Low Viscosity Epoxy Structural Adhesive Cured at Room Temperature for Crack Repair of Subway Tunnel

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Abstract. Epoxy structural adhesive has good mechanical properties, especially high adhesion, low shrinkage rate, and high stability, widely used in steel plate reinforcement, crack repair, bridge splicing, and concrete bonding, etc. However, due to the high cross-linking density and high internal stress after curing, its shortcomings, such as brittleness, the poor performance of fatigue resistance and heat resistance, limit its application in special track engineering. In this work, two kinds of epoxy structural adhesives (EPA-1, EPA-2) with low viscosity and room temperature curing were synthesized by selecting different bisphenol A epoxy resin and active diluent as component A and modified amine curing agent as component B. The results showed that EPA-1 and EPA-2 presented significant toughness compared with the classic construction adhesive (AralditeXH160). The yield strengths of EPA-1 and EPA-2 were 4.88 MPa and 13.13 MPa, and the shear strengths were 11.93 MPa and 13.08 MPa, respectively, showing good adhesive properties. In addition, the viscosities of EPA-1 and EPA-2 were 127 mPa·s and 308 mPa·s, respectively, and their decomposition temperatures were all above ~280 °C, which indicated that the self-made epoxy structural adhesives could be used for the repair of cracks in the vibration subway tunnel.

Keywords. Epoxy structural adhesive, low viscosity, room temperature curing, crack repair, subway tunnel.

1. Introduction
Epoxy resin is a kind of active polymer containing epoxy or epoxy alkyl group. Its performance depends on the combination of epoxy resin and curing agent [1]. Due to the chemical activity of the epoxy group, the cross-linking produces a network structure, which promotes the epoxy resin to have the advantages of large adhesive ability, low curing shrinkage, excellent mechanical properties, safe and reliable construction, etc. [2-3], and is widely used in the fields of electronics, automotive, aerospace, railway, energy, construction [4-5]. However, due to the high cross-linking density and high internal stress after curing, its shortcomings, such as brittleness, the poor performance of fatigue resistance and heat resistance, limit its application in special track engineering [6]. Ding et al. [7] synthesized a potential curing agent of EGE-2-MI (ethyl glycidyl ether-2-methylimidazole derivative) for epoxy resin E-51. The results showed that, compared with the unmodified E-51/2-MI system, the tensile strength of EGE- E-51/2-MI system increased to 41.05 MPa from 26.78 MPa, and the shear...
The viscosity of epoxy structural adhesive with toughness and low viscosity, which can be cured at room temperature, for repairing all kinds of cracks in railway tunnels.

In this work, two epoxy structural adhesives (EPA-1 and EPA-2) with low viscosity and curing at room temperature were synthesized by using different bisphenol A epoxy resins and active diluents as component A and modified amine curing agent as component B. Their viscosity, gelation time, tensile strength and shear strength cannot be used as a structural adhesive. Therefore, it is necessary to design a kind of epoxy structural adhesive with toughness and low viscosity, which can be cured at room temperature, for repairing all kinds of cracks in railway tunnels.

2. Experimental

2.1. Materials

CYD-115 epoxy resin (epoxy equivalent of 180-194), CYD-118 epoxy resin (epoxy equivalent of 194-205) were provided by Shanghai Yueyi Chemical Co. Ltd.; XY-501B-3 diluent (epoxy equivalent of 185-200), XY-622 Diluent (epoxy equivalent of 128-135) were obtained from Anhui Xinyuan Tech. Co. Ltd.; JA-1 modified amine curing agent (live hydrogen equivalent of 50-60), JA-123 modified amine curing agent (live hydrophone equivalent of 45-65) were provided by Sichuan Aopai Epoxy Auxiliary Tech. Co. Ltd.; Araldite XH160 epoxy adhesive was purchased from Huntsman Co.

2.2. Sample Formula

The formula of epoxy structural adhesives is shown in Table 1. The amount of curing agent (CA) required for each 100 grams of resin mixture is calculated according to the following equation (1) and (2) [9].

\[
EEW_{mix} = \frac{W_{mix}}{EEW_a + EEW_b}
\]

\[
CA(phr) = \frac{\text{Amine Hep wt} \times 100}{EEW_{mix}}
\]

where, \( EEW_a \), \( EEW_b \) and \( EEW_{mix} \) are the epoxy equivalent of epoxy resin, active diluent, and their mixture, respectively; \( W_a \), \( W_b \) and \( W_{mix} \) are the mass of epoxy resin, active diluent, and their mixture, respectively.

| Sample | Component A | Weight (g) | Component B | Weight (g) | Viscosity (mPa·s) |
|--------|-------------|------------|-------------|------------|------------------|
| EP-1   | CYD-118     | 10.0 g     | JA-123      | 3.2 g      | 127              |
|        | XY-501B-3   | 3.6 g      |             |            |                  |
| EP-2   | CYD-115     | 10.0 g     | JA-1        | 3.0 g      | 308              |
|        | XY-622      | 3.0 g      |             |            |                  |
| XH160  | Araldite XH160A | 10.0 g    | Araldite XH160B | 3.0 g    | 316              |

2.3. Performance Test

The viscosity of epoxy structural adhesive was measured by NDJ-9S digital display viscometer at 25 °C according to ASTM D 1084 test standard. Gelation time of structural adhesive was measured by CT-V type gelation time time tester. Scanning electron microscopy (SEM) was carried out by JSM IT500A.
Tensile strength was measured at 25 °C by GOTECH AI-7000M according to ASTM D-638 test standard after cure. Shear strength was measured at 25 °C by GOTECH AI-7000M according to ISO 4587 test standard. Thermogravimetric analysis (TGA) was carried out from 30 °C to 800 °C in nitrogen atmosphere at a speed of 10 °C/min by METTLER TOLEDO.

3. Results and Discussion

3.1. Viscosity
The viscosity of the samples is shown in Table 1. At 25 °C, the viscosities of EPA-1 and EPA-2 are 62 mPa-s and 120 mPa-s, respectively, close to XH160 with viscosity of 95 mPa-s, which can meet the requirements of engineering perfusion.

3.2. Gelation Times at Different Temperatures
The gelation time of epoxy structural adhesives at different temperatures of 50 °C, 70 °C, 90 °C and 120 °C was shown in Figure 1. According to the equation (3) [9], the gelation time (t) of each epoxy structural adhesives at room temperature (25 °C) can be deduced from

\[ E_a = 2.303RT \times \log t \]  

(3)

where, \( E_a \) is the activation energy, \( T \) is the temperature, and \( R \) is the gas constant of 8.314 J/(mol·K).

The gelation time of EPA-1, EPA-2 and XH160 at 25 °C was 50 min, 40 min and 29 min, respectively. The relatively long gelation time of these epoxy structural adhesives can meet the construction time of perfusion process.

![Figure 1](image)

**Figure 1.** Gelation time of epoxy structural adhesives at different temperatures.

3.3. Mechanical Properties
As shown in Figure 2, XH160 showed obvious brittle fracture with tensile fracture strength of 28.77 MPa and steel-steel shear strength of 13.02 MPa, while EPA-1 and EPA-2 showed obvious toughness with yield phenomenon at 4.88 MPa and 13.13 MPa, respectively. The tensile fracture strength of EPA-1 and EPA-2 is 10.64 MPa and 18.58 MPa, and the steel-steel shear strength is 11.93 MPa and 13.08 MPa, respectively. Although the tensile strength of the self-made epoxy structural adhesives is lower than that of XH160, the shear strength is similar. For the rail tunnel, especially the subway tunnel, it is inevitable to bear the frequent vibration caused by the train running, so it is essential to increase the toughness of the adhesive material.
3.4. Microstructures
The SEM images of the tensile fracture section of the epoxy structure adhesives are shown in figure 3. There are many obvious microcracks in EPA-1 and EPA-2 sections, and the fracture direction tends to be dispersed. When affected by external forces, the microcracks absorb capacity, presenting a ductile fracture. However, the tensile fracture of XH160 is smooth and belongs to obvious brittle fracture, which is consistent with the tensile stress-strain curve shown in figure 2.

3.5. Thermal Stability
The thermal decomposition temperature of materials is an important symbol to measure the thermal stability of materials. The TG curves of epoxy structural adhesives after curing for 7 days are shown in figure 4. About 5% of the slight weight loss of EPA-1 occurs at 130-310 °C, which may be due to a small number of epoxy resin small molecules that do not participate in the curing reaction or the curing reaction is incomplete, leading to the existence of some low molecular flexible chain segments, which decompose first when the temperature rises. The maximum thermal decomposition temperature of EPA-1 is 318 °C. There is almost no weight loss up to 250 °C for EPA-2 and XH160 with the maximum thermal decomposition temperatures of about 278 °C and 293 °C, respectively. The results showed that the self-made epoxy structure adhesive had good thermal stability and could be used in high temperature environment.
Figure 4. TG curves of epoxy structural adhesives.

4. Conclusion
Epoxy structural adhesive is widely used as a new type of construction reinforcement agent with the advantages of good adhesive performance, high strength and convenient process. In this work, two kinds of two-component epoxy structural adhesives with low viscosity and high strength were synthesized by choosing different bisphenol A epoxy resins, using active diluent to reduce their viscosity and modified amine curing agent to meet the cross-linking curing conditions at room temperature. The results showed that the composite epoxy structural adhesives had lower viscosity and toughness. It's worth noting that EPA-2 with the low viscosity of 308 mPa·s, the tensile strength of 18.58 MPa and the shear strength of 13.08 MPa could be used to repair cracks in subway tunnels.

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