A Review on Road Material Performance and Engineering Application Feasibility of Different Grades of Cold-Laid Asphalt Mixtures

Fuzhou Shi, Zhiyuan Lü*, Chu Huang, Wei Ren

School of Civil Engineering, Lanzhou University of Technology, Lanzhou 730050, Gansu, China

*Corresponding author's e-mail: 298630382@qq.com

Abstract. Hot-mix asphalt (HMA) production involves substantial energy consumption and carbon emissions. Cold-laid asphalt mixtures (CMA) offer an alternative, but insufficient strength can limit their application. This study used a toughened epoxy system to modify CMA. The selected formulation contained 14% diluent, 12% epoxy resin, 4.9% curing agent, 3% toughening agent and 0.5 wt% carboxymethyl-β-cyclodextrin (CM-β-CD). The road performance of mixtures with LB-13, AC-20 and AC-25 gradations was evaluated. Among the tested mixtures, AC-25 showed the highest high-temperature stability and retained Marshall stability, whereas LB-13 showed the highest low-temperature failure strain and flexural strength. The laboratory results indicate the potential of the modified mixtures for pavement applications. Compliance with project-specific requirements and performance in the field require further verification.

Keywords: Toughened epoxy cold-laid asphalt; Road performance; Aggregate gradation; Engineering feasibility; Pavement materials

1 Introduction

Cold-mix asphalt has attracted interest because of its potential to reduce production energy use and emissions, although strength development and moisture resistance remain important considerations [1–5]. This study modified cold-laid asphalt mixtures with a toughened epoxy system. Proportioning tests were used to select a formulation containing 14% diluent, 12% epoxy resin, 4.9% curing agent and 3% toughening agent. Carboxymethyl-β-cyclodextrin (CM-β-CD) was added at 0.5 wt% to improve interfacial interactions and mechanical properties. Mixtures with LB-13, AC-20 and AC-25 gradations were then prepared to compare their road performance.

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2 Preparation process

JB-90# base asphalt was heated until fully fluid. Component A, the toughening agent, CM-β-CD and a compatibilizer were added. The mixture was stirred at 140 °C and 500 r/min for 30 min, then held at 140 °C for 2 h. After cooling to 80 °C, the diluent was added, and the mixture was stirred at 200 r/min for 15 min without further heating. At 60 °C, an anti-stripping agent and component B were added, followed by manual stirring for 5 min to obtain the cold-patching asphalt binder. The curing-agent addition temperature was kept at or below 60 °C to control the reaction between polyamide 651 and the epoxy resin.

3 Determination of binder component proportions

Rotational viscosity at 60 °C and 1-day mass loss at 25 °C were used as response indicators. A four-factor, three-level orthogonal experiment was conducted to compare component proportions. Table 1 reports the experimental combinations and measured results.

Epoxy composites containing carboxyl-terminated butadiene–acrylonitrile rubber (CTBN) and E51 epoxy resin were prepared using the selected formulation. CM-β-CD was added at 0, 0.5, 1.0 and 2.0 wt%, and mechanical tests were used to compare these dosages.

Table 1. Results of the orthogonal experiment

Run	A Solvent oil (%)	B Component A (%)	C Component B proportion	D CTBN (%)	Viscosity at 60 °C (mPa·s)	1-day mass loss (%)
1	12	10	0.30	1	2055	0.97
2	12	12	0.35	2	1935	1.16
3	12	14	0.40	3	2415	1.01
4	14	10	0.35	3	1475	1.06
5	14	12	0.40	1	1555	1.43
6	14	14	0.30	2	1615	1.82
7	16	10	0.40	2	695	1.91
8	16	12	0.30	3	785	2.16
9	16	14	0.35	1	1115	2.37

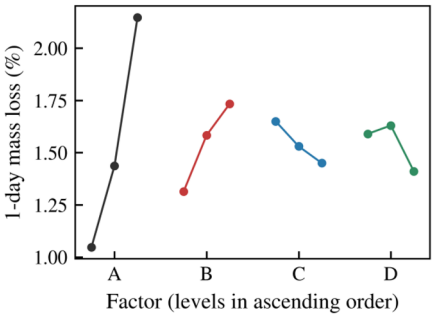


Fig. 1. Factor-level mean 1-day mass loss (left).

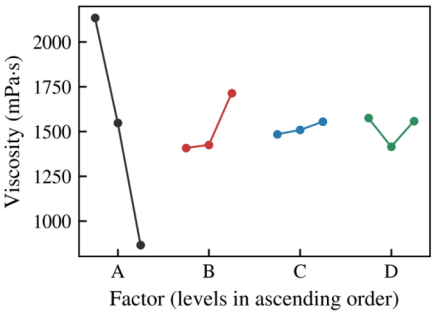


Fig. 2. Factor-level mean rotational viscosity at 60 °C (right).

Figures 1 and 2 show the mean response at each factor level in Table 1. The observed influence was greatest for solvent oil, followed by E51 epoxy resin, CTBN and the curing-agent proportion. Increasing the solvent-oil content reduced viscosity and increased 1-day mass loss. The curing-agent proportion had the smallest effect on these short-term response indicators.

Two candidate formulations were compared using mass loss and rotational viscosity. The formulation containing 3% toughening agent was selected to improve toughness.

4 Determination of CM-β-CD dosage

The tensile strength, elongation at break and tensile modulus of the epoxy composites were measured to compare CM-β-CD dosages. The results are shown in Fig. 3.

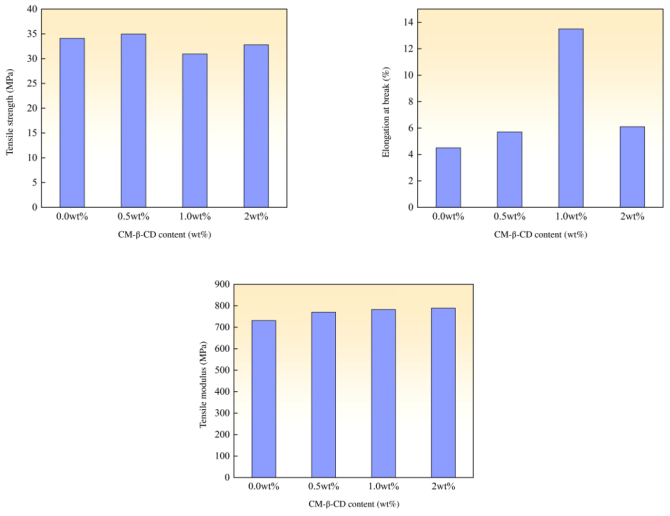


Fig. 3. Mechanical properties of the epoxy composites: tensile strength (upper left), elongation at break (upper right) and tensile modulus (lower panel).

The maximum tensile strength was 34.9 MPa at 0.5 wt% CM-β-CD. Tensile strength decreased at higher dosages. Elongation at break reached 13.5% at 1.0 wt%, while tensile modulus increased with CM-β-CD content. These trends may be associated with energy dissipation by the CTBN phase and interactions involving CM-β-CD. Related epoxy-toughening mechanisms have been discussed in the literature [6–8]. A dosage of 0.5 wt% was selected to balance strength, ductility and modifier consumption.

5 Properties of the cold-patching asphalt binder

5.1 Adhesion test

Adhesion was assessed using water immersion, with the result shown in Fig. 4.



Fig. 4. Aggregate surface after the adhesion test.

No obvious asphalt stripping was observed on the aggregate surface after immersion, indicating favorable adhesion under the test conditions [9].

5.2 Storage stability

Phase separation during storage can affect binder consistency. Storage stability was assessed by comparing the viscosity of the upper and lower portions of the binder, following the approach cited in [10]. The measured differences are reported in Table 2.

Table 2. Storage stability test results

Test	Viscosity difference (mPa·s)	Mean difference (mPa·s)
1	65.9	63.8
2	62.3	
3	63.1	

The mean viscosity difference was 63.8 mPa·s, indicating limited variation between the upper and lower portions under the storage conditions used in this study.

5.3 Compatibility

Fluorescence microscopy was used to observe the dispersion of the epoxy-containing phase in the cold-patching asphalt binder (Fig. 5).

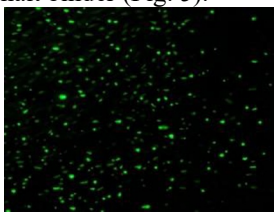


Fig. 5. Fluorescence micrograph of the epoxy-containing binder.

The fluorescent regions were dispersed throughout the observed field, suggesting a relatively uniform distribution at the scale of the micrograph.

5.4 High-temperature rheological properties

A dynamic shear rheometer (DSR) was used to evaluate the complex shear modulus G*, phase angle δ and rutting parameter G*/sin δ (Fig. 6). The complex modulus includes the storage modulus G′, associated with elastic energy storage, and the loss modulus G″, associated with energy dissipation. The phase angle describes the balance between the elastic and viscous responses.

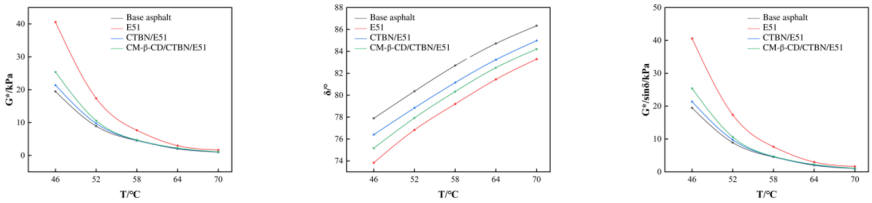


Fig. 6. DSR results: complex shear modulus (left), phase angle (middle) and G*/sin δ (right).

As temperature increased, δ increased and both G* and G*/sin δ decreased for all four binders. This indicates a more viscous-dominated response and reduced resistance to shear deformation at higher temperatures. At the lower temperatures tested, the CM-β-CD/CTBN/E51 binder had a higher G*/sin δ than the base and CTBN/E51 binders. The differences became smaller as temperature increased.

5.5 Low-temperature creep properties

The base, E51, CTBN/E51 and CM-β-CD/CTBN/E51 binders were tested using a bending beam rheometer (BBR) at −12, −18 and −24 °C. Figures 7 and 8 show the creep stiffness S and creep rate m, respectively.

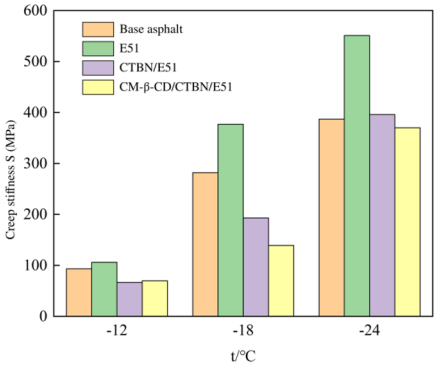


Fig. 7. Creep stiffness S.

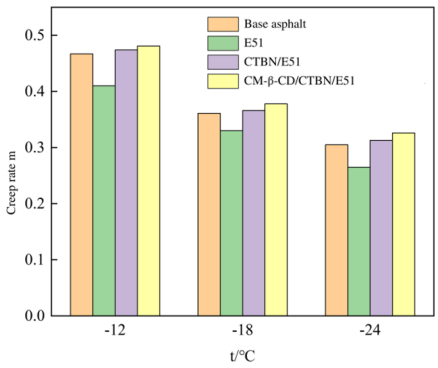


Fig. 8. Creep rate m.

Adding CM-β-CD increased m relative to the CTBN/E51 binder at the three test temperatures. Creep stiffness decreased at −18 and −24 °C, although this reduction was not observed at −12 °C. The results suggest that the effect of CM-β-CD depends on the test temperature.

5.6 FTIR analysis

Fourier transform infrared (FTIR) spectroscopy was used to compare the CTBN/E51 and CM-β-CD/CTBN/E51 binders and examine changes in their characteristic absorption bands (Fig. 9).

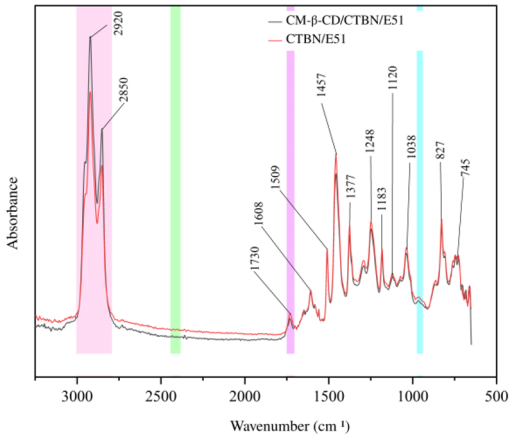


Fig. 9. FTIR spectra of the two modified binders.

Both spectra show prominent C–H stretching bands in the 2800–3000 cm^{-1} region. Differences in band intensity are consistent with changes in the local chemical environment after CM-β-CD addition. Such differences may be associated with interfacial interactions, but FTIR peak-intensity changes alone do not establish a specific hydrogen-bonding, crosslinking or inclusion mechanism.

The proposed contributions of epoxy ring opening and interactions between CM-β-CD and CTBN require confirmation using verified peak assignments and complementary characterization. The spectra are therefore used here as qualitative evidence of changes in the composite system.

6 Mixture performance tests

Mixtures with LB-13, AC-20 and AC-25 gradations were evaluated as candidate materials for the upper, middle and lower surface courses, respectively. Figures 10–13 compare Marshall stability, dynamic stability, retained Marshall stability and low-temperature bending performance.

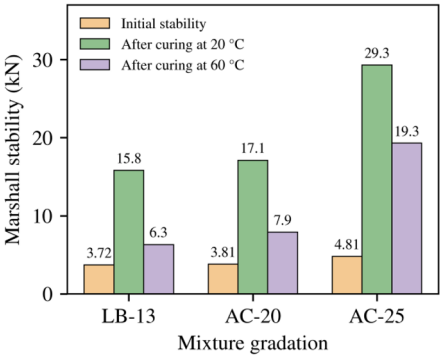


Fig. 10. Marshall stability.

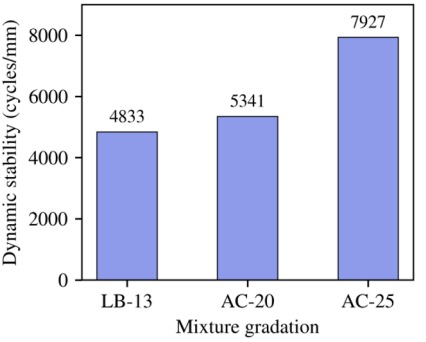


Fig. 11. Dynamic stability.

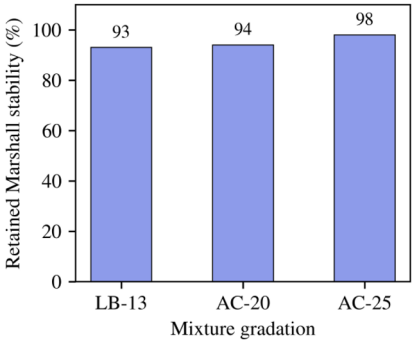


Fig. 12. Retained Marshall stability (left).

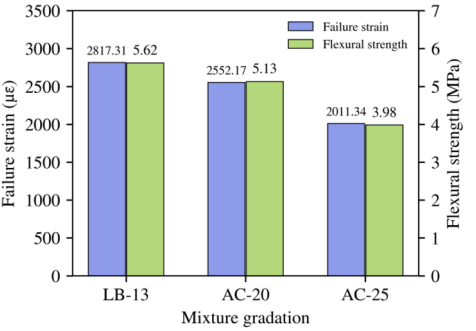


Fig. 13. Low-temperature bending results (right).

AC-25 had the highest Marshall stability after curing at both 20 and 60 °C. Its dynamic stability was 7927 cycles/mm, compared with 4833 and 5341 cycles/mm for LB-13 and AC-20. Retained Marshall stability was 93%, 94% and 98% for LB-13, AC-20 and AC-25, respectively.

LB-13 had a failure strain of 2817.31 με and a flexural strength of 5.62 MPa. The corresponding values were 2552.17 με and 5.13 MPa for AC-20, and 2011.34 με and

3.98 MPa for AC-25. Thus, LB-13 had the highest low-temperature deformation capacity and flexural strength among the tested gradations, while AC-25 had the lowest values.

These results identify a trade-off between high-temperature stability and low-temperature bending performance. Suitability for a specific pavement course requires comparison with the relevant climate-dependent limits and test conditions in the applicable specification, such as JTG F40-2004 [11]. The present comparisons do not establish that all three mixtures satisfy every requirement for high-grade highways.

7 Conclusions

A CM-β-CD-containing toughened epoxy system was used to modify cold-laid asphalt mixtures with LB-13, AC-20 and AC-25 gradations. The selected CM-β-CD dosage was 0.5 wt%, at which the epoxy composite achieved a tensile strength of 34.9 MPa. Among the mixtures tested, AC-25 showed the highest high-temperature stability and retained Marshall stability, LB-13 showed the highest low-temperature failure strain and flexural strength, and AC-20 gave intermediate results. These laboratory findings support further investigation of the modified mixtures for pavement applications. Field trials, project-specific compliance checks and long-term durability monitoring are needed before full-depth structural use can be established.

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