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Characterization of air voids in cold in-place recycling mixtures using X-ray computed tomography

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HIGHLIGHTS

- X-ray CT was utilized to find the characteristics of air voids in CIR mix.
- The air void gradation of CIR mix was well fitted by the Weibull function.
- The differences in air voids between CIR and HMA mixes were fully quantified.

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ABSTRACT

With the increasing application of cold in-place recycling (CIR) techniques, many performance studies have been done, but they rarely focus on the internal structure of CIR mixture. The objective of this study is to investigate the characteristics of air voids in CIR mixtures with the X-ray computed tomography (CT) and digital image processing (DIP) methods. The volume, size, and number of air voids in CIR specimens were statistically analyzed considering different aggregate gradations and compaction methods. The two-parameter Weibull function was used to model the air void gradation of CIR mixtures. Especially, the differences in air voids between CIR and hot mix asphalt (HMA) mixtures were fully quantified. According to the results of this study, with coarser aggregate gradation, the CIR mixture tends to have larger size and less number of air voids. Comparing with the Superpave gyratory compactor (SGC) method, the Static Load compaction produces relatively small air voids. The distributions of air void number in specimen depths for the three compaction methods are different. The scale and shape parameters in Weibull function are both sensitive to the changes in aggregate gradation and compaction method. The substantial difference of air voids between CIR and HMA mixtures is in the aspect of the air void number rather than the air void size. Overall, this study provides a solid foundation for future research in exploring the internal structure and mix design of CIR mixtures.

1. Introduction

Cold in-place recycling (CIR), an asphalt pavement rehabilitation technique that uses 100% of the reclaimed asphalt pavement (RAP) materials, has become a common practice around the world. The CIR project is undertaken with a recycling train which consists of tanker trucks, milling machines, crushing and screening units, mixers, pavers, and rollers. It involves the processing of the existing asphalt pavement and the treatment with bituminous or chemical additives to produce a restored pavement layer [1]. The RAP is first milled and subsequently mixed with emulsion, water, and other additives as needed. The whole operation is completed while the pavement is being recycled without the application of heat. The CIR technique is considered to be more cost effective and environmentally sustainable compared with other reconstruction methods. It can be used to remove surface irregularities and cracks, eliminate rutting, potholes, and raveling, modify existing aggregate gradations and provide an improved pavement surface with shorter construction periods.

Although the CIR is being used widely, there is currently no nationally accepted method for the CIR mix design process and most state highway agencies have their own procedures [2]. With the increasing application of CIR technique, numerous studies have been conducted to evaluate the performance of CIR

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mixtures. They mainly focus on characteristics such as compaction, curing time, early strength, stability, thermal cracking, fatigue cracking and moisture damage using experimental test methods [3–7]. Comparisons between hot mix asphalt (HMA) and CIR are often conducted when investigating these characteristics. The common volume of air voids for CIR mixture is between 8% and 14% from experience in the field while the typical target volume of air voids for HMA is between 4% and 6%. The air voids play an important role in determining the resistance of asphalt mixtures to pavement distresses. The difference in volume of air voids is believed to be an important factor affecting the performance of CIR mixtures.

Twenty-four CIR roads in Iowa were examined through field tests [8]. Better performance was observed on CIR roads with higher volume of air voids. However, from other experimental results, it was verified that CIR mixtures with higher volume of air voids were determined to be more susceptible to moisture damage [9]. These two inconsistent results indicate that it is not sufficient to only focus on the volume of air voids. Specimens with the same total volume of air voids may have different air void distributions and consequently exhibit distinctive properties [10]. Therefore, more characteristics such as size, number, structure and distribution of air voids in CIR mixtures should be studied.

In this paper, the X-ray CT technique along with digital image processing (DIP) method is used to analyze the characteristics of air voids in CIR specimens considering different compaction methods and aggregate gradations. A mathematical model based on the two-parameter Weibull function is developed to describe the distribution of air voids size at each depth of a specimen. The Weibull distribution is introduced in this research to model the air void gradation and the differences in air void characteristics between CIR and HMA specimens. Statistical considerations are provided.

2. Literature review

Use of the X-ray computed tomography (CT) has increased in civil engineering materials research in recent years. It has been proven to be a powerful, nondestructive tool to visualize the three-dimensional internal structure of HMA specimens [11–14]. Computer automated procedures processing the digital images captured by X-ray CT have been developed to quantify the internal structure of asphalt concrete. The resulting images consist of 256 levels of gray intensity displaying differences in density at every point in two-dimensional slices throughout the specimen. It was verified that CT technique is highly sensitive to small differences (<1%) in density between materials [15]. The three volumetric compositions in dense graded asphalt concrete (AC) mixtures including the air void, asphalt mastic and coarse aggregate can be identified separately according the measured gray levels that correspond to different densities within the specimen [16].

To evaluate the effect of air void distribution on the moisture susceptibility of asphalt mixtures, HMA specimens were prepared using different gradations and compaction angles in the Superpave gyratory compactor (SGC). It was emphasized that specimen preparation may significantly influence the air void distribution in HMA [17]. The size and shape of coarse aggregate in asphalt mixtures were evaluated based on the image analysis. The accuracy of the volume computation was validated by comparing the calculated results with their actual values measured in laboratory [18]. The influence of compaction methods on the internal structure of HMA mixture has been studied. Comparing with vibratory compactor, a more horizontal orientation was found for the coarse aggregate particles in HMA compacted in the SGC [19]. The volume and number of air voids in the static compaction specimens are larger than Marshall specimens [20].

The X-ray CT was also used to quantify the level of damage in the dynamic complex modulus and flow number tests [21]. Series of indexes were developed to describe the internal structure of asphalt mixtures. Delaunay triangulations and a simplified model were used to evaluate the distribution of aggregate particles. The average radius of air voids was calculated to study the size distribution of air voids in specimens. The particle orientation was measured as the angle between the major axis of the particle and the horizontal line [22]. These studies mostly addressed the air void characterization of HMA, while the internal structure of CIR mixtures has received little consideration.

3. Materials and mix design

Most CIR projects are constructed in the field without the addition of new aggregates and the whole process is performed at ambient temperatures. Comparing with HMA mixtures, some adjustments are generally required for workability, coating, and stability in the mix design of CIR mixtures. In this paper, representative samples of the RAP were obtained from one worksite in Jiangsu Province, China and they were evaluated to properly design the CIR mixture. Due to the lack of unified mix deign method, the design procedure of the CIR mixture was performed according to the CIR specification of Jiangsu Province [23]. The collected RAP materials were sorted by a series of standard sieves after they were dried in the oven. The specific gravity of the extracted RAP aggregates was approximately 2.55 and the water absorption was about 1.8%. The CIR samples with different gradations, such as CIR-13, CIR-20 and CIR-25 (cold in-place recycling mix with a fixed nominal maximum aggregate size), were prepared in laboratory using 100% of RAP materials following the recommended gradation guidelines. The three CIR gradations that were used are shown in Fig. 1.

A cationic slow-setting (CSS-1) asphalt emulsion was selected as a recycling additive to be compatible with the RAP materials. It provides adequate workability time to ensure good dispersion with dense graded aggregates. The residue content of the asphalt emulsion was measured to be 64.5%. Considering the properties from Marshall Stability, Flow, Indirect Tensile Strength and Resilient Modulus, the optimum CSS-1 emulsion contents for CIR-13, CIR-20, and CIR-25 mixtures were 3.8%, 3.5% and 3.3%, respectively by weight of the RAP. Portland cement, which can improve the early strength of CIR mixtures, was added at 1.5% by weight of RAP materials. Apart from these recycling additives, water was required for adequate coating and compaction. It was added before the addition of the other additives. The optimum total moisture content consisted of extra pre-wet water and water from emulsion which was determined to be 4.3% using coating tests. Three different compaction methods, including Marshall, SGC and Static Load compaction, were used to prepare the CIR samples. The corresponding specimens compacted by 50 blow Marshall or 30 gyration SGC compaction were both formed using 101.6 mm diameter molds getting a target height of around 63.5 mm. The Static Load specimens were compacted using a designed mold size of 80 mm × 80 mm × 60 mm. The target air voids for all CIR samples was 11% ± 0.5%.

To compare the difference in air voids between CIR and HMA mixtures, the AC mixtures with three different nominal maximum aggregate sizes (NMAS) were designed as AC-13, AC-20, and AC-25. According to the field construction, modified asphalt binder styrene-butadiene-styrene (SBS) PG 76-22 was used for AC-13 and asphalt binder 70# PG 64-22 was used for AC-20 and AC-25. The aggregate gradations and mix design results of AC mixtures are described in Table 1. These AC samples were all compacted under the 75 blow Marshall compaction and the target air void content was designed to be 4.5% ± 0.5%.

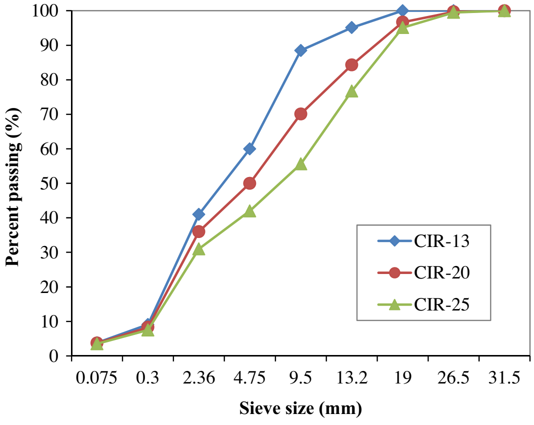

Fig. 1. Three typical gradations for CIR mixtures.