# Volumetric and Rutting Analysis on Degradation of Aggregate and Asphalt Reclaimed Asphalt Pavement

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**ABSTRACT**

**The performance of a hot asphalt mixture as a road surface layer is subject to deterioration due to the effects of traffic loads and weather conditions. The process of asphalt aging is characterized by a decline in physical properties and alterations in aggregate composition. To maintain the integrity of the road surface, the surface layer is periodically removed and recycled. This study aims to simulate the process of aggregate and asphalt degradation as an asphalt aging process. The study proposes a model with five levels of asphalt physical property decline and four levels of Coarse Aggregate (CA), arranged into 20 variations. The analysis results indicate that a decrease in the percentage of CA reduces stability and increases air cavities, while an increase in asphalt penetration on specific CAs increases cavity volume and stability. The correlation test results demonstrate that the mixture with optimal CA strengthens resistance to deformation, especially at low-temperature conditions. However, at temperatures of 40 °C and 55 °C, the initial deformation rate increases sharply. The degraded mixture exhibits a decrease in deformation resistance at high temperatures. The findings of this study can be used to ascertain the optimization of the residual value of the performance of asphalt concrete mixtures for recycling processes involving reconditioning aggregate and asphalt.**

***Keywords-pavement degradation; asphalt; aggregate; volumetric; deformation rate***

## I. INTRODUCTION

The condition of the road surface layer is subject to changes in aggregate composition due to vehicle loads and a decrease in asphalt penetration values due to variations in temperature and other environmental factors during the period of road use. These changes affect the performance of the road surface layer, and recognizing aggregate and asphalt conditions is essential for determining the recycling process of the surface layer. The content of mineral fillers has a significant impact on pavement performance; therefore, an optimal composition is necessary. A deficiency of mineral fillers can lead to a decline in stability and durability, while an excess can result in increased stiffness. Achieving the optimal mixture of contents is vital for maximizing the service life of the pavement [1]. The deterioration of road pavement performance poses a significant challenge in the management of road pavements. Excessive vehicle load factors, such as rutting and diminished surface roughness, can precipitate road damage. A substantial decline in performance occurs when vehicle overload exceeds 30% of the design strength, which directly impacts the pavement's life span [2, 3]. The gradual change in groove deformation is attributed to the rate of change in rutting as a function of traffic load, which is higher in temperate and hot climate areas [4]. The impact of temperature on the asphalt mixture is significant due to the nature of the viscoelastic plastic material, which exhibits distinct changes in strength and modulus at different climatic conditions. Environmental and climate factors are also identified as contributors to diminished road performance. Increases in temperature, ranging from 23 °C to 50 °C, directly lead to an increase in vertical strain and stress on the pavement surface, which is directly correlated to the pavement layer's deflection value [5]. The reduction in the physical properties of aggregates and asphalt, such as aggregate size gradation and penetration, contributes to a decrease in bond strength between aggregates and asphalt. This phenomenon is also influenced by the physico-chemical characteristics of the material [6]. Pavement surface damage can additionally occur due to the degradation of quality pavement materials, which can directly cause deformation of the surface layer. Accumulated permanent strain is correlated with the shear strength properties of the aggregate [7]. Changes in pavement performance due to the environment, temperature, and climate have an effect of 27% on the changes in shear strength and rutting potential due to deformation in the pavement layer. This factor is considered when formulating a material performance reduction model [8]. Road maintenance is carried out to ensure that the condition of the pavement and the function of the road remain in good condition. Wheel groove damage on pavement structures is caused by traffic loads on the same track. Climate conditions and environmental conditions are additional factors that accelerate road damage. The form of damage is contingent upon the type of pavement structure and the quality of the materials used for various types of structural layers, along with the technique and quality of pavement construction [9]. The development of recycling technology is currently an alternative for environmentally friendly road maintenance and can reduce production costs. The usage of Reclaimed Asphalt Pavement (RAP) in the mixture is a strategy to enhance the physical characteristics of aggregates and asphalt, thereby optimizing mixture performance. The improvement of aggregate gradation and the physical properties of asphalt binders is essential to achieving the optimal mixture composition. The method of reusing RAP aggregates necessitates the knowledge of their dimensions when mixing them with new aggregates in their prescribed proportions. The RAP material gradation composition exhibits a suitability level of approximately 82.29% in the Asphalt Concrete Wearing Coarse (AC-WC) blending gradation, indicating a high potential for reuse in blending the same layer [10].

The suitability level of degraded aggregates is dependent upon the extent of road damage, with higher levels of damage resulting in lower suitability ratings for aggregate dimensions due to degradation. The RAP material can achieve maximum mixture characteristics through the identification of its physical properties and the combination of new aggregates to restore the composition of the aggregate dimensions. The degradation process is contingent upon the aggregate and asphalt contained within the RAP material. Numerous studies have demonstrated that a blend of 70% new asphalt and RAP material yields a suitable mixture bond composition [11]. The aggregate size significantly impacts the adhesion of asphalt surfaces to the aggregate. Several studies have shown that the effect of size and moisture on CA significantly affects the adhesion of asphalt aggregate [12, 13]. The proportion of CA and Fine Aggregate (FA) in the RAP material is an essential factor that affects volumetrics. The composition of aggregate size 2.2 mm exerts a substantial influence on the volume of air cavities [14, 15]. The availability of CA in the mixture has been demonstrated to have a significant impact on the density and performance of the mixture. The improvement in CA composition has been shown to directly enhance resistance to cracking [16, 17]. However, an increase in FA in the mixture, which is possible due to use, results in a reduction in pavement performance. The integration of FA has shown to induce adhesion failure within the mixture [18, 19]. The physical properties of asphalt also influence the performance of the mixture in general. The main form of asphalt aging is thermo-oxidative aging, which causes asphalt to become stiff and brittle [20, 21]. Furthermore, thermo-oxidative aging causes the asphalt surface to become rougher and continues to increase throughout the aging process, due to changes in sulfoxide groups [22]. The effect of temperature due to Ultraviolet (UV) rays on the aging process of asphalt is significant at temperatures above 50 °C [23]. It is noteworthy that increasing UV radiation has a detrimental effect on the characteristics of asphalt in the mixture, as evidenced by a decrease in phase angle, rutting, and complex modulus, which increases with the aging process due to UV temperature [18]. The increase in stiffness value and decrease in viscous modulus under aging conditions result in a reduction of the asphalt mixture's elasticity, thereby leading to the formation of ruts or surface cracks [24]. In such cases, the implementation of an overlay design process or the removal of the affected layer with new material is necessary in order to restore the surface layer's structural integrity [25]. The identification of the material's physical characteristics can serve as a guide for assessing the performance of hot asphalt mixtures in old pavements. It is necessary to identify the physical properties and attributes of aggregate and asphalt to maximize reuse as recycled material in the old pavement resulting from stripping. Conducting volumetric and rutting analysis of asphalt aging mixtures and aggregate dimension recovery can optimize the adequate stripping time in road maintenance with the material recycling process. The usage of the asphalt mixture recycling process necessitates an analysis of the material's condition for reuse. A road maintenance strategy that involves the removal of the surface layer as a faster-recycled material will yield a significant proportion of the material in good condition. Conversely, if the road repair process is conducted too late, the material is likely to have undergone substantial changes, leading to its degradation, hence reducing its utility. This study aims to analyze the performance of the aggregate asphalt mixture on the material condition before and after changes in aggregate composition due to loading and degradation of asphalt performance, combined with simulation of changes in rutting owing to wheel loading. By analyzing the characteristics of the degraded mixture, the condition of the aggregate and asphalt composition can be determined regarding its deformation resistance, so that the decision regarding the application of the road pavement recycling process can be made.

## II. MATERIALS AND METHODS

### *A. Asphalt*

This study was conducted using two different types of asphalt binders. First, the new asphalt pen 60/70 was sourced from Pertamina, while the hard asphalt was sourced from PT. Olah Bumi Mandiri. The second type of asphalt was extracted from a mixture of asphalt obtained by stripping the road surface layer with a Pen value of less than 5. In this study, variations in penetration values were formed by mixing the two types of asphalt in four different penetration compositions, depending on the composition of the two types of asphalt. The mixing process was performed using an automatic mixer at a speed of 2,500 rpm for a duration of 30 minutes at a temperature of 135 °C, incorporating a new asphalt content ranging from 0% to 35%. The outcomes of this mixing process revealed a decline in penetration and ductility values, as shown in Figure 1, accompanied by an increase in the softening point and flash point of the asphalt.

(a)

(b)

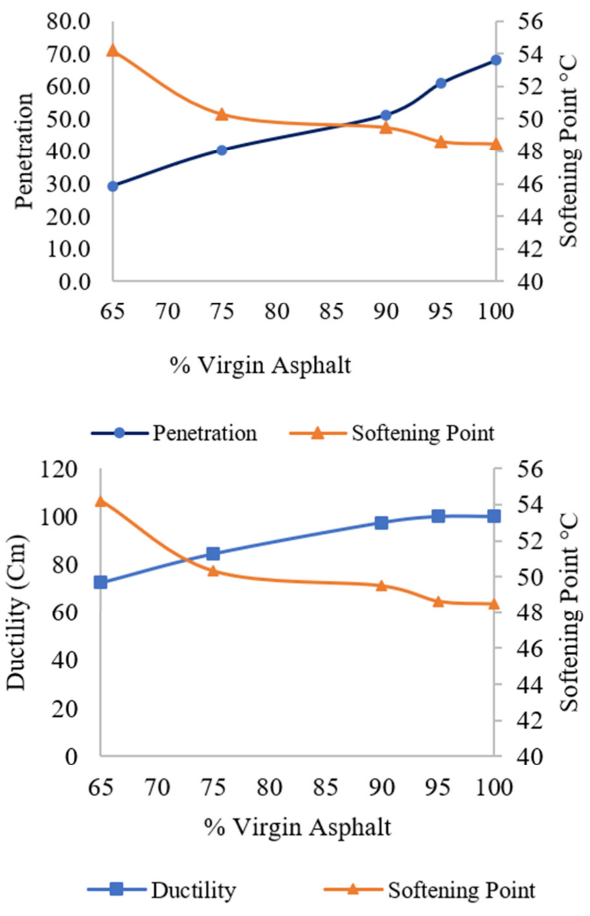


Fig. 1. Modified asphalt characteristic: (a) penetration, (b) ductility.

Physical tests were conducted to ascertain the characteristics of the binder, as presented in Table I, from the five variations of binders. The new asphalt binder, Pen 60/70, was used as a control value (Pen 70), while four variations (Pen 60, Pen 50, Pen 40, and Pen 30) were ustilized as asphalt variations in this study. The decrease in asphalt penetration value indicates the change in the asphalt aggregate mixture at the onset of construction until the performance of the mixture diminishes due to traffic loads and the environment as RAP material. The decrease in the physical properties of asphalt is achieved by reducing the penetration properties of asphalt at intervals of ±10 mm and Pen 61, obtained by adding 5% hard asphalt, and Pen 50 with the addition of 10% hard asphalt. Penetration values of 40 and 30 were determined using 25% and 35% hard asphalt, respectively. The process of adding hard asphalt reveals the alterations in penetration values and other parameters.

TABLE I. PHYSICAL PROPERTIES OF ASPHALT MODIFICATION

| Properties | Test Method (ASTM) | Aging Asphalt | Pen 70 (VA) | Pen 60 | Pen 50 | Pen 40 | Pen 30 |
|---|---|---|---|---|---|---|---|
| Penetration at 25 °C, 100 g (0.1 mm) | D5 | 4.00 | 68.00 | 61.00 | 51.30 | 40.40 | 29.30 |
| Softening Point (°C) | D36 | 94.78 | 48.30 | 48.64 | 49.50 | 50.32 | 54.20 |
| Flash Point (°C) | D92 | 324 | 275 | 290 | 312 | 320 | 335 |
| Ductility (cm) | D113 | 5.20 | >100 | >100 | 97.50 | 84.50 | 72.50 |
| Specific Gravity | D70 | 1.109 | 1.085 | 1.087 | 1.092 | 1.094 | 1.106 |
| Loss on Heating (%) | D1754 | - | 0.104 | 0.155 | 0.211 | 0.245 | 0.299 |
| Solubility in Trichloroethylene | D86 | 94.60 | 99.35 | 99.30 | 99.27 | 99.07 | 99.01 |

### *B. Aggregate*

The aggregates examined in this study encompass three distinct fractions: coarse, medium, and FAs. These aggregates were obtained from the Karawang area of West Java, and the results of the aggregate characteristic test are presented in Table II. The mixture gradation employed in this study is based on the standard composition of the AC-WC gradation stipulated in the Bina Marga—Indonesia technical specifications. The CA size ranges from 12.5 mm to sieve no. 4 (4.75 mm), while medium and FAs use sizes that pass sieve no. 4 to retained sieve no. 200. The study produced four variations of CA gradation: 39% CA-39, CA-35, CA-32, and CA-27. These gradations signify the variation in aggregate percentage within the asphalt aggregate mixture under the influence of traffic loading on the road pavement structure. The composition of CA-39 aligns with the midpoint of the AC-WC specification curve, serving as a control for the other aggregate variations. The shift in aggregate composition within the RAP asphalt mixture post-extraction highlights the impact of loading on the asphalt aggregate mixture as a surface layer.

TABLE II. AGGREGATE CHARACTERISTIC

| Properties | Unit | CA | Medium Aggregate (MA) | FA |
|---|---|---|---|---|
| Bulk Specific Gravity | $gr/cm^3$ | 2.63 | 2.57 | 2.62 |
| SSD | $gr/cm^3$ | 2.68 | 2.64 | 2.67 |
| Apparent Specific Gravity | $gr/cm^3$ | 2.76 | 2.75 | 2.75 |
| Absorption | % | 1.70 | 1.57 | 1.76 |

The CA variations are categorized based on an increasing Medium Aggregate (MA) content and decreasing CA content, separated by intervals that are away from the median limit. This gradation arrangement, portrayed in Figure 2, is indicative of changes in pavement characteristics due to traffic loading and use. Additionally, this condition can lead to a change in the mixture's behavior due to an increase in the medium fraction and the percentage of aggregate content is provided in Table III.

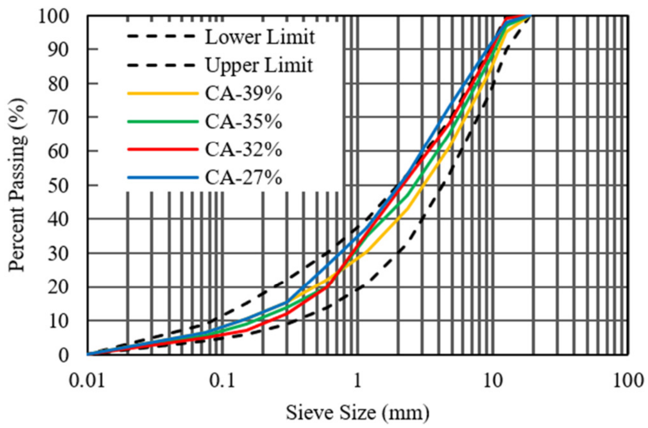


Fig. 2. Sieve analysis of aggregate.

TABLE III. COMPOSITION OF AGGREGATE

| Aggregate | CA-39 | CA-35 | CA-32 | CA-27 |
|---|---|---|---|---|
| Coarse (%) | 39 | 35 | 32 | 27 |
| Medium (%) | 45.5 | 50.5 | 53.5 | 57.5 |
| Fine (%) | 15.5 | 14.5 | 14.5 | 15.5 |

### C. *Mixture Preparation*

The Marshall testing stages in this study were divided into two phases. The first phase was the determination of the Optimum Asphalt Content (OAC) value and the second was the identification of changes in Hot Mix Asphalt (HMA) performance due to changes in the composition of the mixture. The determination of OAC was conducted using asphalt contents of 5%, 5.5%, 6%, 6.5%, and 7% at pen 60/70, with the blending of CA-39 on middle limit gradation aggregates. The OAC value was obtained at 6.8% from the test. The mixture combination was structured into four gradation variations with five asphalt penetration variations, resulting in 20 mixture compositions. Each combination included five test samples, yielding a total of 100 test samples, as presented in Table IV.

TABLE IV. COMBINATION OF ASPHALT AND AGGREGATE

| Variation-1 | Variation-2 | Variation-3 | Variation-4 |
|---|---|---|---|
| CA-39 / Pen 70 | CA-35 / Pen 70 | CA-32/Pen 70 | CA-27 /Pen 70 |
| CA-39 / Pen 60 | CA-35 / Pen 60 | CA-32/ Pen 60 | CA-27/ Pen 60 |
| CA-39 / Pen 50 | CA-35 / Pen 50 | CA-32/ Pen 50 | CA-27/ Pen 50 |
| CA-39 / Pen 40 | CA-35 / Pen 40 | CA-32/ Pen 40 | CA-27/ Pen 40 |
| CA-39 / Pen 30 | CA-35 / Pen 30 | CA-32/ Pen 30 | CA-27/ Pen 30 |

### D. *Marshall Test*

The preparation of specimens and subsequent evaluation is conducted in accordance with the AASHTO T 245-97 standard. Prior to the mixing process, the aggregate is heated at 160 °C, while the asphalt is heated at 150 °C and both are amalgamated at a temperature of 150 °C. Preceding the incorporation of the asphalt aggregate mixture into the mold, the spatula is heated and waterproof paper is placed on the bottom of the mold. The asphalt aggregate mixture is subsequently placed into a Marshall mold with a diameter of 101.6 mm and a height of 63.5 mm. The compaction process involves applying a load of 75 times on both the top and bottom sides by turning the mold over. The compaction process uses a load of 4.535 kg and a free fall of 457.2 mm. The molded sample is then stored at ambient temperature for a 24-hour period prior to its removal from the mold. The manufacture of Marshall samples adheres to the standards outlined in RSNI M-01-2003. Subsequent to the 24-hour period of ambient temperature storage, the sample is immersed in a water bath maintained at 60 °C for a duration of 30 minutes. Testing was carried out with the Marshall tool, as depicted in Figure 3, in order to determine the volumetric, flow, and stability values of the mixture in each variation.

Fig. 3. Marshall test.

### E. *Wheel Tracking Test*

Track loading testing is a method used to evaluate the resistance to deformation due to repeated loading at a specified temperature, according to AASTHO T324 and EN 12697-22 Hamburg Wheel Tracking (HWT). The procedure includes the preparation of a cylindrical sample, followed by testing with a moving wheel that exerts a fixed load of approximately 705 N on the sample. The test is conducted for 10,000 cycles or until significant deformation is observed. The deformation of the sample is measured by periodically analyzing the traces created by each wheel cycle, as shown in Figure 4.

### F. *Statistical Analysis*

An analysis was carried out on the Marshall parameters of the volumetric characteristics, with a focus on the impact of alterations in asphalt properties and aggregate gradation on the performance of the mixture, which was based on simulations that were thoroughly compiled. The study employed linear regression to ascertain the effect of diminishing asphalt properties and fluctuations in aggregate percentages on the performance of the mixture, subjected to a 95% confidence level. The value of the *F*-test results (sig-*F* <0.05) was used to ascertain the effect of all independent variables on the dependent variable, while the value of the *T*-test results (*P*-value <0.05) was used to test the impact of each independent variable partially on the dependent variable. The coefficient of determination ($R^2$) measures the model's ability to explain the dependent variables:

$$Y_i = \beta_0 + \beta_1 X_{i_1} + \beta_2 X_{i_2} + \cdots + \beta_{p-1} X_{i_{p-1}} + \varepsilon_i \quad (1)$$

where $Y$ is the dependent variable, $X$ is the independent variable, $\beta_0$ is the intercept/intersection with the vertical axis, $\beta_1$, $\beta_2$, ...., $\beta_{p-1}$ are the regression model parameters, and $\varepsilon_i$ are the residuals, independently and normally distributed. The *r*-value is a measure of the correlation between interrelated variables. It indicates the influence of changes in the physical properties of asphalt and the aggregate fraction content in the mixture on the latter's performance:

$$r = \frac{n\Sigma xy - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\Sigma y^2 - (\Sigma y)^2]}} \quad (2)$$

The partial or simultaneous correlation of the two variables enables the calculation of the effect of reduced penetration of the asphalt's physical properties and changes in aggregate gradation.

Fig. 4. Hamburg wheel tracking test.

## III. RESULTS AND DISCUSSION

### A. Volumetric Characteristics of CA Degradation and Penetration Value

This study examined the impact of reducing the asphalt penetration value on various CA compositions (CA-39, CA-35, CA-32, and CA-27). The asphalt correlation value to volumetric parameters, Void in Mineral Aggregate (VMA), Void Filled Asphalt (VFA), and Void in Mix (VIM), exhibited a value greater than 0.95, as illustrated in Table V. Notably, VIM and VMA exhibited negative values in relation to the decrease in asphalt penetration value, indicating their impact on the reduction in value while exerting an opposite effect on the VFA value. As displayed in Table VI, the results of the Analysis of Variance (ANOVA) test for the variable volumetric Marshall test with the asphalt penetration value demonstrate that the *P*-value is less than 0.05. This finding indicates that the asphalt penetration value has a significant impact on the volumetric value.

TABLE V. THE CORRELATION OF VOLUMETRIC AND ASPHALT LEVEL

| Asphalt | Pen-70 | Pen-60 | Pen-50 | Pen-40 | Pen-30 |
|---|---|---|---|---|---|
| VMA | -0.993 | -0.993 | -0.986 | -0.983 | -0.981 |
| VFA | 0.995 | 0.995 | 0.996 | 0.986 | 0.987 |
| VIM | -0.993 | -0.992 | -0.992 | -0.982 | -0.981 |

TABLE VI. F AND P VALUES OF ASPHALT

| Volumetric Characteristics | | Pen-70 | Pen-60 | Pen-50 | Pen-40 | Pen-30 |
|---|---|---|---|---|---|---|
| VMA | *F*-value | 134.00 | 124.74 | 71.10 | 56.12 | 50.29 |
| | *F*-crit | 3.478 | 3.478 | 3.478 | 3.478 | 3.478 |
| | *P*-value | 0.007 | 0.008 | 0.014 | 0.005 | 0.005 |
| VFA | *F*-value | 203.89 | 218.79 | 230.46 | 69.27 | 74.92 |
| | *F*-crit | 3.478 | 3.478 | 3.478 | 3.478 | 3.478 |
| | *P*-value | 0.005 | 0.004 | 0.004 | 0.014 | 0.013 |
| VIM | *F*-value | 133.39 | 124.73 | 132.35 | 55.60 | 50.35 |
| | *F*-crit | 3.478 | 3.478 | 3.478 | 3.478 | 3.478 |
| | *P*-value | 0.007 | 0.008 | 0.007 | 0.017 | 0.019 |

The findings of the correlation test of volumetric values on each aggregate composition demonstrate that CA, MA, and FA exhibit a comparable degree of correlation, as presented in Table VII. This study focuses on the impact of CA on HMA as a road pavement structure material. Table VIII presents the effect of variations in CA content on HMA employing a statistical approach. The VMA correlation values for CA-39 and CA-35 are positive, indicating an increase in VMA values, while for CA-32 and CA-27, the values are negative.

TABLE VII. CORRELATION VALUE OF AGGREGATE

| Aggregate | VMA | VFA | VIM |
|---|---|---|---|
| CA | -0.5830 | 0.5245 | -0.5483 |
| MA | 0.5663 | -0.5019 | 0.5287 |
| FA | -0.5296 | 0.4545 | -0.4869 |

TABLE VIII. THE CORRELATION OF VOLUMETRIC AND AGGREGATE LEVEL

| Aggregate | CA-39 | CA-35 | CA-32 | CA-27 |
|---|---|---|---|---|
| VMA | 0.860 | 0.836 | -0.832 | -0.837 |
| VFA | -0.781 | -0.708 | 0.888 | 0.837 |
| VIM | 0.797 | 0.757 | -0.873 | -0.930 |

The *F*-value for all volumetric values exceeds the *F*-crit. This finding indicates that both variables can be considered statistically significant. Additionally, the *P*-value of all volumetric variables is less than 0.05, as portarayed in Table IX. Figure 5 shows the impact of alterations in asphalt penetration value and aggregate composition on the volumetric value of the Marshall test results. The VFA value, derived from the interplay between the asphalt penetration value and CA composition, exhibits a substantial variation in its response to changes. The identification of shifts in CA gradation has been demonstrated to influence the volumetric performance of the mixture. However, previous studies have not examined the simultaneous effect of a decline in asphalt penetration on various forms of aggregate degradation [18]. The decrease in CA composition has increased the VFA value. In this study, CA-39 has an aggregate composition at the midpoint of the ACWC gradation limit specification as a reference for other aggregate compositions (CA-35, CA-32, and CA-27). The decrease in the percentage of CA in all combinations of asphalt and aggregate demonstrates an increase in the VIM value.

TABLE IX. RESULTS OF F AND P VALUES ON AGGREGATE LEVEL

| Volumetric Characteristics | | CA-39 | CA-35 | CA-32 | CA-27 |
|---|---|---|---|---|---|
| VMA | *F*-value | 90.112 | 903.095 | 13.951 | 7.008 |
| | *F*-crit | 3.478 | 3.478 | 3.478 | 3.478 |
| | *P*-value | 0.002 | 0.001 | 0.033 | 0.077 |
| VFA | *F*-value | 90.112 | 903.095 | 13.951 | 6.893 |
| | *F*-crit | 3.478 | 3.478 | 3.478 | 3.478 |
| | *P*-value | 0.002 | 0.001 | 0.033 | 0.079 |
| VIM | *F*-value | 38.286 | 193.192 | 25.193 | 19.069 |
| | *F*-crit | 3.478 | 3.478 | 3.478 | 3.478 |
| | *P*-value | 0.008 | 0.002 | 0.015 | 0.022 |

However, the increase in VIM value in CA-39 and CA-35 decreased the VIM value due to a decrease in asphalt penetration value. A decrease in CA percentage greater than 4% (CA-32 and CA-27) showed a change in the form of an increase. The decrease in penetration value in CA-32 and CA-27 affected the increase in VIM value. The pattern of increase in VIM value was similar to the change in VMA value due to the decrease in CA content or decrease in asphalt penetration value in HMA. The pattern of change in VFA was different from that of VIM and VMA. The VFA value decreased as the CA content decreased. However, for CA-39 and CA-35, the decrease in asphalt penetration affected the increase in VFA, as shown in Figure 5.

## *B. Effect of Combination of Asphalt and Aggregate Degradation on Marshall Performance*

The relationship between asphalt and aggregate material degradation and the volumetric value of the mixture, including VMA, VFA, and VIM is examined and the results demonstrate that each variation of asphalt penetration and CA responds differently to Marshall's performance. The positive correlation of CA-39 and CA-35 on VMA value indicates that increasing the asphalt penetration results in a larger cavity volume in the mixture. Conversely, an increase in CA has been observed to decrease VMA. This finding indicates that CA exhibits superior efficacy in filling the space between particles. The relationship between the changes in VMA values and the combination of asphalt penetration and CA percentage is significant, while the lowest VMA values are attained under conditions where asphalt penetration and CA percentage fall within the middle of the upper and lower limits of aggregate specifications. Conversely, higher VMA is observed at the extremes of low asphalt penetration and high CA. The findings of this study indicate a positive correlation between the decreasing asphalt penetration and increasing CA percentage, which is indicative of an increase in VMA, as evidenced in Figure 6. The correlation between the VFA values and CA-32 shows a strong positive relation, indicating that an increase in CA-32 corresponds to a greater number of cavities filled with asphalt. Conversely, CA-39 and CA-35 exhibit a negative correlation, suggesting that an increase in asphalt penetration leads to a decrease in VFA, as seen in Figure 7, indicating that fewer cavities are filled with asphalt. The VFA correlation data demonstrate that an increase in CA results in a decrease in VFA, as larger cavities are not completely filled with asphalt.

(a) (b) (c)

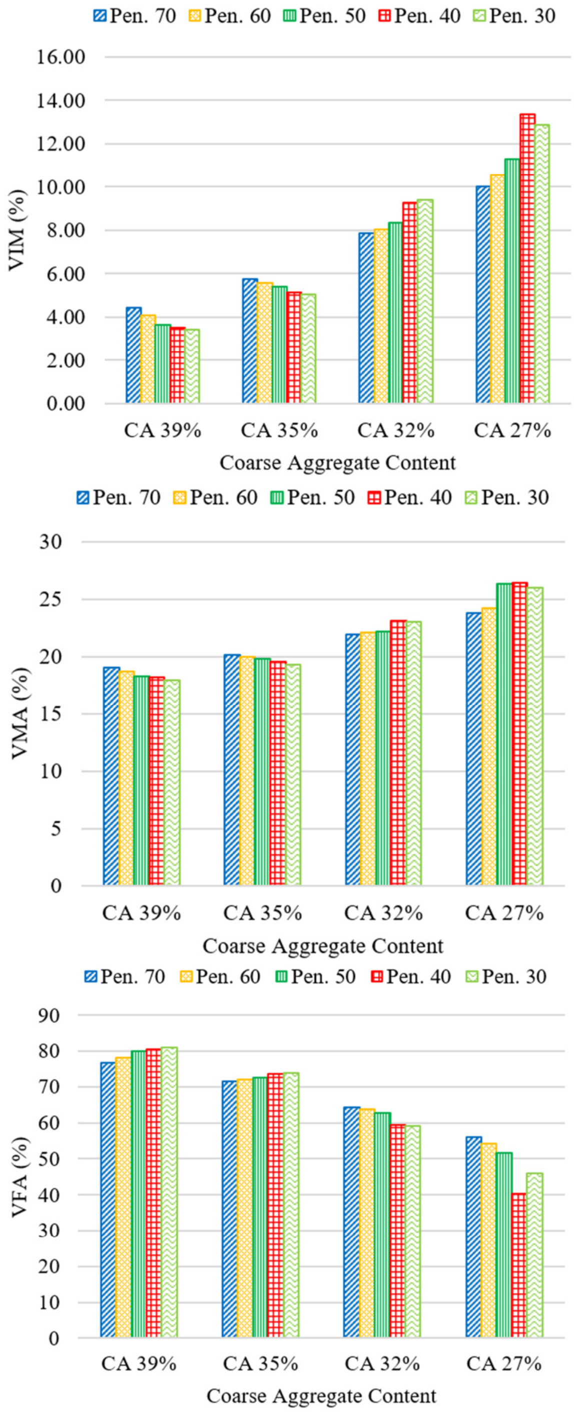


Fig. 5. Volumetric characteristics of asphalt mixtures: (a) VIM, (b), VMA, (c) VFA.

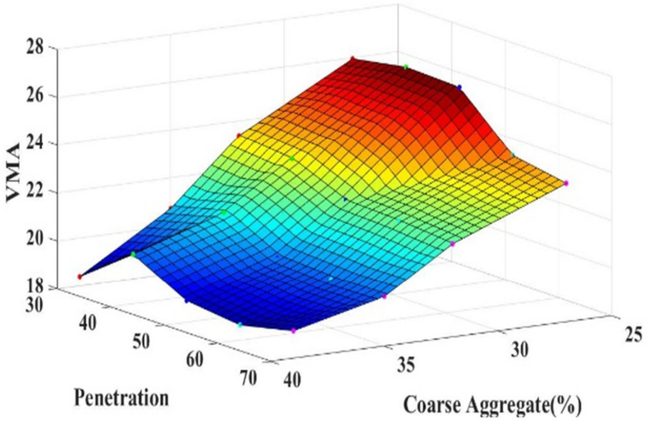


Fig. 6. 3D VMA relationship due to penetration change at each % CA.

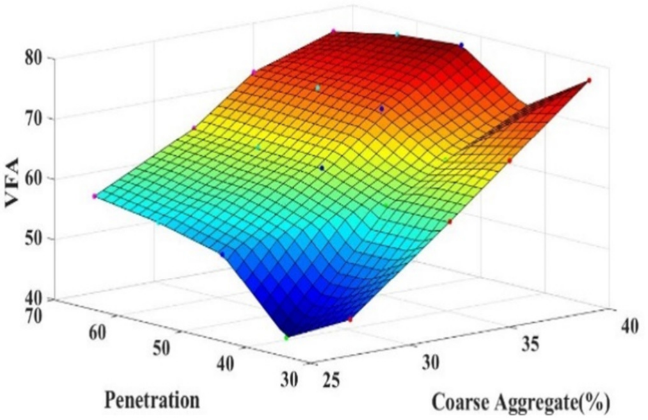


Fig. 7. 3D VFA relationship due to penetration change at each % CA.

The present study explores the relationship between asphalt penetration and VIM in CA-39 and CA-35, finding a positive correlation between the two variables. This suggests that higher asphalt penetration increases VIM, resulting in a greater number of air cavities in the mixture. Conversely, CA-32 and CA-27 exhibit a strong negative correlation. This indicates that an increase in asphalt penetration leads to a decrease in VIM, suggesting that the number of air cavities in the mixture decreases. Consequently, the mixture becomes denser, with an increase in the asphalt penetration value, as presented in Figure 8. This multivariate regression analysis was conducted for the purpose of constructing a behavioral model for the experimental result groups using (1), as presented in Table X.

### *C. Effect of Temperature on Rutting Characteristics*

Deformation testing was conducted on samples CA-39, CA-35, and CA-32. This variation was selected due to its strong consistency value against the form of degradation of the pavement mixture material due to use. The results of the HWT test utilizing temperature variations of 25 °C, 40 °C, and 55 °C have resulted in changes in rut depth, as shown in Figures 9 and 10, which reveal the equation form of the curve with the power function form [26], as:

$$D_i = a.(N_i)^b \qquad (3)$$

where *Di* is the value of wheel groove deformation due to the track, while coefficients *a* and *b* are the characteristic parameters of HMA that can be identified through track testing (HWT).

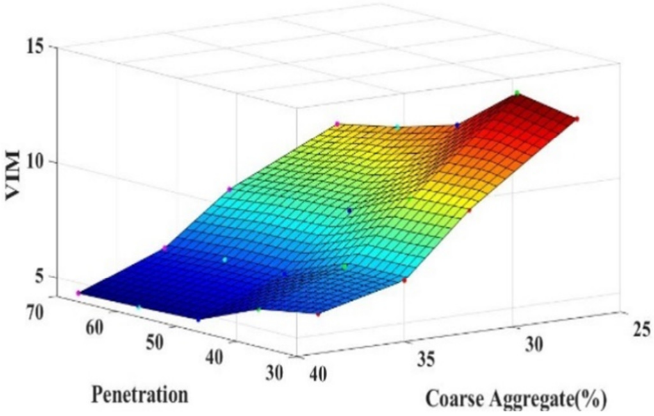


Fig. 8. 3D VIM relationship due to penetration change at each % CA.

TABLE X. CONSTANT OF ASPHALT AND CA VARIABLE EQUATION

| Volumetric (*Y*) | $\beta_0$ | $\beta_1$ | $\beta_2$ | $R^2$ |
|---|---|---|---|---|
| VMA | 39.8886 | 0.0056 | -0.5647 | 0.8772 |
| VFA | -14.6415 | -0.0107 | 2.4476 | 0.9057 |
| VIM | 29.4329 | 0.0003 | -0.6656 | 0.8769 |

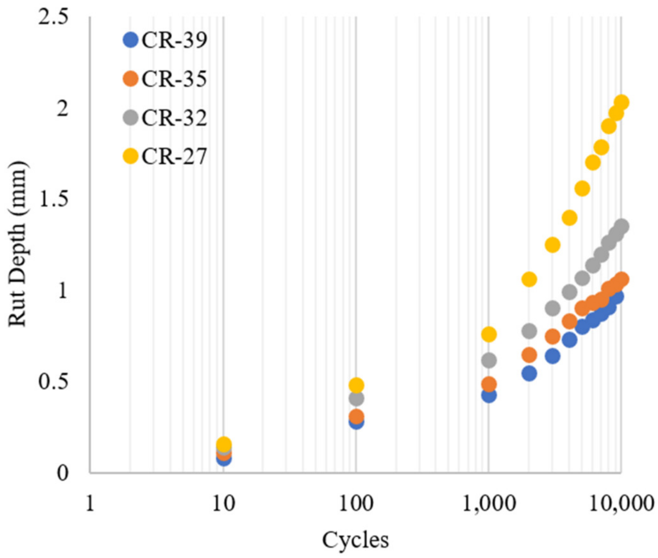


Fig. 9. Deformation on different CA at 25 °C.

As depicted in Table XI, changes in parameters a and b can be identified at 25°C for four HMA degradation conditions. The results of track tests at temperatures of 40 °C and 55 °C are presented in Tables XII and XIII, respectively. The partial CA reduction affects the deformation depth; however, the effect of temperature changes on the resulting deformation depth has not been fully resolved [19]. A decline in CA content within HMA results in an augmentation of the rut depth value, progressing from the initial track to the 10,000th track. The alterations in the constant, as illustrated in Tables XI-XIII, signify an escalation in deformation depth. Furthermore, an increase in temperature from 25 °C to 40 °C results in an augmentation of the constant value a by 43% for CA-39, 78% for CA-35, 68% for CA-32, and 250% for CA-29. These data suggest that a decrease in CA content renders HMA more susceptible to elevated temperatures. Specifically, at 25 °C, CA-39 exhibited a constant value of 0.0431, which increased to 0.0616 at 40 °C, reaching 0.4916 at 55 °C, as shown in Figure 11. CA-29, at a temperature of 25 °C, as HMA with the lowest CA content, displays a constant value of 0.0761. These data indicate that a decrease in CA content at the same temperature increases deformation changes by 77%.

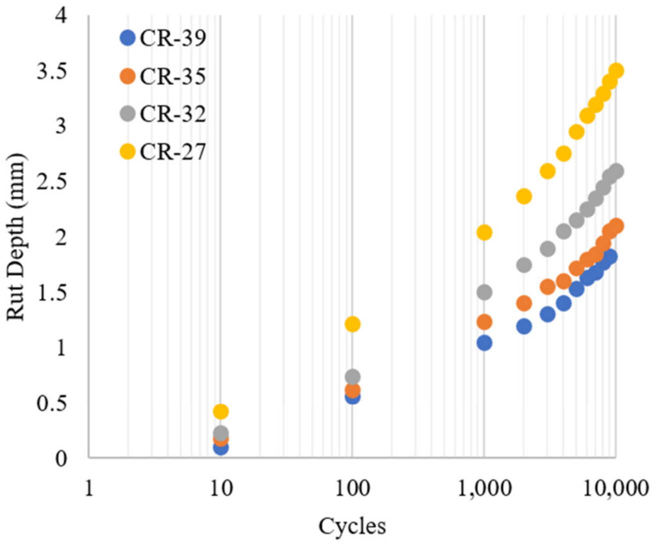


Fig. 10. Deformation on different CA at 40 $^0$C.

TABLE XI. DEFORMATION CONSTANT VALUE AT TEMPERATURE 25 °C

| 25 °C | *a* | *b* | $r^2$ |
|---|---|---|---|
| CA-27 | 0.0761 | 0.3542 | 0.991 |
| CA-32 | 0.0779 | 0.3086 | 0.993 |
| CA-35 | 0.0596 | 0.3153 | 0.994 |
| CA-39 | 0.0431 | 0.3411 | 0.991 |

TABLE XII. DEFORMATION CONSTANT VALUE AT TEMPERATURE 40 °C

| 40 °C | *a* | *b* | $r^2$ |
|---|---|---|---|
| CA-27 | 0.2660 | 0.2836 | 0.991 |
| CA-32 | 0.1311 | 0.3310 | 0.985 |
| CA-35 | 0.1062 | 0.3298 | 0.979 |
| CA-39 | 0.0616 | 0.3803 | 0.974 |

TABLE XIII. DEFORMATION CONSTANT VALUE AT TEMPERATURE 55 °C

| 55 °C | *a* | *b* | $r^2$ |
|---|---|---|---|
| CA-27 | 0.9375 | 0.2547 | 0.985 |
| CA-32 | 0.5903 | 0.2837 | 0.99 |
| CA-35 | 0.6077 | 0.2519 | 0.995 |
| CA-39 | 0.4916 | 0.2537 | 0.996 |

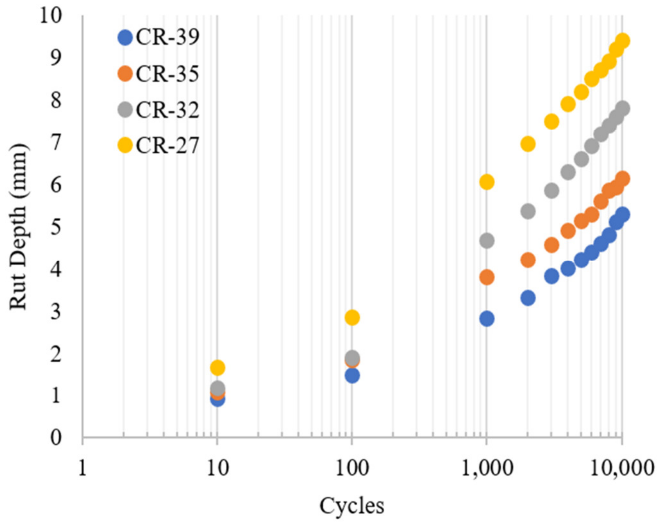


Fig. 11. Deformation on different CA at 55 $^0$C.

## IV. CONCLUSIONS

This study provides an analysis of how material properties, specifically asphalt penetration and Coarse Aggregate (CA) degradation, affect the performance and durability of Hot Mix Asphalt (HMA). The analysis results show that asphalt penetration and aggregate degradation significantly affect the bulk density, stability, flow, and deformation rate. Balancing these parameters is essential for the long-term optimization of asphalt mixes.

- - The decrease in CA in HMA exhibits a consistent decrease in the volumetric performance of the mix ($P < 0.05$ and $r > 0.70$).
- - A significant P value in CA indicates a substantial impact on the volume of asphalt voids and fills. Multivariate regression analysis shows that the percentage of CA is more important in influencing the volumetric value compared to asphalt penetration.
- - Higher temperatures accelerate the deformation rate for all asphalt mix variations. At 40 °C and 55 °C, CA degradation causes a significant increase in deformation of 77% at 25°C, and over 70% at 40 °C and 55 °C.

The novelty of the current work lies in the detailed quantification of these effects through multivariate regression analysis, which explores the relative dominance of the CA properties over asphalt penetration in influencing key volumetric parameters. In addition, the synergistic effects of material degradation and high temperature on the deformation rates are highlighted, providing practical insights for optimizing HMA mixes under different environmental conditions. This study offers valuable knowledge regarding the combined effects of material and environmental factors on HMA performance, providing practical information to improve pavement longevity and refine maintenance strategies.

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