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Effect of Nano Zeolite Filler Substitution on Marshall and Volumetric Characteristics of AC-WC Mixtures

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ABSTRACT

The performance of Asphalt Concrete–Wearing Course (AC-WC) mixtures is strongly influenced by filler characteristics that control mechanical resistance and volumetric stability. Although nano zeolite has demonstrated potential for improving asphalt mixture performance, previous studies mainly focus on binder modification or advanced performance-based tests, limiting their applicability in routine mix design practice. Consequently, the role of nano zeolite as a filler substitute in conventional hot mix AC-WC mixtures evaluated using fundamental Marshall parameters remains insufficiently explored, and the optimum substitution level for practical pavement applications has not been clearly established. This study aims to evaluate the effect of nano zeolite filler substitution on the Marshall and volumetric characteristics of AC-WC mixtures and to determine the optimum substitution level based on standard mix design criteria. The Optimum Asphalt Content (OAC) was determined at 6.04% and applied as a constant asphalt content. Nano zeolite was used as a partial replacement of cement filler at substitution levels of 0%, 25%, 50%, 75%, and 100%. Evaluated parameters included Marshall stability, flow, Marshall Quotient (MQ), density, VIM, VMA, and VFA. The results indicate that a 50% nano zeolite substitution yields the optimum performance, producing the highest Marshall stability and MQ while satisfying specification limits. These findings provide practical guidance for applying nano zeolite as an alternative filler in AC-WC mixtures using conventional Marshall based mix design.

1. Introduction

Flexible pavement systems remain widely adopted due to their constructability and economic advantages; however, their performance is highly sensitive to material composition, particularly under increasing traffic loads and aggressive climatic conditions [1]. In Asphalt Concrete–Wearing Course (AC-WC) mixtures, filler plays a crucial role in controlling the rheological behavior of asphalt mastic, influencing mixture stiffness, durability, and volumetric stability. Conventional fillers such as cement or limestone powder are commonly used; nevertheless, their effectiveness in enhancing long-term pavement performance remains limited under severe service conditions [2]. Recent advancements in pavement materials research have highlighted the potential of nano-materials to improve asphalt mixture performance due to their high specific surface area and enhanced physicochemical interaction with asphalt binder. Nano zeolite, characterized by its porous aluminosilicate structure and adsorption capability, has attracted attention as a modifier capable of improving asphalt–aggregate adhesion and internal mastic structure, thereby contributing to enhanced mixture cohesion and resistance to deformation under repeated traffic loading [3]. Despite these promising characteristics, the effectiveness of nano zeolite in asphalt mixtures—particularly when applied as a filler substitute in conventional AC-WC mixtures—has not yet been comprehensively evaluated using fundamental Marshall-based performance parameters, leaving uncertainty regarding its practical implementation and optimum dosage. Several studies have reported that nano zeolite can enhance stiffness, moisture resistance, and rutting performance of asphalt mixtures. However, most existing investigations concentrate on binder-level modification, warm mix asphalt applications, or advanced performance tests such as dynamic modulus and wheel tracking, which do not explicitly capture the role of nano zeolite as a filler in controlling Marshall based mixture behavior, thereby limiting direct implementation in routine mix design practice [4].

Moreover, studies that specifically evaluate nano zeolite as a filler substitute in conventional hot mix asphalt, particularly AC-WC mixtures, remain scarce. The interaction between nano zeolite filler content and fundamental Marshall parameters such as stability, flow, and volumetric characteristics has not been sufficiently synthesized or quantified [5]. As a result, the determination of an optimum nano zeolite substitution level that satisfies standard Marshall criteria and supports practical pavement design [6]. Therefore, this study aims to systematically evaluate the effect of nano zeolite filler substitution on the Marshall and volumetric characteristics of AC-WC mixtures using conventional Marshall-based mix design [7]. By focusing on widely applied testing methods and filler level modification, this research seeks to bridge the gap between nano-material innovation and practical asphalt mixture design, providing experimentally grounded guidance for pavement engineering applications [8].

2. Research Method

Based on the objectives of this study, the research method applied was experimental laboratory research. This method was selected to evaluate the effect of nano zeolite substitution as filler on the performance of asphalt concrete mixtures. The experimental program involved preparing asphalt mixtures with varying nano zeolite contents and testing their Marshall characteristics under controlled laboratory conditions. The procedures and testing stages were conducted in accordance with Bina Marga 2018 Specifications to ensure reliability and applicability of the results [9].

3. Description and Technical

This research was conducted through a laboratory-based experimental approach focusing on the evaluation of Asphalt Concrete – Wearing Course (AC-WC) mixtures incorporating nano zeolite as a filler substitute. The technical stages consisted of material characterization, Marshall mix design, determination of Optimum Asphalt Content (OAC), preparation of Marshall specimens with nano zeolite substitution, and analysis of Marshall characteristics [10].

3.1 Sample Preparation

The population of this study comprised AC-WC asphalt mixtures using penetration grade 60/70 asphalt binder, coarse and fine aggregates, cement filler, and nano zeolite filler. The research samples were Marshall specimens prepared in the laboratory. A total of 24 specimens were used, consisting of 9 specimens for determining the Optimum Asphalt Content (OAC) and 15 specimens for nano zeolite filler substitution testing. This population represents standard AC-WC mixtures commonly applied in Indonesian flexible pavement construction.

3.2 Sampling Techniques

A purposive sampling technique was applied by selecting specific mixture variations based on the determined OAC and predefined nano zeolite substitution levels. The OAC was established at 6.04% based on Marshall analysis. Subsequently, filler substitution variations of 0%, 25%, 50%, 75%, and 100% nano zeolite (by weight of filler) were prepared, with three specimens for each variation. This technique ensures controlled evaluation of nano zeolite effects while minimizing variability from other mixture parameters.

3.3 Definition of Variable Operations

The independent variable was the percentage of nano zeolite used as a substitute for cement filler. The dependent variables included Marshall Stability, Flow, Marshall Quotient (MQ), bulk density, Voids in Mix (VIM), Voids in Mineral Aggregate (VMA), and Voids Filled with Asphalt (VFA). The controlled variables comprised asphalt binder type (Pen 60/70), aggregate gradation, Optimum Asphalt Content (6.04%), mixing and compaction temperature, and compaction energy (75 blows per side). This variable framework isolates the influence of nano zeolite substitution on Marshall performance.

Table 1. Nano zeolite Variation Code

Variation Code	Nano zeolite Content (% of filler)	Cement Filler Content (% of filler)	Description
NZ-0	0%	100%	Control mixture using cement filler only
NZ-25	25%	75%	Partial substitution of cement filler with nano zeolite
NZ-50	50%	50%	Balanced substitution of cement and nano zeolite filler
NZ-75	75%	25%	Dominant nano zeolite filler substitution
NZ-100	100%	0%	Full substitution using nano zeolite filler

Source: Asphalt Laboratory, Universitas Almuslim (2025)

3.4 Instrument Analysis Tool

The primary testing instrument used was the Marshall Stability Testing Apparatus. Supporting equipment included an asphalt mixing unit, Marshall molds, a compaction hammer, an oven, a water bath, and a precision balance. All testing procedures followed the Bina Marga 2018 Specifications for asphalt mixture testing. The use of standardized equipment ensures accuracy, repeatability, and comparability of test results [11].

3.5 Data Analysis Techniques

Data analysis was conducted using descriptive and comparative quantitative methods. Marshall parameters from each nano zeolite substitution level were compared with specification limits and analyzed to identify performance trends. Regression analysis was employed to examine the relationship between nano zeolite content and Marshall characteristics. This analysis approach enables the identification of the optimum nano zeolite substitution level based on practical pavement performance criteria. substitution level based on practical pavement performance criteria and Marshall stability requirements.

4. Results and Discussions

4.1 Results of Aggregate Testing and Sieve Analysis

Physical properties testing of coarse and fine aggregates was conducted to evaluate their suitability as constituent materials for Asphalt Concrete–Wearing Course (AC-WC) mixtures. The aggregates used in this study were sourced from PT. Krueng Meuh Quarry. The test parameters included bulk specific gravity, saturated surface-dry (SSD) specific gravity, apparent specific gravity, and water absorption, in accordance with relevant standards [12].

Table 2. Results of Physical Properties Testing of Coarse and Fine Aggregates

Physical Properties of Aggregate	Coarse Aggregate 19.1 mm (3/4”)	Coarse Aggregate 9.5 mm (3/8”)	Fine Aggregate	Description
Bulk specific gravity	2.766	2.561	2.464	Passed
Saturated surface-dry (SSD) specific gravity	2.825	2.619	2.520	Passed
Apparent specific gravity	2.940	2.720	2.610	Passed
Water absorption (%)	2.131	2.288	2.266	Passed

Source: Asphalt Laboratory Test Results (2025)

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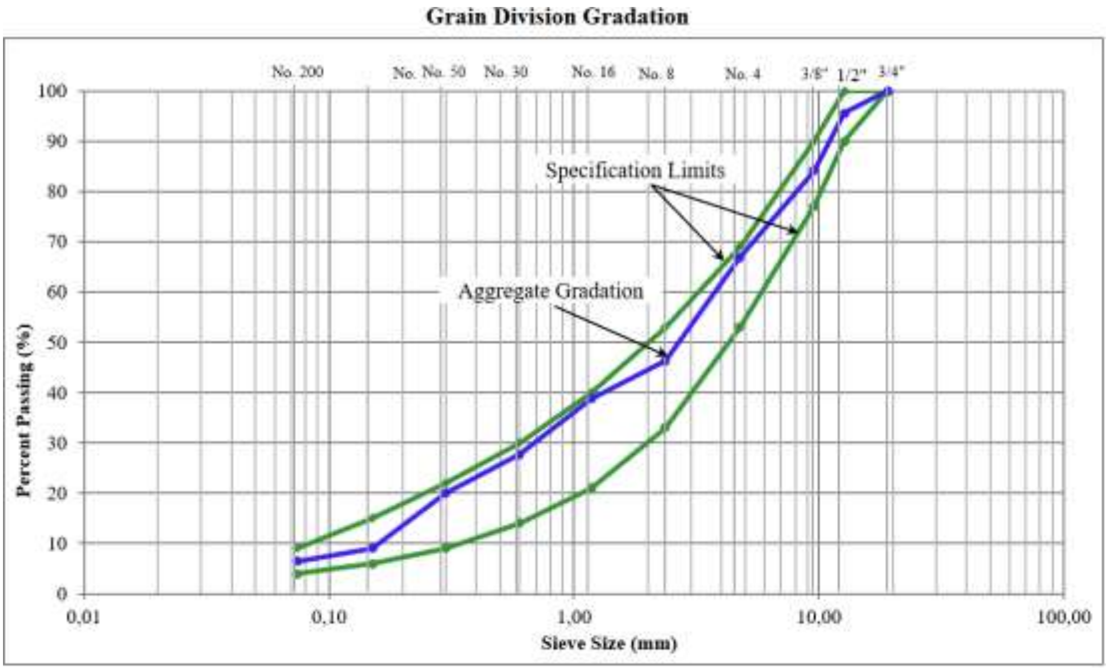

Source: Asphalt Laboratory Test Results (2025)

Figure 1. Aggregate Gradation Curve for AC-WC Mixture

The physical properties test results in Table 2 indicate that the coarse and fine aggregates used in this study satisfy the technical requirements for AC-WC mixtures. Bulk specific gravity values ranged from 2.464 to 2.766, indicating adequate aggregate density to support structural performance. Water absorption values ranged from 2.13% to 2.29%, remaining below the allowable limit and indicating low aggregate porosity, which is beneficial for enhancing asphalt–aggregate adhesion and reducing moisture susceptibility. The aggregate gradation curve presented in Figure 1 lies entirely within the AC-WC specification limits, demonstrating a dense and continuous gradation. This gradation ensures effective interlocking between aggregate particles while providing sufficient void space for asphalt binder accommodation [13]. Overall, the physical properties and gradation characteristics confirm that the aggregates are suitable for AC-WC mixtures and provide a reliable foundation for evaluating the effect of nano zeolite filler substitution on Marshall performance.

4.2 Results of Asphalt Binder Physical Properties Testing

The physical properties testing of the asphalt binder was conducted to ensure that the penetration grade 60/70 asphalt used in this study met the technical requirements for Asphalt Concrete–Wearing Course (AC-WC) mixtures. The test parameters included specific gravity, penetration, ductility, and softening point, as summarized in Table 3.

Table 3. Results of Physical Properties Testing of Shell Asphalt 60/70

No.	Asphalt Physical Properties	Unit	Result	Specification
1.	Asphalt specific gravity	-	1,034	>1
2.	Penetration	(0,1 mm)	64	60-70
3.	Ductility	Cm	128	>100
4.	Softening point	°C	51	>48

Source: Asphalt Laboratory Test Results (2025)

The test results indicate that the asphalt binder had a specific gravity of 1.034, exceeding the minimum requirement and indicating good material uniformity. The penetration value was 64 (0.1 mm), which falls within the specified range for penetration grade 60/70 asphalt, reflecting appropriate stiffness for surface course applications. The ductility value reached 128 cm, exceeding the minimum requirement and demonstrating adequate flexibility to resist cracking under traffic loading and temperature variation. In addition, the softening point was recorded at 51°C, which is higher than the minimum specification limit, indicating satisfactory resistance to deformation at elevated temperatures. Overall, the physical properties of the asphalt binder comply with the relevant specifications and confirm its suitability as a binding material for AC-WC mixtures [14]. These results provide a reliable basis for evaluating the influence of nano zeolite filler substitution on the Marshall characteristics of asphalt mixtures without interference from binder-related deficiencies.

4.3 Marshall Test Results for Optimum Asphalt Content (OAC) Determination

Marshall testing was conducted to determine the Optimum Asphalt Content (OAC) of the AC-WC mixture using penetration grade 60/70 asphalt binder. The evaluation was performed at asphalt contents of 5.54%, 6.04%, and 6.54%, with analyzed parameters including Marshall stability, flow, Marshall Quotient (MQ), bulk density, Voids in Mix (VIM), Voids in Mineral Aggregate (VMA), and Voids Filled with Asphalt (VFA) [15].

Table 5. Summary of Marshall Test Results for Penetration Grade 60/70 Asphalt

No	Marshall Characteristics	Optimum Asphalt Content (OAC)			Spec Dept. Pu (2018)
		5,54	6,04	6,54	
1	Stability (kg)	1.014	1.124	1.060	Min. 800
2	Flow (mm)	3,40	3,25	3,35	2 - 4
3	Marshall Quotient (kg/mm)	298,29	345,00	316,29	Min. 250
4	Bulk Density	2,290	2,321	2,277	-
5	Voids in Mix (VIM) (%)	5,6	3,6	4,7	3 - 5
6	Voids in Mineral Aggregate (VMA) (%)	16,6	15,9	17,9	Min. 15
7	Voids Filled with Asphalt (VFA) (%)	66,4	77,4	73,5	Min. 65

Source: Asphalt Laboratory Test Results (2025)

As presented in Table 5, the highest Marshall stability was obtained at an asphalt content of 6.04%, reaching 1,124 kg, indicating the optimum load-bearing capacity compared to other asphalt contents. The flow value at this asphalt content was 3.25 mm, which falls within the specified range of 2–4 mm, reflecting a balanced condition between mixture stiffness and plastic deformation. The highest Marshall Quotient was also recorded at 6.04%, with a value of 345.00 kg/mm, indicating favorable strength and rigidity of the mixture. Volumetric parameters at the asphalt content of 6.04% showed VIM of 3.6%, VMA of 15.9%, and VFA of 77.4%, all of which comply with the Bina Marga 2018 specifications. In addition, the highest bulk density value (2.321) was achieved at this asphalt content, indicating the most compact mixture structure. Based on the overall evaluation of Marshall parameters and supported by Figure 2, the asphalt content of 6.04% satisfies all specification requirements and provides the best Marshall performance [16]. Therefore, the Optimum Asphalt Content (OAC) was determined to be 6.04% and was subsequently used as a constant asphalt content in the evaluation of nano zeolite filler substitution in the next stage of the study.

4.4 Marshall Test Results of AC-WC Mixtures with Nano zeolite Filler Substitution

Marshall testing was performed on Asphalt Concrete–Wearing Course (AC-WC) mixtures at the Optimum Asphalt Content (OAC) of 6.04% to evaluate the effect of nano zeolite filler substitution. The substitution levels consisted of 0%, 25%, 50%, 75%, and 100% nano zeolite by weight of total filler, with each variation represented by three Marshall specimens. The evaluated parameters included Marshall stability, flow, Marshall Quotient (MQ), bulk density, Voids in Mix (VIM), Voids in Mineral Aggregate (VMA), and Voids Filled with Asphalt (VFA) [17].

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Table 6. Marshall Test Results with Nano zeolite Filler Substitution at OAC 6.04%

No	Marshall Characteristics	Optimum Asphalt Content (OAC)					Spec Dept. Pu (2018)
		0%	25%	50%	75%	100%	
1	Stability (Kg)	1098,42	1185,63	1235,87	1190,54	1105,31	Min. 800
2	*Flow* (mm)	3,32	3,14	3,06	3,11	3,28	2 - 4
3	MQ (Kg/mm)	330,86	377,27	404,52	382,98	336,98	Min. 250
4	*Density*	2,3148	2,3276	2,3359	2,3298	2,3146	-
5	VIM (%)	3,82	3,41	3,18	3,29	3,79	3 - 5
6	VMA (%)	16,08	15,79	15,68	15,82	16,12	Min. 15
7	VFA (%)	76,31	78,46	79,58	78,91	76,18	Min. 65

Source: Asphalt Laboratory Test Results (2025)

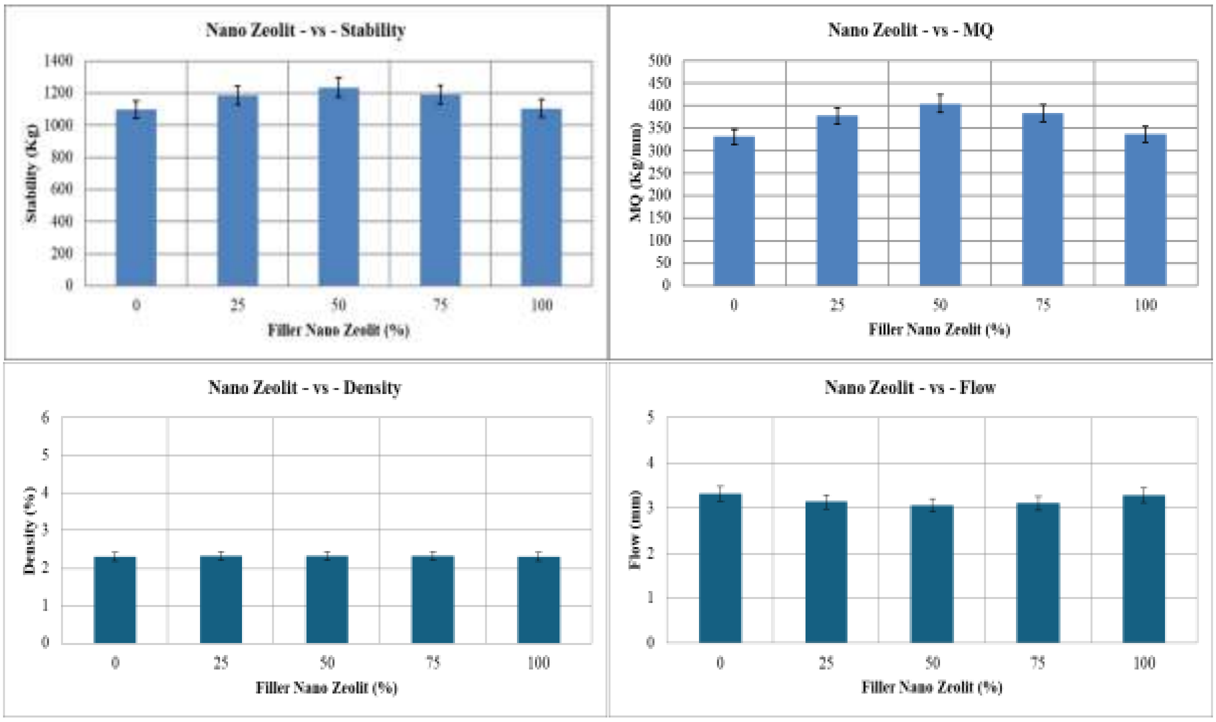
The test results show that all mixtures satisfied the Marshall specification requirements. As presented in Table 6, Marshall stability increased with increasing nano zeolite content up to a substitution level of 50%, reaching a maximum value of 1,235.87 kg. This result indicates improved load-bearing capacity due to the micro-filling effect of nano zeolite, which enhances the interaction between the asphalt binder and aggregates. Beyond this level, stability values decreased, although they remained above the minimum specification limit. A similar trend was observed for the Marshall Quotient. The highest MQ value (404.52 kg/mm) was achieved at 50% nano zeolite substitution, indicating the optimum balance between mixture stiffness and resistance to plastic deformation. Flow values for all substitution levels ranged between 3.06 and 3.32 mm, remaining within the specified limits and demonstrating that nano zeolite incorporation did not adversely affect mixture flexibility [18].

Volumetric properties exhibited relatively minor variations across all mixtures. Bulk density slightly increased up to the 50% substitution level and then decreased at higher substitution levels. The values of VIM (3.18–3.82%), VMA (15.68–16.12%), and VFA (76.18–79.58%) were all within the specification ranges, indicating a stable internal void structure. These results confirm that nano zeolite substitution did not negatively influence the volumetric characteristics of the AC-WC mixtures. Overall, the results demonstrate that nano zeolite can be effectively used as an alternative filler in AC-WC mixtures. The optimum performance was achieved at a 50% substitution of cement filler with nano zeolite, which provided the highest Marshall stability and Marshall Quotient while maintaining acceptable flow and volumetric properties. This substitution level was therefore identified as the most effective composition for improving Marshall performance at the selected OAC [19].

4.5 Effect of Nano zeolite Filler on Mechanical Marshall Properties

The effect of nano zeolite filler substitution on the mechanical Marshall properties of AC-WC mixtures at the Optimum Asphalt Content (OAC) of 6.04% is illustrated in Figure 2. The results demonstrate that nano zeolite significantly modifies the internal structure of the asphalt mixture, influencing strength, stiffness, and compaction characteristics. Marshall stability increased progressively with nano zeolite substitution up to 50%, reaching a maximum value of 1,235.87 kg, before decreasing at higher substitution levels. This behavior indicates that nano zeolite particles effectively fill micro-voids within the asphalt mastic, resulting in a denser and more cohesive binder–aggregate matrix. The improvement in stability reflects enhanced resistance to load-induced deformation, which is particularly important for AC-WC layers subjected to repeated traffic loading [20].

A similar trend was observed for the Marshall Quotient (MQ), which peaked at 404.52 kg/mm at 50% substitution. The increase in MQ indicates an optimal balance between mixture stiffness and load-bearing capacity. At higher nano zeolite contents, the reduction in MQ suggests that excessive filler may increase mixture stiffness without proportional strength gain, limiting the effectiveness of further substitution.

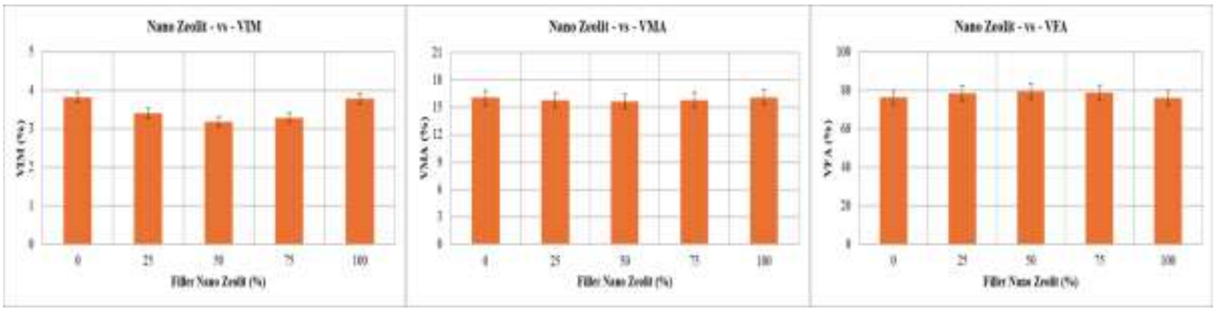


Source: Marshall Test Results, Asphalt Laboratory (2025)
Figure 2. Effect of Nano zeolite Filler on Marshall Properties of AC-WC

Flow values remained within the specification limits across all substitution levels, indicating that the incorporation of nano zeolite did not adversely affect mixture flexibility or induce brittleness. This finding confirms that the enhanced stiffness observed at the optimum substitution level did not compromise the deformation capacity of the mixture. Bulk density exhibited a slight increase up to the 50% substitution level, reflecting improved compaction efficiency and reduced internal voids, followed by a marginal decrease at higher substitution levels due to filler over-saturation. Overall, the combined mechanical trends shown in Figure 2 confirm that a 50% nano zeolite filler substitution provides the most effective improvement in mechanical Marshall performance. This substitution level enhances stability and stiffness while maintaining adequate flow and density, thereby offering an optimal balance between strength, durability, and workability for AC-WC mixtures [21].

4.6 Effect of Nano zeolite Filler on Volumetric Characteristics

The effect of nano zeolite filler substitution on the volumetric characteristics of AC-WC mixtures at the Optimum Asphalt Content (OAC) of 6.04% is illustrated in Figure 3. The evaluation was based on changes in Voids in Mix (VIM), Voids in Mineral Aggregate (VMA), and Voids Filled with Asphalt (VFA), which collectively describe the internal void structure and durability potential of asphalt mixtures. As shown in Figure 3, VIM values decreased from 3.82% in the control mixture to a minimum of 3.18% at 50% nano zeolite substitution, indicating improved mixture densification due to the micro-filling effect of nano zeolite particles. At higher substitution levels, VIM slightly increased but remained within the specified range, suggesting that excessive filler content limits further void reduction without causing instability [22].



Source: Marshall Test Results, Asphalt Laboratory (2025)
Figure 3. Effect of Nano zeolite Filler on Volumetric Characteristics

VMA values exhibited minimal variation across all substitution levels, remaining within 15.68–16.12%, which indicates that nano zeolite substitution did not disrupt the aggregate skeleton or adversely affect the overall gradation structure. This stability in VMA confirms that the volumetric framework of the mixture was well maintained. VFA values increased with nano zeolite substitution, reaching a maximum of 79.58% at 50% substitution, reflecting improved asphalt coating efficiency and binder distribution. At higher substitution levels, VFA showed a slight decrease, indicating reduced effectiveness of additional nano zeolite in enhancing asphalt filling. Overall, the volumetric trends presented in Figure 3 confirm that 50% nano zeolite filler substitution provides the most favorable volumetric performance. This substitution level improves mixture densification and asphalt coating while maintaining stable void structure, supporting the optimum mechanical performance observed in previous sections [23].

5. Conclusion and Suggestion

5.1 Conclusion

This study evaluated the effect of nano zeolite filler substitution on the Marshall and volumetric characteristics of Asphalt Concrete–Wearing Course (AC-WC) mixtures at the Optimum Asphalt Content of 6.04%. The results show that nano zeolite filler significantly improves the performance of AC-WC mixtures when used at an appropriate substitution level. The optimum performance was achieved at 50% nano zeolite filler substitution, which produced the highest Marshall stability of 1,235.87 kg and the maximum Marshall Quotient of 404.52 kg/mm, indicating enhanced load-bearing capacity and stiffness. At this substitution level, the mixture also exhibited an optimum flow value of 3.06 mm and the highest bulk density of 2.3359, reflecting good compaction and deformation resistance. Volumetric characteristics at 50% nano zeolite substitution showed balanced values, with VIM of 3.18%, VMA of 15.68%, and VFA of 79.58%, all satisfying specification requirements. Overall, partial substitution of conventional filler with 50% nano zeolite provided the best mechanical and volumetric performance, demonstrating its effectiveness as an alternative filler material for AC-WC mixtures.

5.2 Suggestion

Further research is recommended to evaluate the long-term performance of nano zeolite-modified asphalt mixtures under varying environmental and loading conditions. Advanced performance tests, such as rutting resistance, moisture damage susceptibility, and durability under aging conditions, should be conducted to support field application. In addition, microstructural analysis is suggested to better understand the interaction mechanism between nano zeolite, asphalt binder, and aggregates. Exploring different nano zeolite sources and particle sizes may also provide insights for optimizing mixture design and improving pavement sustainability.

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