International Journal of GEOMATE, Dec., 2025 Vol.29, Issue 136, pp.11-19
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2025.136.4747
Geotechnique, Construction Materials and Environment

INFLUENCE OF COARSE AGGREGATE CONTENT IN RECYCLED ASPHALT MIXTURES ON RUTTING AND RESILIENT MODULUS

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*Corresponding Author, Received: 28 Aug. 2024, Revised: 06 Nov. 2025, Accepted: 09 Nov. 2025

ABSTRACT: The use of recycled asphalt (RAP) as a road maintenance material has been widely applied. The use of RAP is expected to reduce maintenance costs and have a positive impact on the environment. This study assesses the performance of recycled asphalt mixtures that undergo changes in gradation within the coarse aggregate (CA) fraction and the asphalt aging process, resulting from traffic loads and weather fluctuations. Four mixture variations were designed using different coarse aggregate (CA) contents of 39%, 35%, 27%, and 23%, representing progressive material degradation levels corresponding to field aging conditions. Each mixture was tested for rutting and resilient modulus under controlled temperature and loading cycle to evaluate performance degradation. Tests included Marshall tests, resilient modulus (MR), and wheel tracking tests. Results indicate that susceptibility increases with higher temperatures and lower CA, while the resilient modulus decreases linearly ($r = 0.995$, $R^2 = 0.88$). A 16-22% increase in rut depth and a 35-42% reduction in MR were observed when CA decreased from 39% to 23% at 50 °C. Rutting behavior and deformation rates, influenced by temperature and decreasing CA content, were found to be strongly correlated in each mixture variation. These conditions provide information on the tendency of recycled mixtures to undergo degradation and asphalt aging processes, serving as a guide for determining the optimal time to carry out the recycling process. Economic calculations optimize the use of new materials in road maintenance through recycling.

Keywords: Degradation Aggregate, Rutting, Pavement Performance, Temperature

1. INTRODUCTION

Reclaimed Asphalt Pavement (RAP) technology requires the addition of new asphalt due to aging, as well as new aggregate. Both are intended to restore the performance of the asphalt-aggregate mixture to that of asphalt concrete. This technology is economically beneficial and environmentally sustainable. The characteristics of the RAP mixture are strongly influenced by the quality of the materials used in the previous asphalt concrete mixture. Therefore, identification of the aggregate and asphalt contained within it is necessary. Mixing old and new asphalt produces RAP asphalt with characteristics that differ from both the old and new asphalt. The inclusion of 40% RAP in the mixture consistently yields optimal performance, despite a decrease in viscosity [1]. Due to loading and the influence of road surface temperature, asphalt ages, resulting in increased stiffness and decreased strain, which makes it susceptible to cracking due to temperature fluctuations and traffic loads. Aggregate degradation due to traffic loads and weather changes the internal structure of the asphalt concrete mixture. Changes in aggregate size can occur due to traffic loads, directly affecting the stability of the road pavement. Changes in coarse aggregate size cause the mixture to degrade into gap gradations, impacting the resulting volumetric value due to changes in aggregate shape [2,3]. Changes in the shape and size of aggregate grains cause a decrease in the coarse aggregate content. Coarse aggregate significantly influences the mixture's characteristics; a higher aggregate content can increase resistance to cracking by inhibiting crack development [4]. Similarly, aggregate shape has a significant influence on asphalt mixture performance. For example, angular aggregate shape can improve the mechanical performance of asphalt mixtures due to the interlocking of aggregate particles [5,6]. Volumetric analysis of asphalt concrete can indicate its performance based on its optimum asphalt content. Aggregate gradation significantly affects the mixture's volumetric parameters and its mechanical rutting parameters [7]. Asphalt concrete degradation occurs gradually, resulting from a decrease in the physical properties of the aggregate and asphalt in the mixture due to loads and environmental conditions on the road. A decrease in CA, as a form of aggregate degradation in HMA, consistently reduces mixture performance [8]. Changes in aggregate gradation affect the performance and mechanism of water susceptibility, with finer gradations tending to cause adhesion failure. Conversely, the fine aggregate content more significantly influences the compressive strength of asphalt [9,10]. The physical properties of asphalt also impact the overall performance of asphalt concrete. The asphalt aging process includes thermo-oxidative aging. This process of increasing asphalt stiffness through decreased penetration and increased softening point demonstrates the impact of thermo-oxidation on rheological properties [11,12], and the rheology of asphalt changes due to the effect on the properties of asphalt concrete mixtures. Oxidative aging increases the roughness of the surface of asphalt, primarily due to the presence of sulfoxide groups and premature aging effects resulting from high temperatures [13]. The impact of temperature on aging becomes significant at 70°C, while at temperatures below 50°C, the effect is negligible [14]. Notably, increased ultraviolet (UV) radiation alters the properties of asphalt in the mixture. The decrease in phase angle, rutting, and complex modulus increases with the aging process. UV radiation significantly accelerates asphalt aging by increasing stiffness and elasticity through changes in rheological parameters [15]. Laboratory analysis reveals that increasing the temperature significantly alters the Resilient Modulus (MR) value of asphalt concrete. Increasing the temperature from 40 °C to 50 °C affects the resilient modulus value, resulting in a consistent decrease in the performance of Hot-Mix Asphalt (HMA) mixtures [16,17]. Evaluation of the performance of road surfaces with asphalt concrete surface layers involves assessing both aggregate and asphalt conditions during service. The development of a Highway Design and Maintenance (HDM) model to predict performance degradation deterministically by analyzing the relationships between pavement aging, structural strength, traffic load conditions, and environmental factors, including traffic load, strength, age, and rutting, has been effectively used [18]. The purpose of this study was to develop a method for investigating the characteristics of asphalt concrete that degrade during service, thereby obtaining optimal road maintenance costs. Physical conditions were identified through Marshall test performance, rut deformation due to wheel tracking tests, and the resilient modulus (MR) using a universal material testing apparatus. Tests were conducted on asphalt concrete with varying CA content and asphalt penetration values to illustrate the degradation of aggregate and asphalt. While previous studies have focused primarily on the mechanical behavior of recycled asphalt mixture, limited attention has been given to the influence of material degradation on long-term performance. This research addresses that gap by emphasizing the practical significance of degradation analysis in pavement management.

2. RESEARCH SIGNIFICANCE

The road maintenance process is a crucial aspect in maintaining optimal pavement performance throughout its service life. One way to carry out road maintenance is through an approach that focuses on identifying degradation of aggregate and asphalt materials. Analysis of rutting performance due to repeated traffic and environmental temperature, simulated by research with degraded asphalt concrete conditions. This research contributes to the understanding of the complexity of the relationship between temperature, aggregate, and asphalt degradation in asphalt concrete, as measured by Marshall parameters, resilient modulus, and resistance to rutting deformation. To achieve these objectives, a series of laboratory experiments was designed to simulate different degradation levels and evaluate their impact on rutting performance.

3. MATERIALS AND METHODS

The decision to replace the asphalt concrete road surface layer is based on indications of rutting depth as part of the RAP process. Rutting depth is caused by changes in aggregate size, particularly coarse aggregate, and a decrease in asphalt performance, indicated by a decrease in penetration values. The process of measuring the degradation level of asphalt concrete performance uses a laboratory experimental approach, simulating various aggregate and asphalt degradation conditions to determine the mixture characteristics resulting from the decline in material physical properties. The preparation of aggregate and asphalt variations begins with identifying RAP conditions through simulations of asphalt concrete degradation levels. Simulations are constructed by categorizing high, medium, and low CA mixture proportions as a form of aggregate degradation and decreasing asphalt penetration as a combination of aggregate and asphalt properties in degraded asphalt concrete. Next, the degraded concrete variations are tested to develop a degradation model that reflects the effects of track loading and ambient temperature, as shown in Fig. 1.

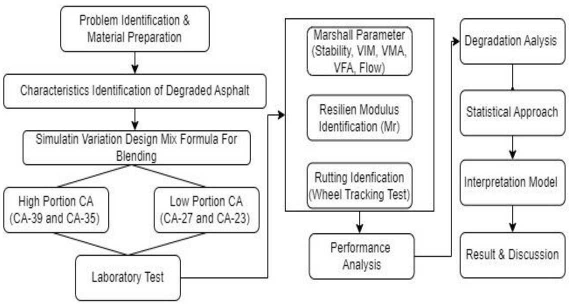


Fig.1 Research Flowchart

3.1 Performance Parameters

Road damage simulation is illustrated with the rutting depth level. The decision to establish road maintenance with RAP is reviewed at the level of asphalt concrete degradation. In conditions of minor damage, the level of asphalt concrete degradation is also low so that asphalt and aggregate substitution is small. Conversely, a high level of damage results in a greater amount of new material use. Damage classification is also displayed based on deformation value. Rut depth value in FHWA-RD-03-031, Rut Depth < 6 mm is classified as light damage, 6-12 mm is classified as moderate damage, 12-25 mm is classified as high damage [19].

3.2 Degradation Simulation Design

3.2.1 Asphalt Binder

This study was conducted using two types of asphalt binders: Pen Asphalt 60/70 and RAP-extracted asphalt. This RAP material was first processed through an extraction process to obtain the RAP binder. The second stage involves mixing the 60/70 pen asphalt and the RAP binder in a specific composition. Pure asphalt binder/virgin asphalt (VA) was used as a control (AS-1), while the other four samples (AS-2), (AS-3), (AS-4), and (AS-5). The results of the identification of the physical properties of asphalt in each variation are presented in Table 1.

3.2.2 Aggregate Design

The aggregates consist of three types of fractions with varying grain sizes: fine, medium, and coarse. The characteristics of the aggregates were tested using sieve tests, specific gravity tests, and absorption tests. The aggregate gradation refers to the Bina Marga standard specifications for Asphalt Concrete Wearing Coarse (AC-WC) surface layers, shown in Figure 2. The selected CA contents of 39%, 35%, 27%, and 23% were determined to represent both the practical gradation range specified in the Bina Marga standard for AC-WC and the expected variation due to aggregate degradation during recycling. Specifically, 39% corresponds to the control gradation. Lower CA levels (35%, 27%, and 23%) simulate progressive degradation and finer gradation conditions typically observed in recycled asphalt mixture. This approach demonstrated that repeated traffic loading and laboratory compaction induce aggregate crushing and a reduction in particle size. Therefore, the reduced CA contents represent field-equivalent degradation levels [21].

3.2.3 Marshall Parameter Identification

The sample preparation and testing procedure refers to the AASHTO T 245-97 standard and using Marshall test (Fig 3a). The mixing process involves heating the aggregate at 160°C and the asphalt at 150°C. The mixing and compaction temperature of RAP is relatively in the range of 150 °C to 181 °C [20]. The compaction process consists in applying a load of 75 times to the top and bottom sides by inverting the mold. The compaction process uses a 4,535-gram load and a free fall of 18 inches (457.2 mm). The sample is then stored for 24 hours at room temperature to be removed from the mold. The Marshall sample preparation refers to RSNI M-01-2003. After the sample is placed at room temperature, it is then soaked in a water bath at 60°C for 30 minutes before the Marshall testing process. Voids in mineral aggregate (VMA), Voids filled with asphalt (VFA), and voids in mixture or air voids (VIM) are shown in table 2.

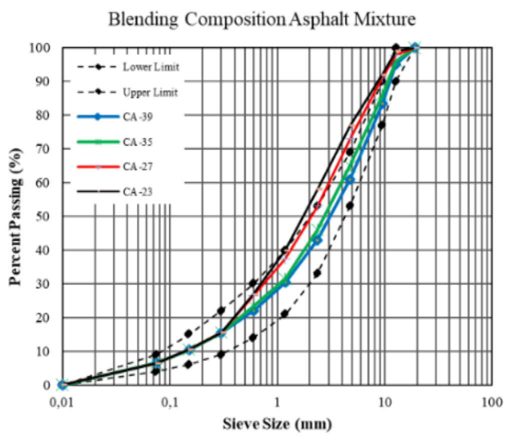


Fig.2 Aggregate size variations

Table 2. Marshall Test Results

Parameters	Asphalt Mixtures Performance				Unit
	CA-39	CA-35	CA-27	CA-23	
Stability	1079.01	869.02	575	529.5	Kg
Flow	3.5	3.9	4.9	5.95	mm
VMA	19.13	20.68	26.37	27.58	%
VFA	76.05	68.75	49.4	46.46	%
VIM	4.58	6.46	13.34	14.76	%
MQ	308.29	222.83	117.35	88.99	kg/mm

Table 1. Physical Properties of Asphalt

Properties	Test Method (ASTM)	Aging Asphalt	AS-1	AS-2	AS-3	AS-4	AS-5
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

3.2.4 Modulus Resilient Identification

Universal Material Testing Apparatus (UMATTA) testing (Fig 3b) was used based on ASTM D 4123-82 UMATTA procedure [22]. The UMMATA test sample was in the form of a Marshall sample using indirect stress at five variations of CA content at a temperature of 25 °C (Eq. 1)

$$\mathrm{MR} = \frac{\sigma_d}{\varepsilon_r} \quad (1)$$

MR : Resilient modulus (MPa), $\sigma_d =$ cyclic deviator stress applied (MPa) , $\varepsilon_r =$ Recoverable (resilient axial strain measured after each load cycle (mm/mm). Where MR is the Resilient Modulus, σ_d is the Deviator Stress, and ε_r is the Resilient Strain.

3.2.5 Rut Depth Identification

Wheel Tracking Machine (WTM) testing (Fig 3c), with 1,260 passes, to evaluate the permanent deformation resistance of asphalt mixtures to repeated loads, conducted by AASHTO T324-23 standards. The test sample is an asphalt concrete slab with dimensions (30 cm x 30 cm x 5 cm), then tested at temperatures of 25 °C, 40 °C, and 55 °C, representing typical and extreme surface temperatures observed in tropical regions such as Indonesia. A wheel load of 700 N moves repeatedly over the sample surface, Fig. 3c. The total number of loading cycles was selected based on equivalent traffic loading to approximately years of heavy vehicle traffic on major highways. The depth of the wheel tracks (rut depth) is measured periodically to indicate the rate of deformation and the resistance of the mixture to permanent deformation [23,24]. The results of the track test are shown in Fig 4.

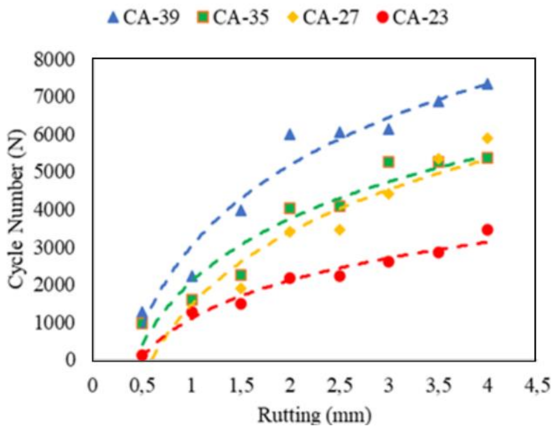


Fig.4 Rutting Temperature 25 ^{O}C

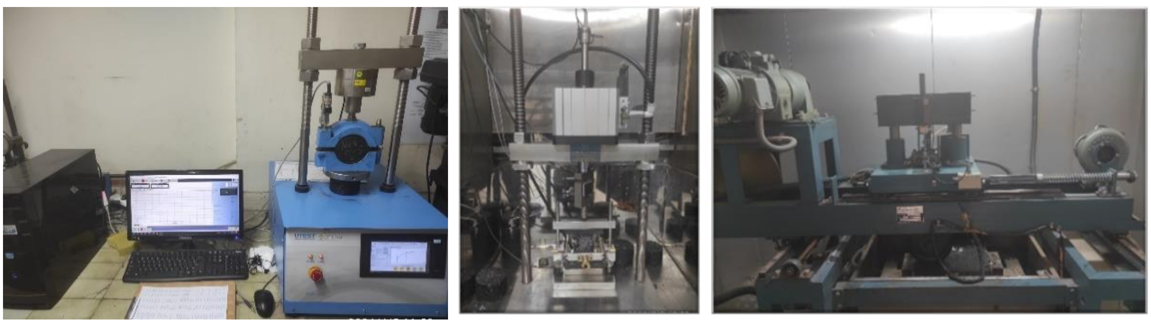
4. RESULTS AND DISCUSSIONS

4.1 Influence of CA content on Resilient Modulus

The Umatta test results show that decreasing CA content affects the Resilient Modulus value. Statistical analysis reveals a robust positive correlation (r = 0.995) between the coarse aggregate (CA) content and the Resilient Modulus (MR). Testing at a temperature of 25°C shows changes in the MR value of test samples with different CA contents. At the highest CA content (39%), the MR value is 4,148.5 MPa. When the CA content is reduced to 23%, the MR value decreases to 2,483.66 MPa, representing 60% of the MR value at 100% CA. Table 4 illustrates the change in MR level resulting from the reduction of CA in the asphalt concrete mixture. The decrease in MR level indicates that CA content is a key factor affecting the stiffness of the asphalt concrete mixture [25].

Table 3. Resilient Modulus Test Results

Mixture Type	Total Hor. Def. um	Peak Load (N)	Resilient Modulus (MPa)	Standard Dev.	MR % Coef. of Var.
CA-39	4.95	2.004	4,148.5	24.28	0.58
CA-35	5.50	2.001	3,728.6	47.89	1.28
CA-27	7.27	2.016	2.938	39.80	1.35
CA-23	8.85	1.986	2.483.6	31.47	1.26



(a) (b) (c)

Fig. 3 Marshall Test (a), Umatta Test (b), Wheel Tracking Machine Test (c)

Table 4. Resilient Modulus of Asphalt Concrete Degradation

Modulus of Resilience 25 °C				
Mixture	CA-39	CA-35	CA-27	CA-23
(MPa)	4.148,5	3.728,66	2.938,00	2.483,66
Level MR	100%	90%	71%	60%

The reduction in resilient modulus with decreasing coarse aggregate content indicates that the continuity of the aggregate skeleton strongly influences the structural stiffness of the recycled asphalt mixture. Maintaining a coarse aggregate content above 35% preserves at least 82% of the initial resilient modulus at 25°C, suggesting adequate stiffness and load-bearing capacity for service conditions. However, when the CA content falls below this threshold (CA-27 and CA-23), the loss of interlocking content and increased binder film thickness lead to a nonlinear stiffness drop of up to 40%, which accelerates rutting under repeated loading. These findings highlight the importance of preserving coarse aggregate fractions during aggregate processing to ensure the mechanical integrity and durability of recycled pavement.

4.2 The effect of temperature and CA on Rutting Deformation

Changes in asphalt concrete performance due to CA degradation can be categorized by observing deformation changes throughout the cycle. At 25 °C, performance degradation was observed to be linear with decreasing CA, with CA-39 serving as the control (100% performance). At the same number of cycles, the rut depth increased in CA-35, resulting in an 82% decrease in asphalt concrete performance.

Table 5. Rutting in Different Temperatures

Rutting 25 °C				
N Cycle	CA-39	CA-35	CA-27	CA-23
2.500	0.51	0.600	0.750	0.910
5.000	0.56	0.690	0.860	0.970
7.500	0.61	0.770	0.920	1.010
10.000	0.68	0.820	0.950	1.030
Average %	**100%**	**82%**	**68%**	**60%**
Rutting 40 °C				
2.500	1.19	1.430	1.850	2.500
5.000	1.22	1.490	1.900	2.600
7.500	1.23	1.530	1.930	2.670
10.000	1.27	1.570	1.980	2.700
Average %	**0%**	**82%**	**64%**	**47%**

Performance degradation was also observed in CA-27 (68%) and CA-23 (60%). Increasing the temperature to 40 °C further decreased the performance of asphalt concrete, as shown in Table 5.

The deformation behaviour of aggregate and asphalt degradation at a 25 °C temperature reveals changes in asphalt concrete performance, as shown in Fig. 5. At a medium temperature of 40 °C, the material becomes susceptible to rutting, particularly when the mixture's performance deteriorates. Rutting behaviour at medium temperature can be seen in Fig. 6.

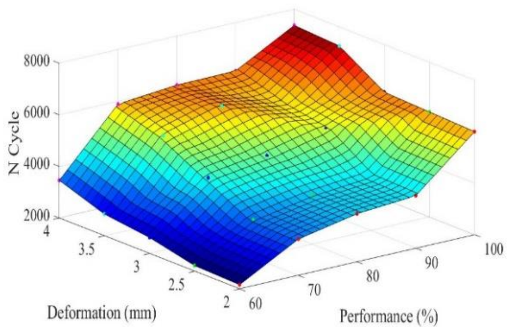


Fig.5 Rutting Behaviour N Cycle Temperature 25 °C

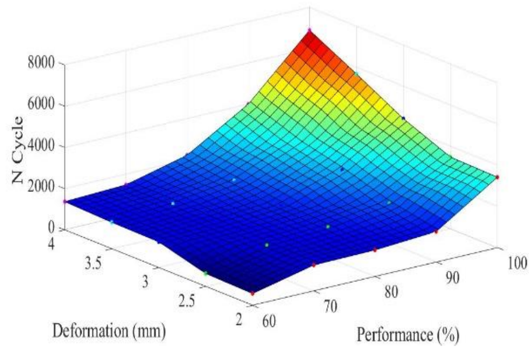


Fig.6 Rutting Behaviour N Cycle Temperature 40 °C.

4.3 Influence of Coarse Aggregate and Temperature on Rutting Prediction of Asphalt Concrete

The rutting deformation approach uses rutting changes at each trajectory change by determining the deformation acceleration. Increasing rutting values due to changes in CA content within the same cycle indicate different deformation velocities.

The deformation velocity in cycle i is illustrated by the deformation value (d) in cycle (N), as shown in Figure 7. The relationship d_i/N_i cycle N_i forms a power function that has the following form:

$$d_i/N_i = A\,.\,(N_i)^{-B} \quad (3)$$

A and B are characteristic parameters of asphalt concrete, which in this study are demonstrated by variations in the degradation of the CA composition at temperatures of 25°C, 40°C, and 55°C.

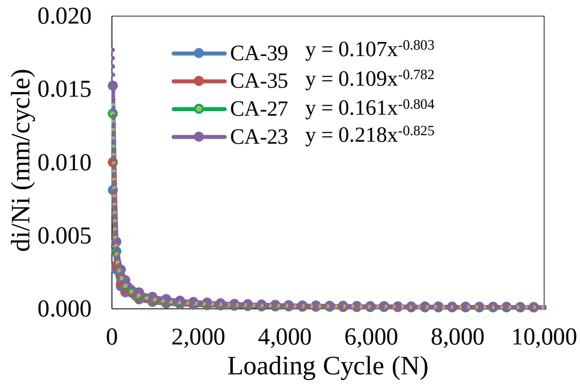


Fig.7 Rate of Deformation 25°C

Table 6 illustrates the change in deformation velocity (y) as a function of the number of cycles to N (x). At a temperature of 25 °C, the CA content influences the deformation velocity formula. A decrease in CA content affects the value of coefficient *A* from formula (3). Coefficient *A* increases due to a reduction in CA content, while coefficient *B* fluctuates between 0.782 and 0.825.

Table 6. Rate of Deformation d_i/N_i

Mixture	25 ^{0}C	40 ^{0}C	55 ^{0}C
CA-39	$y = 0.107x^{-0.803}$	$y = 0.217x^{-0,796}$	$y = 0.425x^{-0,729}$
CA-35	$y = 0.109x^{-0,782}$	$y = 0.338x^{-0,825}$	$y = 0.517x^{-0,714}$
CA-27	$y = 0.161x^{-0,804}$	$y = 0.545x^{-0,853}$	$y = 0.620x^{-0,720}$
CA-23	$y = 0.218x^{-0,825}$	$y = 0.681x^{-0,842}$	$y = 0.984x^{-0,756}$

Changes in temperature from 25°C to 40°C resulted in an increase in the constant A value in each model, which indicates an increase in the deformation rate. Meanwhile, the exponent B value at different temperatures of 25°C showed almost the same value. From Table 6, the coefficient A value increases with temperature changes, as well as a decrease in CA content, which causes an increase in the coefficient A value. The A value indicates the initial deformation of the groove shape in the initial concrete due to repeated track loads.
Identification of the characteristics of coefficients A and B indicates partial rutting behaviour due to CA and temperature factors. Figure 8 shows a negative relationship between coefficients A and CA, where coefficient A decreases as CA increases, with a slope varying from -0.0305 to -0.006. The level of model determination is also observed to be prominent, with R^2 reaching > 0.8. The rutting accumulation exhibited a nonlinear trend for all mixtures, with a distinct acceleration phase observed in finer gradations (CA-27 and C-23). At higher CA contents (CA-39 and CA-35), the deformation increased gradually and followed a linear pattern, indicating stable aggregate interlock and effective load transfer. However, when the CA portion dropped below 30%, a critical threshold was observed, beyond which rutting growth accelerated significantly, especially under elevated temperatures> 50 °C. This behavior suggests the onset of plastic flow instability due to the collapse of the aggregate skeleton and the domination of the binder film.

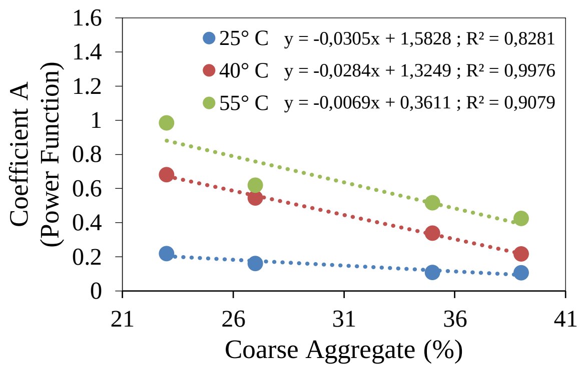


Fig.8 Coefficient Power Function with Coarse Aggregate (%)

The response surface model was developed using Response Surface Methodology (RSM) with a multivariate Polynomial Regression (MPR) approach of i-th order polynomials (i > 1) [26], which allows the description of complex interactions between independent variables, namely the percentage of Coarse Aggregate (x) and temperature (y), on the response variable coefficient A. The polynomial equation used in Eq.4

$$Z = z0 + ax + by + cx^2 + dy^2 + fx \qquad (4)$$

Where Z is the A Power value, with zo being the intercept, a and b being the linear coefficients, c and d representing the quadratic effects, and f the interaction between x and y, the R^2 value of 0.971 and p-values (<0,05) indicates that the model can explain more than 97% of the variation in the data with a high level of fit of the model to the response observations.

Table 7. Quadratic Regression Model Parameters

Model Parameter	
$\mathbf{Z = z_0 + ax + by + cx^2 + dy^2 + f}$	
Coefficient	A (Power Function)
z_0	-0.2855
a	-0.2030
b	0.0233
c	0.0285
d	-0.0002
f	0.0047

Table 7 shows a negative linear coefficient a (-0.2030), indicating that an increase in the percentage of Coarse Aggregate reduces the power A value. A positive linear coefficient b (0.0233) indicates that an increase in temperature can increase the power A value. The quadratic coefficients c and d indicate a nonlinear effect so that changes in the size of the aggregate or temperature are not proportional to the

response.
The positive interaction coefficient f (0.0047) shows that the combination of high Coarse Aggregate and temperature can increase the power A value, seen at the peak of the RSM contour in the red zone (Fig. 9)

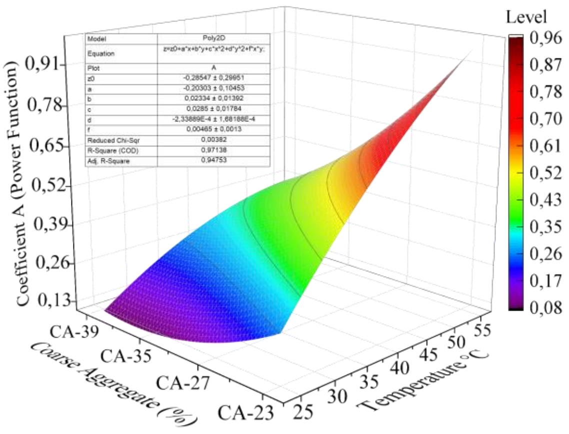


Fig.9 Coefficient Power Function A with Regression Characteristic

Fig. 9 shows a surface contour with a blue-to-red gradient, where blue indicates low A Power values and red indicate high values. The blue zone appears at low combinations of CA and temperature, while the red zone occurs at high combinations, indicating a positive interaction between CA and temperature. The smooth and continuous contour indicates a gradual and consistent change in A Power value, so the model can be applied to field implementation in terms of predicting the relationship between CA and Temperature. Response surface analysis shows that mixtures with medium to high CA at medium temperatures produce high A Power values, thereby increasing the flexibility and stability of the mixture. Temperature control is important to keep it within the appropriate range, especially for high CA mixtures, to prevent damage or early deformation of the mixture. The CA-temperature interaction analysis has been described, showing that the regression increases significantly with increasing temperature, especially for mixtures with lower CA content. At 25°C, the slope for CA-23 is 0.218, but increases sharply to 0.984 at 55°C, indicating a fourfold increase. The temperature change indicates that mixtures with lower CA rely more on the asphalt matrix, which softens at high temperatures, leading to disproportionate deformation. In contrast, mixtures with higher CA-39 exhibit a more stable response due to stronger aggregate interlock and higher stiffness.

5. CONCLUSION

The research results concluded that aggregate degradation and changes in the binder material's characteristics have a significant impact on the performance of asphalt concrete. The changes that occur are as follows:

1. Aggregate degradation significantly affects the resilient modulus of the mixture. A decrease in Coarse Aggregate linearly decreases the Modulus Resilient performance.
2. The deformation rate is high in the initial cycles and then decreases with increasing cycles.
3. A reduction in Coarse Aggregate indicates that the mixture's performance needs to be improved to maintain deformation resistance, especially at increased temperatures.
4. Statistically, a decrease in Coarse Aggregate and an increase in temperature result in a rise in rutting during the initial cycles.
5. A simulation of Coarse Aggregate; real conditions in the field can be different due to the influence of humidity, environmental conditions, and even pavement conditions due to variations in traffic load, which have the potential to accelerate degradation and affect deformation characteristics and resilient modulus.

The findings of this study demonstrate that reducing the coarse aggregate content and aging asphalt have a significant impact on rutting performance and resilient modulus in RAP mixtures, particularly under high temperatures. Maintaining the coarse aggregate fraction above 35% preserves at least 80% of the initial modulus, emphasizing its critical role in recycled mixture design.

Future research should verify the laboratory-based degradation model through long-term field performance monitoring, microstructural characterization (using SEM or FTIR), and binder aging kinetics analysis to enhance the mechanistic understanding of RAP mixtures under traffic and temperature variations. Furthermore, future studies can integrate the developed model to determine the optimal timing for effective pavement maintenance using recycled asphalt materials, leading to a performance-based maintenance framework that enhances sustainability and cost efficiency throughout the pavement life cycle.

6. ACKNOWLEDGMENTS

Directorate of Research, Technology, and Community Service of the Directorate General of Higher Education, Research, and Technology, Ministry of Education, Culture, Research, and Technology, published this research through the funding of the Doctoral Dissertation Program (PDD) 2024, funded under no. NKB – 960 / UN2. RST / HKP. 05.00 / 2024.

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