

Research Article

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Preparation of cardanol-based curing agent for underwater drainage pipeline repairs

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Abstract: The underwater curing agents have demonstrated promising potential in various applications, especially in underwater repair engineering, yet have proven considerable challenging. Here, we report a cardanol-based curing agent for epoxy resin that achieves robust adhesion to steel and concrete substrates both in air and underwater. Cardanol, paraformaldehyde, and *m*-phenyldimethylamine are selected as the polymeric monomers to synthesize curing agent by Mannich reaction in the absence of chemical cross-linker agents. The coating is completely cured within 46 ± 1 min in air and 54 ± 2 min under water with an adhesion of 0 or 1 and a hardness of 5H. The impact strength, shear strength, and tensile strength of coating on underwater concrete were $9.58 \pm 0.41 \text{ kJ}\cdot\text{m}^{-2}$, 13.1 ± 0.3 , and $10.5 \pm 0.2 \text{ MPa}$, respectively, demonstrating exceptional flexibility and mechanical strength as well as favorable hydrophobicity. This work paves the way for the rehabilitation of underwater drainage network for urban infrastructure and water conservancy projects.

Keywords: drainage pipeline repairs, concrete, epoxy resin, underwater curing agent, cardanol

1 Introduction

Drainage pipeline is an essential element of urban infrastructure and water conservancy platform, undertaking a number of functions such as drainage and sewage disposal. Drainage pipeline networks in cities along the Yangtze River and even in the whole China, especially the traditional concrete pipes, generally suffer from the problems of aging and leakage, which seriously affects drainage efficiency and pollution prevention and treatment. Therefore, the rehabilitation of the underwater pipeline network is imminent. However, the limited space and complex environment of the drainage network puts forward stringent requirements for the coating technology, especially the curing of coating in the moisture- and water-related environment.

Epoxy resins are widely used in anti-corrosion coatings because of superior mechanical performance, chemical resistance, insulation, and good adhesive properties (1–4). However, epoxy resins applied for underwater drainage pipeline rehabilitation require the involvement of an underwater curing agent. Low molecular weight epoxy needs to be converted into three-dimensional crosslinked thermoset networks using suitable curing agents to achieve better performance (5,6). Currently, the majority of the curing agents available for underwater curing are modified amine curing agents, of which the most commonly used are phenalkamines prepared by Mannich modification (7). Phenalkamines, as a promising curing agent, combine the unique properties of aliphatic amines and polyamides and are suitable for humid conditions (5). Biosourced materials are widespread for being eco-friendly and having unique properties. Jayaprakash et al. (8) prepared nanocomposites by water evaporation using cellulose nanofibers (CNFs) as fillers and natural rubber (NR) latex as the matrix, the study found that pineapple fruit residue-based CNFs enhance mechanical and thermal properties of NR composites. Batubara et al. (9) fabricated hybrid nanocomposite films composed of chitosan, cinnamaldehyde, *Nigella sativa* or blackseed oil, and silver nanoparticles biosynthesized in *Azadirachta indica* or neem leaves' extract, and the films were biodegradable in soil and showed good thermal

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stability. Pradeepa et al. (10) developed three sisal fiber-reinforced sodium alginate composites, and the untreated sample with the maximum sodium alginate gum concentration had significantly enhanced mechanical properties and low moisture absorption rate. Jie et al. (11) fabricated an innovative environmentally friendly nanofiber membrane adsorbent by electrospinning chitosan using urushiol as the cross-linking agent, thereby achieving rapid and high-capacity adsorption of Cr(vi) in water. Hu et al. (12) synthesized a high-strength polyvinyl alcohol-based hydrogel by vermiculite and lignocellulosic nanofibrils for electronic sensing, and the hydrogel exhibits a natural formulation, high mechanical strength, and electrical conductivity. In addition, biosourced materials exhibit exceptional performance in emerging applications, particularly within the realm of sensors and energy devices. Liu et al. (13) developed a biodegradable aerogel that possesses sensing and fire-warning capabilities, utilizing resource-abundant graphite and green carboxymethyl cellulose. These resultant aerogels exhibit exceptional electrical conductivity and mechanical strength. The authors, Trano et al. (14), designed a lignin-based membrane through the crosslinking of a pre-oxidized Kraft lignin matrix with an ethoxylated difunctional oligomer, and the lignin-based electrolyte attains significant electrochemical performances. Manarin et al. (15) developed biobased gel polymer electrolyte membranes via the esterification reaction of a cardanol-based epoxy resin, and these membranes exhibited excellent electrochemical stability toward potassium metal and suitable ionic conductivity. Amici et al. (16) proposed a composite gel polymer electrolyte consisting of a highly cross-linked polymer matrix, containing a dextrin-based nanosponge and activated with a liquid electrolyte. The nanosponge allows good ionic conductivity at room temperature. Because of these sustainability advantages, biosourced materials quickly replace synthetic composites in composites. Cardanol is a natural and environmentally friendly material extracted from cashew shell oil (17–20) and is an essential raw material for the production of phenalkamines (21). Moreover, the presence of a long C15 aliphatic chain and aromatic ring in cardanols provides exceptional flexibility, hardness, and hydrophobicity, rendering them appropriate candidates for curing agent feedstocks (22–24).

Furthermore, a lot of literatures (5,7,21,23,25–27) reported that underwater cardanol-based curing agents are developed

for epoxy resin, but these studies in the laboratory are mainly concentrated on the steel substrate and very few studies referred to the concrete substrates to evaluate the performance of the coatings, especially the moisture and underwater concrete substrates.

Here we prepare a cardanol-based curing agent suitable for underwater curing of drainage pipeline networks by Mannich reaction using cardanol, paraformaldehyde (PA), and *m*-phenyldimethylamine (MXDA) as monomers. The structure of the curing agent is confirmed by Fourier transform infrared spectra (FTIR) and ^1H nuclear magnetic resonance spectra (^1H NMR). The effects of monomer molar concentration and reaction condition on the viscosity and the amine value of the curing agent are investigated. Furthermore, the hardness, adhesion, curing time, and mechanical properties of coatings prepared by mixing cardanol-based curing agents with commercial epoxy resin E44 in different ratios to steel and concrete substrates both in air and underwater are also studied. In addition, commercial MXDA is used for comparative study. More importantly, modified MXDA achieves higher shear strength (13.1 ± 0.3 MPa), higher tensile strength (10.5 ± 0.2 MPa), and more rigid and harder film compared with commercial MXDA.

2 Materials and methods

2.1 Materials

Cardanol, PA, and epoxy resin (E44) are purchased from Shanghai Liming Chemical Co., Ltd. MXDA and perchloric acid are purchased from Sinopharm Chemical Reagent Co., Ltd. All the chemicals are industrial grade and used without further purification.

2.2 Preparation of the curing agent

The curing agent is prepared by the one-pot method (Figure 1). First, 3.02 g cardanol and 1.77 g MXDA are placed into a 500 mL four-necked round-bottom flask at room temperature (22–25°C). The 500 mL four-necked round-

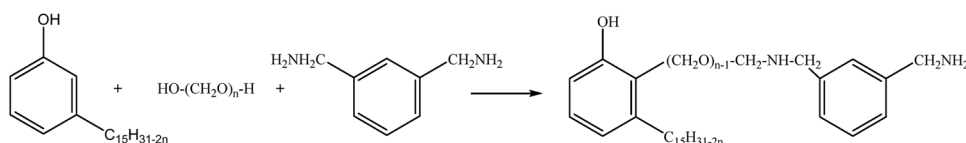


Figure 1: Reaction scheme for the preparation of curing agent.

bottom flask is suspended in a temperature-controlled water bath on a programmable hotplate with an external temperature probe and equipped with a magnetic stirrer and reflux condenser. The mixture is stirred for 20–30 min at a rotor speed of 600 rpm until all the chemicals are dissolved. Subsequently, the mixture is slowly heated to 80°C at a rate of 1°C·min⁻¹ under stirring at 600 rpm, and then, an equal amount of 0.33 g PA is mixed into the mixture in five portions at intervals of 2 min. The solution is continued to be slowly heated to 100°C at 1°C·min⁻¹ and maintained condensation reflux for 4 h under stirring at 600 rpm. When the reaction is completed, the curing agent is obtained by decompression distillation and dehydration.

2.3 The fabrication of coatings

Curing agents are mixed with epoxy resins with 1:1.2, 1:1.3, 1:1.4, and 1:1.5 ratios. Similarly, an unmodified curing agent (commercial MXDA) serves as a control. The mixture is coated on mild steel substrates and cured for 16–24 h at the ambient environment to get a completely dried coating. The dry coating thickness is controlled at 120 ± 20 μm. Besides, the mixture is coated on a concrete substrate soaked in water for 24 h and then cured for 24 ± 2 h underwater. The dry coating thickness is controlled at 150 ± 20 μm.

2.4 Characterizations

To test the structure and properties of the prepared samples, various characterizations are conducted.

2.4.1 ¹H NMR analysis

¹H NMR spectra of as-prepared samples are carried out by spectrometer (Bruker Avance neo 400) with deuterated dimethyl sulfoxide (DMSO-d₆) or deuterated chloroform (CDCl₃) as solvents.

2.4.2 FTIR analysis

Fourier transform infrared spectra of as-prepared samples are acquired using a Nicolet 6700 IR spectrophotometer (Bruker, Bremen, Germany) in the wavelength range of 500–4,000 cm⁻¹.

2.4.3 Amine value measurements (28)

The amine value is measured by the nonaqueous titration method with perchloric acid and calculated using the following equation:

$$AN(\text{mgKOH/g}) = \frac{cV \times 56.1}{m} \quad (1)$$

where c is the concentration of the perchloric acid standard solution, V is the consumption of the standard solution, and m is the mass of a sample.

2.4.4 Viscosity measurements

The viscosity of the prepared samples is measured according to GB/T 2994-1995 and acquired using an NDJ-5S digital rotary viscometer at 25°C.

2.4.5 Hardness measurements

The hardness of coatings is measured according to GB/T 6739-2022 and acquired using a QHQ-type pencil hardness tester.

2.4.6 Adhesion strength measurements

The adhesion strength of coatings is evaluated by the scribe tester according to GB/T 9286-2021.

2.4.7 Surface drying time measurements

The surface drying time of coatings is evaluated according to GB/T 1728-2020. The surface drying is tested three times and averaged.

2.4.8 Water absorption measurements

To measure water absorption of coatings, the coating with known weight is immersed in water for 24 h at room temperature. The water absorption is calculated according to the following equation based on the weight difference between the coating before and after immersion (23).

$$M_t = \frac{W_t - W_0}{W_0} \times 100\% \quad (2)$$

where M_t is the water absorption, W_t is the weight of the sample after immersion in water, and W_0 is the weight of the sample before immersion in water.

2.4.9 Water contact angle measurements

The hydrophobicity of the coatings is determined by the water contact angle and measured by a contact angle analyzer (JCY-3, Suzhou Qi Le Electronic Technology Co., Ltd., Suzhou, China). The contact angle is tested five times and averaged.

2.4.10 Mechanic properties measurements

The tensile strength is tested according to GB/T 50081-2003 and the tensile rate of the universal tester (Jinjian, China) is $5 \text{ mm} \cdot \text{min}^{-1}$. The shear adhesive strength is tested according to GB/T 7124-2008 and the tensile rate is $5 \text{ mm} \cdot \text{min}^{-1}$. The impact strength is investigated according to the method of the no-notched Charpy impact plastics sample. These data are tested five times and averaged.

3 Results and discussion

3.1 Structure of the curing agent

The structure of the curing agent is determined by ^1H NMR spectrum (CDCl_3 is used as the solvent). As shown in Figure 2,

the peaks at about 6.64–7.05 and 7.28–7.59 ppm are the protons of benzene rings. The peak assignments of $-\text{OH}$ are observed at 9.68 ppm, and the peaks at 0.88–5.43 ppm belong to C15 long aliphatic chains of cardanol. The peaks at about 5.43 ppm belong to the protons of ethylene on C15 long aliphatic chains. Compared to the spectrum of the MXDA and cardanol, the ^1H NMR spectrum of the curing agent has similar peaks that correspond to the main chain of polymers. In addition, the new emerging peaks at about 3.76–4.80 ppm can be observed in ^1H NMR spectrum of the curing agent and the attenuation of $-\text{NH}_2$ peaks, which demonstrate that the curing agent was successfully synthesized through reaction.

Moreover, the structure of the curing agent is further confirmed through FTIR spectra. FTIR spectra of MXDA, cardanol, and as-prepared curing agent are shown in Figure 3. MXDA exhibits two characteristic peaks at near $3,400 \text{ cm}^{-1}$, which are ascribed to the N–H stretching vibrations. The sharp peak at $1,300 \text{ cm}^{-1}$ is observed due to the stretching vibrations of the C–N. The distinct absorption peaks appear at 1,458, 1,489, and $1,623 \text{ cm}^{-1}$, corresponding to the C=C stretching vibration of the aromatic ring. Absorption peaks around 2,860, 3,360, and $3,006 \text{ cm}^{-1}$ are assigned to the $-\text{CH}_2-$ stretching vibration, O–H stretching vibration, and C=H stretching vibration, respectively.

The FTIR spectrum of as-prepared curing agent shows the absorption peak between $3,200$ and $3,500 \text{ cm}^{-1}$ due to

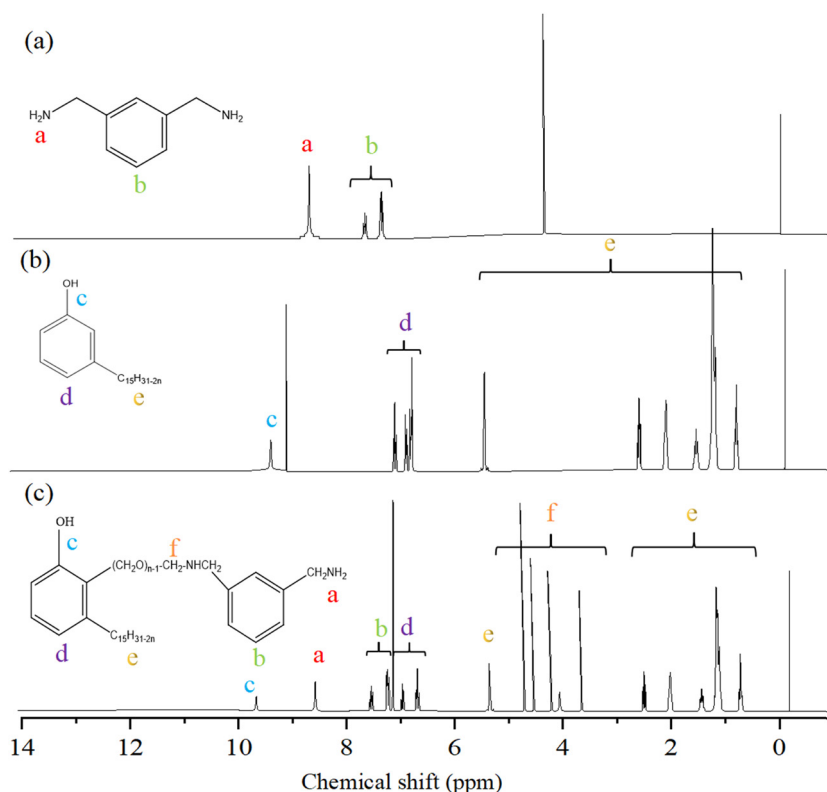


Figure 2: ^1H NMR spectra: (a) MXDA; (b) cardanol; and (c) as-prepared curing agent.

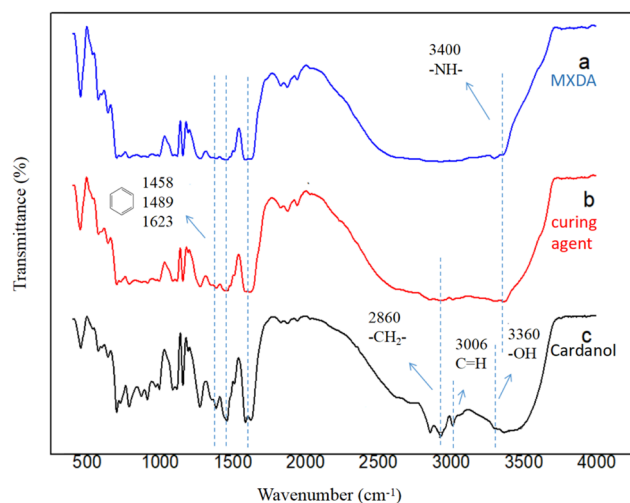


Figure 3: FTIR spectra: (a) MXDA; (b) cardanol; and (c) as-prepared curing agent.

the overlap of the stretching vibration peak between the N–H generated by the reaction and the phenolic hydroxyl. The FTIR spectrum of as-prepared curing agent not only contains the long C15 aliphatic chains of cardanol but also exhibits the N–H absorption peaks of MXDA. Moreover, there is no peak observed in the region between 1,735 and 1,750 cm^{-1} , suggesting that the curing agent does not contain C=O functional group; therefore, confirming the PA is completely reacted. The absorption peak at 880–730 cm^{-1} represents the substitution of ortho, indicating that the active H on the ortho position of phenol is replaced by the intermediates of formaldehyde and amine. The above results indicate that the curing agent was successfully synthesized.

3.2 Effect of different molar concentrations of monomer

The properties of thermosets depend on the kind of polyamine and molecular weight of the resultant phenalkamine. However, the curing characteristics depend on amine value (29). The effect of the different concentrations of monomer on viscosity and the amine value of the curing agent is evaluated. The ratios of MXDA to PA and cardanol are (1, 1.1, 1.2, 1.3, 1.4):1, respectively. The ratios of PA to MXDA and cardanol are (0.9, 1.0, 1.1, 1.2, 1.3):1, respectively. The ratio of curing agent to epoxy resin is 1:1.3. The mixtures coated on steel substrate are evaluated for hardness, adhesion, and drying time.

The viscosity and the amine value of the curing agents with various concentrations of MXDA are shown in Figure 4. The viscosity of curing agent decreases from 9,374 to 4,901

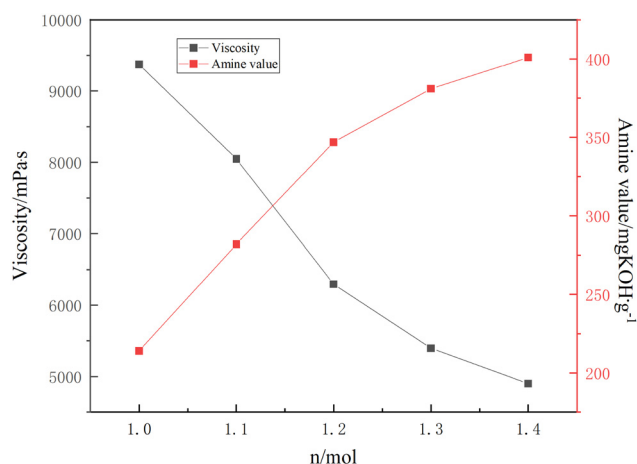


Figure 4: Effect of MXDA concentration on the viscosity and the amine value of curing agent.

mPa·s and the amine value of curing agent increases from 214 to 401 $\text{mgKOH}\cdot\text{g}^{-1}$, respectively, as the MXDA concentration increases from 1.0 to 1.4. As a result of the ring-opening polymerization reaction between the epoxy groups and the amine, the amine value gradually decreases, indicating that the reaction is nearly complete.

All coatings exhibit excellent adhesion (0 or 1) to the steel substrate because the phenolic hydroxyl groups in the curing agent and the structure of the epoxy resin can form chemical bonds with the hydroxyl on the surface of the substrate (Table 1). It is observed that the hardness of coatings with low concentration of MXDA is stronger than the coatings with high concentration of MXDA, which could be attributed to the fact that the straight chain molecules in the excess MXDA are free into the network structure of the coating after the reaction is completed. Furthermore, drying time decreases with increasing MXDA concentration. The more active hydrogen in the molecule involved in the reaction, the shorter of curing time, indicating that the curing rate of coatings essentially depends on the amine value of the curing agent. The results show that the curing agent with an MXDA concentration of 1.3 exhibits optimum curing performance.

The viscosity and amine value of the curing agent prepared by different PA concentrations are shown in Figure 5.

Table 1: Effect of the curing agent prepared by different MXDA concentrations on the coating performance

Characterization	1:1:1	1.1:1:1	1.2:1:1	1.3:1:1	1.4:1:1
Pencil hardness/H	6	6–5	5	5	4
Adhesion/series	0	0	0–1	0–1	1
Surface drying time (min)	62 ± 1	55 ± 2	52 ± 2	50 ± 2	49 ± 1

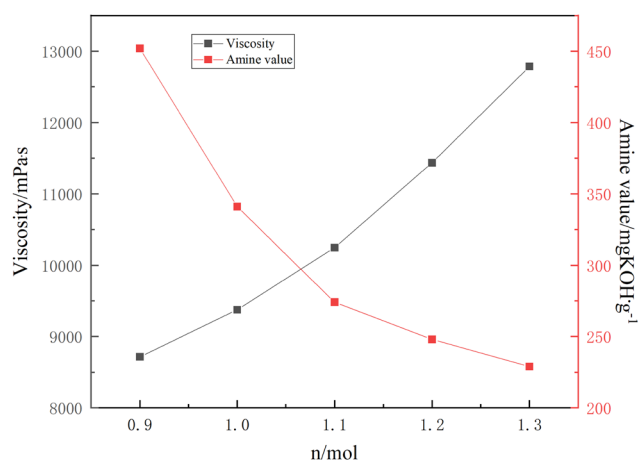


Figure 5: Effect of the PA concentration on the viscosity and amine value of curing agent.

As the concentration of PA increases, the color of the curing agent changes from a light brown to a dark brown with white colloidal matter (Table 2). The white colloidal pieces could be unreacted PA or phenolic intermediates. It could be inferred that excessive PA is detrimental to the reaction process because the increase of viscosity of the system weakens adequate mixing. The amine value of the curing agent decreases as the concentration of PA increases. Therefore, the reaction of MXDA, PA, and cardanol is accelerated as the PA concentration increases, leading to a rapid increase in the degree of polymerization and the average molecular weight of the product.

Table 3: Effect of the as-prepared curing agent with different PA concentrations on the coating performance

Characterization	0.9:1:1	1.0:1:1	1.1:1:1	1.2:1:1	1.3:1:1
Pencil hardness/H	6	6	5	4	4
Adhesion/series	1	1	1	0–1	0
Surface drying time (min)	52 ± 2	48 ± 1	51 ± 1	55 ± 3	62 ± 2

The coatings cured with different PA concentrations show excellent adhesion (a rating of 0 or 1). The coatings cured with different concentrations of PA exhibited rigid and harder films, while the hardness decreased as the concentration of PA increased. Moreover, the surface drying time decreases and then increases with increasing PA concentration. The results indicate that the curing agent prepared with a PA concentration of 1.0 provides the best curing performance (Table 3).

3.3 Effect of reaction condition

The effect of reaction temperature and reaction time is investigated by testing viscosity and amine value at 80, 90, 100, 110, and 120°C and at 3.0, 3.5, 4, 4.5, and 5 h, respectively.

As shown in Table 4, the curing agent exhibits a white colloidal matter accompanied by a small amount of

Table 2: Effect of PA concentration on the physicochemical properties of curing agent

$n(\text{PA}):n(\text{MXDA}):n(\text{cardanol})$	Colour and viscosity
0.9:1:1	Light brown liquid, transparent and viscous
1:1:1	Brown liquid, transparent and viscous
1.1:1:1	Dark brown liquid, transparent and viscous
1.2:1:1	Dark brown liquid, transparent and viscous, and with some white colloidal pieces
1.3:1:1	Dark brown liquid, transparent and viscous, and with some white colloidal pieces

Table 4: Effect of reaction temperature on physicochemical properties of curing agent

Temperature $T/^\circ\text{C}$	Reaction processes	Colour and viscosity
80	Some white gelatinous substances were attached to the wall of the bottle	Light brown liquid, transparent, and viscous
90	A small amount of granular material was deposited at the bottom of the bottle	Dark brown liquid, transparent, and viscous
100	No sedimentation	Dark brown liquid, transparent, and viscous
110	No sedimentation	Dark brown liquid, transparent, and viscous
120	No sedimentation	Dark brown liquid, transparent, and viscous

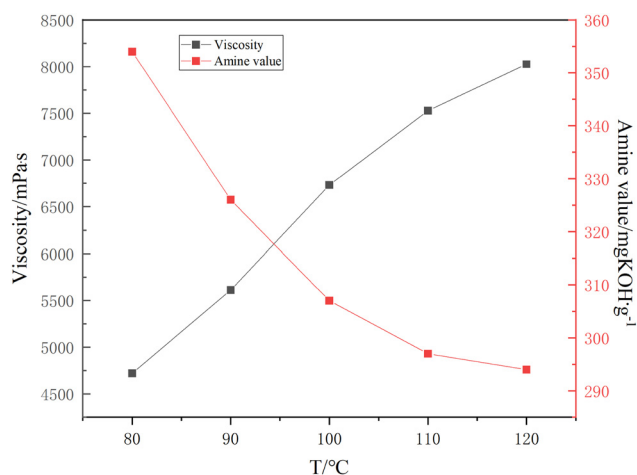


Figure 6: Effect of reaction temperature on viscosity and amine value of curing agent.

granular intermediate of phenolic aldehyde. When the reaction temperature is increased to 100°C, the precipitates disappear, confirming that the reaction is totally completed. Therefore, the reaction of the monomers to generate products is accelerated as the temperature increases, and the amount of active hydrogen on the amine is continuously consumed, leading to that the amine value decreases and the viscosity rises, respectively (Figure 6).

All coatings display extremely favorable adhesion to the steel substrate, achieving a rating of 0 or 1 (Table 5). Coatings cured with curing agents with higher preparation temperatures provide better adhesion and hardness than those cured with curing agents with lower preparation temperatures. The set-to-touch time is gradually prolonged with

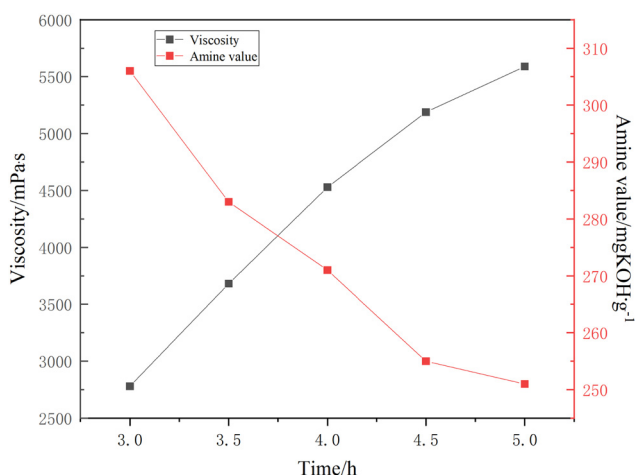


Figure 7: Effect of reaction time on viscosity and amine value of curing agent.

increasing reaction temperature. It can be attributed to the fact that the increase in reaction temperature led to the sufficient ring-opening addition reaction and reduction of reactive hydrogen on primary amines. The results show that the curing agent prepared with a reaction temperature of 100°C exhibits optimal curing properties.

As can be seen from Figure 7, the amine value decreases as the reaction time increases. However, the viscosity changes in the opposite trend to the amine value. In addition, for the amine value, the viscosity, and the coating performance, the reaction time shows a similar trend as the reaction temperature. The results show that the curing agent prepared with a reaction time of 4.5 h exhibits optimal curing properties (Tables 6 and 7).

Table 5: Effect of the as-prepared curing agent with different reaction temperature on the coating performance

Characterization	80°C	90°C	100°C	110°C	120°C
Pencil hardness/H	4	5	5	5–6	6
Adhesion/series	1	1–0	0	0	0
Surface drying time (min)	46 ± 3	48 ± 2	49 ± 2	53 ± 1	55 ± 3

Table 7: Effect of the as-prepared curing agent with different reaction time on the coating performance

Characterization	3.0 h	3.5 h	4.0 h	4.5 h	5.0 h
Pencil hardness/H	4	4–5	5	5	5–6
Adhesion/series	1	1	1–0	0	0
Surface drying time (min)	58 ± 2	52 ± 1	51 ± 2	48 ± 1	46 ± 2

Table 6: Effect of reaction time on physicochemical properties of curing agent

Reaction time (h)	Reaction processes	Colour and viscosity
3	Some white gelatinous substances were attached to the wall of the bottle	Light brown liquid, transparent, and viscous
3.5	A small amount of granular material was deposited at the bottom of the bottle	Light brown liquid, transparent, and viscous
4	No sedimentation	Dark brown liquid, transparent, and viscous
4.5	No sedimentation	Dark brown liquid, transparent, and viscous
5	No sedimentation	Dark brown liquid, transparent, and viscous

Table 9: Comparison of coating performance using modified and unmodified curing agents

Characterization	Surface drying time (min)	Adhesion/series	Pencil hardness/H	Impact resistance ($\text{kJ}\cdot\text{m}^{-2}$)	Shear strength (MPa)	Tensile strength (MPa)
MXDA	73 ± 1	3	3	7.41 ± 0.23	9.4 ± 0.2	4.9 ± 0.1
Modified MXDA	54 ± 2	1	5	9.58 ± 0.41	13.1 ± 0.3	10.5 ± 0.2

3.4 The performance of the coatings

The performance of the coatings is further investigated in both air and underwater environments. The curing agent synthesized by the optimal synthetic process is employed for these studies (the ratio of MXDA to the PA and cardanol is 1.3:1:1, a reaction temperature set at 100°C , and a reaction duration of 4.5 h).

Table 8 demonstrates surface drying time, water contact angle, and water absorption of the coatings coated mild steel substrates. It was observed that, when the ratio of epoxy resin in the coating is low, the water absorption of the coating is less.

The water contact angle decreases with increasing epoxy resin concentration in the coating, indicating that the presence of C15 long aliphatic chains and phenyl rings increases the hydrophobicity of the coating and limits the diffusion of water through coatings. Moreover, when the ratio of the curing agent to the epoxy resin is 1:1.3, the coating exhibited the shortest surface drying time. Overall, the curing agent to epoxy resin ratio of 1:1.3 is chosen to prepare the coatings and to evaluate the underwater curing performance of the coatings.

Table 9 shows the underwater curing performance of the curing agent (the modified MXDA) and unmodified MXDA. It can be seen that the surface drying time of the coating cured with modified MXDA (54 min) is shorter than that of the coating cured with MXDA (73 min). The hardness of the coating cured with modified MXDA on concrete substrates is 5H, while the hardness of the coating cured with unmodified MXDA is only 2H. Mechanically, the shear strength of coating cured with modified MXDA reached 13.1 ± 0.3 MPa compared to the MXDA (9.4 ± 0.2 MPa), which is

much higher than previously reported curing agents for underwater applications.

The tensile strength of the coating with modified MXDA is 10.5 ± 0.2 MPa, which is 2.14 times higher than that of pristine MXDA (4.9 ± 0.1 MPa). The dramatic enhancement in mechanical strength is attributed to the reinforcing network formed by the strong interactions between the homogeneous and ordered structure of the curing agent and the compactness of the coating, while C15 long aliphatic chains in the structure provide flexibility to the coating. Therefore, results suggest that coatings cured with modified MXDA exhibit better adhesion and mechanical strength than the coatings cured with MXDA.

4 Conclusion

In conclusion, a cardanol-based curing agent is successfully synthesized *via* the Mannich reaction using cardanol, PA, and MXDA. The effects of monomer ratio and reaction conditions on the properties of the curing agent have been investigated. The optimal performance of the coatings is achieved when the ratio of curing agent to epoxy resin is 1:1.3. Moreover, the coatings cured with modified MXDA exhibit superior shear strength (13.1 ± 0.3 MPa) and tensile strength (10.5 ± 0.2 MPa) compared to those cured with MXDA. Considering the advantages of ideal mechanical characteristics and exceptional adhesion both in air and under water, the cardanol-based curing agent has potential applications in the emergency rehabilitation of damaged drainage pipelines.

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Table 8: Effect of curing agent and epoxy resin ratio on coating performance

Characterization	1:1.2	1:1.3	1:1.4	1:1.5
Surface drying time (min)	58 ± 2	46 ± 1	53 ± 2	62 ± 2
Water absorption (%)	0.75	0.87	1.21	1.51
Water contact angle ($^\circ$)	89.23 ± 1.01	87.67 ± 0.23	85.34 ± 0.43	82.19 ± 0.27

methodology, validation, writing – review & editing. Yali Guo: supervision, writing – review & editing. Ning Fang: investigation, supervision, resources, writing – review & editing. Jingxiang Li: validation, resources, writing – review & editing. Zheng Li: validation. Junhan Li: data curation. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

Data availability statement: The raw/processed data are available from the corresponding author on a reasonable request.

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