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Performance Evaluation Study of Solvent-Based Cold-Mix Cold-Lay Asphalt Mixture for Underground Tunnel Roadways

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SUMMARY: *This paper focuses on cosolvent and diluent to investigate the road performance of solvent-based cold-mix cold-lay asphalt mixture. The mix proportion design of the solvent-based cold-mix solution was conducted, and its workability and road performance were validated through relevant experiments. The results demonstrate that the workability and road performance of this cold-mix asphalt mixture can meet the technical requirements of hot-mix asphalt mixtures and satisfy the service requirements of asphalt pavements. Overall, the performance of the solvent-based cold-mix asphalt mixture is excellent, and the findings of this study can provide technical references for the application of cold-mix asphalt mixtures in engineering practice.*

KEYWORDS: *Road Engineering; Cold-Mixture Asphalt Pavement; Experimental Methods; Evaluation Indicators.*

1 Introduction

Asphalt structural surfaces have gradually become the main structural form of underground roadway structural surfaces, especially high-grade underground roadway structural surfaces, in China over the past few decades due to their advantages of solid and flat surfaces, good durability, and ease of maintenance and repair [1]. However, due to various unfavorable factors such as low design level, poor construction quality, harsh natural climate, and severe load-bearing overload in the past, the underground tunnel structures constructed in China often fail to meet their designed service life, resulting in extensive damage. If not repaired in a timely manner, the damage to the structures will further worsen, seriously affecting their service life [2].

Due to the traditional construction method of hot mix and hot lay for asphalt structural surfaces, the maintenance department of underground tunnel structural surfaces tends to use mature hot mix asphalt mixtures for repair after structural damage occurs. Although the use effect is still acceptable in some areas, its disadvantages are also obvious. Firstly, the hot mix asphalt mixture consumes a large amount of energy during the mixing and paving process, while generating highly polluting smoke and dust, which is contrary to China's current high standards and strict requirements for environmental protection and resource conservation; Secondly, hot mix asphalt mixture requires high mixing equipment, and the mixed mixture must be used as soon as possible, which greatly limits the application of hot mix asphalt mixture in remote mountainous areas; Again, considering the requirements for fire prevention in forest areas, hot mix asphalt mixtures that require high temperature conditions for mixing and paving are difficult to apply on a large scale in forest areas; Finally, when laying hot mix

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asphalt mixture, it is required that the ambient temperature should not be too low [3]. However, in cold regions, the laying temperature from November to April of the following year cannot meet the requirements. During this period, the diseases that occur on the structural surface can only be dealt with on the second day of the following year. This not only seriously affects the comfort and safety of driving, but also further damages such as frost heave and frost heave caused by rain and snow entering the structural surface from the damaged structural surface can significantly reduce the service life of the structural surface. In this context, cold mixed and cold laid asphalt mixtures, which have many advantages such as low environmental pollution, can be mixed and spread at room temperature, wide temperature range, low cost, and easy storage and transportation, are gradually shining in road damage repair. With the continuous expansion of the application scenarios of cold mixed and cold laid asphalt mixtures, researchers are no longer satisfied with using cold mixed materials only for road repair, but also hope to comprehensively improve the road performance of cold mixed materials through technical means, and ultimately apply them to the paving of public structural surface layers to reduce the dependence on hot mixed and hot laid asphalt mixtures in current road construction [4]. However, through investigation and analysis of the performance characteristics and practical application of different types of cold mix asphalt mixtures on the market, it is found that the domestically produced cold mix materials currently promoted and used in Heilongjiang Province generally have problems such as low early strength, slow strength generation, and poor water stability. The main reason is that commercial solvent based cold mix asphalt is difficult to adapt to the adverse climate in cold regions, so targeted improvements are needed for solvent based cold mix asphalt. In addition, the theoretical research on cold mix asphalt mixture is not deep enough, and the evolution law of mechanical properties of binder and mixture is still unclear. The technical indicators, quality control system, construction technology and evaluation related to cold mix asphalt mixture still need to be improved.

This study takes the evolution law of mechanical properties of binders (asphalt and mortar) and mixtures (mortar and mixture) as the starting point and foothold, providing ideas for solving the current problems of cold mix materials. Specifically, the study of the evolution law of the mechanical properties of binders can provide the optimal time period for the construction of the mixed material after mixing based on the temperature at the construction site; The study of the evolution law of flexural tensile strength of asphalt binder is beneficial for clarifying the low-temperature fracture performance of the mixture and gaining a deeper understanding of the applicability of solvent based cold mixed and cold laid asphalt in low-temperature environments. This study clarifies the strength generation mechanism of solvent based cold mixed and cold laid asphalt mixtures, reveals the inherent reasons for the insufficient performance of existing cold mixed and cold laid asphalt mixtures, and proposes practical and effective performance improvement techniques for mixtures based on indoor experiments and practical engineering. This has significant implications for improving the road performance of solvent based cold mixed and cold laid asphalt mixtures and lays a good foundation for the promotion and application of mixtures in cold regions.

2 Related research

2.1 Research Status of Asphalt Mixtures

In order to overcome the problem of difficulty in timely repairing structural pits and grooves in harsh weather or low temperature environments, foreign countries began to pay attention to the research of cold repair materials for pits and grooves in the 1930s. In the mid-20th century, research in the former Soviet Union found that the performance of cold patch asphalt mixtures was mainly related to the viscosity of cold patch asphalt and the amount of mineral powder added. The amount of mineral powder added should be adjusted appropriately according to the viscosity of cold patch asphalt. Due to the low viscosity of cold patching asphalt, the mineral powder content is usually as high as 15% to 30% to ensure the strength and durability of the cold patching asphalt mixture [5]. In the 1980s, the SHRP-H program conducted extensive on-site and indoor research on the effectiveness of pit repair materials and methods used under low temperature conditions in winter, making outstanding contributions to the maintenance of structural surfaces. In the 1990s, in order to adapt to different climatic conditions and meet the requirements of all-weather construction, Japan developed two types of cold patching asphalt mixtures: room temperature type and low-temperature type, and put forward suggestions for the technical requirements of cold patching asphalt mixtures. Subsequent practical applications have shown that its product has excellent road performance and has been widely used in structural surface repair. However, most of the cold repair asphalt mixture uses emulsified asphalt as the binder, resulting in higher production costs. In 2001, the New Jersey Department of Transportation compared the performance of pit cold repair materials such as QPR2000, IAR, Performix, PermaPatch, Suitkote, UPM, and WesPro. The results indicate that compared to other products, QPR2000 cold patching asphalt mixture has significant performance advantages. [6] conducted a systematic study on the design methods and evaluation system of cold patching asphalt mixtures. A design program for cold patching asphalt mixture has been established, and corresponding evaluation methods have been proposed for the technical performance of cold patching asphalt mixture, including construction workability, stability, cohesiveness, and water stability. [7] explored the performance requirements and evaluation methods of cold patch asphalt mixtures based on the actual damage of structural surfaces in the Tokyo area, and established a high durability all-weather cold patch asphalt mixture standard applicable to the Tokyo area. [8] introduced an improved technology for producing cold patch asphalt using emulsion. This technology has been used for actual structural surface repair for many years, and several test roads have been in use for up to 15 years. The sampling analysis results show that although the porosity of the cold patching asphalt mixture is high, its low-temperature crack resistance and durability are very good, and only a small number of cracks are generated at the repair site. Moreover, the test results of the extracted cold patching asphalt binder once again indicate that its aging degree is very low. [9] conducted a study and comparison of the performance of various cold patch asphalt mixtures using Maguire stability test, indirect tensile test, and Hamburg wheel tracking test. The research results indicate that the anti-rutting ability of dense graded cold patching asphalt mixture samples is significantly higher than that of open graded samples, and the water resistance of cold patching asphalt mixture is highly correlated with the dust content and coarse aggregate ratio in the grading.

2.2 Research on the Performance of Asphalt Mixtures

In current research, the correlation between the performance of asphalt, asphalt emulsion, and asphalt binder and the performance of asphalt mixtures is a hot topic in the study of asphalt mixture performance. Asphalt, as a bonding material in asphalt mixtures, has a significant correlation with the properties of the asphalt mixture. [10] studied the correlation between asphalt evaluation indicators and the road performance of the mixture. The experimental results showed that there was a strong correlation between the softening point of asphalt and the rutting resistance of the mixture, as well as between asphalt adhesion and the crack resistance of the mixture. [11] found through studying the correlation between the aging indicators of asphalt and asphalt mixtures that the macroscopic indicators of low-temperature asphalt have a good correlation with the strength, modulus, and other properties of asphalt mixtures. [12] studied the relationship between the viscosity changes of solvent based cold mix asphalt and the strength growth of cold mix asphalt mixture. After testing with 8 different combinations of binders and aggregates, the results showed that curing at 110 ℃ for 24 hours can be used to predict the road performance of cold mix asphalt mixture after complete curing. Moreover, the stability and rutting resistance of cold mix made of high viscosity asphalt are almost comparable to those of hot mix. [13] found through studying the influence of asphalt rheological properties on the induced self-healing process of asphalt concrete that the zero shear viscosity of asphalt plays a key role in the realization of induced healing of asphalt concrete. In addition to the good correlation between the properties of asphalt and asphalt mixture, there is also a strong correlation between the performance of asphalt emulsion and mixture. [14] proves through the results that as the powder to binder ratio increases, the construction and workability of the mixture deteriorate. Therefore, a reasonable powder to binder ratio should be determined in actual production. [15] compared the effects of different powder to binder ratios and fillers on the high and low temperature performance of the mixture. The results showed that a reasonable powder to binder ratio and filler type can improve the high-temperature rutting resistance of the mixture, but the low-temperature cracking resistance decreases. [16] established a microscale cohesive damage model based on mechanical performance tests of asphalt binder. The analysis results of the model showed that the asphalt binder with added additives had a smaller microscale damage area, which was significantly reduced in strength degradation at the mixing layer. [17] explored the correlation between the complex modulus of asphalt emulsion and the dynamic modulus of the mixture. The results showed that the changes in asphalt type and powder to binder ratio had a significant impact on the dynamic modulus of the mixture, while the effects of mixture grading, aggregate and mineral powder types were not very significant. In addition to research on asphalt and asphalt emulsion, the performance of asphalt binder dispersed in asphalt emulsion dispersion medium with fine aggregates as dispersed phase also has a good correlation with the performance of asphalt mixture. Related research has also received widespread attention. [18] used recycled fine aggregates to prepare asphalt binder, and after curing for 7 and 28 days, studied the effect of air entraining agent content on compressive strength and flexural strength. [19] studied the effect of the proportion of recycled iron powder (RIP) replacing natural sand on the strength, durability, and compressive strength of asphalt binder. It was found that a RIP replacement ratio of 30% significantly improved the performance of asphalt binder. [20] studied the nonlinear viscoelastic characteristics of adhesive sand and established a relevant model to predict the deformation of the mixture. The results showed that considering the influence of the nonlinear viscoelasticity of adhesive sand, the error between the predicted values of the model and the experimental values was smaller. [21] attempted to study the feasibility of replacing some natural fine aggregates with glass residue, and found that the highest strength was achieved when the glass residue replacement rate was 50%. However, all asphalt binder proportions exhibited high capillary coefficients, which may lead to a decrease in water stability.

2.3 Research on the Growth Law of Mixture Strength in Section 2.3

Many researchers have explored the strength growth law of cold mix asphalt mixtures, hoping to provide guidance for the design and construction of cold mix asphalt mixtures. For example, [22] explored the effects of curing temperature and curing time on the strength of cold mix asphalt mixtures, and proposed a linear hyperbolic maturity function to predict the strength growth of cold mix materials under different curing schemes, with an accuracy of over 95%. The linear hyperbolic maturity function model used is as follows:

$$M(t) = \frac{t}{a + b \cdot t} \tag{1}$$

where, $M(t)$ is maturity; t is the curing time; α and b are constants related to the curing temperature.

[23] treated six different types of cold mix asphalt mixtures (four dense gradation and two open gradation) with four different curing methods, and conducted Marshall stability, wear test, and rutting test to study the effects of short-term curing, long-term curing, and moisture on structural surfaces. The results of the experiment indicate that the dense graded cold mix material has higher Marshall stability and rutting resistance than the open graded cold mix material. At the same time, the wear resistance of the cold mix material is highly correlated with the thickness of the asphalt film on the aggregate surface. [24] draws on the methods used in the field of cement concrete to evaluate strength development and proposes a maturity method suitable for cold mix asphalt materials. Research has shown that there is a strong correlation between maturity and stiffness within a certain range of temperature and duration adjustments, which can predict short-term and long-term material properties under known environmental temperature conditions. The correlation model between maturity and stiffness used is as follows:

$$E(t) = E_0 \cdot \left(1 - e^{-k \cdot M(t)}\right) \tag{2}$$

where, $E(t)$ is the stiffness at time t; E_0 is the final stiffness; k is a constant related to the material; $M(t)$ is maturity (which can be calculated from the above linear hyperbolic maturity function).

[25] used Marshall test, indirect tensile test, and Hamburg rutting test to test the rutting resistance and water stability of 9 different cold mix materials (5 dense gradation and 4 open gradation). The test results showed that the dense gradation cold mix material had higher resistance to permanent deformation than the open gradation cold mix material, and the proportion of coarse aggregate would affect the water damage resistance and rutting resistance of the open gradation cold mix material. [26] conducted Marshall tests, indirect tensile tests, and rutting tests to study the engineering characteristics of cold mix asphalt mixtures. In the study, they cured the cold mix asphalt mixture at 20 ° C for one day to simulate initial stability, and cured it at 60 ° C for 3, 7, and 14 days to simulate service life. The results indicate that the curing time, nominal maximum particle size, curing temperature, and solvent based cold mix and cold lay asphalt type will have an impact on the performance of cold mix materials.

2.4 Analysis of Research Status

Due to its unique advantages, cold mixing and cold paving technology has gradually attracted the attention and importance of researchers at home and abroad. At present, the technology in this field has been relatively mature abroad, with relevant research and practical application in the fields of emulsified, foam, solvent and reactive cold mix and cold paving asphalt mixtures. Although the research in this field started late in China, through the continuous efforts of relevant universities and research institutes, various low-cost cold mix and cold paving asphalt products have been developed, which has greatly filled the gap in the field of road maintenance in China. However, the cold mix and cold lay asphalt products currently produced still have problems such as low early strength, slow strength generation rate, and poor water stability. Cold mix and cold lay asphalt mixtures suitable for cold regions still need to be developed. From the existing research on solvent based cold mix asphalt and mixtures, it can be seen that the improvement of the performance of solvent based cold mix asphalt mainly depends on two ways. One is to enhance the performance of asphalt by adding efficient modifiers and enhancers, and the other is to adjust the composition ratio of asphalt to achieve the goal of improving the performance of solvent based cold mix asphalt. Correspondingly, the performance improvement methods of solvent based cold mix and cold lay asphalt mixtures are similar. In addition to traditional methods such as adding fibers, cement, and hydrated lime, water-based epoxy resins, soybean oil, and other materials are also used to improve the performance of solvent based cold mix and cold lay asphalt mixtures. From existing research, there is a significant correlation between the performance of asphalt, asphalt emulsion, asphalt binder, and asphalt mixture. Establishing the interrelationships between asphalt and asphalt mixture, asphalt emulsion and asphalt mixture, and asphalt binder and asphalt mixture is currently a hot research topic. Therefore, when studying the performance of solvent based cold mix and cold lay asphalt mixtures, it is also very important to study the performance of asphalt, binder, and sand. By exploring the performance of asphalt mixtures based on binder theory, the influencing factors of asphalt mixture performance can be further obtained, which can guide the modification and research of solvent based cold mix and cold lay asphalt. Due to the problems of low initial strength and slow strength growth of solvent based cold mix and cold lay asphalt, it is of great significance to study the strength growth law of solvent based cold mix and cold lay asphalt mixtures. Identifying the influencing factors of the strength growth of the mixture and predicting the strength growth of the mixture is currently a problem that needs to be solved in the application process of solvent based cold mix and cold lay asphalt mixtures.

3 Raw Material

The solvent-based cold-mix cold-lay asphalt mixture consists of Cold Mixture Liquid A + Cold Mixture Liquid B + aggregate, with an asphalt-stone ratio of 5%. Cold Mixture Liquid A: epoxy resin + diluent + anti-stripping agent + cosolvent + 70# asphalt.Cold Mixture Liquid B: curing agent.

3.1 Asphalt

The base asphalt used in this study is 70# asphalt. Table 1 shows the relevant data of technical parameters for 70 # base asphalt.

Table 1: Technical Parameters of 70# Base Asphalt

Inspection Project	Unit	Technology Index	Result of Survey	Detection Method
Needle Penetration/25℃	0.1mm	60-80	72	T0604
Softening Point/5℃	℃	≥46	58	T0606
Ductility/10℃	cm	≥15	55	T0605
Ductility/15℃	cm	≥100	138	T0605
Solubility	%	≥99.5	99.8	T0607
60℃Dynamic Viscosity	Pa▪s	≥180	227	T0625
Flash Point(COC)	℃	≥260	285	T0611
Wax Content(Distillation)	%	≤2.2	1.5	T0615
Quality Loss	%	≤0.8	0.03	T0610
Residual Penetration Ratio/25℃	%	≥61	72	T0604
Residual Ductility/10℃	cm	≥6	7.3	T0605

3.2 Cosolvent

The key technology of solvent-based cold mix asphalt lies in reducing the viscosity of the base asphalt, which is typically achieved using flux solvents. The selection of flux solvents should meet the following criteria: (1) It should dissolve well in asphalt, disperse uniformly within the asphalt, and exhibit no significant stratification. (2) It should significantly reduce the viscosity of the asphalt without adversely affecting or only minimally impacting other properties of the asphalt, particularly the adhesion between asphalt and aggregates, which should not be reduced to excessively low levels. (3) It should be economically viable.

Most of the popular flux solvents in the Chinese market are petroleum-based products (such as diesel), rubber oil-based products, and vegetable oil-based products (such as peanut oil, rapeseed oil, soybean oil, tung oil, etc.). Based on the characteristics of underground roadways, the flux solvent must possess a high flash point, low viscosity, and good compatibility with asphalt. Below is a comparative analysis of the performance indicators of several flux solvent products. Table 2 shows the technical parameter related data of different flux solvent products.

Table 2: Technical Parameters of Different Flux Solvent Products

category of the product	ignition point	Flash point	dynamic viscosity (normal temperature)	price	Compatibility with asphalt
	(℃)	(℃)	(Pa▪s)	(CNY / ton)	
petroleum based	350~380	65~75	10^{-4}~10^{-2}	6000~8000	Better
Rubber oil series	200~300	>40	25~300	4000~6000	Better
Vegetable oil series	350~500	>230	10^{-1}~10^{-5}	3000~5000	Better

Through the above comparative analysis and taking into account environmental requirements. The cosolvent employed in this study is a natural oil directly extracted from plants, which can serve as an eco-friendly plasticizer in the rubber industry. Solvent based cold mix asphalt mixtures generally have characteristics such as low viscosity, strong hydrophilicity, flammability, and biodegradability. Table 3 shows the relevant data of co solvent technology parameters.

Table 3: Cosolvent Technical Parameters

Item	Acid value	Gravity (20℃)	Viscosity (100℃)	Peroxide value	Moisture and volatiles	insoluble impurities
	(KOH/(mg/g))	(g/cm^3)	(CSt)	(g/100g)	(%)	(%)
Standard value	≤1.5	Field Test	≤1.0	≤0.125	≤0.10	≤0.05
Test value	0.068	0.955	0.85	0.062	0.051	0.01

3.3 Diluent

For epoxy resin materials, adding an appropriate amount of diluent can effectively reduce their viscosity and improve their construction performance. Diluents also help to adjust the physical properties such as hardness and toughness of cured epoxy resin materials to a certain extent.

In this study, a white bifunctional diluent was selected, which has a relatively low viscosity and no irritating or unpleasant odor, making it suitable for use in enclosed areas such as tunnels. Compared with single epoxy reactive diluents, cured resins have relatively better mechanical performance indicators such as tensile strength, flexural strength, compressive strength, and impact resistance, which helps to improve the service life of tunnel structural surfaces. Table 4 shows the relevant data of diluent technical parameters.

Table 4: Diluent Technical Parameters

Item	Viscosity	epoxy value	Color	Hydrolyzed chlorine	Inorganic oxygen	Moisture
	(CPS/25℃)	(eq/100g)	(APHA)	(ppm)	(eq/100g)	(%)
Test value	10-20	≥0.74	≤40	≤1000	≤0.005	≤0.1

3.4 Epoxy Resin

Epoxy resin is a white gel like liquid, which is formed by chemical reaction of bisphenol a and epichlorohydrin. This material has a relatively high purity, which promotes its relatively better performance in mechanical strength, chemical resistance, heat resistance, and other aspects. Table 5 shows the relevant data of epoxy resin technical parameters.

Table 5: Epoxy Resin Technical Parameters

Item	Epoxide Equivalent	Color	Flash Point	Viscosity	Hydrolyzed chlorine	Gravity
	(g/eq)	/	(℃)	(cps,25℃)	(ppm)	(g/cm^3,25℃)
Test value	184~190	1.0max	150	12000~15000	1000	1.16

3.5 Curing Agent

By improving the amine curing agent, it has the characteristics of fast drying speed, fast low-temperature curing performance, good flexibility, and excellent corrosion resistance. The improved amine curing agent has relatively better compatibility with low polarity resins such as coal tar epoxy. Table 6 shows the relevant data of curing agent technical parameters.

Table 6: Curing Agent Technical Parameters

Item	Activated hydrogen equivalent	Viscosity	Chromatic number (iron-cobalt colorimetric)	Amine value
	(g/eq)	(mPa·s@40℃)	/	(mgKOH/g)
Test value	134	600~2600	<15	250~290

3.6 Anti-stripping agent

The main function of anti stripping agent is to enhance the adhesion of asphalt mixture. The main mechanism of this functional additive to improve the water resistance of the structural surface is to enhance the interfacial bonding force between asphalt and aggregate, which can effectively prevent damage such as stripping, loosening, and potholes of asphalt structural surface, and extend the service life of the structural surface.

4 Mixture Performance Evaluation

4.1 Experimental Study on the Effects of Epoxy Resin and Curing Agent Properties

In the experiment, the asphalt aggregate ratio of AC-13 cold mix asphalt mixture was 5%, and the relevant experimental parameter settings are shown in Table 7. The experimental testing indicators include the curing time, workability performance, and structural surface performance of the asphalt mixture. Table 8 shows the experimental design table for different epoxy resin and curing agent contents.

Table 7: Mineral aggregate gradation

Aggregates Standard	Coarse aggregate			Fine Aggregate	Mineral Powder
	9.5~16	4.75~9.5	2.36~4.75	0.075~2.36 (Manufactured sand)	/
Mass Ratio	28%	30%	7%	32%	3%

Table 8: Experimental Design Table for Different Contents of Epoxy Resin and Curing Agent

Number	Raw material consumption(%)					Remark
	Epoxy Resin	Diluent	Curing Agent	Cosolvent	70# Asphalt	
Test 1	30%	8%	18.90%	21.55%	21.55%	Cosolvent: Asphalt=5:5
Test 2	30%	8%	13.50%	24.25%	24.25%	
Test 3	30%	8%	16.20%	22.90%	22.90%	
Test 4	27%	6%	13.50%	26.75%	26.75%	
Test 5	27%	6%	16.20%	25.40%	25.40%	
Test 6	27%	6%	18.90%	24.05%	24.05%	
Test 7	24%	4%	16.20%	27.90%	27.90%	
Test 8	24%	4%	18.90%	26.55%	26.55%	
Test 9	24%	4%	13.50%	29.25%	29.25%	

Note: The structural ratio of diluent material is linearly related to the proportion of epoxy resin in it, and is independent of the raw material ratio of cosolvent and 70 # asphalt.

4.1.1 Analysis of Workability Test Results

(1) Experimental steps: Weigh 500g of mineral aggregate and mix it with a cold mix solution to observe its processing performance. Monitor the curing status every 30 minutes to determine the curing time of the material.

(2) Experimental Results: The test results are shown in Table 9 below. Workability is rated on a scale of 1 to 5, with 1 being the best and 5 being the worst.

Table 9: Workability Test Results

Number	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
workability	5	1	2	1	2	5	2	2	1
Curing Time (h)	2.5~3.0	Uncured	Uncured	Uncured	2.0~2.5	1.5~2.0	3.0~3.5	2.5~3.0	Uncured

(3) Analysis of Test Results

a. The workability of cold-mix asphalt mixtures is reflected in the uniformity of particle distribution, the completeness of cold-mix solution coating, and the level of fluidity. It serves as a key indicator for evaluating the difficulty of construction. Workability directly impacts construction efficiency and project quality, making it a primary consideration in the development of cold-mix solutions.

Based on the analysis of Table 3, the workability of cold-mix asphalt mixtures is correlated with two factors:(1) The ratio of epoxy resin to diluent. A lower ratio of epoxy resin to diluent results in higher fluidity and better workability.(2) The total content of cosolvent and asphalt. Higher total content of cosolvent and asphalt leads to increased fluidity and improved workability.In summary, within a reasonable range, increasing the proportion and content of diluent and cosolvent enhances the viscosity-reducing effect of Cold Mixture Liquid A, thereby improving workability.

b. The curing time of cold-mix asphalt mixtures significantly influences strength development, construction operability, and structural quality. Excessively short curing time may compromise transportation, laying, and compaction processes, leading to quality defects. Conversely, prolonged curing time delays traffic opening, potentially resulting in reduced load-bearing capacity and crack formation.

4.1.2 Analysis of Pavement Performance Test Results

(1) Test Procedures

a. Marshall Test: Weigh 4800g of mineral aggregate according to the mix proportion, add the cold-mix solution, and prepare 5 Marshall specimens following the test specifications. After curing at ambient temperature for 12 hours and immersing in water for 30-45 minutes, measure the Marshall stability, flow value, and Marshall modulus.

b. Rutting Test: Weigh 30kg of mineral aggregate according to the mix proportion, add the cold-mix solution, and prepare 3 specimens following the test specifications. After curing at ambient temperature for 14 hours and additional conditioning in a constant temperature chamber at 60°C for 6 hours, determine the dynamic stability.

The relationship model between dynamic stability and mixture composition used is as follows:

$$DS = \alpha \cdot (ER + CA) + \beta \cdot \frac{CO}{AS} + \gamma \tag{3}$$

where, *DS* stands for dynamic stability; *ER* is the content of epoxy resin; *CA* is the content of curing agent; *CO* is the content of cosolvent; *AS* stands for asphalt content; α, β and γ are regression coefficients.

(2) Test Results: The test results are presented in Table 10 and Figure 1~Figure 4. Figure 1 shows the Marshall stability test results of the ratio of epoxy resin to curing agent. Figure 2 shows the experimental data of the ratio of epoxy resin and curing agent to flow value. Figure 3 shows the Marshall stability test data for the combination content of epoxy resin and curing agent. Figure 4 shows the experimental data of the combination content flow value of epoxy resin and curing agent.

Table 10: Marshall Test Results

Number	Marshall stability (KN)	flow value (mm)	Marshall modulus MS/FL	dynamic stability per millimeter
Test 1	14.6	1.5	9.7	79157
Test 2	3.4	4.1	0.8	2187
Test 3	7.3	4.2	1.7	8978
Test 4	3.8	4.3	0.9	6251
Test 5	11.6	2.9	4.0	37558
Test 6	12.3	2.2	5.6	51468
Test 7	7.7	3.1	2.5	21473
Test 8	8.1	2.5	3.2	32541
Test 9	2.5	3.5	0.7	1508

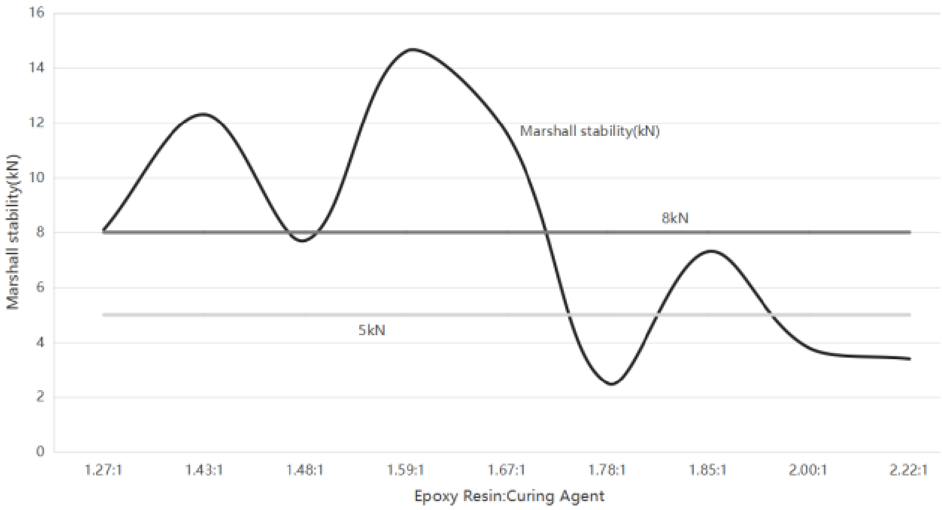

Figure 1: Epoxy resin to curing agent ratio~Marshall Stability

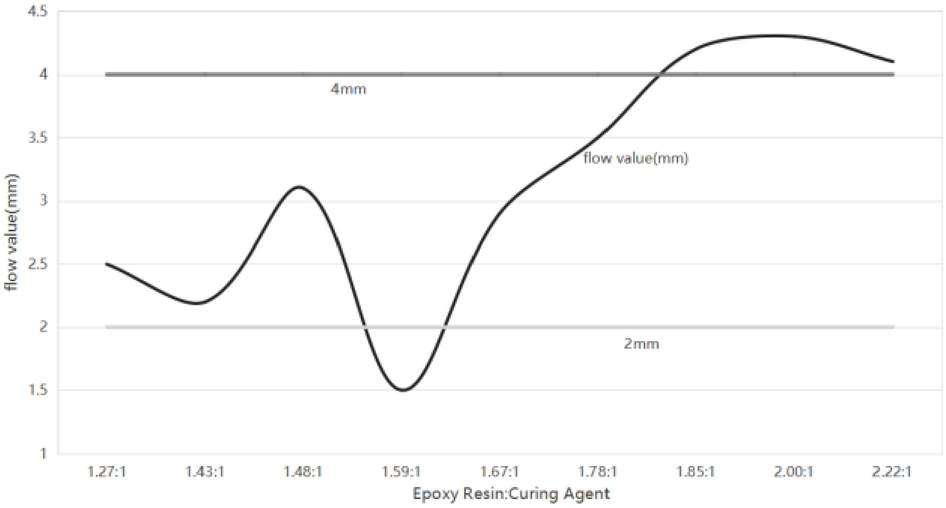

Figure 2: Epoxy resin to curing agent ratio~Flow Value

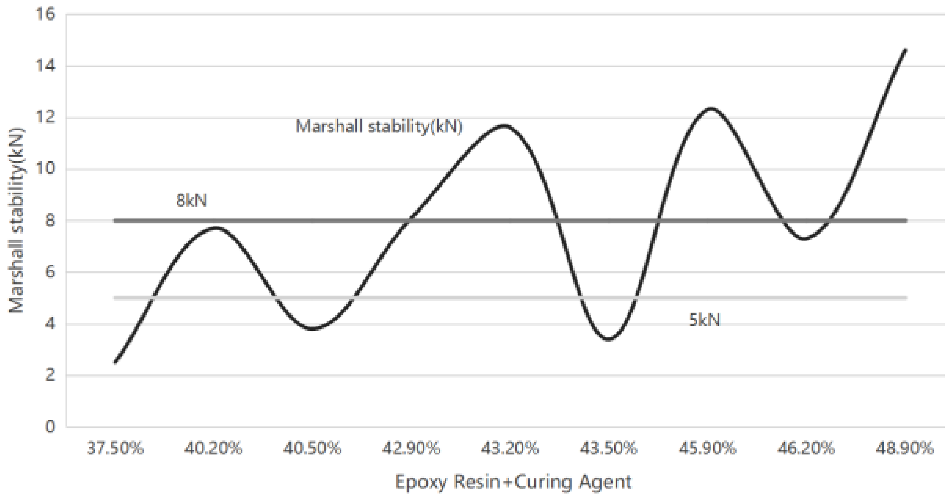

Figure 3: Combined content of epoxy resin and curing agent~Marshall Stability

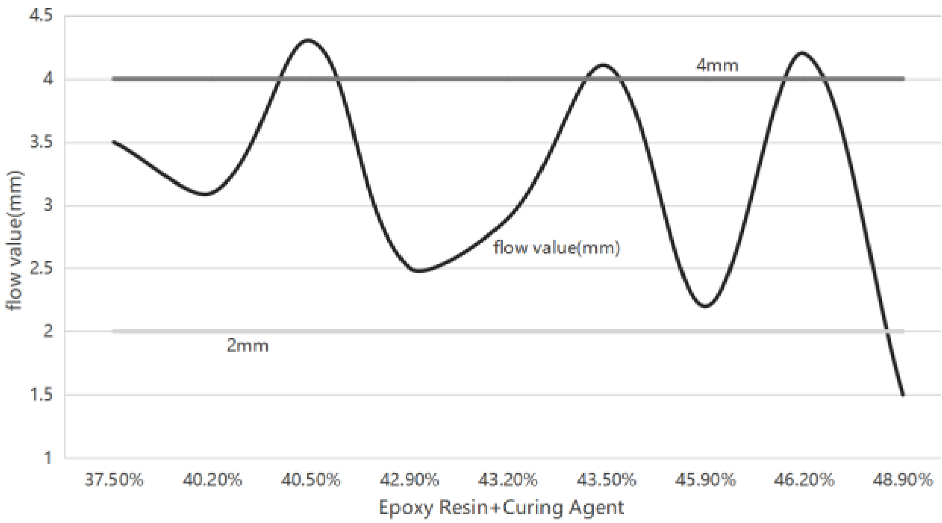

Figure 4: Combined content of epoxy resin and curing agent~Flow Value

(3) Analysis of Marshall Test Results

Figure 5 shows the dynamic stability experimental data of the combination content of epoxy resin and curing agent. Figure 6 shows the dynamic stability experimental data of the ratio of epoxy resin to curing agent.

a. According to the strength variation pattern observed in Marshall tests, within a specific range, a smaller epoxy resin-to-curing agent ratio combined with a higher total content of epoxy resin and curing agent results in greater Marshall stability and a smaller flow value.

b. According to the relevant specifications, for heavy-duty traffic in hot summer zones, the Marshall stability must not be less than 8 kN, and the flow value (FL) should range between 2 mm and 4 mm.Based on the aforementioned tests, the results of Test 2, 3, 4, 7, and 9 do not meet the specification requirements, while the results of Test 1, 5, 6, and 8 comply with the specifications and can be further analyzed to determine the optimal mix proportion.

c. Based on the aforementioned workability test results, Test 1 and 6 demonstrate poor workability.

d. Compared to the test results of Test 8, Test 5 Mixing ratio, despite having higher costs, demonstrates shorter curing time and higher Marshall stability.

e. Based on the comprehensive test results, the mixing ratio of test 5 is identified as the optimal formulation in this study.

(4) Analysis of Rutting Test Results

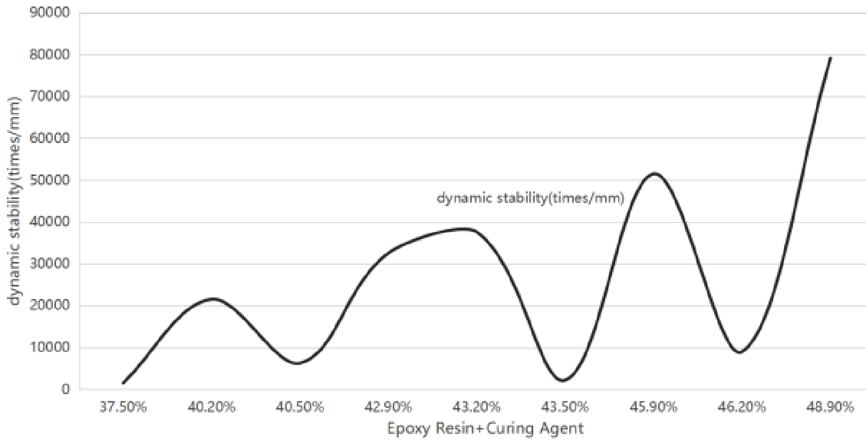

Figure 5: Combined content of epoxy resin and curing agent~Dynamic Stability

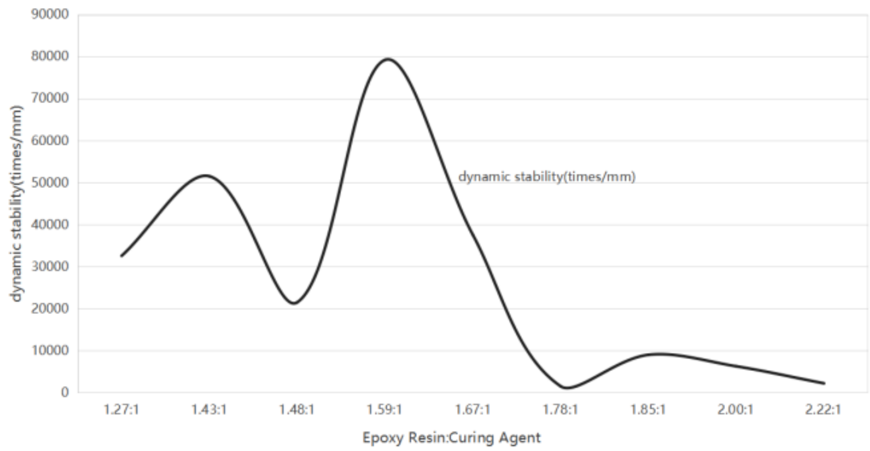

Figure 6: Epoxy resin to curing agent ratio~Dynamic Stability

According to the Table 10 and Figure 5, 4-6, the dynamic stability in hot summer zones must not be less than 800 cycles/mm. Based on the aforementioned test results, Tests 1, 3, 5, 6, 7, and 8 meet the specification requirements. The variation trend of dynamic stability is similar to that of Marshall stability.

In summary, based on the comprehensive analysis of workability tests, Marshall tests, and Rutting tests, Test 5 Mixing ratio is identified as the optimal mix proportion.

4.2 Effect of Cosolvent and Asphalt on the Performance of Cold-Mix Asphalt Mixture

Based on the previous test results, further experimental analysis was conducted on the cosolvent and asphalt content using the Test 5 mixing ratio as the baseline. Due to the slight lack of integrity and the presence of certain stripping phenomena in the aforementioned test specimens, an anti-stripping agent was added at a proportion of 0.6%. Table 11 shows the experimental design table for the changes in cosolvent and asphalt content.

Table 11: Experimental Design Table for Varying Contents of Cosolvent and Asphalt

Number	Raw material consumption(%)						Remark
	Epoxy Resin	Diluent	Curing Agent	Anti-Stripping Agent	Cosolvent	70# Asphalt	
1	27%	6%	16.20%	0.60%	20.1%	30.1%	Cosolvent: Asphalt=4:6
2	27%	6%	16.20%	0.60%	22.6%	27.6%	Cosolvent: Asphalt=4.5:5.5
3	27%	6%	16.20%	0.60%	25.1%	25.1%	Cosolvent: Asphalt=5:5
4	27%	6%	16.20%	0.60%	27.6%	22.6%	Cosolvent: Asphalt=5.5:4.5
5	27%	6%	16.20%	0.60%	30.1%	20.1%	Cosolvent: Asphalt=6:4

4.2.1 Analysis of Workability Test Results

(1) The experimental procedure is the same as described previously.

(2) Test results: The test results are presented in Table 12. Workability is rated on a scale of 1 to 5, with 1 being the best and 5 being the worst.

Table 12: Workability Test Results

Number	Test 1	Test 2	Test 3	Test 4	Test 5
workability	5	4	2	1	1
Curing Time(h)	1.5~2.0	1.5~2.0	2.0~2.5	2.0~2.5	2.5~3.0

(3) Analysis of Test Results

a. Based on Table 12, under the condition of a constant total content of cosolvent and asphalt, a higher ratio of cosolvent to asphalt results in greater fluidity and better workability. Test 4, 5 demonstrates the best workability. This is because vegetable oil-based flux solvents are inherently low-viscosity organic liquids. When mixed with asphalt, they exert a diluting and viscosity-reducing effect through physical and chemical interactions. The molecules of the flux solvent penetrate between large molecular aggregates such as asphaltenes and resins, increasing the molecular spacing. This effectively weakens the compactness of the network structure formed by asphaltenes and resins, thereby reducing the intermolecular forces (van der Waals forces) and significantly enhancing the fluidity of the entire system while markedly decreasing its viscosity.

b. Based on Table 12, under the condition of a fixed total content of cosolvent and asphalt, a higher ratio of cosolvent to asphalt results in a longer curing time. Test 5 exhibits the longest curing time. This is because the oil-modified asphalt formed after the reaction between the flux solvent and the asphalt also exerts a diluting effect on the epoxy resin, thereby extending the curing time between the epoxy resin and the curing agent.

c. Test 5 demonstrates the best workability and the longest curing time. Thus, it can be concluded that Test 5 represents the optimal mix proportion in terms of construction performance.

4.2.2 Analysis of Pavement Performance Test Results

(1) The experimental procedure is the same as described previously.

(2) The test results are shown in Table 13 and Figure 7, Figure 8.

Table 13: Marshall Test Results

Number	Marshall stability	flow value	Marshall modulus	dynamic stability
	(KN)	(mm)	MS/FL	times / mm
Test 1	14.1	3.0	4.7	41102
Test 2	12.2	2.7	4.5	39902
Test 3	10.3	2.9	3.6	37558
Test 4	7.5	3.1	2.4	34875
Test 5	5.5	3.2	1.7	29875

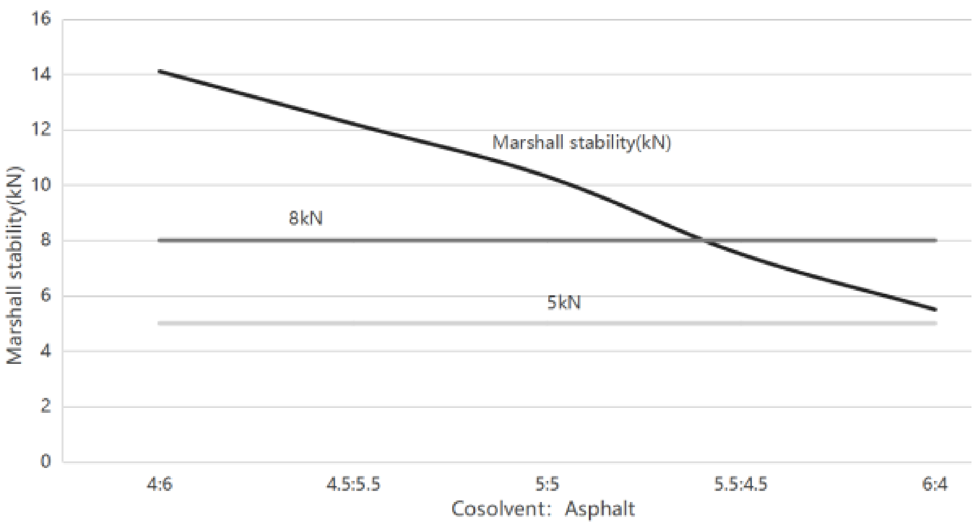

Figure 7: Cosolvent-Asphalt Ratio~Marshall Stability

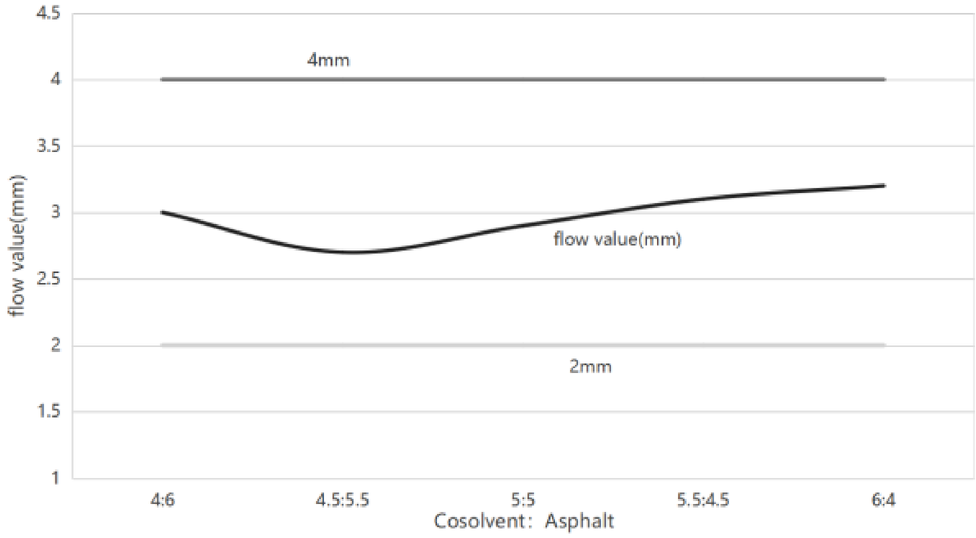

Figure 8: Cosolvent-Asphalt Ratio~Flow Value

(3) Analysis of Marshall Test Results

a. Based on Table 13, under the condition of a fixed total content of cosolvent and asphalt, a smaller ratio of cosolvent to asphalt results in greater Marshall stability and a smaller flow value.

b. At the same time, due to the thinning and loss of the asphalt film, the overly fluid asphalt is prone to being squeezed and displaced between aggregates under compaction and traffic loads, or even "punctured" by the aggregates. This results in uneven or excessively thin effective asphalt film thickness, causing a sharp decline in the adhesive force between aggregates. The direct consequence is that the asphalt mixture exhibits low Marshall stability, insufficient cohesion, and extremely poor early-stage strength after formation, making it highly susceptible to permanent deformations such as rutting and pushing. As the flux solvent gradually volatilizes and ages, the strength of the mixture will gradually recover and increase over time. Therefore, the ratio of the flux solvent to asphalt should ensure full compaction of the asphalt mixture as a prerequisite, maximize the retention of the original adhesive properties of the asphalt binder, guarantee sufficient early-stage strength to resist loads, and maintain good long-term pavement performance.

c.According to Table 13 and Figure 7, 4-8, the test results of Tests 4 and 5 do not meet the specification requirements, while the results of Tests 1, 2, and 3 comply with the specifications and can be further analyzed to determine the optimal mix proportion.

d. Combined with the workability test results, Test 3 demonstrates the best workability.

e. From an economic perspective, Test 3 has the lowest cost.

f. Based on the comprehensive test results, Test 3 Mixing ratio is identified as the optimal formulation in this study.

(4) Analysis of Rutting Test Results

Based on Table 13 and Figure 9, the test results of Tests 1, 2, 3, 4, and 5 all meet the specification requirements. The variation trend of dynamic stability is similar to that of Marshall stability.

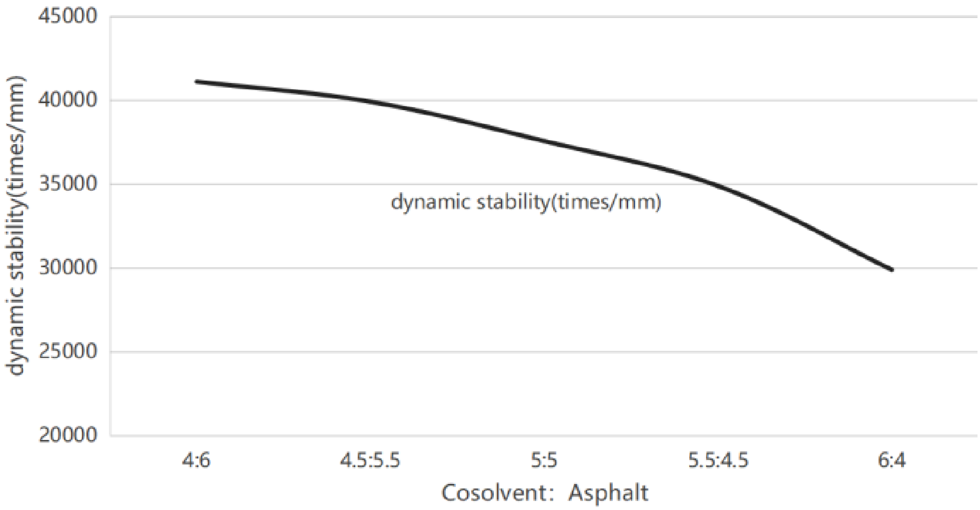

Figure 9: Cosolvent-Asphalt Ratio~Dynamic Stability

In summary, based on the comprehensive analysis of Workability tests, Marshall tests, and Rutting tests, Test 3 Mixing ratio is identified as the optimal mix proportion.

5 Conclusion

Based on the Workability test, Marshall Test, and Rutting Test, this paper draws the following conclusions:

(1) Cold-mixed and cold-laid asphalt pavement is most suitable for underground roadways with special external environments.

(2) The diluent selected for this study is a bifunctional reactive diluent, and the flux solvent is vegetable oil.

(3) When the ratio of epoxy resin: diluent: curing agent is 27%: 6%: 16.2%, the epoxy resin can achieve complete curing. The workability and curing time basically meet the requirements, and the pavement performance such as Marshall stability and dynamic stability is higher than that of hot-mix asphalt mixture, which also complies with the economic requirements.

(4) Under the condition that the contents of epoxy resin, diluent, curing agent, cosolvent, and base asphalt have been determined, with the addition of 0.6% anti-stripping agent, the construction performance, pavement performance, and economic efficiency of the cold-mix asphalt mixture are optimal.

(5) The research on solvent-based cold-mix cold-laid asphalt mixture is still in its initial stage. Subsequent research will be carried out on the mixture in terms of material technical requirements, mix proportion design method, performance evaluation, construction equipment, construction technology, and environmental impact assessment.

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