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Influence of binder grade, gradation, temperature and loading rate on R-curve of asphalt concrete

Shu Yang [a,*], Andrew F. Braham [b]

[a] Department of Civil Engineering, Hunan University, Changsha 410082, China
[b] University of Arkansas, 4190 Bell Engineering Center, Fayetteville, AR 72701, USA

HIGHLIGHTS

- Polymer modification impacts the crack initiation parameters of cohesive energy.
- Testing temperature impacts fracture energy, cohesive energy and energy rate.
- R-curve can be used to understand the performance of asphalt concrete.

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ABSTRACT

The R-curve method is widely applied in characterizing a vast range of materials. However, research on R-curves in asphalt concrete is very limited. In previous research, the R-curve method was developed to characterize and quantify the fracture resistance of asphalt concrete. In this paper, a more comprehensive experimental matrix for R-curve research was performed to enlarge the potential envelope of R-curve in asphalt concrete. Thus, this research studied the influence of binder grade, aggregate size, testing temperature, and loading rate on R-curve extractions: fracture energy, cohesive energy, and energy rate. In conclusion, it is found that R-curve method can benefit the fracture analysis of asphalt concrete. This method can differentiate the fracture resistance of the materials in terms of crack initiation and propagation. Significant findings include the polymer modification only influences cohesive energy; the loading rate only influences the energy rate; and both the NMAS and testing temperature influence the facture energy, energy rate, and cohesive energy.

1. Introduction

Irwin and Kies [12] developed a concept to quantify the crack growth resistance called the Resistance Curve, or R-curve. Krafft et al. [15] postulated and verified the concept of R-curve. An R-curve considers fracture resistance as a function of crack extension. A plot of resistance versus crack length extension can be defined as R-Curve, crack extension occurs when energy release rate equals to the material resistance [25]. R-curve has been widely and successfully applied in vast range of materials such as Ceramic [23], human tooth enamel [4], human bone [9], epoxy adhesives [2], alloy [19], dental porcelain [8], rock [18], and Concrete [22]. The information that R-curve provides to characterize and quantify the fracture resistance can be abundant compare to single number. For example, R-curve can not only predict the life expectancy of materials [20], but can also explain the mechanism of crack initiation and propagation [13] and identify the contribution of crack resistance [27]. R-curve method, in theory, can quantify the fracture resistance of materials that vary from linear elastic material, plastic-elastic material to time-dependent material [3]. In this large range of materials, fracture resistance can be considered as crack driving force, J-integral, or C^* integral corresponding to linear elastic fracture, plastic-elastic fracture and time-dependent fracture. However, according to literature, there is limited research to fully investigate R-curve method for the fracture analysis of asphalt concrete. The earliest literature found that utilized R-curve for asphalt concrete was Mobasher et al. [17]. This research used R-curve method to evaluate the crack propagation properties of asphalt concrete and indicated that R-curve approach provided good measurement of fracture resistance of asphalt concrete. Recently, however, there has been preliminary research on R-curve to further study the fracture resistance of asphalt concrete.

Braham and Mudford [6] applied the R-curve for asphalt concrete to evaluate the fracture resistance. Multiple R-curves at

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* Corresponding author.

E-mail addresses: syang@hnu.edu.cn (S. Yang), afbraham@uark.edu (A.F. Braham).

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different testing temperatures for the same mixture were established. By shifting the curves at different temperature, a master R- Curve was constructed. This study used the master R-curve to quantify and characterize the cracking resistance of asphalt concrete, which evaluated the cracking resistance more comprehensively than a single number parameter. However, this research used CMOD as the crack extension rather than crack length, which was a deviation from traditional R-curve methods in other materials. Yang and Braham [26] constructed R-curve for asphalt concrete using crack length and CMOD respectively and compared the resulting R-curve generated by these two protocols. The crack length protocol captured different shape of R-curve as the CMOD protocol, which indicated that perhaps the relationship between crack length and CMOD was not well understood. Ghafari and Nejad [11] constructed R-curve in asphalt concrete by using SE (B) test to characterize the crack propagation. J-integral was utilized as the fracture resistance to construct R-curve which characterized the elastic-plastic property in fracture of asphalt concrete. Yang and Braham [25] establish R-curve for three types of asphalt concrete considering aging, moisture condition, and temperature. It is found that R-curve can be powerful to characterize and quantify the crack initiation and propagation in asphalt concrete. Because R-curve is a function of crack resistance, it records the whole process of crack development including crack initiation and crack propagation. The crack initiation was quantified by cohesive energy, while the propagation was quantified with fracture energy, which was the combination of both cohesive energy and propagation energy. The research found that the cohesive energy was relatively unchanged between mixtures and external factors, while the overall fracture energy was more sensitive. While previous study of R-curve for asphalt concrete provides a first glimpse to the potential benefits of utilizing R-curves, it did not explore common variables and test conditions in mix design of asphalt concrete.

In this paper, a non-linear parameter, fracture energy is used as the fracture resistance to construct R-curve. This study further investigated the influence of mix-design variables on R-curve in asphalt concrete. There are two considerations to compliment the previous research of R-curve for asphalt concrete. First, this expanded research of R-curve intends to investigate the most fundamental variables in asphalt concrete: asphalt binder Performance Grade (PG) and Nominal Maximum Aggregate Size (NMAS). Second, as asphalt concrete is a viscoelastic material, the testing temperature and loading rate impact the crack behavior significantly. Viscous deformation always associates with the fracture process, know that the energy dissipated in the system is used to create crack, or creep deformation. Therefore, a wide range of temperatures and loading rates were also explored.

2. Objective

The motivation of this research is to fully evaluate the functionality of the R-curve method for agencies to quantify the crack resistance of asphalt concrete in terms of crack initiation and propagation. To achieve this motivation, this paper aims to investigates internal and external factors of R-curve for asphalt concrete including binder grade, aggregate size, testing temperature, and loading rate.

3. Material and methods

To maximize the envelope of R-curve in asphalt concrete, this paper uses the experimental matrix shown in Table 1. The factors (including binder grade, Nominal Maximum Aggregate Size, testing temperature, and loading rate) and levels are chosen to expect significant difference in R-curve behavior of asphalt concrete.

Table 1
Experimental matrix.

Factors	# of Levels	Level
Binder Grade	2	PG 64-22, PG 76-22
NMAS	2	9.5 mm, 25 mm
Test Temperature	3	24 °C*, 0 °C, −24 °C
Loading Rate	2	0.03 mm/min, 1.0 mm/min

* The test result at 24 °C is not included in discussion and the reason will be given in Section 4.3.

3.1. Materials

In this study, the factor of binder grade had two levels, PG 76-22 and PG 64-22. PG76-22 binder used in this research is a SBS polymer modified binder on a neat binder PG64-22. Thermal cracking is usually an issue at low temperature and these two asphalt binders to have the same lower limit of their binder grade. However, fracture behavior of these two binders in asphalt concrete could be different for two reasons. First, the low temperature grading in a Superpave PG is graded by the DSR fatigue test and the Bending Beam Rheometer (BBR) test on binder only. Second, the PG 76-22 was polymer modified with styrene-butadienestyrene (SBS), whereas PG 64-22 was a neat binder without any modification. The purpose of the addition of polymer in the binder is the toughness increment at high temperature, but the polymer may also influence the fracture behavior at low temperature.

The second factor, aggregate, can be influenced by the size of the gradation. A NMAS 9.5 mm is usually applied in surface course, whereas a NMAS 25 mm is usually placed in field as the binder course between surface course and base course. As known, the finer aggregate gradation has more surface area than the courser gradation, thus the binder content is usually higher in finer aggregate gradation to cover the surface area. In asphalt concrete, the matrix between aggregate and asphalt binder is usually the weak point compare to the tensile strength of aggregate itself, so cracks often form at either the interface of the aggregate and matrix or in the matrix itself, not generally in the aggregate. It is usually observed crack growing in the asphalt binder filled voids of the asphalt concrete. Finally, the gradation structures in the asphalt concrete can be very different due to the NMAS, which may result in significant fracture toughness and fracture behavior.

A Superpave mix design was performed for the NMAS 9.5 mm, and NMAS 25 mm gradation, using PG 64-22 binder and targeting 4% air voids. In order to control the viable of binder content that could have added a confounding factor on the cracking behavior of asphalt concrete, this research uses the same binder contents for PG 76-22 binder and PG 64-22 binder. The binder contents determined by the mix design are 5.70% for the 9.5 mm NMAS mixture, and 4.02% for the 25 mm NMAS mixture. The compaction data is recorded during the compaction, the percentage of theoretical maximum specific gravity (G_{mm}) is plotted versus gyration numbers. The testing sample compaction reduced the gyrations according to the compaction curve when compacting to achieve 7% air void to mimic the field air void immediately after the construction and as per standard practice. All the samples experienced two hours aging at the compaction temperature before the compaction.

In addition to the asphalt binder type and aggregate gradation, external factors are also important in asphalt concrete behavior. Due to the viscoelastic nature of asphalt concrete, time and temperature are vital in fracture behavior. This paper used three testing temperatures: −24 °C, 0 °C and 24 °C. The temperature of −24 °C was chosen because of the lower limit of the PG grade for both binder is −22. −24 °C is 2 °C below the lower PG limit. This test temperature for fracture test is established by Braham et al. [7] and is intended to capture the glass transition temperature of the asphalt cement. 24 °C is usually the ambient temperature and significant amount of research is found to perform fracture test at ambient temperature. For example, Faruk et al. [10] at Texas A&M Transportation Institute, found that the room temperature at 25 °C, was the better suited for low binder content asphalt concrete in SCB) test. Wu et al. [21] at Louisiana Transportation Research Center performed the SC(B) test at 25 °C, for the asphalt concrete contains the binder for PG 76-22 and PG70-22. However, since the energy dissipated in the specimen during a fracture tests can be separated into three parts: fracture energy, recoverable strain energy, and creep strain energy [5], fracture testing at ambient temperatures include more than just the energy associated with separating fracture faces. This indicates that fracture is associated with the elastic deformation recoverable) and viscous deformation creep). Li and Marasteanu [16] found that it takes higher external work in a fracture test at higher testing temperature. This may indicate that the creep deformation is larger at higher testing temperature. In other words, the creep energy increases in the system as the increment of the testing temperature. This research did not separate the three types of energy, but the three levels of testing temperature promoted a trend of the change of creep energy and elastic energy. Thus, −24 °C, 0 °C, and 24 °C are chosen to expect to detect the trend. It is known that the effect of time and temperature can be converted by the law of time-temperature superposition. Loading rate is the form of time in a fracture test, a faster loading rate at higher temperature may be equivalent to a slower loading rate at lower temperature. In this paper, two loading rates are considered in the