Construction and Building Materials 102 (2016) 393–402

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Evaluation of fatigue behavior in cold recycled mixture using digital image correlation method

Lei Gao [a,*], Fujian Ni [a], Cheng Ling [b], Jinhai Yan [c]

[a] School of Transportation, Southeast University, Nanjing, Jiangsu Province 210096, China
[b] Department of Civil & Environmental Engineering, University of Wisconsin-Madison, Madison, Wisconsin 53706, United States
[c] National Engineering Laboratory for Advanced Road Materials, Jiangsu Transportation Institute, Nanjing 211112, China

HIGHLIGHTS

- The digital image correlation method was used to capture fatigue behavior.
- The semicircular bending and indirect tensile fatigue tests were both utilized.
- The fatigue properties of CR and HMA mixtures were compared.

ARTICLE INFO

Article history:
Received 16 September 2015
Received in revised form 28 October 2015
Accepted 2 November 2015

Keywords:
Cold recycling
Fatigue behavior
Crack propagation
Digital image correlation

ABSTRACT

Cold recycling (CR) is a reconstruction technique that produces a rehabilitated asphalt pavement without heating materials during the recycling process. It has been widely practiced in recent years, but the fatigue properties of CR mixtures are not fully understood. The objective of this study is to evaluate the laboratory fatigue behavior of CR mixtures with the application of digital image correlation (DIC) technique. The semicircular bending (SCB) and indirect tensile (IDT) fatigue tests were utilized to compare the resistance of CR and hot mix asphalt (HMA) mixtures to crack propagation in the stress-controlled mode of loading. According to the results of this study, the addition of cement to the CR mixture improves the overall fatigue performance; however it decreases the fatigue life of CR mixture under the same stress level. The SCB and IDT fatigue tests are in agreement with each other in ranking the fatigue resistance of different mixtures. The CR mixture has longer fatigue life and larger tensile strain at the failure point than the HMA mixture at lower stress levels. In addition, the contour plots of the horizontal tensile strain of CR specimen demonstrate the cracking path and the three stages of fatigue process. From the full-field strain results of the fatigue test, the two transition points in the fatigue curve are verified as the initial cracking point and fatigue failure point, respectively. Overall, this study provides a better understanding of the fatigue behavior of CR mixtures to improve the mix design and field performance.

1. Introduction

Recycling of asphalt pavement is a way to increase the effectiveness of existing budgets in order to reconstruct more mileage of highway [1]. Compared to traditional rehabilitation techniques, pavement recycling is considered to be more energy conservative and environmentally friendly. Cold recycling (CR) is one form of asphalt pavement recycling, in which the reclaimed asphalt pavement (RAP) materials are processed and laid under ambient temperature without heating. The two typical forms of cold recycling are cold central plant recycling (CCPR) and cold in-place recycling (CIR). Although agencies that utilize CR have different mix design procedures, most of them involve the application of foamed or emulsified asphalt with chemical recycling additives [2]. The specifications relating to performance of CR mixture have not been established yet due to the lack of a good understanding of the material properties, mix design and construction sequence.

As a reconstruction rehabilitation method, the CR technique can remove cracks, eliminate rutting, potholes and raveling, and modify existing aggregate gradations to provide an improved pavement with recycled materials. Under the long-term effects of traffic loading and environment, these distresses reoccurred to the CR pavements. Similar to hot mix asphalt (HMA), one of the most common distresses in CR pavement is the fatigue cracking. The cracking resistance of asphalt mixture in the lab is highly related

* Corresponding author at: 2 Sipailou Rd., Nanjing 210096, China.
E-mail address: gleiseu88@gmail.com (L. Gao).

http://dx.doi.org/10.1016/j.conbuildmat.2015.11.014
0950-0618/

to its fatigue performance in the field. However, limited studies have been conducted in the past on the fatigue behavior of CR mixes in the lab. In previous research some field processed CR samples were evaluated in the asphalt pavement analyzer (APA) fatigue test and they exhibited lower fatigue values compared with HMA [3]. In other research the fatigue properties of CR mixes with foamed or emulsified asphalt were compared through indirect tensile fatigue test [4]. Efforts were also paid to find out the effects of cement content on fatigue property of CR mixtures. By increasing the cement content and resilient modulus, the slope of the fatigue line was decreased, which indicates changing the characteristics of mixes from a typical asphalt mixture to cement treated material [5]. These studies mainly focused on the fatigue life of CR mixtures without considering the crack initiation and propagation during the process of fatigue failure. A better understanding of the fatigue behavior of CR mixtures is required to improve the mixture design and performance, and more advanced fatigue testing methods and criteria needs to be introduced.

The commonly used fatigue tests for HMA mixtures include four point beam fatigue test, single edge notch beam fatigue test, semicircular bending fatigue test, and direct or indirect tensile fatigue test [6–9]. They mostly involve subjecting the asphalt mixture specimens to the repeated loading either under a controlled stress or controlled strain [10]. From the field observation, the strain level remains nearly constant at the bottom of a thin pavement, while stress level remains constant at the bottom of a thick pavement [11]. Therefore, the common practice in lab testing is to employ the strain-controlled mode for mixtures that are used in thin pavements and the stress-controlled mode for mixtures used in thick pavements. Various fatigue criteria have been considered to define the fatigue failure when micro cracks in specimen are combined to macro cracks, which are classified as four categories based on change of modulus, phase angle, specimen homogeneity, and dissipated energy, respectively [12]. Different definitions of fatigue life of asphalt mixtures also exist in the current research. In the APA fatigue test, it was defined as the number of wheel cycles required to weaken the beam enough to cause one millimeter of beam deflection [3]. In other fatigue tests, the widely accepted fatigue failure is defined at the cycle required to reach 50% of its initial flexural stiffness, or the second inflection point in the fatigue curve which shows the relationship between fatigue property and the number of loading cycles. Asphalt pavement fatigue damage is usually treated as a bottom-up cracking failure and the crack propagates through all the layers before reaching the top of the surface [13]. It is important to investigate the crack initiation and propagation of CR mixtures considering the fatigue property.

Digital image correlation (DIC) technique has been successfully applied by the authors to explore the cracking behavior of CR mixtures in the study of low temperature cracking property [14]. Essentially, DIC is an optical metrology based on digital image processing and numerical computing. It provides full-field displacements to sub-pixel accuracy and full-field strains by comparing the digital images of a test specimen before and after deformation [15]. As a non-contact measurement technique, the DIC method was proved to be a powerful tool to measure the surface deformation of specimen, thus pinpointing the location of crack initiation and propagation as well as accounting for non-uniform strain distribution of asphalt concrete [16,17].

In this study the DIC system was utilized to investigate the fatigue behavior of CR mixtures. The indirect tensile (IDT) fatigue test and semicircular bending (SCB) fatigue test are selected due to the relative simple sample preparation process compared to the beam tests. The propagation of fatigue cracks on the surfaces of circular or semicircular specimens was captured and analyzed using the DIC system. The stress-controlled mode of loading was applied in the fatigue tests considering the large thickness of CR pavement in the field.

2. Objectives and scope

The main objective of this study is to evaluate the fatigue behavior of CR mixtures based on the results of two different laboratory fatigue tests involved with DIC technique. The specific objectives are listed as follows:

(1) Compare and analyze the fatigue curves and equations of different mixtures in SCB and IDT fatigue tests under several stress levels.
(2) Find out the effects of Portland cement on the fatigue performance of CR mixture.
(3) Investigate the tensile strain and stiffness modulus of CR and HMA mixtures during the fatigue cracking.
(4) Verify the initial crack point and fatigue failure point locations in the fatigue tests through the full field strains analysis.

3. Materials and mixture designs

The CR materials in this study were all obtained from a single worksite in Jiangsu Province, China and the mix design procedure was abiding by the specification developed by the local Department of Transportation. The RAP materials were collected by large milling machine during construction to ensure the representativeness of gradations. The RAP aggregates consisted of basalt and limestone. The gradation and quality of materials were experimentally tested and assured through the CR specification. The specific gravity of the extracted RAP aggregates was 2.55 with water absorption of 1.8%. The RAP materials were dried and sorted by a series of standard sieves. The CR mixture used 100% of RAP and no fresh aggregate was added. The aggregate gradation of CR mixture which fell within the medium sized gradation limits recommended by the specification is described in Table 1. The CR-20 (Cold Recycled mix with a fixed nominal maximum aggregate size of 19 mm) mixture with a typical gradation was designed. A cationic slow-setting (CSS-1) asphalt emulsion was selected as the recycling additive which provided adequate workability for CR mixture. According to the results from Marshall Stability, Flow, Indirect Tensile Strength, and Resilient Modulus, the optimum asphalt emulsion content was determined as 3.5% by weight of RAP materials. The emulsion was formulated with a high residue asphalt content of 64.5%. The CR mixtures with different cement contents (0%, 1.5%) were prepared. Additional water was added

Table 1
Mix design results of CR and AC mixtures.

Mixtures	CR-20		AC-20	
Optimal asphalt content (%)	3.5 (CSS-1)		4.1 (70#)	
Sieve size	CR-20	Limits	AC-20	Limits
(mm)	Passing percent (%)			
26.5	100	100	100	100
19	96.7	100–90	97.5	100–90
16	92.4	–	87.3	92–78
13.2	84.3	–	72.5	80–62
9.5	70.1	80–60	55	72–50
4.75	50	65–35	39	56–26
2.36	36	50–20	28.6	44–16
1.18	22.2	–	21.7	33–12
0.6	14.5	–	15.3	24–8
0.3	8.3	21–3	8.9	17–5
0.15	6.1	–	6.6	13–4
0.075	3.7	8–2	4.3	7–3