Research on Cold Recycling Technology of Asphalt Pavement

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Abstract. The paper describes the research progress of cold recycling technology based on three traditional stabilizers, and the strength formation mechanisms of different types of the cold-recycled mixture were introduced. The design method of the cold recycling mixture and its defects were analysed. On this basis, the characteristics of the cold recycling technology of each stabilizer in engineering application were summarized, which provided the basis for the selection of stabilizer in the design of cold recycling mixture and the existing problems in the design of cold recycling mixture were revealed, and the development direction of cold recycling technology research in the future was put forward.

Keywords: Road engineering, cold recycled mixture, stabilizer, influencing factors, design methods

1 Introduction

Under the current "dual carbon" background, the cold recycling technology of asphalt pavement, with its characteristics of mixing, construction and compaction at normal temperature, is of great significance for reducing carbon emissions from highway infrastructure construction and developing green transportation. The cold recycling technology can be classified into three methods: on-site cold recycling, plant-mixed cold recycling and full-deep cold recycling. All these three cold recycling methods add stabilizers to re-bond individual asphalt pavement recycled materials (RMAP) together to form a framework, thereby enhancing the material's strength and forming a structural layer to improve water damage resistance. The stabilizing effects of different types of stabilizers on recycled pavement materials vary, and the road grades and pavement layers they are applicable to differ. Therefore, the primary issue faced when applying cold recycling technology is to select the appropriate stabilizer.

J. Zhang et al. (eds.), *Proceedings of the 2026 2nd International Conference on Engineering Management and Safety Engineering (EMSE 2026)*, Advances in Engineering Research 300,
https://doi.org/10.2991/978-94-6239-703-3_4

This article will review the research progress of cold regeneration technology mainly based on three stabilizers. It will summarize the characteristics of each stabilizer's cold regeneration technology in engineering applications from three aspects: the strength formation mechanism of cold regeneration mixtures, performance influencing factors, and design methods, providing a basis for the selection and mix ratio design of stabilizers in cold regeneration applications in engineering. Moreover, propose the development direction of future cold recycled mixture technology.

2 The Strength Formation Mechanism of Cold Recycled Mixtures

2.1 Cold Recycled Cement Mixture

Asphalt mixture recycled materials (RAP) and inorganic recycled materials (RAI) have been subjected to long-term loads and environmental influences, and their performance has tended to stabilize. After the old pavement material is milled and mixed with cement and compacted, a new framework structure is formed. There is no chemical reaction between cement and asphalt, and the hydration products of cement inside the cold recycled mixture are the same as those of pure cement [1]. Therefore, the strength formation pattern of cold recycled cement mixtures is similar to that of ordinary cement-stabilized materials. The growth rate is relatively fast in the early stage of curing, slows down after 28 days of age, and stabilizes after 90 days [2].

2.2 Emulsified Asphalt Cold Recycled Mixture

Among various types of emulsified asphalt, cationic emulsified asphalt is widely used in the cold recycling technology of asphalt pavement due to its advantages such as good adhesion performance, higher early strength, shorter construction period and less environmental impact. The formation of the strength of cold recycled emulsified asphalt mixture is divided into three processes: the adhesion of emulsion and RAP particles during the stirring process, the emulsification of emulsion and the evaporation of water during the curing process, and finally the emulsified asphalt forms a continuous asphalt film on RAP particles to exert the performance of a binder [3].

The adhesion of the binder to the new and old aggregates in the cold recycled emulsified asphalt mixture after paving and compaction plays a key role in resisting water damage before the formation of new effective binders [4]. Therefore, inorganic cementitious materials such as cement and lime are often added to enhance the adhesion between new and old aggregates, thereby improving their early strength and water damage resistance [5]. On the one hand, the hydration of inorganic cementitious materials such as cement will absorb the water in the mixture and emulsion to form hydrates and release a certain amount of hydration heat to accelerate the emulsification of the emulsion [6]. On the other hand, the products formed by hydration create a spatial three-dimensional grid structure in the mixture, which interweaves with the asphalt mortar to form a composite binder, enhancing the adhesion with the old mortar on the RAP surface and improving the mechanical properties of the mixture.

2.3 Emulsified Asphalt Cold Recycled Mixture

After foaming, the viscosity and surface tension of asphalt are significantly reduced, and its volume increases greatly, enabling it to be uniformly mixed with aggregates at room temperature. After milling, the old pavement material is mixed with foam asphalt and cement and compacted to form a new framework structure. The cement continuously undergoes hydration reactions, absorbing water from the mixture to form hydrated bonding aggregate particles and build strength. At this time, the asphalt foam will adhere to the surface of the aggregates in the form of "particles", causing the asphalt between the aggregates to bond in a "spot welding" state. The higher the dosage of fine aggregates, the more dispersed the distribution of asphalt foam particles, and the higher the strength of this "spot welding" -like bonding form. Therefore, the indirect tensile strength of the mixture formed by rolling is also greater [7]. Compared with other cold recycling methods, the most prominent feature of foam asphalt cold recycling mixture is its rapid compaction and shaping, and it can be immediately compacted after spreading, allowing traffic to open up in a short period of time [8].

3 Influencing Factors of Cold Recycled Mixture Performance

3.1 Cement Content

Researchers investigated the influence of different cement dosages on the performance of cold recycled mixtures [9, 10]. The test results showed that adding cement to cold recycled mixtures could significantly enhance mechanical strength, improve water stability, and reduce temperature sensitivity. To prevent the problem of shrinkage and cracking of the mixture, it is recommended that the cement content of the cold recycled cement mixture does not exceed 6%, and the cement content of the cold recycled emulsified asphalt and foamed asphalt mixture is preferably controlled at 1-1.8% [11].

3.2 RAP

The US government conducted extensive research on the application of RAP in grassroots or subgrassroots research at the end of the 20th century and the beginning of this century, as shown in Table 1. Although each study analyzed different types of RAP or added different aggregates, by comparing similar tests in all studies, some general trends can be drawn: (1) the dry density decreases with the increase of RAP dosage. (2) the CBR values decrease with the increase of RAP content. (3) The elastic modulus increases with increasing RAP content.

Table 1. The influence of RAP Dosage on the performance of the base layer [12-18].

Researchers	Whether new aggregates are added	The changing trends of each index as the RAP dosage increases				
		Maximum dry density	Optimum water content	Permeability	CBR	Elasticity modulus
Cooley	Yes	Decrease	Decrease	-	Decrease	-
Garg & Thompson	No	Decrease	Increase	-	Decrease	-
Macgregor	Yes	-	-	No change	-	Increase
Bennert & Mather	Yes	-	Decrease	Decrease	Decrease	Increase
Papp	Yes	Decrease	Decrease	-	-	Increase
Sayed	No	-	Decrease	-	Decrease	-
Taha	Yes	Decrease	No change	Increase	Decrease	-
Trzd-biatowski	No	Decrease	-	Increase	-	-

It can be seen from Table 2 that with the increase of RAP content, both the strength and modulus (stiffness) of the cold recycled cement mixture show a downward trend. This is because the surface of RAP is coated with asphalt mortar, which hinders the hydration reaction between cement and aggregates and affects the formation of the mixture strength [19]. After being stabilized by cement, the modulus and stiffness of the material are reduced, and the anti-deformation ability of the cold recycled cement mixture is improved.

Table 2. Changes in Mechanical Properties of RAP Cold Recycled Mixture [20-25].

Researchers	The changing trends of each index as the RAP dosage increases			Composition of cold recycled mixture
	7d compressive strength	Splitting strength	Compressive rebound modulus	
Peng Zhang	first increase and then decrease	-	-	RAP, New aggregate
Kun Luo	first increase and then decrease	Decrease	Decrease	RAP fine aggregate, New aggregate
Yin Zhao	Decrease	Decrease	-	RAP, New aggregate
Lei Li	Decrease	Decrease	Decrease	RAP, RAI, New aggregate
Quan Yang	first increase and then decrease	first increase and then decrease	-	RAP, RAI, New aggregate
Xu Wu	Decrease	Decrease	Decrease	RAP, RAI, New aggregate
Ning Yang	Increase	Increase	Decrease	RAP, RAI

For asphalt-based cold recycled mixtures, an increase in RAP content generally leads to a decline in the low-temperature crack resistance and fatigue performance of the cold recycled mixtures [26]. In the early stage of strength formation of cold recycled asphalt mixtures, the newly added asphalt will form a continuous asphalt film on the RAP surface and undergo physical layer adsorption with the aged asphalt. Then, as the new and old asphalt blend, the old asphalt will undergo chemical softening. Restore the viscoelastic properties of the old asphalt part.

At present, most of the recycled asphalt pavement materials obtained in engineering projects are milled. After milling, there will be some RAP particles of different sizes adhering together to form "aggregates" in the RAP. There are many voids inside the aggregates, and they will re-separate during the construction mixing and compaction process, resulting in false gradation of the original asphalt mixture and affecting the construction quality [27].

3.3 Other Additives

Limestone as a new aggregate helps the mixture achieve excellent mechanical properties. The modification of emulsified asphalt has broadened the application conditions of asphalt mixtures. And the introduction of cement and lime can accelerate the demulsification process of emulsified asphalt and form a favourable spatial structure. Fibers reduce micro-cracks in the mixture through bridging and anchoring effects [28]. Furthermore, substances such as bio-based additives, waste-derived binders or geopolymers can also be added to enhance their stability.

3.4 Compaction Control Method

The laboratory compaction conditions for cold recycled mixtures vary significantly among countries. Rotary compaction is the most commonly used method in North America. Static pressure is usually adopted in Europe. In Asian countries, the static pressure method and the Marshall compaction method are basically adopted.

In terms of microstructure, the number of voids in specimens compacted by rotational compaction and vibration compaction is greater than that in specimens compacted by other methods, but the average void size is smaller. The distribution of voids in the depth direction shows the feature of "larger in the middle and smaller at both ends" [29]. In conclusion, the factors influencing the performance of cold recycled mixtures are summarized as shown in Figure 1.

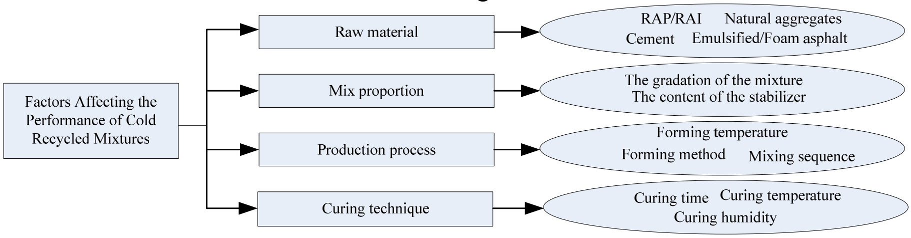

Fig. 1. Influencing factors of cold recycled mixture performance

3.5 Compaction Control Method

The mechanical properties of cold recycled mixtures largely depend on the curing conditions. Research shows [30, 31] that the longer the curing time and the higher the curing temperature, the faster the early strength growth of the cold recycled mixture. Therefore, when constructing under high-temperature extreme weather conditions, the spreading and compaction speed of the mixture should be accelerated to avoid damaging the strength of the cold recycled structural layer.

4 Composition Design of Cold Recycled Mixture

4.1 Compaction Control Method

The main factors to be considered in the proportioning design of cold recycled mixtures include: (1) Price factor; (2) Raw material performance; (3) Policies and Regulations; (4) Traffic requirements. This paper summarizes the technical characteristics of each type of stabilizer cold regeneration mixture, as shown in Table 3.

Table 3. Technical Characteristics of cold Regeneration Mixtures of Different Types of stabilizers

Recycled material type	Cold recycled cement mixture	Cold recycled mixture of foam asphalt	Emulsified asphalt cold recycled mixture
Material type	Rigidity	Flexibility	Flexibility
Applicable layer	Grassroots level, bottom-grassroots level	Base layer, lower layer	Base layer, middle and lower surface layer
Opening hours for traffic	Slow	Fast	Faster
Construction technology requirements	Low	Lower	Lower
The degree of fusion between new and old asphalt	/	Preferably	Good
Stabilizer cost	Low	Higher	Higher
Main forms of disease	Shrinkage crack	Permanent deformation	Permanent deformation

As can be seen from Table 3, for situations where traffic needs to be reopened as soon as possible, foam asphalt that can achieve strength after compaction should be given priority as the stabilizer. For lower-grade road surfaces, in order to reduce costs and construction difficulty, cement can be selected as a stabilizer for on-site cold recycling.

4.2 Compaction Control Method

(1) RAP content

Based on the 7-day unconfined compressive strength test results of cement cold recycled mixtures in reference [29], this paper concludes that at a cement dosage of 5%, The RAP content range applicable to the cold recycled cement mixture for the base and subbase of various grades of highways.

It is worth noting that although the strength requirements can be met by adding a higher amount of cement, in the base design of extremely heavy and super-heavy load grades of expressways and first-class highways, not only are higher strength requirements imposed, but the mixture also needs to have good erosion resistance and fatigue resistance. Therefore, it is not recommended to add RAP in the base of expressways of this grade.

(2) Grading design

Research [29] focused on cement-stabilized cold recycled mixtures with a RAP content of 80%, and delved deeply into the mix proportion design of different 0.6mm sieve hole pass rates. For the mixture with a 4.75mm sieve hole pass rate ranging from 37% to 47%, the average thickness of the mortar film is relatively high. This indicates that the contact force endured by the skeleton particles is relatively large, promoting the uniform transmission of force within the material. Based on this, this study suggests that the passing rate of 0.6mm sieve holes in the cold recycled mixture should not be less than 4% to meet the demand for higher RAP content, and the passing rate of 4.75mm sieve holes should be controlled between 37% and 45%. Based on the above analysis, this study made refined adjustments to the passing rates of these two key sieve hole sizes and proposed the gradation range of the cement cold recycling mixture. For specific details, please refer to Table 4.

Table 4. Gradation Range of cold recycled cement Mixture

Sieve hole size (mm)	The mass percentage passing through each sieve hole (%)	
	I	II
37.5	-	37.5
31.5	100	31.5
26.5	90~100	26.5
19	72~89	19
9.5	47~67	9.5
4.75	37~45	4.75
2.36	17~35	2.36
1.18	-	1.18
0.6	4~22	0.6
	0~7	0.075

(3) Design process

This study proposes the following mix proportion optimization methods for cold recycled mixtures:

Firstly, based on the design level and traffic load conditions, clearly define the technical requirements for cold recycled mixtures.

Secondly, refer to the JTG/T 5521-2019 standard to determine the initial appropriate RAP content.

Then, sieve analysis tests were carried out on RAP and the new aggregates of each grade to obtain the corresponding gradation curves. Based on the gradation range specified in Table 4, precisely determine the proportion of new aggregates of each grade.

Finally, in accordance with the procedures stipulated in the "Test Code for Inorganic Binder Stabilized Materials in Highway Engineering" T0805, a 7-day unconfined compressive strength test was carried out for each optimized combination. The design process is detailed in Figure 2.

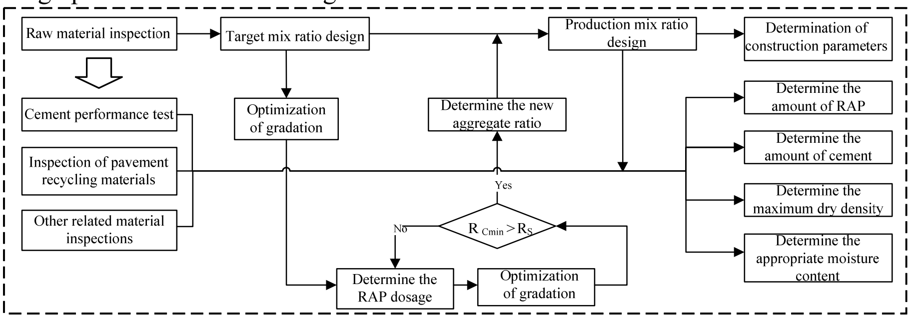

Fig. 2. Design process of cold recycled mixture.

5 Conclusion

This paper conducts a systematic and in-depth analysis of the current research status and development trends of the strength formation mechanism, performance influencing factors, and design methods of cold regeneration mixtures at home and abroad. The specific conclusions are as follows:

(1) Current research mainly focuses on the macroscopic mechanical property evaluation of cold recycled admixtures. In the future, more research be conducted on the influence of RAP addition on the framework structure and damage and failure of cold recycled mixtures from a microscopic scale.

(2) The most suitable cold recycling stabilizer should be selected based on local conditions to maximize the advantages of raw materials and various stabilizers. Improve the road performance of cold recycled mixtures.

(3) Appropriately increasing the passing rate of 0.6mm sieve holes and controlling the passing rate of 4.75mm sieve holes can help improve the internal density and strength distribution of cold recycled mixtures.

(4) Future research should focus on the interaction between old asphalt and asphalt-based stabilizers, and establish a reasonable mathematical relationship model between the key performance indicators of RAP and their blending ratios with asphalt-based stabilizers.

Acknowledgments

The authors gratefully appreciate support from the projects of Science and Technology Project of Transportation Department of Heilongjiang Province (No.HJK2016B016, No.HJK2019B017, No. HJK2019B009, No.HJK2019B003).

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