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Effects of Short-Term Aging on the Compactibility and Volumetric Properties of Asphalt Mixtures Using the Response Surface Method

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Abstract: Several factors affect asphalt binder and mixture characteristics. This makes pavement performance assessment a mounting task. This paper evaluates the effects of short-term aging on compactibility and volumetric properties of asphalt mixtures using the Response Surface Method (RSM). Three different binders were utilized to produce mixtures (type AC-14). Aging temperature, aging duration, and duration in a climate chamber with increased humidity and ultraviolet lighting were considered as independent variables (IV), while compactibility and volumetric properties were regarded as dependent variables (DV). The findings revealed significant impacts of aging temperature and duration on compactibility, air voids, voids in mineral aggregate, and voids filled with asphalt, while duration in the climate chamber exhibited no significant influence on the DVs. The effects of IVs on DVs varied by binder type. This was achieved through an elaborate statistical analysis. The study, finally, demonstrates the RSM's potential to predict changes in responses from mathematical equations—converging with the experimental observation—with excellent accuracy. Potentially, pavement contractors can use this method by replacing haulage duration and mixtures' temperatures during paving in the developed models. It enables them to predict the pavement density and adjust pressure as well as the number of roller passes to achieve the desired requirements.

Keywords: asphalt mixture; short-term aging; Response Surface Method; compactibility; volumetric properties

1. Introduction

Aging is one of the governing factors that influence asphalt binders' and mixtures' properties. To date, several studies have been conducted that demonstrate the effects of aging by varying the asphalt's mixture characteristics. Among others, the binder's performance grade, the binder's content, the aggregates, the filler, and the duration of mixing and construction have been examined for their influence in the pavement's quality [1–6].

According to Hernando and del Val (2013), fatigue cracking, rutting, top-down cracking, shrinkage cracking, reflective cracking, and thermal fatigue cracking have been identified as the most common distresses affecting the service life of pavements [7]. Aging increases the stiffness of the binder and, consequently, of the mixtures, which deteriorate the pavement performance and fatigue life.

It is widely accepted that aging of asphalt mixtures comprises two main phases [8–10]. The first phase, known as short-term aging (STA), takes place during production, up to the laying and compaction stage. There is well-known evidence that the considerably high temperatures for a relatively short period in this phase mainly provoke mechanisms such as volatilization and oxidation [2,5,10]. Successively, during service life, long-term aging (LTA) is the governing coupled reaction–diffusion process that affects the pavement’s performance [9].

Although aging is a well-documented phenomenon in terms of changes in binders’ rheological properties, obstacles arise when it comes to their complex microstructures and chemical composition. Such uncertainties introduce challenges for linking the characteristics of the binder to the mixture’s behavior. Researchers have stressed that these effects can lead eventually to a binder’s embrittlement. Literature shows that aging stiffens the binders and negatively affects their viscosity, which makes the pavement more prone to distress types, such as cracking and raveling [11,12]. Hamzah and Omranian (2016) proved a significant increment in binders’ viscosity by extending the aging duration for 100 min compared to the standard duration (85 min) of a rolling thin-film oven testing (RTFOT) used for simulating short-term aging [13]. Recent studies tend to focus on the effect of temperature used in standardized short- and long-term simulations and their role in rheology and chemistry [14,15]. It was found that short-term aging is more sensitive in temperature changes, as it can result in more severe chemical indices, creating a more polar binder. The increase of polarity can be explained based on the increase of intramolecular forces, such as Coulombic and van der Waals forces, as well as aromatization between the more polar molecules [16,17]. However, the impact of the variation of aging conditions on the changes in mixtures’ volumetric properties has not been studied yet.

This obstacle can be overcome by artificially aging asphalt mixtures in a lab that can fairly reflect realistic environmental conditions. In parallel, there is a widespread recognition that a systematic measurement of the volumetric properties of asphalt mixtures is vital. According to Huner and Brown (2001), the demand for accurate measurement of the mixtures’ volumetric properties has gained attention due to their significant impacts on the design of mixtures and evaluation of the final product [18]. To certify the mixtures’ adequate field performance, the assessment of asphalt mixtures can be indirectly estimated by their volumetric properties [19]. Hence, understanding the potentially detrimental effects of aging on volumetric properties is of utmost importance. Following Sadek et al. (2020), an equivalent level of volumetric properties of plant-produced mixtures can be captured using corresponding lab-produced mixtures [5].

A limited amount of research has described the patterns of varying the short-term aging of asphalt mixtures in terms of their volumetric properties. Thus, this study is focusing on the effects of various short-term aging (STA) procedures on mixture compactibility and volumetric properties. In this regard, the Response Surface Method (RSM) was adopted as a fast, effective, and reliable technique to design the experimental matrix. The RSM can establish the relationships between experimental factors and responses by combining and analyzing a series of experimental designs [20]. The RSM has been effectively used in several studies related to asphalt binders and mixture performance. Recently, Haghshenas et al. (2020) used the RSM to develop a new short-term aging protocol based on different combinations of aging duration, temperature, airflow, and weight of the binder. It was found that the impacts of aging in the RTFOT when reducing aging duration to 45 min, increasing temperature to 180 °C, using only 25 g of binder, and keeping the airflow rate between 3 and 5 L/min were comparable with the existing standard [21]. Khodaii et al. (2012) employed the RSM and studied the aggregate gradation and lime content effects on the tensile strength ratio of dry and saturated asphalt mixtures [22]. Hamzah et al. (2015) evaluated the extended STA effects on the binder rheological properties at intermediate temperatures using the RSM [23]. Another study of Haghshenas et al. (2015) utilized the RSM and modeled the relationship between the ratio of mixture tensile strength and time, hydrated lime, and Zycosoil [24]. In the current study, the Central Composite Design (CCD), a simplifying experimental design for building a second-order model using the RSM, was chosen to design the experimental plans.

In order to predict the changes in mixtures' volumetric properties, this paper aims to unravel the effects of independent variables (IV), including aging temperature, aging duration, and duration that samples were conditioned in the humidity and ultraviolet chamber, as well as their interactions as the main aging parameters during production and construction. The changes in their conditioning were designed using the RSM based on Malaysia's climatic conditions. The developed regression models were validated by a comparison between the actual and the predicted values to develop a reliable approach to forecast and assess the mixture's volumetric properties when subjected to STA.

The paper is outlined in the following way: A brief overview of the study, the materials used, and the aging treatment are first described, followed by the method used to assess the dependent variables (DV), including the compaction energy index and volumetric properties, experimentally and mathematically. The remainder of the article is devoted to the discussion of the convergence of these results and the effect of the independent variables (IVs) on DVs. Finally, the major conclusions and recommendations/limitations of this study are provided.

2. Materials and Methods

2.1. Research Methodology

Understanding the influence of short-term aging on mixtures' volumetric properties can enhance their durability by achieving the optimum requirements. A graphical summary of the experimental plan and objectives is given in Figure 1.

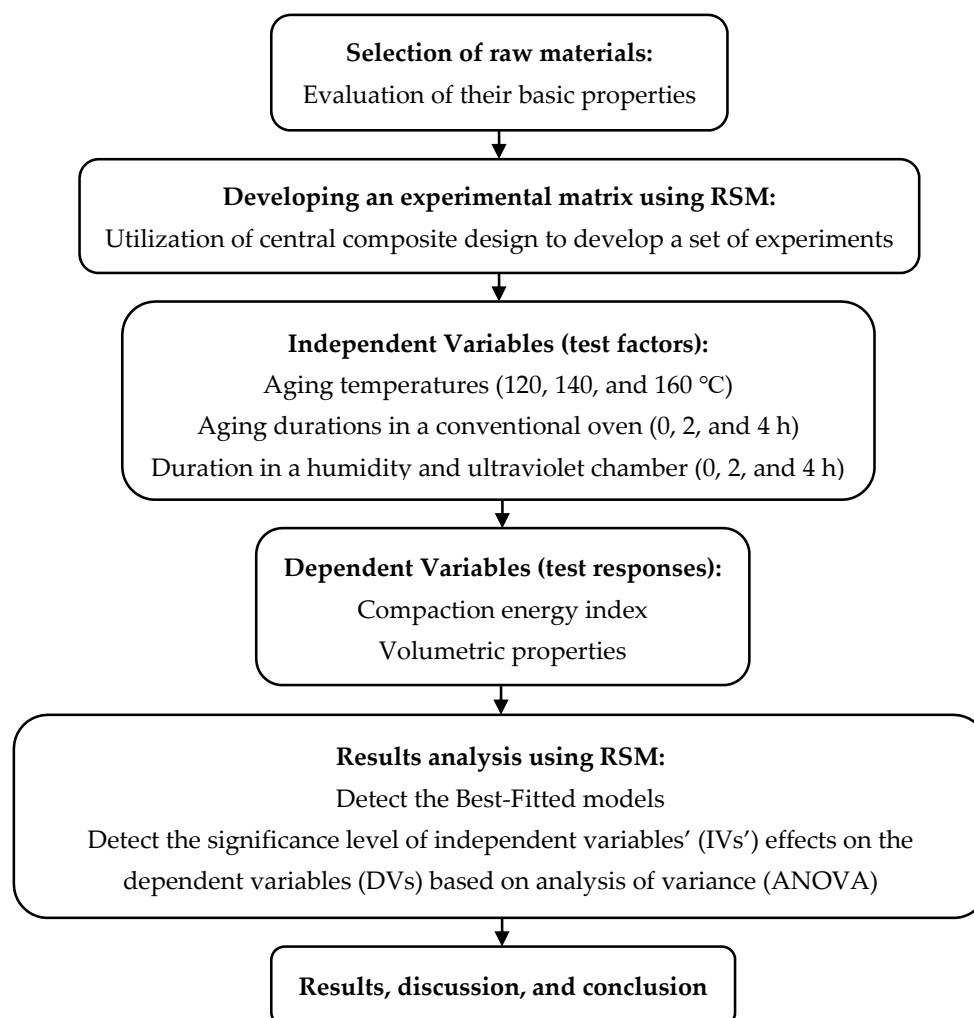


Figure 1. Research flow chart based on the Response Surface Method (RSM).

2.2. Materials

Three different binders—two conventional 80/100 penetration-grade (PG-64) binders supplied from sources A and B and one conventional 60/70 penetration-grade (PG-58) binder supplied from source A—were used in this study. To simplify the nomenclature, binders 60/70 and 80/100 from source A are referred to as A60 and A80, respectively, while binder 80/100 from source B is designated as B80. Granite aggregates (the most common aggregate type in Malaysia), in accordance with the Malaysian Public Works Department (PWD) specifications for an asphalt concrete mixture type AC14, were used [25]. Table 1 shows the basic binders and aggregate properties, as well as the binder content obtained from the mix design used at the asphalt mixing plants that supplied the binders. In addition, two types of mineral fillers, namely hydrated lime (HL) and ordinary Portland cement (OPC) with 2.40 and 3.11 kg/cm³ specific gravity, respectively, were used. Table 2 presents the aggregate gradation as used for asphalt mixture type AC14 [25].

Table 1. Materials' basic properties and asphalt mixtures' binder content.

| Material | Test | Results | Standards | Binder Content | |
|-----------|--|----------------------------|-----------|------------------------|-------|
| Binder | A60 | Penetration at 25 °C (dmm) | 62 | ASTM D 5 | 4.8% |
| | | Softening point (°C) | 50 | ASTM D 36 | |
| | | Ductility at 25 °C (cm) | >100 | ASTM D 113 | |
| | A80 | Penetration at 25 °C (dmm) | 81 | ASTM D 5 | 4.8% |
| | | Softening point (°C) | 47 | ASTM D 36 | |
| | | Ductility at 25 °C (cm) | >100 | ASTM D 113 | |
| | B80 | Penetration at 25 °C (dmm) | 80 | ASTM D 5 | 5.02% |
| | | Softening point (°C) | 46 | ASTM D 36 | |
| | | Ductility at 25 °C (cm) | >100 | ASTM D 113 | |
| Aggregate | Coarse aggregate bulk specific gravity (kg/cm ³) | | 2.62 | AASHTO T85 | |
| | Absorption (%) | | 0.40 | AASHTO T85 | |
| | Course aggregate angularity (%) | | 49.50 | AASHTO TP56 (Method A) | |
| | Fine aggregate bulk specific gravity (kg/cm ³) | | 2.57 | AASHTO T84 | |
| | Absorption (%) | | 0.54 | AASHTO T84 | |
| | Fine aggregate angularity (%) | | 47.30 | AASHTO T33 (Method A) | |
| | Flat and elongated (%) | | 23.30 | ASTM D4791 | |
| | Los Angeles abrasion (%) | | 23.86 | AASHTO T96 | |
| | Aggregate crushing value (%) | | 19.25 | MS 30–8:1995 | |

Table 2. Aggregate gradation.

| Sieve Size (mm) | Lower Limit (%) | Median (%) | Upper Limit (%) |
|-----------------|-----------------|------------|-----------------|
| 20 | 100 | 100 | 100 |
| 14 | 90 | 95 | 100 |
| 10 | 76 | 81 | 86 |
| 5 | 50 | 56 | 62 |
| 3.35 | 40 | 47 | 54 |
| 1.18 | 18 | 26 | 34 |
| 0.425 | 12 | 18 | 24 |
| 0.15 | 6 | 10 | 14 |
| 0.075 | 4 | 6 | 8 |

To prepare the samples, the binder and batched aggregates (approximately 5 kg/batch) were mixed in a large mixer at a temperature between 160 to 170 °C depending on the binder type (a lower temperature was adopted for the softer binders). The loose mixtures were placed inside a conventional oven at compaction temperature to simulate the mixture's short-term aging conditions; as such, the Short-Term-Oven-Aging (STOA) method was adopted based on [26]. The loose mixtures were turned upside down after every hour to ensure that they were aged homogeneously until the selected conditioning time was achieved. A Servopac gyratory compactor was then employed and set at 100 gyrations to compact the loose mixtures. Elwardany et al. (2017) stated that the current standard for artificial binder aging cannot fully reflect mixture aging due to the interaction between binder and aggregate [27]. It was also suggested that ultraviolet light might be the reason for the changed aging

rate of samples from the field. The compacted mixtures were therefore placed in the humidity (H) and ultraviolet (UV) chamber at 25 °C and 85% humidity (as the average of Malaysia's yearly conditions) to simulate the pavement's exposure to environmental conditions during the resting period (after paving until it is opened for traffic, which is considered to be the end of the short-term aging stage). The conditioning in the conventional oven and duration in the humidity and ultraviolet chamber were varied based on the RSM design. It should be noted that the IVs were selected in accordance with the Malaysian specifications and climatic conditions. In the case of aging temperature, 160 °C represents the mixing temperature, while 120 °C is the minimum temperature at which compaction is allowed during construction. After compaction, the pavement must be cooled down for 4 h before traffic is allowed. Since this study was conducted in Malaysia, as a tropical country, it was hypothesized that higher humidity and UV radiation may influence short-term aging. Mixtures were, therefore, conditioned in the humidity and ultraviolet chamber for a maximum of 4 h to simulate the extreme impacts of the pavement's exposure to the environmental conditions.

2.3. Method

One set of experiments (similar for all three binders) was designed using CCD to study the mixtures' susceptibility to age hardening. Aging temperature, aging duration, and duration that samples were conditioned in the humidity and ultraviolet chamber (H & UV) were chosen as independent variables (IV), while maximum specific gravity (G_{mm}), bulk specific gravity (G_{mb}), compaction energy index (CEI), air voids (V_a), effective specific gravity (G_{se}), absorbed asphalt binder (P_{ba}), effective binder content (P_{be}), voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA) were selected as responses or dependent variables (DV), as shown in Table 3.

The G_{mm} was determined using the Rice test in accordance with ASTM D2041 procedures [28]. The G_{mm} of the specimen subjected to different conditions remained unchanged. The G_{mb} for mixtures produced with binders A60, A80, and B80 were 2.46, 2.47, and 2.46, respectively. The G_{mb} was determined based on the Saturated Surface-Dry (SSD) method in accordance with AASHTO T 166 procedures [29]. The CEI refers to the area under the densification curve (from the 8th gyration to 92% of G_{mm}), which was obtained from the Servopac gyratory compactor. The 8th gyration reflects the initial densification derived from the applied load by the paver during the paving process, while 92% of G_{mm} represents pavement density after construction as required by WisDOT specifications [30]. The other dependent variables, V_a , G_{se} , P_{ba} , P_{be} , VMA, and VFA, were calculated using well-known and widely established Equations (1)–(6) [25,31].

$$V_a = (1 - G_{mb}/G_{mm}) * 100 \quad (1)$$

$$G_{se} = \frac{100 - P_b}{(100 - G_{mm}) - (P_b/G_b)} \quad (2)$$

$$P_{ba} = 100 * \left(\frac{G_{se} - G_{sb}}{G_{sb} * G_{se}} \right) * G_b \quad (3)$$

$$P_{be} = P_b * \left(\frac{P_{ba}}{100} * P_s \right) \quad (4)$$

$$VMA = 100 - \frac{G_{mb} * P_s}{G_{sb}} \quad (5)$$

$$VFA = 100 * \frac{VMA - V_a}{VMA} \quad (6)$$

where V_a is air voids, G_{mb} and G_{mm} are bulk and maximum specific gravity, respectively, G_{se} represents effective specific gravity, P_b is the binder content in percent by total weight of a mixture, G_b indicates specific gravity of binder, P_{ba} represents absorbed asphalt binder, G_{sb} is the bulk specific gravity of aggregate, P_{be} shows effective binder content, P_s is the aggregate content in percent by total weight of

the mixture, *VMA* is the percentage of voids in the mineral aggregate, and *VFA* indicates the percentage of voids filled with asphalt.

Table 3. Matrix of experimental design.

| Binder | No. | Factors or IVs | | | Responses or DVs | | | | |
|--------|-----|------------------|--------------|------------|-------------------------------|------------|-----------|---------|---------|
| | | Temperature (°C) | Duration (h) | H & UV (h) | G_{mb} (g/mm ³) | CEI (a.u.) | V_a (%) | VMA (%) | VFA (%) |
| A60 | 1 | 140 | 4 | 2 | 2.38 | 59.4 | 4.1 | 13.4 | 69.8 |
| | 2 | 140 | 2 | 2 | 2.38 | 54.1 | 3.8 | 13.2 | 71.4 |
| | 3 | 160 | 4 | 0 | 2.38 | 47.0 | 3.5 | 13.0 | 72.7 |
| | 4 | 120 | 0 | 0 | 2.39 | 58.0 | 3.7 | 13.1 | 71.7 |
| | 5 | 120 | 0 | 4 | 2.38 | 55.5 | 3.7 | 13.2 | 71.5 |
| | 6 | 140 | 2 | 4 | 2.38 | 55.9 | 4.0 | 13.4 | 70.1 |
| | 7 | 140 | 2 | 2 | 2.39 | 51.9 | 3.7 | 13.1 | 71.7 |
| | 8 | 120 | 4 | 0 | 2.36 | 66.1 | 4.3 | 13.7 | 68.5 |
| | 9 | 140 | 2 | 2 | 2.38 | 51.9 | 4.0 | 13.3 | 70.3 |
| | 10 | 160 | 2 | 2 | 2.38 | 41.6 | 3.3 | 12.8 | 74.0 |
| | 11 | 160 | 0 | 4 | 2.38 | 31.9 | 3.0 | 12.5 | 75.9 |
| | 12 | 160 | 4 | 4 | 2.37 | 46.5 | 3.6 | 13.0 | 72.5 |
| | 13 | 160 | 0 | 0 | 2.34 | 31.9 | 3.0 | 12.5 | 75.9 |
| | 14 | 140 | 0 | 2 | 2.38 | 48.7 | 3.5 | 12.9 | 73.1 |
| | 15 | 140 | 2 | 0 | 2.35 | 57.4 | 4.0 | 13.3 | 70.4 |
| | 16 | 120 | 2 | 2 | 2.37 | 64.1 | 4.2 | 13.5 | 69.3 |
| | 17 | 140 | 2 | 2 | 2.37 | 54.8 | 3.9 | 13.3 | 70.7 |
| | 18 | 140 | 2 | 2 | 2.38 | 56.7 | 3.9 | 13.2 | 71.0 |
| | 19 | 120 | 4 | 4 | 2.38 | 65.4 | 4.3 | 13.6 | 68.6 |
| A80 | 20 | 140 | 4 | 2 | 2.39 | 51.6 | 3.5 | 12.4 | 72.0 |
| | 21 | 140 | 2 | 2 | 2.39 | 47.8 | 3.3 | 12.2 | 72.8 |
| | 22 | 160 | 4 | 0 | 2.39 | 46.7 | 3.4 | 12.3 | 72.1 |
| | 23 | 120 | 0 | 0 | 2.40 | 46.2 | 3.3 | 12.2 | 73.3 |
| | 24 | 120 | 0 | 4 | 2.40 | 49.2 | 3.3 | 12.2 | 73.0 |
| | 25 | 140 | 2 | 4 | 2.39 | 48.4 | 3.4 | 12.1 | 72.1 |
| | 26 | 140 | 2 | 2 | 2.39 | 48.0 | 3.3 | 12.2 | 73.0 |
| | 27 | 120 | 4 | 0 | 2.38 | 56.6 | 3.7 | 12.6 | 70.6 |
| | 28 | 140 | 2 | 2 | 2.39 | 48.5 | 3.3 | 12.2 | 72.9 |
| | 29 | 160 | 2 | 2 | 2.39 | 39.8 | 3.3 | 12.2 | 72.8 |
| | 30 | 160 | 0 | 4 | 2.39 | 29.5 | 2.9 | 11.8 | 75.8 |
| | 31 | 160 | 4 | 4 | 2.38 | 48.0 | 3.3 | 12.2 | 73.3 |
| | 32 | 160 | 0 | 0 | 2.39 | 29.6 | 2.9 | 11.8 | 75.7 |
| | 33 | 140 | 0 | 2 | 2.39 | 41.5 | 3.1 | 12.1 | 74.0 |
| | 34 | 140 | 2 | 0 | 2.38 | 48.0 | 3.4 | 12.3 | 72.5 |
| | 35 | 120 | 2 | 2 | 2.39 | 54.5 | 3.4 | 12.3 | 72.2 |
| | 36 | 140 | 2 | 2 | 2.39 | 48.8 | 3.2 | 12.1 | 73.5 |
| | 37 | 140 | 2 | 2 | 2.38 | 48.9 | 3.3 | 12.2 | 73.0 |
| | 38 | 120 | 4 | 4 | 2.39 | 58.5 | 3.7 | 12.6 | 70.3 |
| B80 | 39 | 140 | 4 | 2 | 2.40 | 35.0 | 2.9 | 14.2 | 79.3 |
| | 40 | 140 | 2 | 2 | 2.40 | 30.9 | 3.0 | 14.2 | 79.0 |
| | 41 | 160 | 4 | 0 | 2.40 | 34.6 | 3.7 | 14.9 | 75.1 |
| | 42 | 120 | 0 | 0 | 2.41 | 34.8 | 2.6 | 13.9 | 81.2 |
| | 43 | 120 | 0 | 4 | 2.36 | 34.5 | 2.6 | 13.9 | 81.4 |
| | 44 | 140 | 2 | 4 | 2.40 | 32.6 | 2.8 | 14.0 | 80.2 |
| | 45 | 140 | 2 | 2 | 2.40 | 32.8 | 3.0 | 14.3 | 78.8 |
| | 46 | 120 | 4 | 0 | 2.40 | 41.7 | 3.4 | 14.6 | 76.6 |
| | 47 | 140 | 2 | 2 | 2.40 | 30.9 | 3.3 | 14.5 | 77.6 |
| | 48 | 160 | 2 | 2 | 2.39 | 30.0 | 3.5 | 14.6 | 76.4 |
| | 49 | 160 | 0 | 4 | 2.40 | 26.4 | 2.7 | 14.0 | 80.6 |
| | 50 | 160 | 4 | 4 | 2.39 | 34.2 | 2.9 | 14.2 | 79.3 |
| | 51 | 160 | 0 | 0 | 2.39 | 25.5 | 2.4 | 13.7 | 82.4 |
| | 52 | 140 | 0 | 2 | 2.40 | 30.5 | 2.9 | 14.1 | 79.9 |
| | 53 | 140 | 2 | 0 | 2.39 | 31.9 | 2.8 | 14.1 | 80.1 |
| | 54 | 120 | 2 | 2 | 2.40 | 41.0 | 3.0 | 14.2 | 79.0 |
| | 55 | 140 | 2 | 2 | 2.39 | 32.6 | 3.0 | 14.3 | 78.8 |
| | 56 | 140 | 2 | 2 | 2.38 | 32.5 | 2.7 | 14.0 | 80.6 |
| | 57 | 120 | 4 | 4 | 2.39 | 42.5 | 3.1 | 14.3 | 78.5 |

It should be mentioned that G_{se} , P_{ba} , and P_{be} remained unchanged for each binder, since G_{mm} , P_b , P_s , G_{sb} , and G_b did not change. The G_{se} for mixtures produced with binders A60, A80, and B80 were 2.64, 2.66, and 2.66 (g/mm³), respectively. The P_{ba} for mixtures produced with binders A60, A80, and B80 were 0.74%, 1.01%, and 0.11%, respectively. The P_{be} for mixtures produced with binders A60, A80, and B80 were 4.09%, 3.84%, and 4.91%, respectively.

The RSM determined the DVs of this study by designing the experiment plans and subsequently applying the regression models. In this regard, linear, quadratic, cubic, and two-factor interaction (2FI) as regression models were evaluated for each sample. The robustness and accuracy of models were determined based on their sequential F-tests, lack-of-fit tests, and R^2 , and the best-fitted model was adopted for further analysis. The significance of each IV was tested using Analysis of Variance (ANOVA). Insignificant IVs were then eliminated, and the best-fitted models were proposed to predict the responses. The Design-Expert 6.0.6 software was used to conduct the analysis. In normal procedures, we have three binders and three different aging conditions with three intervals. This means that we should produce at least 81 specimens to evaluate the mixtures' performance (without replications). However, the RSM enabled us to test only 57 samples, including 5 replications at the center point.

3. Results

It is clear from Table 3 that G_{mb} only slightly changed, which can be correlated with the small variation of aggregate gradation and binder content during mixing and compaction procedures. It can be seen that IVs affect CEI, V_a , VMA, and VFA. The variation of the aging condition influences the binders' stiffness and viscosity, as discussed in the introduction, which directly results in detectable changes in CEI, V_a , VMA, and VFA.

To formulate the correlation between IVs and DVs from Table 3, ANOVA results were determined (Table 4). It should be noted that four different regression models were studied (as explained in Section 2.3), but Table 4 only presents the ANOVA results of the best-fitted regression model for each specific combination (the best-fitted regression model was chosen based on a higher R^2). Table 4 provides the following statistical parameters: Sum of squares as the value to determine the dispersion of the data points or variance and variability in the observed data, F-value as the ratio between the mean sum of squares to the error mean sum of squares, and "Prob > F", which is also known as the p -value, as the probability of obtaining results as extreme as the observed data. The significant effects of IVs on DVs can be determined based on values of "Prob > F" that are less than 0.05. The explanations regarding variables are provided in the footnote of Table 4.

Table 4. Analysis of Variance (ANOVA) results.

| Binders | Responses | Best-Fitted Model | Factors | Sum of Squares | F Value | Prob > F |
|---------|-----------|-------------------|----------------|----------------|---------|-----------|
| A60 | CEI | Quadratic | A | 1215.29 | 360.50 | <0.0001 * |
| | | | B | 340.59 | 101.03 | <0.0001 * |
| | | | C | 2.87 | 0.85 | 0.3800 |
| | | | A ² | 25.69 | 7.62 | 0.0221 * |
| | | | B ² | 9.21 | 2.73 | 0.1327 |
| | | | C ² | 1.31 | 0.39 | 0.5478 |
| | | | AB | 17.20 | 5.10 | 0.0503 |
| | | | AC | 0.85 | 0.25 | 0.6273 |
| | | | BC | 0.18 | 0.05 | 0.8210 |
| | V_a | Quadratic | A | 1.39 | 228.80 | <0.0001 * |
| | | | B | 0.79 | 130.78 | <0.0001 * |
| | | | C | 0.00 | 0.10 | 0.7530 |
| | | | A ² | 0.07 | 11.08 | 0.0088 * |
| | | | B ² | 0.05 | 7.84 | 0.0207 * |
| | | | C ² | 0.02 | 2.73 | 0.1329 |
| | | | AB | 0.00 | 0.00 | 0.9648 |
| | | | AC | 0.00 | 0.05 | 0.8257 |
| | | | BC | 0.00 | 0.00 | 0.9648 |

Table 4. Cont.

| Binders | Responses | Best-Fitted Model | Factors | Sum of Squares | F Value | Prob > F |
|---------|----------------|-------------------|----------------|----------------|---------|-----------|
| A60 | VMA | Quadratic | A | 1.16 | 210.15 | <0.0001 * |
| | | | B | 0.66 | 118.44 | <0.0001 * |
| | | | C | 0.00 | 0.18 | 0.6807 |
| | | | A ² | 0.06 | 10.47 | 0.0102 * |
| | | | B ² | 0.03 | 6.04 | 0.0363 * |
| | | | C ² | 0.01 | 2.38 | 0.1575 |
| | | | AB | 0.00 | 0.00 | 0.9631 |
| | | | AC | 0.00 | 0.06 | 0.8175 |
| | | | BC | 0.00 | 0.02 | 0.8898 |
| | VFA | Quadratic | A | 45.80 | 230.86 | <0.0001 * |
| | | | B | 25.79 | 130.02 | <0.0001 * |
| | | | C | 0.03 | 0.14 | 0.7154 |
| | | | A ² | 2.36 | 11.91 | 0.0073 * |
| | | | B ² | 1.58 | 7.96 | 0.0200 * |
| | | | C ² | 0.52 | 2.61 | 0.1409 |
| | | | AB | 0.03 | 0.16 | 0.7007 |
| | | | AC | 0.00 | 0.02 | 0.8774 |
| | | | BC | 0.00 | 0.00 | 0.9631 |
| A80 | CEI | Quadratic | A | 507.09 | 613.86 | <0.0001 * |
| | | | B | 427.58 | 517.62 | <0.0001 * |
| | | | C | 4.22 | 4.11 | 0.0631 |
| | | | A ² | 3.92 | 4.75 | 0.0500 * |
| | | | B ² | 8.96 | 10.84 | 0.0064 * |
| | | | C ² | 0.01 | 0.01 | 0.9216 |
| | | | AB | 31.88 | 35.02 | 0.0002 * |
| | | | AC | 1.70 | 1.87 | 0.2047 |
| | | | BC | 0.01 | 0.01 | 0.9225 |
| | V _a | Linear | A | 0.27 | 45.67 | <0.0001 * |
| | | | B | 0.47 | 78.26 | <0.0001 * |
| | | | C | 0.00 | 0.20 | 0.6588 |
| | VMA | Linear | A | 0.22 | 44.59 | <0.0001 * |
| | | | B | 0.38 | 76.13 | <0.0001 * |
| | | | C | 0.01 | 1.67 | 0.2163 |
| | VFA | Linear | A | 10.46 | 38.58 | <0.0001 * |
| | | | B | 18.20 | 67.09 | <0.0001 * |
| | | | C | 0.01 | 0.04 | 0.8392 |
| B80 | CEI | Quadratic | A | 190.53 | 121.37 | <0.0001 * |
| | | | B | 132.64 | 84.50 | <0.0001 * |
| | | | C | 0.32 | 0.21 | 0.6604 |
| | | | A ² | 19.82 | 12.63 | 0.0062 * |
| | | | B ² | 0.01 | 0.01 | 0.9371 |
| | | | C ² | 0.89 | 0.57 | 0.4701 |
| | | | AB | 0.52 | 0.33 | 0.5790 |
| | | | AC | 0.00 | 0.00 | 0.9912 |
| | | | BC | 0.01 | 0.01 | 0.9344 |
| | V _a | Linear | A | 0.03 | 0.48 | 0.5002 |
| | | | B | 0.82 | 13.48 | 0.0023 * |
| | | | C | 0.07 | 1.21 | 0.2885 |
| | VMA | Linear | A | 0.02 | 0.51 | 0.4846 |
| | | | B | 0.64 | 13.80 | 0.0021 * |
| | | | C | 0.06 | 1.268 | 0.2778 |
| | VFA | Linear | A | 0.89 | 0.46 | 0.5100 |
| | | | B | 27.66 | 14.18 | 0.0019 * |
| | | | C | 2.20 | 1.13 | 0.3050 |

Note: A—aging temperature; B—aging duration; C—duration in the humidity and ultraviolet (H & UV) chamber; AB—the interaction between aging temperature and aging duration; AC—the interaction between aging temperature and duration in the H & UV chamber; and BC—the interaction between aging duration and duration in the H & UV chamber. * denotes the significant values. To propose accurate regressions, factors with Prob > F of more than 5% or insignificant factors were eliminated.

The results show that conditioning the samples in the H & UV chamber has no significant effects on the responses, which is in line with the results outlined by [26]. This can be expected to be true to a certain extent, since samples were placed in the H & UV chamber after compaction, which limited the H and UV penetration rate. It can also be seen that the effects of IVs on DVs vary depending on the binder type. For instance, the interaction of aging duration and temperature exhibits significant impacts on the CEI of mixtures produced with binder A80, while it exhibits no significant effect on the corresponding value of mixtures containing binder A60. To propose the best-fitted models, the IVs with Prob > F of more than 0.05 (or those IVs that exhibit no significant impact on DVs) are discarded from the developed/proposed mathematical models.

The developed equations and their statistical analysis results are presented in Table 5. The results show that all developed models acceptably fit the results based on the Prob > F of less than 0.05. It can also be seen that the lack of fit is insignificant, which is desirable. The fitted models exhibit an acceptable precision in accordance with R^2 . These three values (Prob > F, lack of fit, and R^2) indicate the great capability of the RSM method to develop regression models and predict mixtures' compactibility and volumetric properties under a broad fluctuation range of aging conditions. From the predictive equations related to mixtures produced using binders A60 and A80, the aging temperature exhibits a negative impact on CEI, V_a , and VMA, while it has a positive impact on VFA. This indicates that an increase in the aging temperature causes a reduction in the CEI, V_a , and VMA, while it increases VFA. However, aging duration exhibits the opposite impacts on the corresponding values, where increasing the aging duration increases CEI, V_a , and VMA, while VFA is decreased. These results are in agreement with the findings outlined by [32]. In the case of mixtures produced with binder B80, the aging duration trend exhibits similar effects on the CEI, V_a , VMA, and VFA, while the aging temperature only affects CEI and has no influence on other responses. This can be attributed to the higher binder content of these mixtures. In other words, excess binder content in mixtures can act as a lubricant and thus eases the aggregate movement [33]. The excess binder can also fill the voids, which directly affects V_a , VMA, and VFA. The results also show that extending the aging duration causes binder hardening, which results in increases in CEI, V_a , and VMA, but decreases in VFA. The dominant effects of aging duration over aging temperature can be determined from the positive effects of the interaction of aging temperature and aging duration on the CEI equations in the cases of mixtures produced using binders A60 and A80.

Table 5. Statistical analysis and model equations.

| Binder | Responses | Title | Sum of Squares | DF | F Value | Prob >F | Model Type |
|--------|-----------|------------------|--|----|---------|---------|-----------------|
| A60 | CEI | Model | 1638.80 | 4 | 131.97 | <0.0001 | Quadratic (Sig) |
| | | Residual Error | 43.46 | 14 | | | |
| | | Lack of Fit Test | 26.95 | 10 | 0.65 | 0.7343 | (Not Sig) |
| | | R^2 | >0.97 | | | | |
| | | Equation | $CEI = -11.02 \times A + 5.84 \times B - 3.73 \times A^2 + 1.47 \times A \times B + 54.52$ | | | | |
| | V_a | Model | 2.39 | 4 | 115.61 | <0.0001 | Quadratic (Sig) |
| | | Residual Error | 0.07 | 14 | | | |
| | | Lack of Fit Test | 0.04 | 10 | 0.39 | 0.8963 | (Not Sig) |
| | | R^2 | >0.97 | | | | |
| | | Equation | $V_a = -0.37 \times A + 0.28 \times B - 0.13 \times A^2 - 0.10 \times B^2 + 3.88$ | | | | |
| | VMA | Model | 1.98 | 4 | 107.47 | <0.0001 | Quadratic (Sig) |
| | | Residual Error | 0.06 | 14 | | | |
| | | Lack of Fit Test | 0.03 | 10 | 0.35 | 0.9181 | (Not Sig) |
| | | R^2 | >0.96 | | | | |
| | | Equation | $VMA = -0.34 \times A + 0.26 \times B - 0.12 \times A^2 - 0.085 \times B^2 + 13.26$ | | | | |
| | VFA | Model | 78.64 | 4 | 116.28 | <0.0001 | Quadratic (Sig) |
| | | Residual Error | 2.37 | 14 | | | |
| | | Lack of Fit Test | 1.09 | 10 | 0.34 | 0.9225 | (Not Sig) |
| | | R^2 | >0.97 | | | | |
| | | Equation | $VFA = 2.14 \times A - 1.61 \times B + 0.77 \times A^2 + 0.60 \times B^2 + 70.81$ | | | | |

Table 5. Cont.

| Binder | Responses | Title | Sum of Squares | DF | F Value | Prob >F | Model Type |
|--------|----------------|------------------|--|----|---------|---------|-----------------|
| A80 | CEI | Model | 1000.39 | 6 | 201.84 | <0.0001 | Quadratic (Sig) |
| | | Residual Error | 9.91 | 12 | | | |
| | | Lack of Fit Test | 8.98 | 8 | 4.79 | 0.0735 | (Not Sig) |
| | | R ² | >0.99 | | | | |
| | | Equation | $CEI = -7.12 \times A + 6.54 \times B - 1.11 \times A^2 - 1.68 \times B^2 + 2 \times A \times B + 48.31$ | | | | |
| | V _a | Model | 0.74 | 2 | 65.21 | <0.0001 | Linear (Sig) |
| | | Residual Error | 0.09 | 16 | | | |
| | | Lack of Fit Test | 0.08 | 12 | 4.48 | 0.0798 | (Not Sig) |
| | | R ² | >0.89 | | | | |
| | | Equation | $V_a = -0.17 \times A + 0.22 \times B + 3.31$ | | | | |
| | VMA | Model | 0.61 | 2 | 57.94 | <0.0001 | Linear (Sig) |
| | | Residual Error | 0.08 | 16 | | | |
| | | Lack of Fit Test | 0.08 | 12 | 5.18 | 0.0625 | (Not Sig) |
| | | R ² | >0.87 | | | | |
| | | Equation | $VMA = -0.15 \times A + 0.20 \times B + 12.21$ | | | | |
| | VFA | Model | 28.66 | 2 | 56.20 | <0.0001 | Linear (Sig) |
| | | Residual Error | 4.08 | 16 | | | |
| | | Lack of Fit Test | 3.83 | 12 | 5.11 | 0.0641 | (Not Sig) |
| | | R ² | >0.87 | | | | |
| B80 | CEI | Model | 348.84 | 3 | 108.28 | <0.0001 | Quadratic (Sig) |
| | | Residual Error | 16.11 | 15 | | | |
| | | Lack of Fit Test | 12.52 | 11 | 1.27 | 0.4438 | (Not Sig) |
| | | R ² | >0.95 | | | | |
| | | Equation | $CEI = -4.37 \times A + 3.64 \times B + 2.33 \times A^2 + 32.19$ | | | | |
| | V _a | Model | 0.82 | 1 | 13.74 | 0.0018 | Linear (Sig) |
| | | Residual Error | 1.02 | 17 | | | |
| | | Lack of Fit Test | 0.88 | 13 | 1.88 | 0.2845 | (Not Sig) |
| | | R ² | >0.44 | | | | |
| | | Equation | $V_a = 0.29 \times B + 2.96$ | | | | |
| | VMA | Model | 0.64 | 1 | 13.98 | 0.0016 | Linear (Sig) |
| | | Residual Error | 0.78 | 17 | | | |
| | | Lack of Fit Test | 0.68 | 13 | 1.93 | 0.2764 | (Not Sig) |
| | | R ² | >0.45 | | | | |
| | | Equation | $VMA = 0.25 \times B + 14.20$ | | | | |
| | VFA | Model | 27.66 | 1 | 14.54 | 0.0014 | Linear (Sig) |
| | | Residual Error | 32.33 | 17 | | | |
| | | Lack of Fit Test | 27.64 | 13 | 1.81 | 0.2985 | (Not Sig) |
| | | R ² | >0.46 | | | | |
| | | Equation | $VFA = -1.66 \times B + 79.19$ | | | | |

Note: DF—degree of freedom; A—aging temperature in °C; B—aging duration in hours.

These models can be used as quantitative tools to determine the effects of different aging conditions (which mixtures experience during mixing and construction procedures, such as long mixture haulage distance or delayed paving) on compactibility and volumetric properties. In other words, once any undesirable changes in mixtures are identified (for instance, delay in delivery), these models can be used to provide an efficient approach for the construction sector to solve issues related to a mixture's compactibility and volumetric properties. For instance, a pavement's desirable V_a is achievable by adjusting roller vibration frequency and amplitude.

For a better understanding of the relation between DVs and IVs, 3D contour plots, normal plots of the residuals, and plots of the actual versus predicted results were generated. However, since the trend was similar for all mixtures, only plots for the asphalt mixtures produced using binder A60 are shown in Figure 2. From the 3D contour plots, elevating the aging duration increases CEI, V_a , and VMA, but decreases VFA. On the contrary, increasing aging temperature decreases CEI, V_a , and VMA, but increases VFA. However, these trends fluctuate according to variations in aging condition. The 3D

contour plots also show that increasing aging duration at 160 °C exhibits higher influence on DVs compared to the aging duration increase at 120 °C. This can be inferred based on the steeper slope of aging duration effects at a higher temperature compared to the corresponding values at a lower temperature. This outcome was expected, since aging is more severe at higher temperatures compared to lower temperatures. More specifically, Figure 2 indicates that the air voids were approximately 3.6% at 120 °C, while they were reduced to slightly below 3% when the temperature was elevated to 160 °C. Similarly, the CEI was reduced by temperature increase, which can be correlated with a reduction in the binders' viscosity, which reduces the energy requirement and eases the compaction. Furthermore, the RSM's great capability to estimate the IVs with respect to the DVs can be inferred from the even or normal distribution of residuals along the fitting lines (Figure 2). The plots of the actual versus predicted results can also affirm this inference, where all predicted IVs from mathematical equations fit into the experimental observations with excellent accuracy. These findings clarify the RSM's robustness and reliability to predict the effects of IVs on the corresponding DVs. It should be noted that the number "2" in the actual-versus-predicted graph refers to a point when two data exhibited the same value.

The main effects of aging temperature and aging duration on DVs (determined using Minitab software) can be observed from Figures 3 and 4, respectively. In the case of mixtures produced with binder A60, the slope changes show that increasing temperature from 120 to 140 °C exhibits less impact on DVs compared to temperature changes from 140 to 160 °C (steeper slope indicates higher impacts). Conversely, increasing aging duration shows that the first two-hour aging has higher effects on DVs (based on the steeper slope) compared to the last two hours. The aging temperature exhibits slightly higher impacts on DVs compared to the aging duration. The maximum discrepancies of aging temperature's effects on CEI, V_a , VMA, and VFA are 35.5%, 18.5%, 5%, and 6%, respectively, while the maximum discrepancies of aging duration's effects on the corresponding values are 27%, 16%, 4%, and 4%, respectively. The results from mixtures produced using binder A80 indicate that increasing the aging temperature from 120 to 140 °C exhibits less impact on CEI compared to temperature increase from 140 to 160 °C, while in the cases of V_a , VMA, and VFA, the slopes remain approximately unchanged. The increase in aging duration for the first two hours exhibits higher effects on CEI compared to the increase of aging duration from 2 to 4 h. However, the trend of aging duration's effects on V_a , VMA, and VFA remains approximately unchanged, as can be understood from the steady slope. Despite the IVs' effects on DVs of mixtures produced using binder A60, aging temperature exhibits lower impacts on the DVs of mixtures produced using binder A80 compared to the aging duration. The maximum discrepancies of aging temperature's effects on CEI, V_a , VMA, and VFA are 29%, 9%, 2.5%, and 3%, respectively, while the maximum discrepancies of aging duration's effects on the corresponding values are 38%, 20%, 3.5%, and 4%, respectively.

The scenario varied for mixtures produced with binder B80. The steeper slope of the increase of temperature from 120 to 140 °C exhibits this interval's higher impact on CEI compared to temperature changes from 140 to 160 °C. However, the temperature's increase from 120 to 140 °C exhibits approximately no impact on V_a , VMA, and VFA, and the slopes remain approximately unchanged, while temperature changes from 140 to 160 °C cause the corresponding values to vary. The aging duration's increase for the first two hours exhibits lower effects on CEI compared to the aging duration's increase from 2 to 4 h, while this trend is opposite in the V_a , VMA, and VFA scenarios based on the steeper slope. This phenomenon might be attributed to the higher binder content of the mixtures produced using binder B80. Higher binder content can reduce temperature variation's impact by acting as a lubricant and filling the voids in the mixture, while aging duration causes more oxidation, volatilization, and age hardening of the binder, which results in a higher aging duration impact. Similarly to the mixtures produced using binder A80, aging temperature exhibits lower impacts on the DVs of mixtures produced using binder B80 compared to the aging duration. The maximum discrepancies of aging temperature's effects on CEI, V_a , VMA, and VFA are 22.5%, 3.5%, 1%, and 1%,

respectively, while the maximum discrepancies of aging duration's effects on the corresponding values are 23.5%, 21%, 4%, and 4%, respectively.

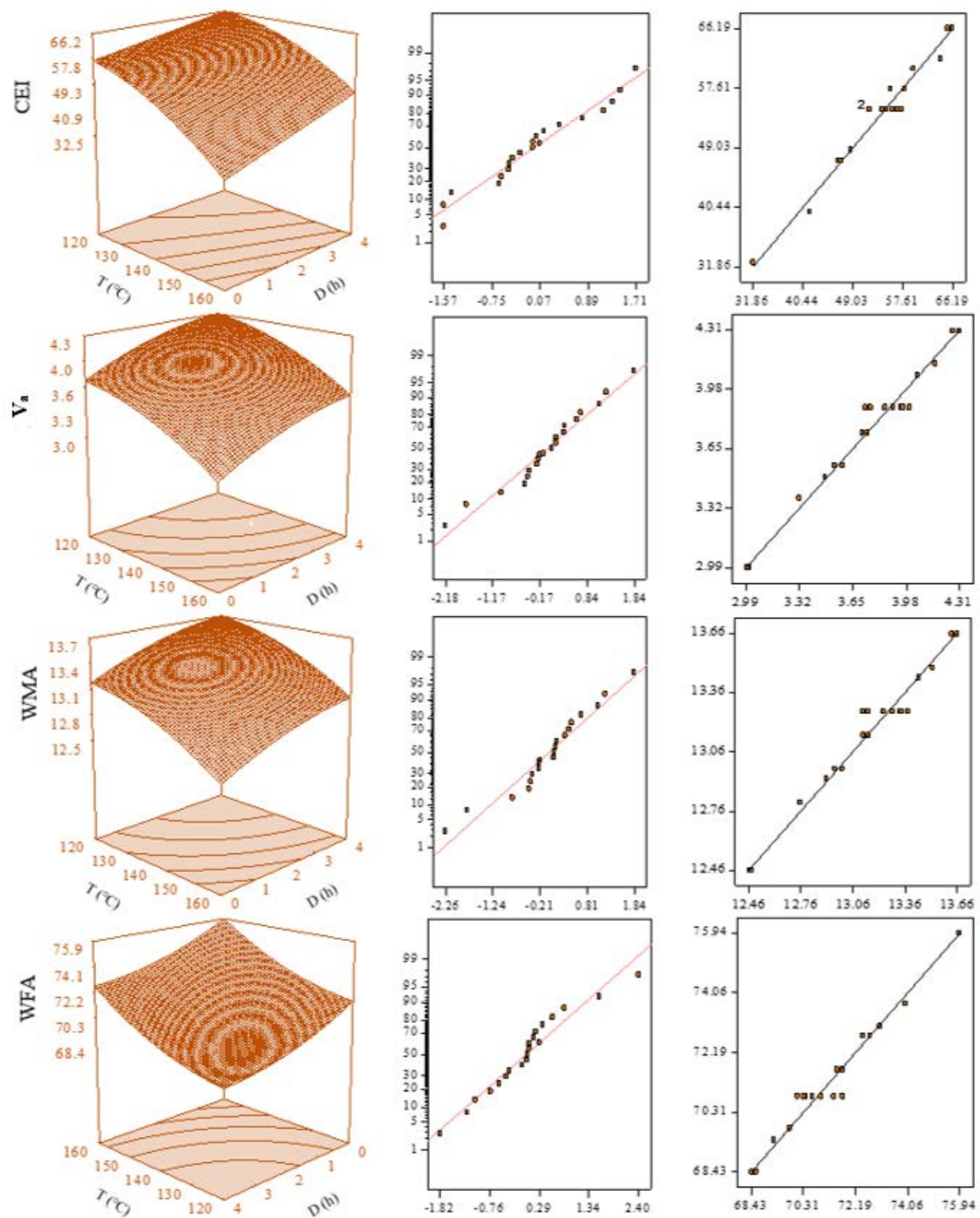


Figure 2. From left to right: (a) 3D contour plots, (b) normal plot of residuals, and (c) predicted vs. actual plot of responses for asphalt mixtures produced using binder A60.

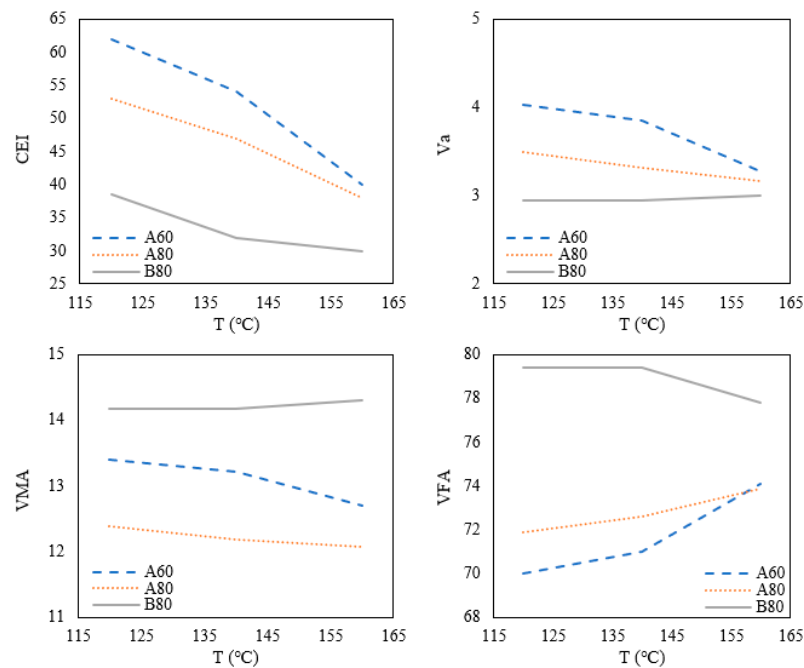


Figure 3. The main effects of aging temperature on responses.

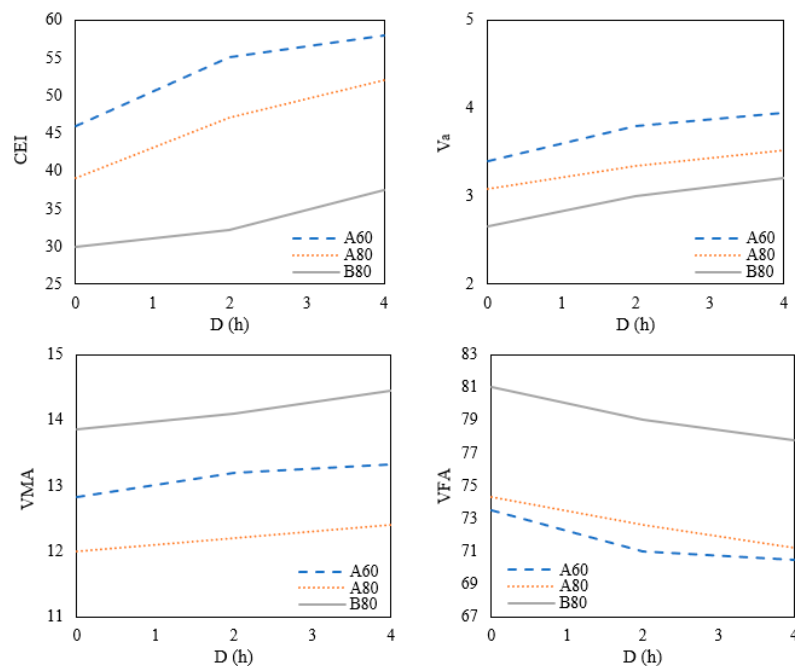


Figure 4. The main effects of aging duration on responses.

According to Douries (2004), binder types and binder content are among the factors that influence mixtures' compactability and volumetric properties [34]. The results show that mixtures containing a stiffer binder result in higher CEI and V_a . The VMA and VFA of these mixtures are also higher compared to those produced using binder A80. This indicates that stiffer binders are harder to be compacted due to their higher viscosity, which directly affects mixtures' volumetric properties. This finding is in agreement with the results outlined by [13,35]. According to the results, the maximum CEI, V_a , VMA, and VFA of mixtures produced using binder A80 are 57.2, 3.7%, 12.6%, and 75.2%, respectively, while the corresponding values of mixtures produced using binder B80 are 42.5, 3.3%, 14.5%, and 81.2%. These discrepancies can be correlated with the higher binder content of mixtures produced using binder

B80, where excess binder content can both ease the compaction and fill the voids. It can also be related to the variance in binder aging (evaporation rate of light oil fractions), since they were collected from different sources. The main effect plots show that the effects of aging temperature and aging duration on mixtures vary by binder type. The results also support that aging temperature exhibits a higher influence on the compactibility and volumetric properties of mixtures produced with the stiffer binder. Simultaneously, the aging duration exhibits a higher influence on the corresponding values of the mixture produced with softer binders. The higher aging temperature effects on the mixtures produced using a stiffer binder can be attributed to the higher viscosity of their binder, which can easily be affected by the variation of temperature. However, the higher effects of aging duration on the mixtures produced using softer binders can be attributed to the higher volatilization rate and temperature susceptibility of these binders compared to stiffer binders. The effects of different distillation processes on binder aging were outlined in previous studies [36].

4. Conclusions

This study quantified the effects of the aging temperature, aging duration, and duration in the humidity and ultraviolet chamber (referred to as IVs) on mixture compactibility and volumetric properties (referred to as DVs). The conclusions are as follows.

The overall results indicate that IVs (individually and together) significantly affect CEI, V_a , VMA, and VFA, while they exhibit no significant influence on G_{mm} , G_{mb} , G_{se} , P_{ba} , and P_{be} . The statistical analysis results reveal that extended aging duration in the humidity and ultraviolet chamber has no significant effect on mixtures' compactibility and volumetric properties. Furthermore, the results showed that increasing the aging temperature increases CEI, V_a , and VMA, while it decreases VFA. However, the aging duration exhibits opposite impacts on the corresponding values. Mixtures produced using stiffer binders exhibited higher energy requirements for compaction, which resulted in a higher CEI. The higher binder content acted as a lubricant and eased the compaction procedure, which might be favorable after temperature loss during compaction. The results showed that IVs' impacts on DVs were highly related to the mixture binder type. In this study, it was demonstrated that the RSM exhibits the great capability of quickly and precisely evaluating the compactibility and volumetric properties of mixtures at various conditions. The mathematical equations proposed by the RSM fit into the experimental observations with acceptable accuracy (R^2 up to 0.97). This indicates that these models are precise and practical in predicting the IVs' effects on the DVs. In order to achieve the best pavement volumetric properties, the proposed models can be employed by the construction sector as a beneficial and efficient approach to managing and planning the construction process, which can directly enhance pavement performance and durability. For instance, as stated by Hu et al. (2017), additional compaction may reduce air voids, which, in turn, increases density and reduces the raveling potential [35]. It is, therefore, recommended that by conducting preliminary studies, construction companies can evaluate the impact of unforeseen circumstances, such as delays in mixture delivery to the site or temperature drops during paving. Since the mixtures' conditioning in the humidity and ultraviolet chamber has no significant effect, it would be favorable to replace this parameter with the number of roller compactor passes, which can be simulated by varying the number of gyrations. The new design can determine the optimum passes to achieve the target density and air void percentage at different conditions.

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