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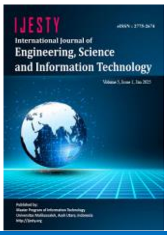

The Effect of Carbon Nanotubes on the Marshall Characteristics of AC-WC Asphalt Mixture

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Abstract

Carbon Nanotubes (CNTs) are cylindrical nanostructures with exceptional mechanical strength, high electrical conductivity, and excellent heat transfer capabilities, making them a promising additive in asphalt mixtures. This study investigates the effect of CNTs on the Marshall parameters of Asphalt Concrete-Wearing Course (AC-WC) mixtures using 60/70 penetration asphalt. CNTs were added to asphalt at 60°C, followed by coarse and fine aggregates preheated to 150°C. Marshall parameter tests were conducted on the samples, and the results showed a significant increase in stability compared to conventional asphalt. Asphalt stability increased by 9%, with the highest value obtained at a CNT concentration of 0.015%, reaching 2177.83 kg. The optimal stability was achieved at a CNT concentration of 0.015%. This study demonstrates that CNTs can be effectively utilized to enhance the performance of AC-WC asphalt mixtures. The flow values decreased as the CNT content increased because CNTs make the asphalt mixture stiffer, improving temperature resistance.

Keywords: *Stability, Flow, Marshall Test, Carbon Nanotubes, Asphalt Mixture.*

1. Introduction

Highways are one of the essential components in transportation infrastructure that play an important role in supporting the economic growth of a region. One type of pavement often used in its application is the Asphalt Concrete Wearing Course (AC-WC), a surface layer to withstand vehicle loads and extreme weather.

However, due to rapid population growth and increasing mobility, the need for high-quality road infrastructure is increasingly urgent [1]. Along with the increasing demand for roads to transport goods and services between regions, it is essential to meet construction requirements regarding density, strength, and durability. One way to achieve this is to increase efficiency by developing asphalt mix quality [2].

Asphalt modification has become an innovative solution to improve road pavement performance. This type of asphalt is enhanced with additives to extend its service life, reduce its melting point, and increase its resistance to cycles due to heavy traffic loads. With technological advances, much research has been done to create asphalt mixes more resistant to damage, ensuring more reliable and durable roads.

One of the latest innovations is the use of Carbon Nanotubes (CNTs) [3] [4] [5] [6], cylindrical carbon structures with diameters on the nanometer scale. CNTs offer high strength, superior electrical properties, and good heat conduction capabilities. These characteristics make CNTs more stable, elastic, and flexible than carbon structures [7]. With a structure like a rolled graphene sheet, CNTs have unique properties that can improve the performance of asphalt materials. Two types of CNTs that are often used are single-walled nanotubes (SWNTs) and multi-walled nanotubes (MWNTs), with SWNTs generally having smaller diameters and more attractive mechanical properties [8]. Previous studies have shown that the addition of Multi-Walled Carbon Nanotubes (MWCNTs) to asphalt mixtures provides significant improvements in various material properties [9] [10] [11] . For example, asphalt nanocomposites with 1% and 2%

MWCNTs have been tested, showing increased viscosity, reduced penetration, and increased softening points, so that asphalt binding becomes more resistant to temperature changes. At low temperatures, the addition of 2% MWCNTs increases stiffness and reduces the relaxation rate, which makes the bond more resistant to cold-induced cracks. In addition, the use of 2% MWCNTs in asphalt mixtures has been shown to improve rheological properties, resistance to permanent marriage, and resistance to melting [12] [13] [14] . Based on the results of this study, this study aims to integrate CNTs into asphalt mixtures as additives. With this approach, it is expected that the stability of the material will increase compared to conventional asphalt, have a lower melting point to deal with extreme temperatures, and better resistance to the impact of traffic loads. This innovation is expected to be a solution to create stronger, more durable, and more efficient road hardness.

2. Literature Review

Asphalt is an adhesive, brownish-black, air-resistant, and viscoelastic hydrocarbon. Asphalt is often called Bitumen; Bitumen is an adhesive material (thick cement material), black or dark in colour, solid or semi-solid, which can be obtained in nature or as a production result. Bitumen can be asphalt, tar, or pitch. Asphalt can be obtained in nature or as a residue from petroleum refining; tar is a condensate resulting in the destructive distillation of coal, petroleum, wood, or other organic materials, while pitch is obtained as a residue from the fractional distillation of tar. Tar and pitch are not obtained in nature but are chemical products. Of the three types of Bitumen above, only general asphalt is used as a material for forming road pavements, so Bitumen is often referred to as asphalt. Asphalt is thermoplastic, which melts when heated and freezes again if the temperature drops. This property is used in the road pavement construction process. The amount of asphalt in the pavement mixture ranges from 4 - 10% based on the weight of the mix or 10 - 15% based on the volume of the mixture.

Asphalt Concrete Layer is a layer in road construction consisting of coarse aggregate, fine aggregate, filler, and hard asphalt, which are mixed, spread, and compacted at a specific temperature. Based on its function, the asphalt concrete layer has three types of mixtures, namely, Easton as a wearing layer, also known as AC-WC (Asphalt Concrete Wearing Course), with a minimum nominal thickness of 4 cm; Easton as a binder layer, also known as AC-BC (Asphalt Cocrete-Binder Course), with the minimum nominal thickness is 6 cm; lactation as a foundation layer, also known as AC-Base (Asphalt Concrete-Base) with minimum nominal thickness is 7.5 cm.

Aggregate is generally defined as a complex and dense formation of the earth's crust [12]. ASTM defines aggregate as a material consisting of solid minerals in large masses or fragments. Aggregate is the main component of the road pavement structure, namely 90-95% aggregate based on weight percentage or 75-85% aggregate based on volume percentage. Thus, the quality of the road pavement is determined by the properties of the aggregate and the results of mixing the aggregate with other materials. Aggregates used in road paving include coarse and fine aggregates.

The filler in the asphalt concrete mixture is a material that passes the No. 200 sieve (0.075 mm). The functions of the filler are to fill the space between fine and coarse aggregates and increase density and stability; fill cavities and increase the contact area between aggregate grains so that it can increase the strength of the mixture; when mixed with asphalt, the filler will form a high-consistency binder that binds the aggregate grains together; and reduces air voids.

CNT is a graphite sheet that forms a tube. This graphite sheet is composed of hexagonal bonds of sp3 carbon atoms. CNT types can generally be divided into single-walled carbon nanotubes (SWNT) and multi-walled carbon nanotubes (MWNT). The properties of carbon nanotubes and their uses in the industrial sector include their significant mechanical strength [15]. [15]. SWNT-type carbon nanotubes have a tensile strength of 50-100 GPa and a large Young's modulus of 1-2 Tpa. While MWNT-type carbon nanotubes have tensile strength and Young's modulus of 11-63 GPa and 270-950 GPa, respectively, have high electronic conductivity, strength, and flexibility can make CNTs potentially control nano-scale structures [16]

3. Materials And Methods

The materials used in this study include asphalt with a 60/70 penetration grade, coarse aggregates in the form of crushed stone (sizes 3/4" and 3/8"), fine aggregates in the form of sand and stone dust, filler (Portland cement type I), and nanomaterial additives in the form of CNTs. Physical property testing was carried out on all aggregates, including both coarse and fine aggregates. The physical properties tested for coarse aggregates included specific gravity, absorption, unit weight (for both 3/4" and 3/8" sizes), and sieve analysis. The physical properties tested for fine aggregates included unit weight, water content, specific gravity, and sieve analysis. The mix design calculations were performed once the physical properties met the standards [10] for asphalt mixtures. Test specimens were produced by adding CNTs at concentrations of 0.005%, 0.01%, 0.015%, 0.02%, and 0.025% by weight of asphalt. The asphalt-forming aggregates weighed according to the mix design, were heated before being mixed with CNTs. After preparing the test specimens with varying asphalt and aggregate contents, the specimens were immersed in water for 30 minutes and 24 hours. Marshall testing was then conducted to determine Marshall parameters such as density, stability, voids filled with asphalt (VFA), voids between aggregate grains (VMA), voids in the mixture (VIM), flow, and Marshall Quotient [17]. [18]

Data analysis was conducted to assess the physical properties of the materials before moving on to the phase of creating test specimens for the flexible pavement Asphalt Concrete - Wearing Course (AC-WC). This test aimed to determine the characteristics of the materials used in the AC-WC asphalt. The testing included aggregate density testing, coarse aggregate density testing, acceptable aggregate density testing, and sieve analysis. The mix design planning process followed the General Specifications of Bina Marga (2018), which outlines the procedure for planning and calculating asphalt mixtures. Mix planning determines the proportions of asphalt mixture components to ensure they meet technical specifications. This study involved five variations of additives with three test samples for each variation.

Test specimen preparation ensured the asphalt met the specified requirements[19]. The aggregates for the asphalt mixtures were dried and heated in a dryer before being placed into the mixer. A total of 1200 grams of coarse aggregate, fine aggregate, and filler was used for each test specimen. The mixture of coarse aggregates, fine aggregates, and filler was heated to 160°C. The asphalt was heated to a mixing temperature of 50°C. CNTs were added according to the specified variations. Once the aggregate reached 150°C, the heated mixture was combined with the CNT-modified asphalt and stirred thoroughly. Afterwards, the mixture was placed into the prepared mould. Standard compaction was performed at 145°C using a compactor with 2x75 impacts per specimen. After compaction, the specimen was cooled and removed from the mould using an ejector. The compacted specimen was marked, and its thickness was measured with a calliper (accuracy of 0.1 mm). The specimen was weighed in its dry state to determine its dry weight, then soaked in water for 30 minutes and 24 hours. After washing, the specimen was wiped dry, weighed in a saturated surface dry (SSD) state, and weighed in water using a Donagen basket. Finally, the specimen was placed on the lower segment of the Marshall testing apparatus, with the upper segment positioned above it and the flow meter installed above one of the guide rods.

4. Results and Discussion

4.1. Marshall Parameters at Optimum Asphalt Content

The optimum asphalt content for the test specimens is first determined. The procedure for preparing the specimens follows the guidelines set by the Indonesian National Standard (SNI) and the 2018 General Specifications for Road and Bridge Construction Works. Based on the sieve analysis results for each grain gradation, the material distribution is as follows: coarse aggregate makes up 44%, fine aggregate 51%, and filler 5%. The calculated optimum asphalt content (Pb) is 5.235%, as shown in Table 1.

Table 1. Targeted optimum asphalt content

Sample	I	II	Optimum Asphalt Content	IV	V
Asphalt Content (%)	4%	4,5%	5%	5,5%	6%

The mix proportions for the AC-WC mixture are determined based on the optimum asphalt content. For each variation, the asphalt weight is calculated as follows: 48 grams for 4% asphalt content, 58 grams for 4.5%, 60 grams for 5%, 66 grams for 5.5%, and 72 grams for 6% asphalt content. To achieve a total mixture weight of 1200 grams, the weight of asphalt is subtracted from the total, and the remaining amount is divided according to the percentage of each aggregate component. The mix proportion to determine the optimum asphalt content is shown in Table 2.

Table 2. Mix proportion to determine the optimum asphalt content

Asphalt content (%)	Material						Total (gr)
	CA (gr)	MA (gr)	Dust (gr)	Sand (gr)	Filler(gr)	Asphalt (gr)	
4	184,32	322,56	414,72	172,80	57,60	48	1200
4,5	183,36	320,88	412,56	171,90	57,30	54	1200
5	182,40	319,20	410,40	171,00	57,00	60	1200
5,5	181,44	317,52	408,24	170,10	56,70	66	1200
6	180,48	315,84	406,08	169,20	56,40	72	1200

The results of the Marshall parameters at different asphalt contents are presented in Table 3. This table provides a comprehensive overview of how each parameter, density, stability, flow, MQ, VMA, VIM, and VFA—varies across different asphalt contents and whether they meet the requirements specified in the 2018 Bina Marga Revision 2 standards. The data highlights the asphalt content levels at which each parameter meets or fails to meet the specified criteria, offering valuable insight into the optimal asphalt content for achieving the desired mix performance.

Table 3. Marshall parameters at different asphalt contents

Asphalt Content (%)	*Density* (gr/cm^3)	VMA (%)	VIM (%)	VFA (%)	*Stability* (Kg)	*Flow (mm)*	MQ (Kg/mm)
4	2,33	14,32	7,12	50,32	1539,17	3,44	457,21
4,5	2,31	15,42	7,23	53,15	1673,11	3,40	492,36
5	2,37	13,67	4,21	69,26	1740,81	3,32	526,75
5,5	2,35	14,79	4,35	70,56	1779,67	3,07	626,18
6	2,32	16,28	4,95	69,58	1737,07	3,34	520,17

As shown in Table 4, the Marshall parameters that meet the specifications outlined in the 2018 Bina Marga Revision 2 for the AC-WC asphalt mixture are achieved at % asphalt content of 6%. At this asphalt content, all the required Marshall parameters, density, stability, flow, MQ, VMA, VIM, and VFA comply with the specified standards, indicating that this asphalt content provides the optimal mixture performance according to the Bina Marga guidelines.

Table 4. Recapitulation of Marshall parameters at different asphalt contents for AC-WC asphalt mixture

No	Criteria	Specification	Asphalt Content (%)				
			4	4,5	5	5,5	6
1	Density	-					
2	VMA	min15 %					
3	VIM	3.0-5.0 %					
4	VFA	min 65 %					
5	Stability	min 800 kg					
6	Flow	2.0-4.0 mm					

7	MQ	250 kg/mm	
		Optimum Asphalt Content	**6%**

3.1. Marshall Parameters of AC-WC Asphalt Mixture with CNTs Addition

The material proportions of the AC-WC asphalt mixture at the optimum asphalt content of 6%, incorporating varying dosages of carbon nanotubes (CNTs) at 0.005%, 0.01%, 0.015%, 0.02%, and 0.025% by weight of asphalt, are shown in Table 5.

Table 5. Mix proportions of materials for AC-WC asphalt mixture with the addition of CNTs

CNT (%)	Material							Total (gr)
	CA (gr)	MA (gr)	*Dust (gr)*	Sand (gr)	*Filler (gr)*	Asphalt (gr)	CNT (gr)	
0	180,48	315,84	406,08	169,2	56,4	72	0	1200
0,005	180,48	315,84	406,08	169,2	56,4	72	3,6	1203,6
0,01	180,48	315,84	406,08	169,2	56,4	72	7,2	1207,2
0,015	180,48	315,84	406,08	169,2	56,4	72	10,8	1210,8
0,02	180,48	315,84	406,08	169,2	56,4	72	14,4	1214,4
0,025	180,48	315,84	406,08	169,2	56,4	72	18	1218

The effect of CNTs on the Marshall parameters of AC-WC asphalt mixture is depicted in Figures 1 to 4. Overall, adding CNTs slightly increases the asphalt mixture's density, though this change is not substantial [20]. Notably, the stability value of the mixture increases with CNTs concentrations from 0.005% up to 0.015%. This increase is attributed to enhanced cohesion between the aggregates due to a more significant amount of asphalt surrounding them, which increases the mixture's density and contact area, thereby improving stability. However, when CNTs exceed 0.015%, the stability value begins to decrease, likely due to the transition of asphalt from a binder to a lubricant beyond an optimal threshold. The stability of the mixture reaches a minimum value of 1000 kg, with values recorded at various CNTs concentrations as follows: 1893.3 kg for 0.005%, 2069.1 kg for 0.01%, 2177.8 kg for 0.015%, 2156.6 kg for 0.02%, and 1953.1 kg for 0.025%. The increase in stability at 0.015% CNTs is notable, showing a 25% improvement over the control sample. All CNTs concentrations meet the Bina Marga 2018 Revision 2 specifications for stability, as shown in Figure 2.

For the flow parameter, which is required to fall between 2 mm and 4 mm according to the Bina Marga standards, all CNTs addition levels also comply, with a general trend of decreasing flow as CNTs content increases. This reduction in flow indicates a stiffer mixture, which improves the mixture's ability to resist deformation under load while maintaining the flow within the acceptable range. If the flow fell below 2 mm, the mixture would become too stiff and prone to cracking, while a flow above 4 mm would make the pavement too deformable.

Regarding the MQ, all CNTs concentrations meet the minimum requirement of 250 kg/mm, with values increasing as the CNTs content rises: 600.5 kg/mm at 0.005%, 715.4 kg/mm at 0.01%, 835.4 kg/mm at 0.015%, 847.5 kg/mm at 0.02%, and 814 kg/mm at 0.025%. The highest MQ value was observed at 0.02% CNTs, suggesting improved stiffness and cohesion of the mixture. However, a slight decrease is noted at higher CNTs contents, which could indicate the onset of reduced flexibility and increased plasticity.

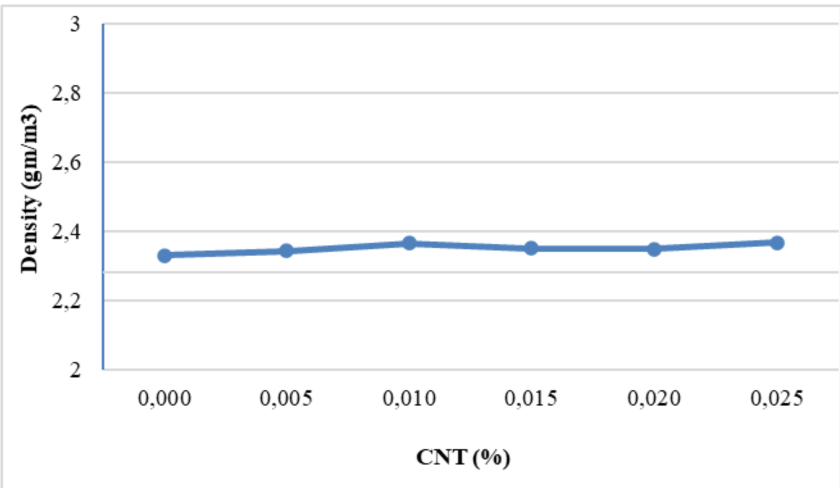

Fig 1. Density of AC-WC asphalt with CNTs addition

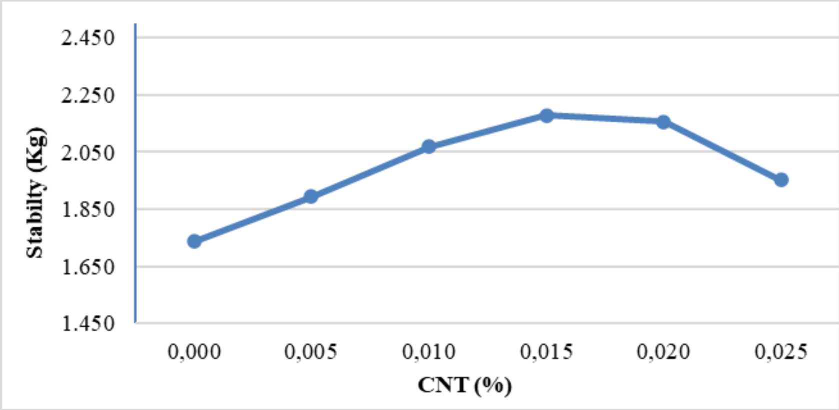

Fig 2. Stability of AC-WC asphalt with the addition of CNTs

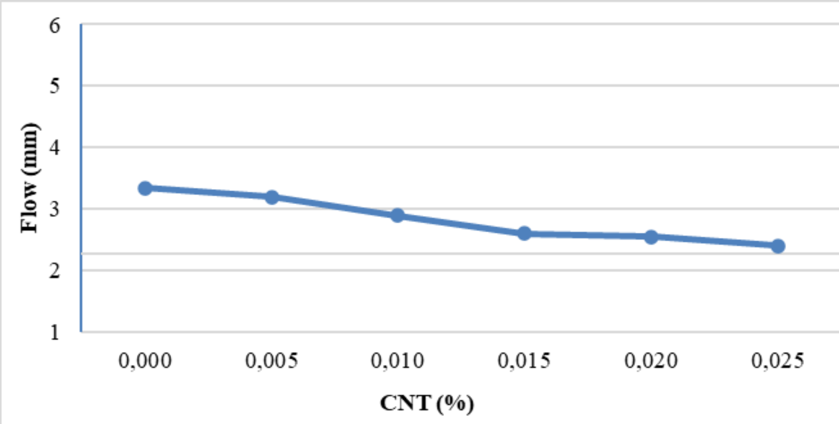

Fig 3. Flow of AC-WC asphalt with CNTs addition

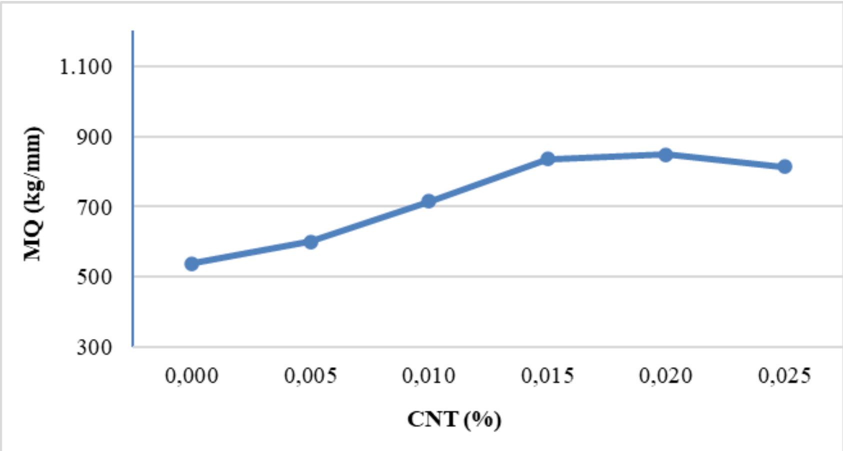

Fig 4. MQ AC-WC asphalt mixture with CNTs addition

5. Conclusions

The addition of CNTs to the AC-WC asphalt mixture demonstrates a positive impact on the mixture's performance, enhancing its mechanical properties and durability. CNTs improve the physical and chemical properties of the asphalt, increasing its stiffness and viscosity and enhancing the overall performance of the asphalt mixture. Specifically, the study found a 25% increase in the stability value by adding 0.015% CNTs compared to the control sample. Additionally, the flow of the mixture decreased by 18% as the CNT concentration increased, contributing to a higher melting point of the asphalt and more excellent aggregate compaction. This improved compaction results in enhanced stability, demonstrating the potential of CNTs to optimize the performance and durability of asphalt mixtures for better long-term pavement performance.

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