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Investigation of early-stage strength for cold recycled asphalt mixture using foamed asphalt

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HIGHLIGHTS

- The moisture content, ITS and SD were prominently affected by the curing stage especially 0~3 days natural curing.
- Cement enhances the early strength while foamed asphalt affects the long-term strength of CRMF.
- The fracture path was developed along the water membrane at the early stage.
- Air void amounts of different curing period has a little difference and it is mainly caused by destruction of air void.
- Variations of the voids amounts almost had no effect to the Weibull distribution of air voids in CRMF.

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ABSTRACT

This papers aims at investigating the strength properties of cold recycled mixtures using foamed asphalt (CRMF) at its early-stage of curing. Indirect tensile strength (ITS) and deformation-strength test were used to figure out the early-stage strength development law of the CRMF. Through image processing and analysis the fracture interface characteristics of CRMF were identified. Statistical methods were used to analyze the amounts of air voids in the CRMF specimens and a two-parameter Weibull model was used to describe the distribution of air voids in the CRMF using X-ray computed tomography (CT) technique. The results indicated that moisture content had a significant effect on the strength of CRMF. Moreover, cement only affected the early strength while the foamed asphalt affected the long-term strength of CRMF. The fracture path was developed along the weak interface where there was moisture membrane especially at 0–3 days curing. The asphalt mastic may be broken off forming the fracture path as the curing continuing after 3 days of curing. The X-ray CT test indicated that a weak hydration products interface was destroyed and two voids were interconnected to become one large void. However, variations of the voids amounts had almost no significant effect to the Weibull distribution of air voids in CRMF. The findings helps us to understand well to the development mechanism of early-stage strength of CRMF and lead us to new approaches to improve the early-stage strength.

1. Introduction

As the global warming and air pollution gets worse, low carbon economy has become the focus of human development. However, energy conservation and emissions reduction in the field of traffic engineering plays a major role in low-carbon economy. Nowadays, cold recycling technology attracts more and more attention in the rehabilitation of existing asphalt pavements due to lack of aggregates, budget constraints as well as energy efficiency and environmental protection [1–3].

About 70–90% of reclaimed asphalt pavement (RAP) is used by cold recycled (CR) technology and is widely used in subgrade or in asphalt pavement structure in China [4]. Thus, CR technology has became one of the most popular means of pavement maintenance. Different from hot mix asphalt, cold recycled pavement using foamed asphalt still needs some curing time, after the completion of construction. Furthermore, the strength of mixture formed gradually as the internal moisture evaporates. Extensive research shows that curing conditions have a distinct influence in the strength of the CR mixtures. The performance of CRMF is significantly affected by the moisture content and curing period [5]. H.D. Lee confirmed that ITS of CRMF increased slowly during the early-stages of the curing period, but obviously increases rapidly during late-stages of the curing period, through uncovered and

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semi-covered curing procedures [6]. In addition, the hydration process could be hindered due to lack of water as the moisture evaporates faster [7].

Ample researches have been conducted regarding the strength of CR mixture both in the field or laboratory. Adding active fillers such as cement, lime and others could dramatically improve the strength both at early and final curing stages. Cement content and moisture evaporation were the most important factors that influenced the strength increase during the early-stage at room temperature [8]. The bonding force between foamed asphalt mastic and aggregate couldn't completely form, unless most of the water between them evaporated [9]. Significant increase on modulus and ITS was found by using cement filler, and the resistance performance to moisture damage was obviously improved especially in its early-stage [10–13]. Meanwhile, failure strain by low temperature bending test decreased by adding high-volume cement [14]. However, cement as an active filler also resulted in shrinkage cracking of the CR mixture pavement [15].

So far from literature review, a number of researches have been conducted on the mechanical properties of the CR mixtures. Most of them use experimental test methods to concentrate on the performance characteristics such as compaction methods, strength, thermal cracking, moisture damage or shear parameters [5–8,10–18]. However, these studies have not taken micro-scale characteristic of the CR mixtures, such as regularity of air voids and asphalt distribution in CR mixtures. As it is common knowledge that void volume of asphalt mixtures has a significant influence on its properties. Air voids parameters such as volume, size, number and spatial distribution regularity of air voids in CR mixtures were statistically analyzed using X-ray CT technique [19]. The mechanical strength and air voids distribution of CR mixtures was conducted considering different curing temperature [20]. Nevertheless, dispersion condition of foamed asphalt is another crucial factor to the performance of the CR mixtures using foamed asphalt [21]. Fracture face image process method was utilized to describe the fracture information of CR mixtures. In addition, fracture aggregate ratio of surface area (FASA) and fracture faces asphalt coverage (FFAC) was used to evaluate the strengths of emulsified and foamed asphalt CR mixtures respectively [9,4].

These studies have primarily examined the behavior of the CR mixtures by studying the key factors that affected its properties and tried to understand the performance in the laboratory or field. To some extent, microscopic mechanics could reflect the macro-properties of CR mixtures. However, little research results have been reported at this point concerning microscopic structures. Moreover, the strength forming mechanism has not been comprehensively and deeply studied. However the early-stage strength has been a snag in its widespread application worldwide [22].

The main objective of this research is to analyze the development mechanism of early-stage strength for CRMF, and figure out the development of voids volume parameters. A simulated field curing method was adopted. Early-stage strengths of CRMF were investigated using the simulated field curing method. Furthermore, the fracture characteristic were studied by fracture face image processing. The numbers and spatial distribution characteristic of air voids in CRMF were analyzed using X-ray CT technique. The development mechanism of early-stage strength of CRMF were analyzed, in accordance with the macro and micro-scale properties.

2. Materials and experiments

2.1. Materials

The CRMF specimens consisted of RAP, virgin aggregate, Portland cement, asphalt and water. Asphalt of 90–100 (dmm) penetration grade was selected in this research. The foamed test was conducted by using Wirtgen WLB10 laboratory equipment. The results of foamed asphalt test are presented in Table 1. As detailed in Table 1, the optimum foaming condition is 150 °C with 1.5% of foaming water by mass of asphalt.

"Black rock", RAP is usually used ignoring the effect of the asphalt binder in RAP [12]. The RAP that was used in this paper was reclaimed from one expressway in Shannxi province, China. The aggregates gradation of CRMF which included RAP and manufactured sand (0–3 mm) is shown in Fig. 1. Furthermore, 80% RAP and 20% manufactured sand (virgin aggregate) were added to CRMF. Besides, 1.5% Portland cement as an active additive was added. Meanwhile, the Portland cement also could be regarded as a filler material and an *anti*-stripping agent to improve the performance of the mixture. CRMF was designed by Marshall Methods. The optimum blending moisture content was 5.3% by the dry mass of aggregates, and the optimum dosage of foamed asphalt was determined as 3.0% by mass of aggregates according to the Marshall Test.

2.2. Curing procedure

Generally, the CRMF specimens were cured in an oven at 40 or 60 °C for a certain number of hours to simulate the long-term curing process. A newly curing method was used to simulate the field condition. Specimens with mold were left for 2hrs at room temperature after preparation. After that, the specimens with mold were sealed at the bottom. Placed all the specimens in manufactured sand with 5.3% water content after which were placed in a big box, and put it outdoor as illustrated in Fig. 2.

The weather condition of Xi'an, China and the date were recorded in Table 2. Nevertheless, the Specimens were covered by a waterproof material on August 26 and 31, 2015 to avoid moisture ingress due to rains. However, when the rainstorm came on September 3, all the specimens were moved into the laboratory for curing. Because of the bad weather, all the curing specimens were placed in the lab to continue curing. However, the specimens of long-term curing were placed into a 40 °C oven for 72 h.

2.3. Experimental procedure

2.3.1. Moisture content test

Moisture content is the weight of the moisture by mass of the dry aggregates and asphalt. The moisture content is calculated after certain simulated field curing periods.

Table 1
The test result of foamed asphalt.

Foaming water content (%)	Foaming temperature (°C)					
	150		155		160	
	Expansion ration (times)	Half-life time (s)	Expansion ration (times)	Half-life time (s)	Expansion ration (times)	Half-life time (s)
1	18	12.3	13	15.8	16	18.1
1.5	22	11.6	22	8.8	20	9.9
2	27	9.8	24	8.2	23	8.3