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Cold recycling of lime-fly ash stabilized macadam mixtures as pavement bases and subbases

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HIGHLIGHTS

- Pavement performance of recycled lime-fly ash stabilized macadam was evaluated.
- Effects of cement contents, gradations, and RM properties were evaluated.
- Relationships between RM properties and pavement performance were developed.

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ABSTRACT

The cold recycling technology has been increasingly used to rehabilitate semi-rigid pavement bases and subbases in China due to the focus of the sustainable development. This paper presents the mechanical and pavement performances of cold recycled lime-fly ash stabilized macadam (LFSM) mixtures using Portland cement as the stabilizing material. The unconfined compressive strength, indirect tensile strength, frost resistance, dry shrinkage (DS) resistance, and temperature shrinkage (TS) resistance of different cold recycled mixtures (CRMs) with three cement contents, two reclaimed materials (RM) sources, and two aggregate gradations were measured, respectively. The locally recommended criteria for RM properties were proposed based on performance correlations between RMs and CRMs. It is found that the gradation optimization by adding appropriate amount of the coarse virgin aggregate (VA) can greatly improve the mechanical strength and pavement performances of CRMs. CRMs with the clean RM do not show significantly worse DS and TS resistance than cement stabilized macadam mixtures with 100% of the VA. The CRM strength is highly affected by the RM strength and angularity. Field investigations confirm the feasibility and application potentials of the cold recycled LFSM layer as pavement bases and subbases.

1. Introduction

Semi-rigid (inorganic binder stabilized) materials have widely been used for pavement engineering in many countries for decades due to advantages of high strength, good loading distribution, reduced thickness requirement, improved workability, and increased resistance to climatic effects [1–9]. Especially in China, the semi-rigid base asphalt or concrete pavement is the predominant structure type for high-level highways and urban roads so far. The lime-fly ash stabilized macadam (LFSM) mixture has been selected as one of the main semi-rigid base or subbase materials since the 1980s. It is composed of aggregates with a proper gradation, 18–25% lime-fly ash of the aggregate weight, and water at the optimum content. The weight ratio of lime to fly ash generally varies from 1:2 to 1:4. The combination of coal fly ash and lime in the wet process generates the calcium silicate hydrate and calcium aluminate hydrate in the gel condition. Subsequently, these hydrates crystallize to form interparticle bonds for cementing aggregates [10]. It supplies an opportunity to use industrial by-products and local materials. Therefore, LFSM is widely accepted as a cost-effective paving material.

A lot of distresses, such as reflective cracking, raveling, and potholes, appear in LFSM bases and subbases under continuous effects of vehicle loading and environmental conditions. These pavement distresses greatly reduce the pavement service quality and driving

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safety. In China, high-level highways and urban roads constructed early have entered into a peak period of reconstruction and rehabilitation. Over 2.2 million tons waste pavement materials are produced every year through the reconstruction and rehabilitation of existing highways [11]. Moreover, a large number of highways and urban roads are faced with upgrading and alignment reconstruction due to the continuous city development. With mounting concerns about the sustainable development, energy savings, greenhouse gases reduction, and conservation of natural resources, the cold recycling technology provides a technically sound, cost-effective, and environmentally friendly method to restore the pavement performance of LFSM bases and subbases [11,12].

Using stabilizing materials can improve the cold recycled mixture (CRM) performance. Stabilizing materials are mainly classified as asphalt binders (foamed asphalt and asphalt emulsion) and hydraulic binders (Portland cement, lime, and fly ash). By comparison of different stabilizing materials, the asphalt stabilized CRM has a low strength at early-age. Therefore, it is easy to generate rutting, moisture damage, and fatigue cracking in the pavement structure using the asphalt stabilized CRM layer [13]. Hydraulic stabilized materials can significantly improve the CRM durability and decrease the permanent deformation [4,14]. However, the cement content should be strictly controlled to avoid the shrinkage cracking. Cost, performance, and climatic conditions should be considered to choose the optimum stabilizing materials type [15]. It is possible to select a single binder, or a combination of two binders, or even a mix of several pre-dosed binders [4]. Portland cement is the most widely used stabilizing material for CRMs in China by the balance of effectiveness and economy.

Recent efforts have been made to study the cold recycling technology of semi-rigid materials. Mráz et al. [2] applied different types of stabilizing materials for recycling the asphalt layer, granular base layer, and cement stabilized macadam (CSM) layer. The CRM with asphalt emulsion and activated fly ash had a higher indirect tensile strength (ITS) at early-age, a similar stiffness modulus, and a similar moisture resistance compared with that with asphalt emulsion and cement. Du [3] investigated the effect of chemical additives on the performance of the asphalt emulsion recycled CSM mixture. Cementitious additives were recommended to be added prior to asphalt emulsion since a higher mechanical strength and resistance to moisture and rutting could be obtained. Ji et al. [16] reported that many factors had significant effects on the strength of the cement stabilized CRM produced by the vertical vibration compaction method, such as the weight ratio of recycled cement base to recycled asphalt pavement, virgin aggregate (VA) content, cement content, and curing day. Cabrera et al. [17] found that adding the biomass bottom ash could improve the strength of the cement stabilized CRM and reduce the required cement content. Shi et al. [18] developed an empirical relationship between the ratio of recycled semi-rigid base materials to recycled asphalt layer materials and the CRM base thickness. Yao [19] evaluated the surface and mechanical properties of recycled LFSM aggregates. The feasibility of using the cement stabilized CRM as pavement bases was validated. Zhang [20] designed a cement stabilized CRM base composed of 80% recycled LFSM materials and 20% VA for a practical project. The mixture 7-day unconfined compressive strength (UCS) values at the cement content of 3.5% reached 4.6 MPa and 5.2 MPa in the laboratory and field, respectively. It was similar to the mechanical strength of the CSM mixture with 100% of the VA. All these studies show the potential application prospect of CRM bases and subbases.

Although the cold recycling technology of semi-rigid materials has been put into practical application in some regions of China, there are still some issues that should be solved urgently. In the current Chinese specification JTG F41-2008 "Technical specifications for highway asphalt pavement recycling" [21], although some specific regulations in terms of the field investigation, raw materials selection, mix design, and construction are provided, only the strength requirement is raised for the CRM base and subbase. However, the other performance has not been considered, such as stiffness, moisture resistance, and shrinkage cracking resistance. More importantly, there are no corresponding evaluation indicators and engineering properties criteria for reclaimed semi-rigid materials. The main objectives of this study are to evaluate the pavement performance of cement stabilized LFSM CRMs and to recommend engineering properties criteria of reclaimed LFSM materials for cold recycling. To accomplish it, the main engineering properties of waste LFSM materials from different sources were measured. After the mix optimization design, the mechanical performance, frost resistance, and shrinkage cracking resistance of the cold recycled LFSM mixture at three cement contents were measured in the laboratory. The recommended control criteria of reclaimed materials (RM) properties and suitable layers for CRMs were proposed based on performance correlations of the RM and CRM. The feasibility of the cold recycling technology was finally validated by engineering practices.

2. Experimental plan

2.1. Materials

2.1.1. Cement and VA

The composite Portland cement graded 42.5R was used as the stabilizing material for cold recycling. The virgin limestone coarse and fine aggregates typically used in the local area were selected for the CRM gradation optimization. The main engineering properties of the VA are shown in Table 1.

2.1.2. Reclaimed LFSM material

Reclaimed LFSM materials were milled from distressed bases of two urban road pavement sections located in Nantong of China. The rock type of recycled aggregates was limestone. Two sections had a similar original pavement structure consisting of a Portland cement concrete (PCC) surface of 24 cm in thickness over a LFSM base of 18 cm in thickness. After the removal of PCC slabs, the cold in-place recycling (CIR) stabilized with cement was conducted on the LFSM base. Then, a CSM base of 18 or 20 cm in thickness and two asphalt concrete (AC) surface layers in a total of 10 or 12 cm (6 or 8 cm + 4 cm) in thickness were overlaid in turn. The 2 cm design thickness variations of the CSM and AC layers between pavement sections were due to variations in traffic levels and pavement elevation criteria. The main engineering properties of the RM measured in the laboratory are also shown in Table 1. RM gradations are shown in Fig. 1.

It is found in Table 1 that RM aggregates have higher water absorption, crushing values, flat-elongated particle contents, and abrasion values compared with the VA. In other words, RM aggregates become worse in the compactibility, mechanical strength, angularity, and abrasion resistance after the long-term service and milling process. Deterioration of engineering properties is mainly due to the hardened paste of lime-fly ash hydration products coating on the surface of RM aggregates. It can be confirmed by observing the aggregate surface as shown in Fig. 2. Besides, the scanning electron microscope (SEM) test was also conducted on dry samples to obtain the microstructure surface morphology. It is clearly seen in Fig. 2 that many small lumps mainly containing SiO_2, Al_2O_3, and $Ca(OH)_2$ adhere to aggregates. A large number of minute air voids are formed on the surface, which is responsible for the higher water absorption. The hardened paste is weak and fragile. It decreases the strength, stiffness and abrasion resistance of RM aggregates. Moreover, many microcracks are formed inside the aggregate during the milling process. It also makes contributions to the poor strength and angularity. This may be solved after recycling because the added cement paste can fill voids and improve the interface bonding. It is also observed in Table 1 that there are obvious differences of engineering properties between RM sources. The RM aggregate from Section 1 have a higher strength (smaller crushing value) and a better angularity (lower flat-elongated particle content). However, the RM aggregate from Section 2 is cleaner (lower clay content) by comparison. Raw material quality, pavement damage severity, milling methods, and storage environmental conditions are possible factors.

2.2. Mix design

According to the previous recycling construction experience, cement contents of 4.0%, 4.5%, and 5.0% were selected for CRMs with 100% of RM aggregates. It is observed in Fig. 1 that two RM gradations are greatly and differently changed under effects of traffic loading and milling machine according to the similar design gradations of two pavement sections during the previous construction period. The RM gradation is too coarse for Section 1. The passing percent values of 4.76 mm,