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Determination of optimal mix from the standpoint of short term aging based on asphalt mixture fracture properties using response surface method

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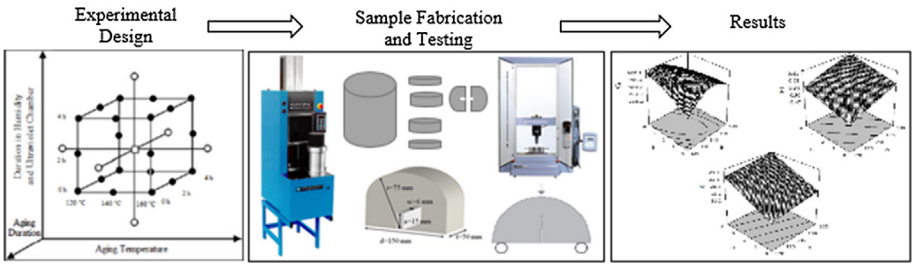
HIGHLIGHTS

- Aging increases mixtures' rutting resistance and resilient modulus, while reduces fatigue resistance.
- The short term aging condition to achieve optimal mix varies with test temperatures and bituminous binder variations.
- Higher aging rate requires at the high temperatures to achieve the optimal mix in terms of fracture resistance.
- The mixtures with softer binders and lower short term aging rate may serve better in cold regions.
- The response surface method exhibits a great capability to detect the optimal mix.

GRAPHICAL ABSTRACT



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ABSTRACT

Over the years, asphalt pavement materials age, causing binder embrittlement which adversely affects pavement service life. This paper employed Response Surface Method (RSM) to determine the optimal mix from the standpoint of short term aging based on mixtures' fracture properties obtained from the Semi-Circular Bending (SCB) test. In order to short term age the mixtures, an experimental matrix was designed based on the central composite design. Aging temperature, aging duration and duration in humidity and ultraviolet chamber were considered as short term aging factors or independent variables (IV). The maximum force, deformation at maximum force, strain at maximum force, stiffness, fracture energy, maximum stress at failure, fracture toughness, velocity of fracture initiation, fragility index, and velocity of crack growth as the SCB test outcomes or dependent variables (DV) were analyzed using RSM. The results showed that the effects of IVs on the DVs change with changes in either binder type or binder content. For instance, the maximum fracture energy of mixtures produced with binder A60 were 3197.8 and 2599.1 J/m^2 at 10 and 30 °C, respectively, while the corresponding values of mixtures produced with binder B80 were 5112 and 1725.9 J/m^2 at 10 and 30 °C, respectively. Aging up to some level exhibited beneficial impacts on mixtures' fracture properties, which was considered as the optimal mix. The short-term aging level of optimal mix for the mixtures with stiffer binder was lower, compared to those produced with softer binders. For example, aging temperature to achieve optimal mix for mixtures

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prepared using binder A60 was 124 °C at 20 °C, while the corresponding value for mixtures produced with binder A80 was 142 °C at the same temperature. Crossing the optimal mix, made the mixtures become brittle, which was not desirable especially at lower temperatures.

1. Introduction

The extent of short term aging, which takes place during production and construction of asphalt mixture, can affect asphalt mixtures' performance. The effects of aging on mixtures' performance can be influenced by variations in binder and aggregate types, mixing and construction durations, and environmental conditions [1]. Short term aging is a result of bituminous binder volatilization and oxidation which increase binder viscosity and results in mixture stiffening. Several studies have been conducted to evaluate aging and its effects on binders' and asphalt mixtures' behavior. Glover stated changes that took place in binder compositions due to aging [2]. Glover et al. [3] also stated that increase in binder carbonyl content due to aging is one of the main reasons caused binder viscosity to increase. Lee et al. [4] reported that increase in the molecular size resulted in the increase in binder viscosity and stiffness which led to mixture brittleness and premature failure in the field. The increment in asphaltene content (the largest component of asphalt binder) and proportion of oxygen in carbonyl and sulfoxides group was also reported based on the FTIR test results [5,6]. Siddiqui et al. employed XRD test to study the aging effects on the crystallite parameters and aromaticity of asphaltene. The results showed no direct correlation between aging and the crystallite parameters of asphaltene [7]. According to Gandhi, asphalt mixture rutting resistance and resilient modulus increase due to aging [8]. The creep rate reduction as aging duration increased was also reported by Li et al. [9]. According to Raad et al. , increased mixture stiffness due to aging led to a reduction in fatigue resistance [10]. Hajj et al. also reported fatigue resistance reduction due to aging [11]. Although aging enhances the load-bearing capacity and permanent deformation resistance of pavements by producing stiffer mixtures, it can also cause or accelerate several distresses such as fatigue, low temperature cracking and moisture damage by reducing pavement flexibility [12,13]. According to Fernández-Gómez et al. [14] cracking and reduction of asphalt fatigue life are the most important damages caused by aging due to the asphalt binder stiffness. The objective of this paper is to determine the optimal mix from the standpoint of short term aging, which can deliver the best mixtures' performance in terms of fracture properties using Response Surface Method (RSM).

The Semi Circular Bending (SCB) test was used to evaluate the effects of aging on fracture properties of asphalt mixtures. The SCB test has recently gained popularity to assess the mixture crack propagation due to its simplicity, repeatability, consistency, and flexibility in testing and evaluation. The SCB test findings can be correlated to the elastic-plastic fracture behavior of asphalt mixture by determining its fracture energy and fracture toughness, hence the mixture fracture resistance. The SCB outcomes such as fracture toughness and fracture energy can be used in linear elastic fracture mechanics (LEFM) analysis as one of principles to characterize mixtures performance [15]. Arabani and Ferdowsi [16] studied asphalt mixtures' performances using SCB test. Indirect Tensile Strength (ITS) and Triaxial Hveem tests were also conducted and their results were compared with the SCB test results. It was found that the SCB is a promising test to evaluate the tensile strength of asphalt mixtures with good repeatability. Comparable trend between SCB, ITS and Hveem test results were also reported. However, the dissimilarity of tensile strength obtained from the SCB and ITS test were found to be related to their different stress states under loading. Mohammad et al. [17] conducted the SCB test to evaluate and compare the performance of laboratory-produced mixtures with the crack pattern obtained from the pavement that has been in service for approximately 10 years. The outcomes showed that cracking rate of the pavement decreased by increment of mixtures fracture resistance. Good correlation between SCB results with the pavement cracking rate was also found in the study. The comprehensive review regarding the SCB test utilization to evaluate fracture properties of asphalt mixtures was provided in the study conducted by Saha and Biligiri [15]. As explained earlier in this section, aging directly influences mixtures stiffness and therefore their fatigue life and fracture properties. Hence, the SCB as a promising test was employed in this study to assess such influences on mixtures fracture properties.

RSM is a statistical-based approach to detect the relation between responses and factors [18]. To be comprehensive, RSM is a sequential procedure, including design of series of experiment, assessing the relationships between factors and outcomes, and finally establishing the optimum conditions based upon these relationships [19]. RSM involves designing an efficient experiment which can reduce variability, time, and cost, develops an understanding system to characterize the complex relation between factors and responses and consequently optimizes the conditions and experimental process using statistical analysis. RSM has recently become more popular in the field of asphalt technology. Tan et al. evaluated and optimized the modified asphalt sealant mix design using RSM [20]. Kavussi et al. studied the effects of aggregate gradation, hydrated lime and Fisher-Tropsch wax content on the indirect tensile strength of warm mix asphalt using RSM [21]. Haghshenas et al. used RSM to optimize the binder, grading, and lime content in stripping process of HMA [22]. Hamzah and Omranian used the same technique to study the aging effects on the behavior of asphalt binders at high temperatures [23]. In another study, Hamzah et al. employed RSM to quantify the adhesion failure due to moisture on the fractured surfaces of warm mix asphalt [24]. It was stated that although the required number of samples significantly reduced with the usage of RSM, the method produced the results with great accuracy. The successful application of RSM technique in the previous studies indicates its capability to characterize the complex behavior of asphalt binders and mixtures.

In this study, an experimental plan was designed using Central Composite Design (CCD). The relationship between aging temperature, aging duration, and duration of conditioning samples in the humidity and ultraviolet chamber (as factors cause aging) are studied to estimate the optimal mix result from short-term aging. These factors' effects on the maximum force, deformation at maximum force, strain at maximum force, stiffness, fracture energy, maximum stress at failure, fracture toughness, velocity of fracture initiation, fragility index, and velocity of crack growth as the responses or dependent variables are also investigated. This paper begins with an abstract which provides an overview of the study. The introduction section covers the literature review of previous related research. These sections are followed by materials and methods which describes the raw material properties, mixture performance test, and experimental plan designed for this research. The next section is results and discussion which deliberates on