optimization. Based on the optical inspection of the wear tracks, we propose the following hypotheses for the wear mechanisms. For L0 (0 wt% Lp-3): The surface after the Taber test showed severe material loss, which, combined with its high hardness and brittleness, suggests a wear mechanism dominated by brittle delamination. For L1 (1 wt% Lp-3): In contrast, the wear track of the optimized coating appeared smoother and more compact. This observation, along with the significantly reduced wear loss, indicates that the wear mechanism may have shifted towards micro-cutting, with the polysulfide segments effectively blunting crack propagation. For L2 (2 wt% Lp-3): The coating surface exhibited signs of plastic deformation, suggesting a mechanism involving ploughing and adhesive wear, likely due to the reduced hardness and load-bearing capacity caused by the excessive soft phase. These interpretations are based on macroscopic evidence and serve as a basis for understanding the performance differences.

The toughening and anti-wear mechanism of an appropriate amount of Lp-3 (≈ 1 wt%) is as follows: the effective crosslinking density of the coating is moderately reduced, and the surface hardness is still maintained at a high level (88.7 HD) with only a slight decrease in T_g . Under the action of grinding wheel shear, the flexible polysulfide segments can absorb impact energy through chain segment slip, microphase separation, and local plastic deformation, effectively inhibiting the rapid propagation of microcracks and reducing the size and shedding rate of wear debris. Lp-3 has a low surface energy ($\approx 28 \text{ mN m}^{-1}$), which reduces the adhesion component between the grinding wheel and the coating interface, and the wear mechanism transforms from brittle spalling to micro-cutting, thus significantly reducing the abrasion loss.

The negative effect of excessive Lp-3 (2 wt%) is mainly reflected in three aspects: The effective crosslinking density is excessively reduced, the surface hardness drops to 83.5 HD, and the indentation depth of the grinding wheel increases, leading to aggravated local stress concentration. The low crosslinking density makes the coating prone to irreversible plastic flow under cyclic shear, forming plough grooves and spalling pits, and the particle size of wear debris increases. Excessive flexible segments form a continuous soft phase, which weakens the load-bearing capacity of the coating surface and leads to the deterioration of wear resistance.

Therefore, 1 wt% Lp-3 is the optimal dosage for the wear resistance of the coating, which not only maintains the high surface hardness of the coating but also significantly improves the wear resistance through the stress dispersion and crack blunting mechanism of flexible segments.

3.4. Effect of Lp-3 Content on Mechanical Strength of Coating

3.4.1. Compressive Strength

The effect of Lp-3 content on the compressive strength of the coating is shown in Figure 6. Compressive strength measurements were performed using cylindrical specimens with a diameter-to-height ratio of 1:1 to minimize geometric bias and substrate-related effects. The compressive strength is measured on cylindrical samples ($\Phi 12 \text{ mm} \times 12 \text{ mm}$) at a loading rate of 0.5 mm/min, which directly reflects the relationship between crosslinking density and mechanical bearing capacity. The unmodified coating (L0) has the highest compressive strength of 98.4 MPa due to the high density of effective crosslinking points per unit volume and the dense and rigid three-dimensional network of the pure epoxy-amine system, and the failure mode is typical brittle shear cleavage.

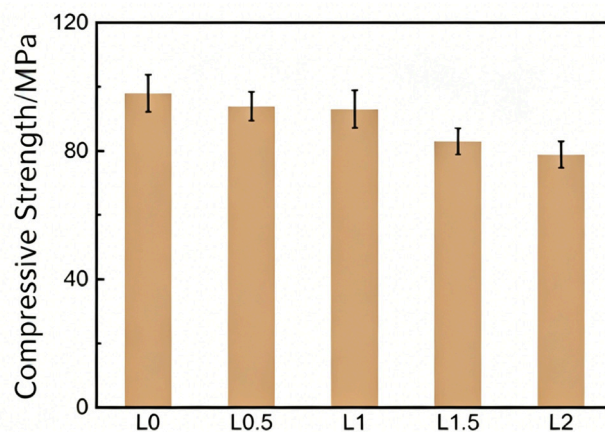


Figure 6. Effect of Lp-3 content on the compressive strength of load-resistant coatings. The columns from left to right correspond to Lp-3 mass fractions of 0%, 0.5%, 1%, 1.5%, and 2%, respectively. Error bars represent the standard deviation ($n = 5$).

After the introduction of Lp-3, the compressive strength of the coating decreases gradually with the increase in Lp-3 content, which provides a quantitative indication of the reduction in crosslink density. The compressive strength of L1 (1 wt% Lp-3) is 88.1 MPa, and the failure morphology changes from brittle cleavage to the coexistence of shear bands and microcracks, indicating that the flexible polysulfide segments start to play a role in stress dispersion. The compressive strength of L2 (2 wt%) drops significantly to 78.1 MPa, and the failure morphology shows significant plastic yield and local collapse due to the obvious phase-separated microdomains in the crosslinked network and the weakened continuity of the load-bearing skeleton. Consequently, the relative crosslink density (ν_e) follows the order: $L0 > L1 > L2$. The reduction in strength is attributed to the dilution of the rigid crosslinking points by the flexible polysulfide chains.

The decrease in compressive strength with the increase in Lp-3 content is fundamentally due to the dilution-toughening dual effect of flexible polysulfide segments on the crosslinked network: on the one hand, the introduction of polysulfide segments improves the mobility of the molecular chain, and the stress can be dissipated through chain segment slip and microdomain plastic deformation; on the other hand, the reduction in crosslinking points leads to the decrease in the continuity of the macroscopic load-bearing skeleton, which is manifested as the decrease in compressive strength at the macroscopic level. Specifically, the incorporation of Lp-3 induces a heterogeneous network structure where the flexible polysulfide segments act as energy-dissipating domains within the rigid epoxy matrix. The coating with 1 wt% Lp-3 achieves the best balance between compressive strength and toughness, which can provide both bearing capacity and energy absorption capacity for the heavy track rolling condition.

3.4.2. Tensile Strength

Contrary to the monotonous decrease in compressive strength, the tensile performance of the coating shows a significant enhancement trend with the increase in Lp-3 content (Figure 7). The static tensile test shows that the unmodified coating (L0) has a low tensile strength of 5.5 MPa and an elongation at break of only 8.3% because the high crosslinking density limits the orientation of molecular chains, and the coating is prone to brittle fracture under tensile load. The tensile strength demonstrates a parabolic relationship with Lp-3 content, fitted by the equation: $y = -4.0x^2 + 8.0x + 5.5$ ($R^2 = 0.98$).

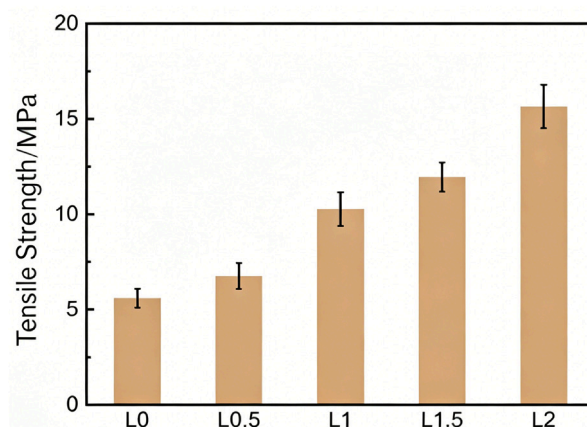


Figure 7. Effect of Lp-3 content on the tensile strength of load-resistant coatings. The columns from left to right correspond to Lp-3 mass fractions of 0%, 0.5%, 1%, 1.5%, and 2%, respectively. Error bars represent the standard deviation ($n = 5$).

With the increase in Lp-3 content from 0 to 2 wt%, the tensile strength of the coating increases approximately linearly: L1 reaches 12.4 MPa, and L2 further rises to 16.1 MPa with an increase of nearly 3 times, and the elongation at break is increased to 25%, showing typical ductile fracture characteristics. The enhancement mechanism of tensile performance is mainly attributed to the unique structure and reaction characteristics of Lp-3:

- (1) The $-S-S-$ bonds in the polysulfide chain have a low rotation barrier, which can quickly unfold and rearrange along the tensile direction under external force, so that the local high stress is evenly dispersed through chain segment slip, avoiding the concentration of microcracks.
- (2) The thioether crosslinking bonds generated by the thiol-epoxy reaction have both covalent strength and a certain reversibility, and can undergo a fracture-recombination cycle during the tensile process, dissipating a large amount of elastic energy and showing macroscopic strain hardening instead of brittle fracture. This dynamic behavior of disulfide bonds, acting as sacrificial bonds within the polymer network, has been widely reported to enhance toughness and enable self-healing properties in advanced polymeric materials [37].

The maximum tensile strength of 12.4 MPa is approximately 2.3 times higher than that of the unmodified coating and is also superior to the polysulfide-modified epoxy systems reported in Ref. [26], demonstrating the efficiency of our stoichiometric control and dual-network design. The different responses of compressive and tensile strength to Lp-3 content indicate that the rigid-flexible characteristics of the epoxy dual-crosslinked network have a specific response to the load type: the compressive strength is dominated by the crosslinking density, while the tensile strength is jointly controlled by the molecular chain mobility and energy dissipation efficiency. This rule provides a low crosslinking-high toughness optimization basis for the coating design under the alternating rolling-tensile condition of heavy tracks.

3.4.3. Shear Strength

In the actual service condition of marine decks, the coating not only bears vertical compression but also faces significant horizontal shear stresses caused by the rolling, abrupt stopping, and steering of heavy tracked vehicles. The shear test results of the coating at a constant rate of 2 mm/min are shown in Figure 8, and the shear strength calculated based on the lap area (25 mm $\times$ 10 mm) is shown in Figure 9.

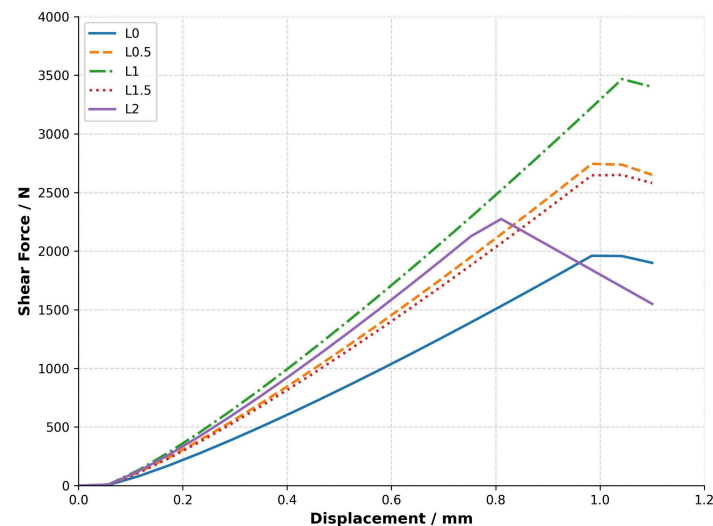


Figure 8. Shear test results of rolling load-resistant coating samples with varying Lp-3 content.

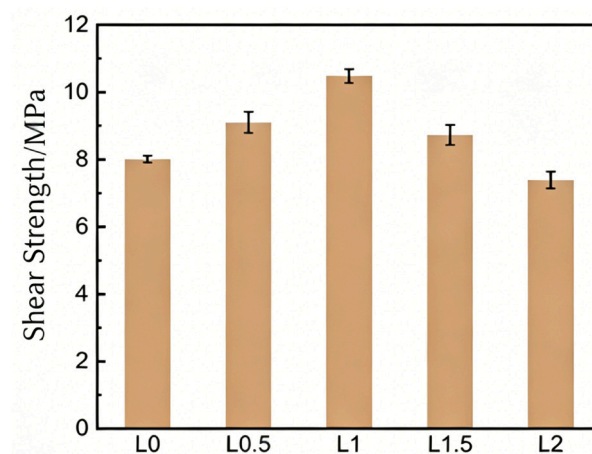


Figure 9. Effect of Lp-3 content on the shear strength of load-resistant coatings. The columns from left to right correspond to Lp-3 mass fractions of 0%, 0.5%, 1%, 1.5%, and 2%, respectively. Error bars represent the standard deviation ($n = 5$).

The shear curve of L0 shows a typical brittle response: the peak load is only 2100 ± 50 N (corresponding to a failure displacement of 1.05 mm), the load drops sharply at the moment of failure, and the fracture surface is flat, showing brittle shear cleavage failure. When the Lp-3 content is 0.5 wt%, the slope of the shear curve slightly decreases, the peak load rises to 2800 ± 50 N (failure displacement 1.30 mm), and a yield platform begins to appear, indicating the initial improvement of shear toughness.

The shear curve of L1 (1 wt% Lp-3) is the most optimized: the peak load reaches 3400 ± 50 N (failure displacement 1.55 mm), a slow decline zone of 0.2 mm appears after the peak, showing ductile shear failure, and obvious wire drawing and fiber bridging can be observed on the fracture surface. The shear strength of L1 is the maximum (10.2 MPa) among all samples. When the Lp-3 content exceeds 1 wt% (L1.5 and L2), the shear curve shows a softening trend: the peak load drops back to 3100 ± 50 N and 2600 ± 50 N respectively, the failure displacement continues to increase (1.70 mm and 1.85 mm), but the yield platform is shortened, and the final failure is mainly plastic slip with a significant decrease in shear strength.

The shear performance optimization mechanism of the coating with 1 wt% Lp-3 is as follows:

- (1) The polysulfide segments, aided by the low-viscosity hyperbranched oligosiloxane (HOR) matrix which ensures their homogeneous distribution, form a flexible molecular network in the shear plane. This network absorbs energy through chain segment slip-orientation during the shearing process and delays crack initiation and propagation.
- (2) The thiol–metal chemical bonding improves the interface adhesion work, and the failure mode of the coating transforms from interface slip to internal shear of the coating, effectively improving the shear bearing capacity.

Excessive Lp-3 (>1 wt%) leads to the decrease in shear strength because:

- (1) The crosslinking density is greatly reduced, the shear modulus of the coating decreases, and the shear yield occurs in advance.
- (2) The volume fraction of the flexible phase is too high to form a continuous soft phase, which weakens the continuity of the load-bearing skeleton and leads to the deterioration of shear performance.

4. Conclusions

In this study, an epoxy–amine/epoxy–thiol dual-crosslinked network anti-rolling load coating was prepared by using liquid polysulfide rubber (Lp-3) as the key crosslinking modifier, and the effect of Lp-3 content (0–2 wt%) on the comprehensive performance of the marine deck coating was systematically investigated. The main conclusions are as follows:

- (1) Lp-3 with an intact main chain structure and abundant active terminal thiol groups can undergo a complete click reaction with epoxy groups in the matrix resin, forming stable C–S–C crosslinking bonds and covalently embedding flexible polysulfide segments into the rigid epoxy–amine network, realizing the molecular-level hard–soft phase synergistic design of the coating.
- (2) The stoichiometric ratio between epoxy groups and total active hydrogens (including both amine and thiol hydrogens) was maintained at 1:1 throughout all formulations. As the Lp-3 content increased from 0 to 2 wt%, the fraction of epoxy groups reacting with thiol hydrogens increased from 0% to approximately 15%, while the amine reaction fraction decreased proportionally.
- (3) The coating achieves the optimal synergy of hard–strong–tough–wear-resistant properties at 1 wt% Lp-3 loading: Shore hardness (88.7 HD) and pencil hardness (8H) remain at a high level, adhesion strength is increased to 7.2 MPa (31% increase), Taber abrasion loss is significantly reduced to 14.8 mg (40% decrease), tensile strength is increased from 5.5 MPa to 12.4 MPa, elongation at break is nearly doubled, shear strength reaches 10.2 MPa, and the failure mode is transformed from brittle cleavage to ductile shear. To objectively justify the selection of the optimal formulation, a Comprehensive Performance Index (*CPI*) was established. The *CPI* is defined as the sum of the percentage improvement in key mechanical properties (adhesion, tensile strength, and shear strength) relative to the unmodified L0 coating, combined with the percentage reduction in wear loss. The calculation is expressed by the following equation:

$$CPI = \Sigma (\Delta \text{Property} / \text{Property}_{L0}) - (\Delta \text{Wear Loss} / \text{Wear Loss}_{L0})$$

Based on this metric, the calculated *CPI* values were 0 for L0, 68 for L0.5, 142 for L1, 105 for L1.5, and 89 for L2. The L1 sample (1 wt% Lp-3) exhibits the highest *CPI* value, which quantitatively confirms that it achieves the best overall balance of properties.

- (4) The modification mechanism of Lp-3 on the anti-rolling load performance of the coating is multi-faceted: forming Fe–S interfacial chemical bonds to enhance interface adhesion; reducing the effective crosslinking density and improving chain segment

mobility to enhance toughness; realizing energy dissipation through microphase separation, chain segment relaxation and crack blunting to inhibit crack propagation; and maintaining the continuity of the load-bearing skeleton to ensure the surface hardness and mechanical bearing capacity of the coating.

- (5) Excessive Lp-3 (>1 wt%) will lead to the excessive reduction in crosslinking density, the decrease in surface hardness and compressive strength, the formation of a continuous soft phase, and the deterioration of wear resistance and shear strength, while the lack of Lp-3 will result in poor toughness, easy crack propagation, and insufficient adhesion and wear resistance of the coating.

Despite the promising results, this study has certain limitations. The current evaluation is primarily based on laboratory-scale tests. Future work will focus on conducting long-term durability studies, including saltwater immersion and cyclic thermal loading tests, to assess the coating's performance in simulated marine environments. Furthermore, detailed microstructural characterization (e.g., SEM) of the worn surfaces will be performed to provide direct evidence of the proposed wear and toughening mechanisms, which will further broaden the impact of this work.

This research realizes the synergistic optimization of the key performance indicators of marine deck anti-rolling load coatings, and provides a new formulation and technical parameters for the design of functional coatings under heavy-duty dynamic service environments. The dual-crosslinked network design strategy and the multi-mechanism synergistic modification method demonstrate distinct advantages over conventional single-phase modification techniques, providing a more effective route to achieving the long-sought balance between hardness and toughness in marine protective coatings. From a practical application standpoint, the next critical step would be to validate the coating's performance under simulated service conditions, such as full-scale deck panels subjected to repeated rolling loads from tracked vehicles in a marine environment, to bridge the gap between laboratory-scale results and real-world applicability.

Author Contributions: Conceptualization, Z.L. and J.H.; methodology, Z.L. and Y.L.; investigation, Y.L.; formal analysis, Z.L. and Y.L.; data curation, Z.L. and Y.L.; writing—original draft preparation, Z.L.; writing—review and editing, J.H.; supervision, Z.L.; project administration, Z.L. and J.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Defense Key Scientific Research Project, grant 342 number 2024705060.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors would like to thank the support provided by the relevant testing centers of Naval University of Engineering and South China University of Technology in performance testing and characterization. During the preparation of this manuscript, Microsoft Office 2016 was used for grammar and spelling editing. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Lp-3	Liquid Polysulfide Rubber-3
DDCM	4,4'-Diaminodicyclohexylmethane
HOR	Hyperbranched oligosiloxane resin
FT-IR	Fourier Transform Infrared Spectroscopy
T _g	Glass Transition Temperature
ν _e	Effective Crosslinking Density

References

1. Du, F.; Mo, R.; Guo, Z.; Wang, J. Overview of wear-resistant coatings in marine environments. *J. Mar. Sci. Eng.* **2025**, *13*, 2121. [\[CrossRef\]](#)
2. Gao, M.; Xie, Q.Y.; Liu, Y. Research progress of anti-skid coatings for decks. *Paint Coat. Ind.* **2025**, *55*, 76.
3. Deng, Q.; Wang, T.L.; Bai, Y. Preparation of highly wear-resistant non-skid deck coating and analysis of its non-skid wear resistance. *Chin. J. Ship Res.* **2020**, *15*, 82. [\[CrossRef\]](#)
4. Bai, H.Q.; Zhong, L.S.; Kang, L. Research progress of high strength and toughness coatings on steel/iron surface. *Surf. Technol.* **2021**, *50*, 97. [\[CrossRef\]](#)
5. Kang, S.B.; Ma, G.B.; Jiang, J.M. Preparation of anti-rolling and wear-resistant coatings applied on heavy loaded decks of ships. *Paint Coat. Ind.* **2019**, *49*, 61. [\[CrossRef\]](#)
6. Bai, Y.; Jiang, X.J.; Wang, T.L. Development of new highly wear-resistant heavy load rolling anti-skid coatings and performance characteristics. *China Coat.* **2018**, *33*, 38. [\[CrossRef\]](#)
7. Pei, W.; Pei, X.; Xie, Z. Research progress of marine anti-corrosion and wear-resistant coating. *Tribol. Int.* **2024**, *198*, 109864. [\[CrossRef\]](#)
8. Niu, W.; Qian, J.; Wang, X. Research progress of self-healing coatings on ships against biological pollution: A review. *Coatings* **2025**, *15*, 486. [\[CrossRef\]](#)
9. Li, H.; Li, Y. Research progress on aging test and performance evaluation of marine coatings. *Polym. Degrad. Stab.* **2025**, *241*, 111614. [\[CrossRef\]](#)
10. Wu, L.; Zhang, D.; Zheng, B.; Yu, Z. Corrosion and wear resistance of TiN/TiO₂ composite ceramic coatings deposited by supersonic arc spraying. *Ceram. Int.* **2024**, *50*, 18655. [\[CrossRef\]](#)
11. Momber, A.W.; Irmer, M.; Kelm, D. Damage morphology and force-deflection curves for impact loading of thick multilayer organic protective coating systems. *J. Coat. Technol. Res.* **2023**, *21*, 857. [\[CrossRef\]](#)
12. Zhang, Y.; Luo, G.; Zhang, L. Study on the peeling criterion of anti-ice and wear-resistant coating for polar ships and simulation analysis method of the ship-ice collision process. *Mech. Adv. Mater. Struct.* **2023**, *31*, 9692. [\[CrossRef\]](#)
13. Deng, Y.; Li, Z.; Yin, Z.; Chen, Y. A facile method for constructing scalable and low-cost superhydrophobic coating with anti-corrosion and drag-reduction properties. *Ind. Crops Prod.* **2024**, *216*, 118732. [\[CrossRef\]](#)
14. Singh, K.; Haq, M.I.; Mohan, S. Tribological behavior of novel Al₂O₃-La₂O₃ HVOF composite coatings. *Tribol. Int.* **2024**, *193*, 109427. [\[CrossRef\]](#)
15. Shi, P.; Yin, H.; Zhou, Y. Influence of Mo on Ni-15Cr cladding layers via plasma transferred arc. *Materials* **2022**, *15*, 8381. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Chen, W.; Zhang, J.; Qi, X. Recent progress on anti-slip and highly wear-resistant elastic coatings: An overview. *Coatings* **2023**, *14*, 47. [\[CrossRef\]](#)
17. Huang, H.J.; Wang, P.; Zhao, H.X. The application of anti-slip coatings in PCTC. *China Coat.* **2024**, *39*, 24. [\[CrossRef\]](#)
18. Wu, Z.J.; Cai, J.C.; Jiang, J.Y. Research progress and application prospects of anti-slip properties of polymer material. *China Plast. Ind.* **2025**, *53*, 1–9. [\[CrossRef\]](#)
19. Da, Q.; Ma, G.Z.; Kang, J.J. Research progress on properties of wear and corrosion-resistant high entropy alloy coatings. *Mater. Rep.* **2024**, *38*, 23110145–10. [\[CrossRef\]](#)
20. Liu, G.; Zhang, J.; Pang, X.T. Preparation and properties of diamond-reinforced nickel-based wear-resistant coatings. *Mater. Rep.* **2025**, *39*, 182. [\[CrossRef\]](#)
21. Zhang, Z.J.; Li, X.M.; Zhu, C.J. Effect of Nano-TiB₂ on wear and corrosion resistance of CoCrFeNiSi high-entropy alloy coating. *Mater. Rep.* **2025**, *39*, 187. [\[CrossRef\]](#)
22. Yu, J.J.; Zhao, W.J.; Wu, Y.H. Tribological properties of epoxy composite coatings reinforced with functionalized C-BN and H-BN nanofillers. *Appl. Surf. Sci.* **2018**, *434*, 1311. [\[CrossRef\]](#)
23. Zhou, G.Y. Modification and application progress of liquid polysulfide rubber. *Guangdong Chem. Ind.* **2023**, *50*, 98. [\[CrossRef\]](#)

24. Jiang, T.; Guan, H.L.; Chen, X.R. Effects of liquid polysulfide rubber on dielectric properties of epoxy resin. *J. Xi'an Jiaotong Univ.* **2020**, *54*, 86. [\[CrossRef\]](#)
25. Kou, Y.J.; Zhou, W.Y.; Li, B. Enhanced mechanical and dielectric properties of an epoxy resin modified with hydroxyl-terminated polybutadiene. *Appl. Sci. Manuf.* **2018**, *114A*, 97. [\[CrossRef\]](#)
26. Li, Y.; Deng, J.F.; Sun, Z.Y. Epoxy resin toughened by amino-terminated polysulfide rubber. *Polym. Mater. Sci. Eng.* **2019**, *35*, 100. [\[CrossRef\]](#)
27. Lv, G.C.; Zhang, N.; Huang, M. The remarkably enhanced particle erosion resistance and toughness properties of glass fiber/epoxy composites via thermoplastic polyurethane nonwoven fabric. *Polym. Test.* **2018**, *69*, 470. [\[CrossRef\]](#)
28. Li, X.M.; Cai, X.T.; Hao, X.Y. Research status and development trend of antiskid coating for aircraft carrier deck. *Contemp. Chem. Ind.* **2022**, *51*, 2250. [\[CrossRef\]](#)
29. GB/T 2411-2008; Plastics and Ebonite—Determination of Indentation Hardness by Means of a Durometer (Shore Hardness). China Standard Press: Beijing, China, 2008.
30. GB/T 6739-2006; Paints and Varnishes—Determination of Film Hardness by Pencil Test. China Standard Press: Beijing, China, 2006.
31. GB/T 1731-2020; Determination of Flexibility of Coating and Putty Films. China Standard Press: Beijing, China, 2020.
32. GB/T 5210-2006; Paints and Varnishes—Pull-off Test for Adhesion. China Standard Press: Beijing, China, 2006.
33. GB/T 1768-2006; Paints and Varnishes—Determination of Resistance to Abrasion—Rotating Abrasive Rubber Wheel Method. China Standard Press: Beijing, China, 2006.
34. GB/T 2567-2008; Test Methods for Properties of Resin Casting Body. China Standard Press: Beijing, China, 2008.
35. ISO 527-1:2019; Plastics—Determination of Tensile Properties—Part 1: General Principles. International Organization for Standardization: Geneva, Switzerland, 2019.
36. GB/T 7124-2008; Adhesives—Determination of Tensile Lap-Shear Strength of Rigid-to-Rigid Bonded Assemblies. China Standard Press: Beijing, China, 2008.
37. Lin, C.W.; Liang, C.Y.; Li, J.D.; Liang, Y.; Dong, D. Transparent, Tough, and Self-Healable Elastomer Based on Dynamic Dual Cross-Linking of Coordination and Disulfide Bonds. *ACS Appl. Polym. Mater.* **2024**, *6*, 4516–4524. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.