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Using two-way ANOVA and hypothesis test in evaluating crumb rubber modification (CRM) agitation effects on rheological properties of bitumen

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ABSTRACT

The effect of CRM aspects on rheological properties of asphalt binder such as improvement in the performance grade (PG) for low, intermediate, and high service temperatures are evaluated and the binder's dynamic viscosity changes were studied in this research. Enhancement also resulted in the binder's fatigue and rutting indices. At the same time, the effects of low/high shear blending conditions on the rheological properties were investigated. The effect of interactions between blending conditions and modifier content were studied by utilizing the analysis of variance (ANOVA) method and hypothesis tests.

1. Introduction

1.1. Background

Use of crumb rubber in modification (CRM) of asphalt binders causes improvement in performance of modified asphalt binders both in low and high service temperatures [1]. CRM also improves the performance aspects of the asphalt mixture such as thermal susceptibility, elastic behavior, fatigue cracking resistance and aging stability [1]. Researchers have found that the addition of 10–18% crumb rubber can improve high and low temperature properties of asphalt binders [2–5]. The digestion process of CRM with binder is rather complicated and is dependent on the variables of CRM and binder (i.e., type, percentage, size, grade, etc.) in addition to the mixing conditions (temperature, mixing time, agitation, etc.) [6]. Lee et al. [7] investigated the performance properties of CRM binders due to CRM processing method and percentage through selected SuperPAVE rheological binder tests. The CRM used in Lee et al. study was obtained from two sources. One source used the ambient grinding method to process scrap passenger car tires into crumb rubber and the other used the cryogenic grinding process [7].

The effect of CRM on the properties of the asphalt binders were evaluated in former and current studies [8–15]. In almost all of these research discussions, conclusions are qualitative and based on the raw test results and statistical methods are used scarcely to investigate the results and compare the cases. Thodesen et al. [16] utilized statistical methods in the development of an empirical model to determine $G^*/Sin\,\delta$ in crumb rubber modified binders. They develop the empirical model depicting the changes in values of $G^*/Sin\,\delta$ and failure temperatures. Besides, they use confidence intervals to evaluate these changes. Liu et al. [17] evaluated the performance of different modified binders with different CRM contents, particle size, and CRM type by using the analysis of variance, ANOVA.

1.2. Research objective and scope

The main objective of this research is to evaluate the efficiency of crumb rubber content and low/high shear blending conditions on the binder rheological properties. The comparison between crumb rubber content and low/high shear blending capability on the PG improvement, fatigue and rutting parameters improvement was accomplished by using ANOVA method. Furthermore, the hypothesis test was utilized to compare the efficiency of the low and high shear blending conditions and also to evaluate the measure of effectiveness of each condition for improving the PG of the base binder.

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2. Materials and test methods

2.1. Base binder

A PG58-22 bitumen was selected as the base binder. The base binder was obtained from one of the bitumen production plants in Iran [1]. The characteristics of the base binder are presented in Table 1. The Superpave performance grading (PG) testing protocol (ASTM-D6373) was used to evaluate the base and modified bitumen samples [18] and the PG of binders was specified. High service temperature (HT) for a binder is determined as the temperature at which the $G^*/Sin\,\delta$ is greater than 1 kPa for unaged binder and greater than 2.2 kPa for the rolling thin film oven aged condition (RTFO) (ASTM-D2872) [19]. Low service temperature (LT) is 10 °C less than the temperature at which the pressurized aging vessel (PAV) (ASTM-D6521) [20] aged binder exhibits creep stiffness of less than 300 MPa and an m-value of greater than 0.3 at 60 s of loading (ASTM-D6648) [21]. In addition to the performance requirements at high and low service temperature; there is a limiting maximum stiffness at the intermediate service temperature (IT) to alleviate fatigue cracking, at which the binder's $G^*Sin\,\delta$ in the PAV aged condition does not exceed 5000 kPa. The dynamic shear modulus, G^*, and the phase angle, δ, of binders were determined by a dynamic shear rheometer (DSR) using parallel plate geometry at 10 rad/s (1.59 Hz) (ASTM D7175) [22]. According to the standard test method test specimens were 25 mm in diameter by 1 mm thick for high temperature (HT) tests (46–82 °C) and 8 mm in diameter by 2 mm thick for intermediate temperature (IT) tests (4–40 °C).

The dynamic viscosity tests are accomplished with the rotational viscometer that is the rotating spindle-type viscometer (ASTM-D4402) [23]. Dynamic viscosity determined at 95, 115, 135, 155, 165 and 175 °C for each sample. In each temperature the viscosity measured at the shear strain rate of 1.5–68 (1/sec) by the spindle SC27, which has the diameter of 11.76 mm. The dynamic viscosity test is accomplished on the unaged original binder, RTFO bitumen and PAV bitumen samples to examine the effect of CRM and also evaluate the modification resistance against aging process [1]. Researches show that the PAV aging induced damages to the bitumen–polymer network structure causes changes in the components of the bitumen and degradation of modified binders. The function of the modifier is thus significantly impaired. Eventually the rheological and mechanical properties of the modified binder become similar to the base bitumen [1,24–27].

Table 1
The characteristics of the base asphalt binder.

Penetration grade		60–70
Penetration (0.1 mm) at 25 °C	ASTM D5	70
Softening point (°C)	ASTM D36	48
Saybolt feurol viscosity (s) at 135 °C	ASTM E102	144.6
Ductility (cm) at 25 °C	ASTM D113	>100
Flash point (°C)	ASTM D92	276
Burning point (°C)	ASTM D92	362
Fraas break point (°C)	DIN EN 12593	−15
Trichloroethylin solubility	ASTM D2042	99.95
Penetration after RTFO		38
Ductility after RTFO (cm) at 25 °C		>100
Penetration index (PI)		−0.9

2.2. Bitumen modification

The base bitumen, PG 58-22, was blended with various amounts of crumb rubber, 10–16%. Crumb rubber passing through a No. 50 (0.3 mm) sieve was used for this purpose. The amounts of crumb rubber added to the bitumen were 10%, 14% and 16% of the weight of the base bitumen (PG 58-22). It was added when the base bitumen reached 170 °C and blended for 240 min at 5500 rpm using a high shear homogenizer mixer. In this process mixing temperature and blending speed were selected so that a sufficient vortex was formed in the mixing chamber during the entire process [1]. The low shear blended samples were mixed by a low shear rotary blender at 600 rpm at 170 °C.

3. Test results evaluation

3.1. Fatigue and rutting parameters evaluation

The enhancements resulted due to modification in $G^*Sin\,\delta$, which is known as the fatigue parameter, at 19 °C and $G^*/Sin\,\delta$, the rutting parameter, at 64 °C in comparison with the base binder are shown in Figs. 1 and 2, respectively. As shown in Fig. 1, the $G^*Sin\,\delta$ at 19 °C has a minimum value in 14% crumb rubber content and then increases as the result of increasing the content of crumb rubber (CR) to 16% for both low and high shear blended samples. It can be deducted from Fig. 2 that the rutting parameter, $G^*/Sin\,\delta$, increases as the result of increasing the crumb rubber content in case of both low and high shear blended samples and the maximum enhancement has occurred at 16% CR content. Figs. 3–5 show the $G^*Sin\,\delta$ versus temperature for different CR contents in low/high shear blended samples. It is resulted that the amount of $G^*Sin\,\delta$ for low shear blended samples is less than high shear blended samples over the test temperature range. This indicated that the low shear blending conditions make more enhancements on the IT performance than the high shear blending conditions, which is an unexpected result and can be studied further. Figs. 6 and 7 show

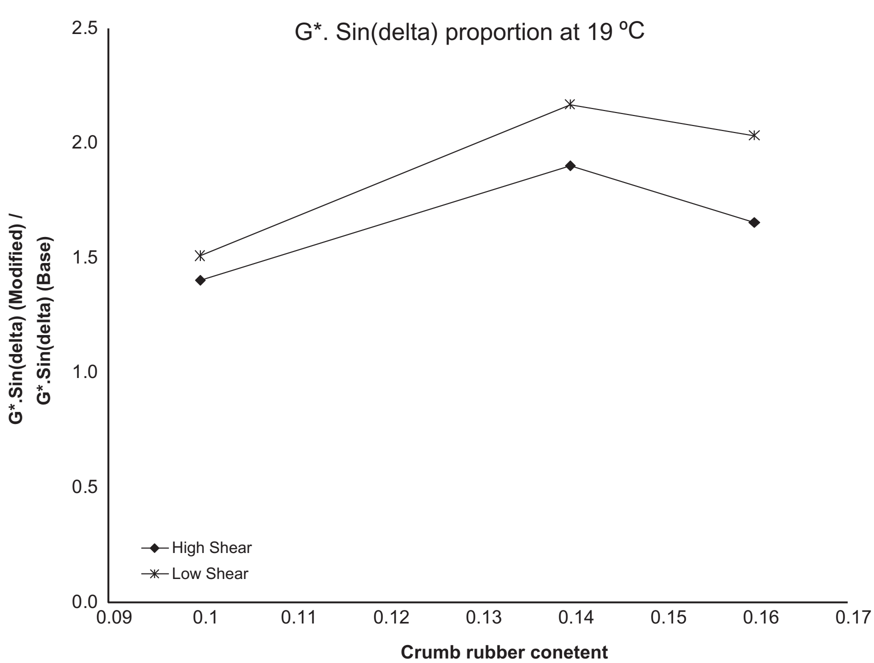

Fig. 1. $G^*Sin\,\delta$ versus crumb rubber content at 19 °C.