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Developing an Environmentally Friendly Semi Warm Asphalt Pavement Mix Using Polymers and Nanocomposite Materials

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Abstract

Road networks are commonly built using hot mix asphalt (HMA). The aim of the sustainable asphalt pavement industry is to reduce gas emissions and mixing temperatures. Half-warm mix asphalt (HWMA) is seen as a viable alternative to HMA, as it is produced and mixed at lower temperatures ranging from 65 to 100 degrees Celsius. Additives are necessary for improving workability during mixing and compaction. This research focuses on developing HWMA at 90 degrees Celsius using nanocomposite materials such as Ethoxylated Nonyl Phenol (NP9), Advera, Natural Zeolite, and Synthetic Zeolite. Chemicals like Epoxy, Zinc oxide, and sytric acid are added in specific percentages by weight of bitumen. The study found that the stability of the Marshall test improved with the use of nanocomposite materials. The optimal percentages of NP9, Advera, Natural Zeolite, and Synthetic Zeolite were determined to be 10%, 0.35%, 0.4%, and 0.5% respectively. Synthetic Zeolite was identified as the most effective material for enhancing asphalt mixture stability and producing eco-friendly HWMA. By using 0.5% Synthetic Zeolite, 5% Epoxy, and 10% Sytric, an eco-friendly HWMA with maximum stability was achieved.

Keywords: Eco-friendly, Hot mix asphalt; Half warm mix asphalt, Nanocomposite materials, Gases emission.

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I. INTRODUCTION

Asphalt pavement is widely used for constructing road networks worldwide [1-5]. Road networks primarily utilize hot mix asphalt (HMA) for construction [6]. Asphalt mixtures are classified based on the temperature at which they are mixed and prepared, which includes cold mix asphalt (CMA), half-warm mix asphalt (HWMA), warm mix asphalt (WMA), and hot mix asphalt (HMA) [6]. The mixing temperatures for these mixtures typically fall within the ranges of 0 to 40 °C, 65 to 100 °C, 110 to 140 °C, and 140 to 180 °C, respectively [7-11]. HWMA is gaining popularity as a viable option for structural road pavement due to its comparable performance to HMA. While CMA is primarily used for road maintenance and low traffic loading conditions, HWMA offers a more robust solution for constructing new roads [12]. The production of such mixtures offers several benefits in terms of environmental impact, technical aspects, ecology, and cost-effectiveness. It reduces emissions of harmful gases, making it an environmentally friendly option. HWMA provides additional advantages compared to HMA in terms of easier laying, compacting, and lower production temperatures. These mixtures also offer logistical benefits by allowing increased hauling distance and improved working conditions, making them safer than HMA during the process of laying and compacting [13]. Moisture-induced damage, also known as stripping, refers to the deterioration of a pavement caused by the loss of adhesive bond between asphalt binder and aggregate surface, as well as the loss of cohesion within the binder, primarily due to water. This process disrupts the integrity of the pavement mixture, leading to accelerated distress modes such as rutting, fatigue cracking, ravelling, potholes, and flushing, thereby reducing the overall life cycle of the pavement. Several factors influence the assessment of stripping in pavements. These include the presence of construction cracks, the content of air voids within the pavement, environmental conditions, and the duration of exposure to moisture. To evaluate stripping, four major standard test methods are commonly used. These methods serve as guidelines for assessing the susceptibility of pavement mixtures to moisture-induced damage [14, 15, 16]. In this paper, nanocomposite materials NP9, Advera, Natural Zeolite, and Synthetic Zeolite are used and added to the control mix by different percentages to produce HWMA. Also, chemicals as Epoxy, Zinc oxide, and Stearic acid are added to the mixture by 5%, 10%, and 10% respectively by weight of bitumen. The stability of different asphalt mixtures is evaluated and compared.

II. RESEARCH OBJECTIVES

The objectives of this study are summarized as follows: -

1. Produce semi-warm asphalt mixtures at a temperature of 90°C by using nanocomposite materials.
2. Reducing the used energy when heating the asphalt and thus reducing the amount of fuel.
3. Producing environmentally friendly asphalt mixes by reducing gases emissions.
4. Improving the lifetime of asphalt.

III. MATERIALS

Bitumen

The bitumen that was used for producing all the specimens that tested later was 60/70 penetration grade and sourced from Suez, Egypt. Laboratory tests were conducted to assess the physical properties of the bitumen. The tests included determining the penetration, softening point, and kinematic viscosity of the bitumen using ASTM standards (specifically ASTM D5-06 for penetration, ASTM D36-06 for softening point, and ASTM D4402-06 for kinematic viscosity) [17, 18, 19,20] are cited in Table 1.

Table 1: Physical Characteristics of Bitumen

Property	Result	Specification limits
Penetration at 25°C (0.1 mm)	66	60 - 70
Kinematic Viscosity at 135˚C	369	+ 320
Softening Point, °C	53	45 - 55

Aggregate

Crushed aggregate sourced from Atta 'a mountain in Suez, Egypt was used in this study. Various experiments and tests were conducted to determine the physical properties of the aggregate. Gradation tests were performed to analyze the distribution of aggregate sizes. The results of these tests, along with the physical properties of the aggregate, were compiled and presented in Table 2. Additionally, the erosion test results for the aggregate are presented in Table 3.

Table 2: Physical Properties of Aggregate

Properties	Aggregate size 1	Aggregate size 2	Specification limits
Specific weight	2.65	2.566	------------
Saturated-dry surface	2.684	2.612	------------
Apparent specific weight	2.743	2.689	------------
Water absorption%	1.27	1.77	≤ 5%

Table 3: Aggregate Erosion

Properties	Aggregate size 1	Aggregate size 2	Specification limits
Percentage of loss after 500 cycles after washing	20.16	19.16	≤ 40%
Percentage of loss after 100 cycles after washing	5.06	4.20	≤ 10%

Nanocomposite Materials

1. Advera

Advera is a synthetic zeolite supplied by PQ Corporation, a leading provider of silicates, silicas, and derivative products globally. Advera is a finely powdered substance that, when added to asphalt mix along with the binder, releases water. This water release creates foaming of the asphalt binder, enhancing workability and improving aggregate coating at lower temperatures. When heated between 185°F and 360°F, Advera releases 21% of its mass as water, resulting in microscopic foaming of the asphalt, which aids in the coating of aggregate particles. This foaming action acts as a temporary asphalt volume extender and lubricant, enabling the mix to be workable and compactable at significantly lower temperatures than traditional Hot Mix Asphalt (HMA). According to PQ Corporation, the mix can be compacted until the temperature drops below 212°F. By incorporating Advera, production and mixing temperatures for the asphalt can be reduced by 30-40 °C compared to conventional HMA. PQ Corporation recommends adding 0.25% of Advera by weight to the mix. Importantly, Advera is considered an inorganic material, similar to aggregate, and does not affect the performance grade of the asphalt binder [21]. Figure 1 shows the sample of Advera as a nanocomposite material.

2. Natural and Synthetic Zeolite

An alternative method of creating foam in the binder involves adding a water-bearing mineral to the mixture along with the binder. This process leads to foaming of the binder and a subsequent reduction in viscosity. Synthetic zeolite, which has undergone hydro-thermal crystallization, is commonly used for this purpose. This zeolite contains approximately 20% water of crystallization, which is released when the temperature exceeds 85 °C. When this additive is introduced to hot binder, it forms a fine mist that enhances workability for a period of 6 to 7 hours [21]. Foaming additives can be combined with aggregates and binder to temporarily enhance workability. However, caution is necessary due to the presence of water vapor during the process. Typically, zeolites are added to the mixture at a weight percentage of 0.25-0.30%. Figure 2 and Figure 3 provide visual representations of a natural zeolite sample and a synthetic zeolite sample, respectively.

Figure 3: Sample of Synthetic Zeolite

Figure 2: Sample of Natural Zeolite

Figure 1: Sample of Advera

3. Ethoxylated Nonyl Phenol (NP9)

Nonylphenol (NP) and nonylphenol ethylates (NPEs) are produced in significant quantities and are commonly released into aquatic environments. NP is a viscous liquid that appears clear to pale yellow in color at room temperature. It has moderate water solubility and moderate vapor pressure [6, 22,23, 24]. Nonylphenol (NP) exhibits moderate volatility. Studies have demonstrated that in certain areas, there can be a process of water-to-air volatilization, leading to substantial atmospheric concentrations of NP substances [25]. In the atmosphere, nonylphenol (NP) undergoes rapid degradation by hydroxyl radicals. As a result, it is not anticipated to persist in the air over an extended period [25]. Figure 4 shows a sample of NP9.

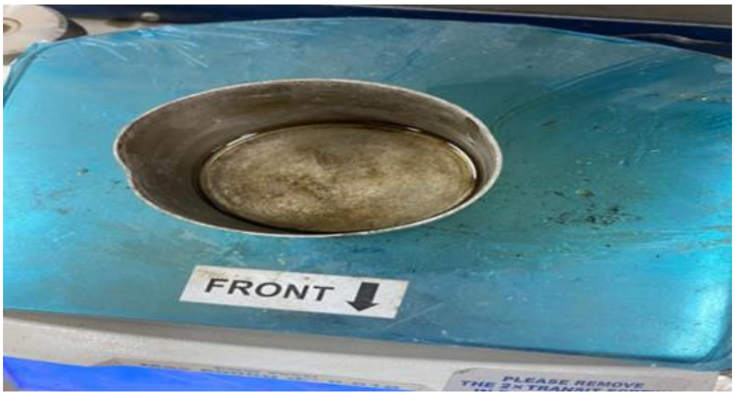

Figure 4: Sample of NP9

IV. EXPERIMENTAL WORK

An experimental study was conducted to evaluate and compare the improvements in the rheological and mechanical properties of bitumen and asphalt mixtures. This was achieved by introducing nanocomposite or polymer materials as additives.

- **Marshall Stability and Flow Tests (T245)**

The AASHTO standard T245 is utilized for a specific test [26, 27, 28]. The testing procedure includes the preparation of Marshall Specimens, which involves subjecting aggregates to a temperature of 160°C for 2 hours to remove any moisture. Similarly, the bitumen is heated at the same temperature and duration. The Marshall Specimens, weighing 1.2 kg, are prepared according to the mix components specified in Table 4. The mixture is then heated using a fire flame at 150°C. The materials are added in a specific order to a metallic bowl: coarse aggregate first, followed by fine aggregate and filler (stone dust), and finally, the bitumen.

Table 4: Mix Components in Marshall Test for Control Mix

Mix Components	Percentage of Components (percent)	Mix Components (gm)
Aggregate 1	30%	360
Aggregate 2	20%	240
Natural sand	15%	180
Crushing sand	33%	396
powder	2%	24
Bitumen 60/70	5%	----
Total weight of specimen		1200

The materials were mixed in a bowl using a mixer for approximately 3.5 minutes at a constant rate of 100 rpm. Once the mixing process was completed, the mixture was manually transferred into a metallic bowl and returned to the oven at the same temperature for 1 hour using Marshall moulds. After the hour had passed, the mixture was placed into the Marshall moulds and compacted by applying 75 blows on each side of the specimen using a Marshall Hammer. Following compaction, the specimens were allowed to cool to ambient temperature and then carefully removed from the moulds. This process successfully produced Marshall specimens of the asphalt mixture type. The Marshall test, conducted according to ASTM D6927–15 [23], aimed to determine various Marshall parameters such as stability, flow, air voids (AV %), voids in mineral aggregate (VMA %), and the mixture unit weight, as presented in Table 5.

Table 5: Asphalt Mixture Characteristics

Asphalt mixture characteristics	Value	Specification Limits
Unit weight (gm)	2.33	---------
Air voids %	4.2	3-5
VMA%	15.6	≥ 15.2
Stability (kg)	1350	≥ 1200
Flow (mm)	2.9	2-4

V. RESULTS

Four different samples were prepared, each containing varying percentages of additives as indicated in the tables. The experimental results were obtained after incorporating all the previously mentioned additives into the samples. They were plotted; presented on graphs and discussed here, as follows:

1. Advera and Other Additives

Stability of control mix (CM) and modified control mix (MCM) with 0.2%, 0.35%, and 0.4% of Advera, 5% epoxy, 10% zinc and 10% Stearic acid are presented in Table 6 and Figure 5. The results indicate that the maximum stability without chemical additives was 783.36 kg for MCM with 0.35% of Advera. Also, it is noticed that the maximum stability with chemical additives was 820 kg for the

MCM with 0.35% of Advera, 5% of Epoxy and 10% of Stearic acid.it can be concluded that it is not recommended to add epoxy alone to MCM in this case it decreases the stability values. In contrast to achieve increasing in the stability values it is recommended to add epoxy with zinc.

Table 6: Stability Values of CM with Additives of Advera and Other Chemical Additives

		1	2	3	4
Samples 1	Additives %	0	0.2% advera	0.35% advera	0.4% advera
	Stability	203.87	755.82	783.36	671.97
Samples 2	Additives %	0	0.35% advera	0.35% advera + 5%epoxy	-
	Stability	203.87	783.36	711.246	-
Samples 3	Additives %	0	0.35% advera	0.35% advera + 5%epoxy	0.35% advera + 5% epoxy + 10% zinc
	Stability	203.87	783.36	711.24	820
Samples 4	Additives %	0	0.35% advera	0.35% advera + 5% epoxy	0.35% advera + 5% epoxy + 10% Stearic acid
	Stability	203.87	783.36	711.24	644.3

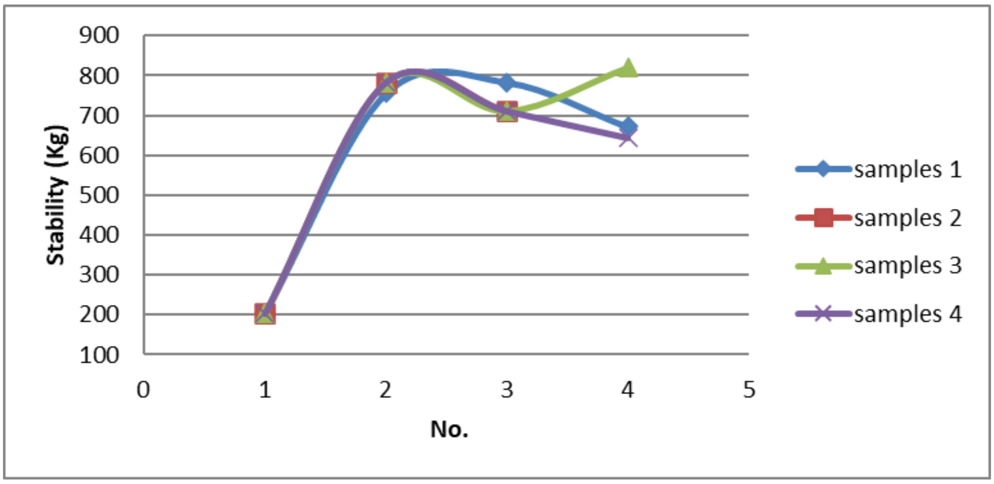

Figure 5: Stability Values of CM with Additives of Advera and Other Chemical Additives

2. Natural and Synthetic Zeolite

2.1 Natural Zeolite and Other Chemical Additives

Stability of CM and MCM with 0.3%, 0.4%, and 0.5% of natural zeolite, 5% epoxy, 10% zinc and 10% Stearic acid are presented in Table 7 and Figure 6. From The results it is observed that the maximum stability without chemical additives was 666.26 kg for MCM with 0.4% of natural zeolite. Also, it is found that the maximum stability with chemical additives was 1278.67 kg for the MCM with 0.4% of natural zeolite, 5% of Epoxy and 10% of Stearic acid. It can be concluded that adding epoxy with zinc or Stearic acid led to achieve increasing in the stability values.

Table 7: Stability Values of CM with Additives of Natural Zeolite and Other Chemical Additives

		1	2	3	4
Samples 1	Additives %	0	0.3% natural zeolite	0.4% natural zeolite	0.5% natural zeolite
	Stability	203.87	593.283	666.264	470.22
Samples 2	Additives %	0	0.4% natural zeolite	0.4% natural zeolite + 5% epoxy	-
	Stability	203.87	666.264	785.128	-
Samples 3	Additives %	0	0.4% natural zeolite	0.4% natural zeolite + 5% epoxy	0.4% natural zeolite + 5% epoxy + 10% zinc
	Stability	203.87	666.264	785.128	1112.106
Samples 4	Additives %	0	0.4% natural zeolite	0.4% natural zeolite + 5% epoxy	0.4% natural zeolite + 5% epoxy + 10% Stearic acid
	Stability	203.87	666.264	785.128	1278.672

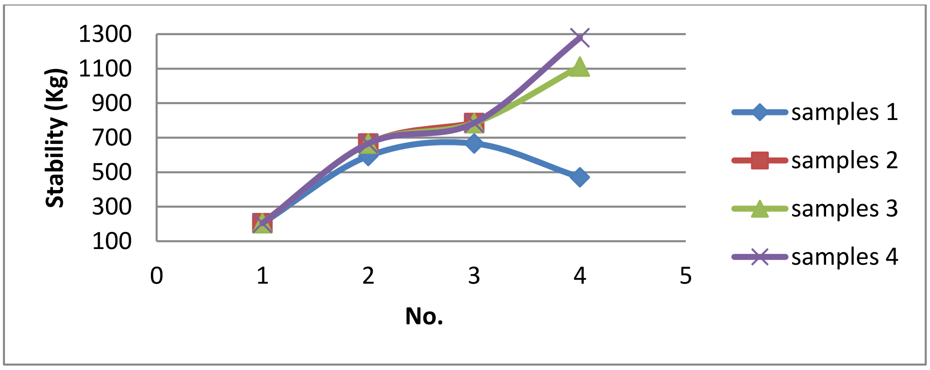

Figure 6: Stability Values of CM with Additives of Natural Zeolite and Other Chemical Additives

2.2 Synthetic Zeolite

Stability of CM and MCM with 0.25%, 0.5% and 0.75% of synthetic zeolite, 5% epoxy, 10% zinc and 10% Stearic acid are presented in Table 8 and Figure 7. From The results it is noticed that the maximum stability without chemical additives was 706.50 kg for MCM with 0.5% of synthetic zeolite. Also, it is observed that the maximum stability with chemical additives was 1341.57 kg for the MCM with 0.5% of synthetic zeolite, 5% of Epoxy and 10% of Stearic acid. It can be concluded that adding epoxy with zinc or Stearic acid led to achieve increasing in the stability values.

Table 8: Stability Values of CM with Additives of Synthetic Zeolite and Other Chemical Additives

		1	2	3	4
Samples 1	Additives %	0	0.25% synthetic zeolite	0.5% synthetic zeolite	0.75% synthetic zeolite
	Stability	203.87	639.234	706.503	602.82
Samples 2	Additives %	0	0.5% synthetic zeolite	0.5% synthetic zeolite + 5% epoxy	-
	Stability	203.87	706.503	837.93	-
Samples 3	Additives %	0	0.5% synthetic zeolite	0.5% synthetic zeolite + 5% epoxy	0.5% synthetic zeolite + 5% epoxy + 10% zinc
	Stability	203.87	706.503	837.93	1144.236
Samples 4	Additives %	0	0.5% synthetic zeolite	0.5% synthetic zeolite + 5% epoxy	0.5% synthetic zeolite + 5% epoxy + 10% Stearic acid
	Stability	203.87	706.503	837.93	1341.572

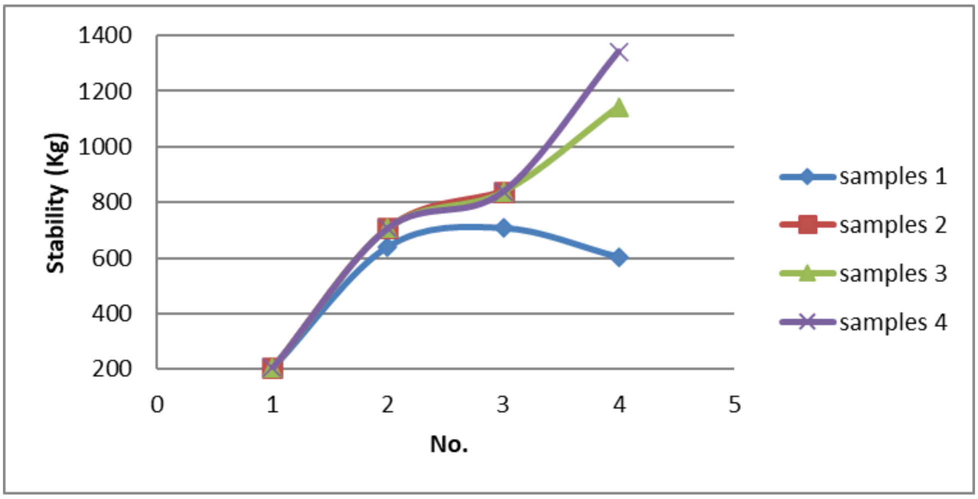

Figure 7: Stability Values of CM with Additives of Synthetic Zeolite and Other Chemical Additives

3. Ethoxylated Nonyl Phenol (NP9)

Stability of CM and MCM with 10%, 20%, and 25% of NP9, 5% epoxy, 10% zinc and 10% Stearic acid by weight of bitumen are presented in Table 9 and Figure 8. The results indicate that the maximum stability was 692.88 kg for MCM with 10% of NP9 by weight of bitumen and without other chemical additives. Also, the results indicate that the maximum stability was 1329.23 kg for the MCM with 0.1% of NP9, 5% of Epoxy and 10% of Stearic acid.

Table 9: Stability Values of CM with Additives of NP9 and Other Chemical Additives

		1	2	3	4
Samples 1	Additives %	0	10% NP9	20% NP9	25% NP9
	Stability	203 .87	692.886	675.495	670.599
Samples 2	Additives %	0	10% NP9	10% NP9 + 5% epoxy	-
	Stability	203 .87	692.886	1034.518	-
Samples 3	Additives %	0	10% NP9	10% NP9 + 5% epoxy	10% NP9 + 5% epoxy + 10% zinc
	Stability	203 .87	692.886	1034.518	1133.764
Samples 4	Additives%	0	10% NP9	10% NP9 + 5% epoxy	10% NP9 + 5% epoxy + 10% Stearic acid
	Stability	203 .87	692.886	1034.518	1329.23

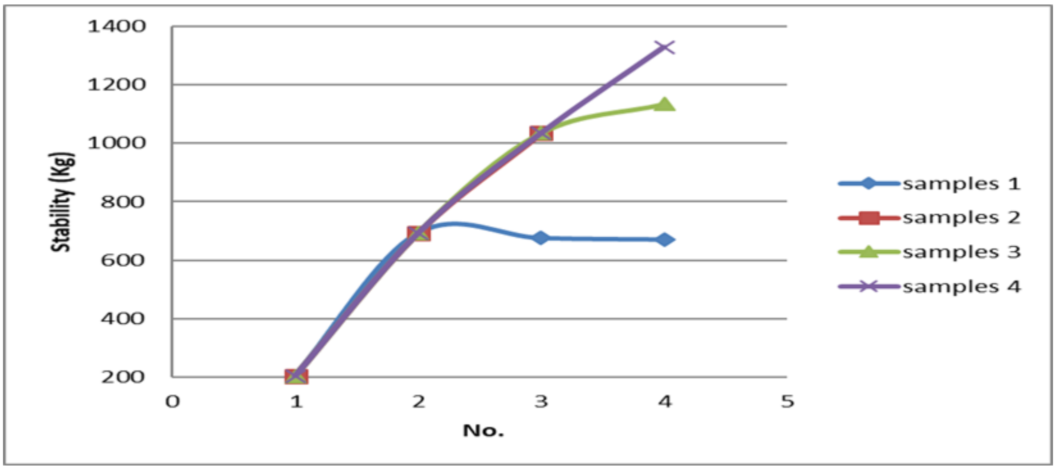

Figure 8: Stability Values of CM with Additives of NP9 and Other Chemical Additives

4. Comparison between Stability of CM and MCM Using Nanocomposite Materials after Adding Epoxy and Zinc Oxide

Stability values of CM and MCM using Nanocomposite materials after adding Epoxy and Zinc are shown in Table 10 and Figure 9. The results indicated that the maximum stability was 1144.23 kg for MCM with 0.5% of Synthetic zeolite, 5% of Epoxy and 10% of Zinc.

Table 10: Stability of CM and MCM Using Nanocomposite Materials after Adding Epoxy and Zinc

Mixtures	Stability (kg)
CM	203.87
MCM (0.35% Advera + 5% Epoxy + 10% Zinc)	820
MCM (10% NP9 + 5% Epoxy + 10% Zinc)	1133.764
MCM (0.4% Natural zeolite + 5% Epoxy + 10% Zinc)	1112.106
MCM (0.5% Synthetic zeolite + 5% Epoxy + 10% Zinc)	1144.236

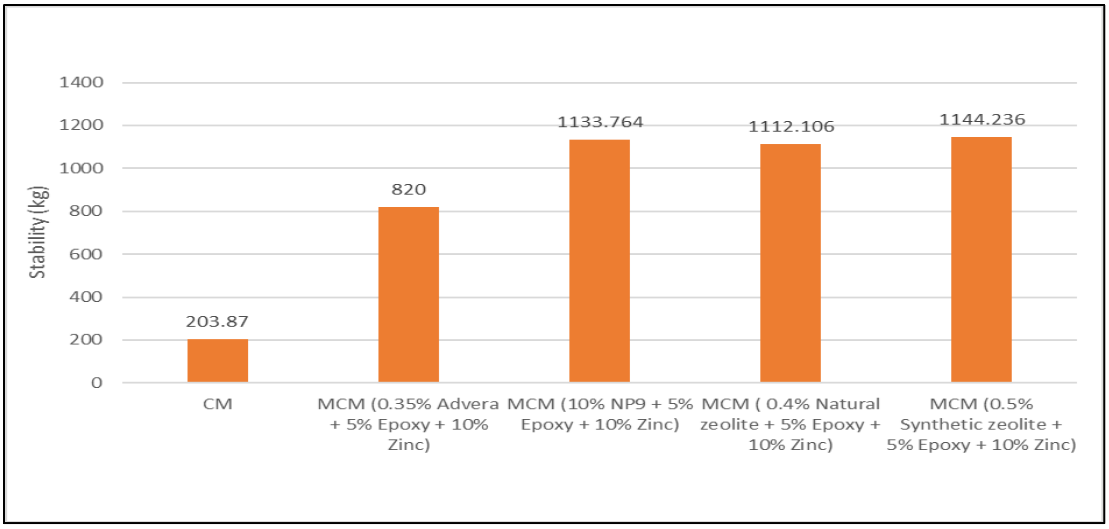

Figure 9: Stability of CM and MCM using Nanocomposite materials after adding Epoxy and Zinc

5. Comparison between Stability of CM and MCM Using Nanocomposite Materials after adding Epoxy and Stearic Acid.

Stability values of CM and MCM using Nanocomposite materials after adding Epoxy and Stearic acid are shown in Table 11 and Figure 10. The results indicated that the maximum stability was 1341.57 kg for MCM with 0.5% of Synthetic zeolite, 5% of Epoxy and 10% of Stearic acid.

Table 11: Stability of CM and MCM using Nanocomposite materials after adding Epoxy and Stearic acid

Mixtures	Stability (kg)
CM	203.87
MCM (0.35% Advera + 5% Epoxy + 10% Stearic acid)	644.3
MCM (10% NP9 + 5% Epoxy + 10% Stearic acid)	1329.23
MCM (0.4% Natural zeolite + 5% Epoxy + 10% Stearic acid)	1278.672
MCM (0.5% Synthetic zeolite + 5% Epoxy + 10% Stearic acid)	1341.572

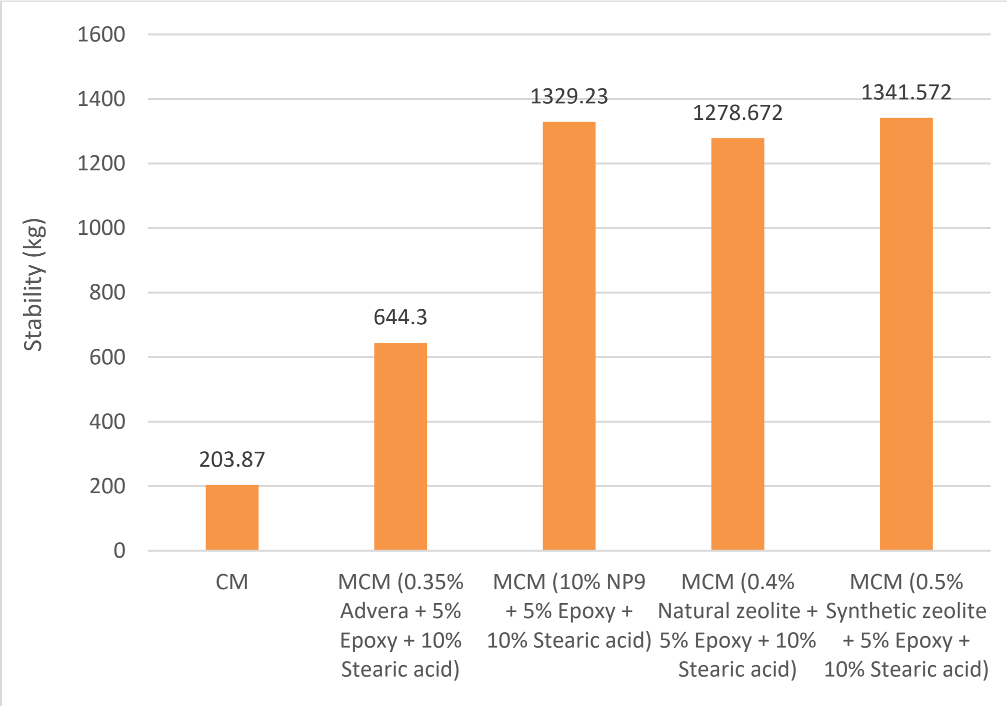

Figure 10: Stability of CM and MCM using Nanocomposite materials after adding Epoxy and Stearic acid

VI. CONCLUSION AND RECOMMENDATIONS

- **Conclusion**

Based on the results obtained from this research, the following conclusions are provided:

1. The Stability of Marshall test is enhanced using nanocomposite materials to produce HWMA at 90^{o}C.

2. 10% NP9 or 0.35% Advera or 0.4% Natural Zeolite or 0.5% Synthetic Zeolite can be selected as the optimum additive content where the stability of CM increases by around 240%, 284%, 227% and 247% respectively.

3. By adding 5% Epoxy and 10% Stearic acid to MCM with 0.35% Advera increase the stability of CM by around 316%.

4. By adding 5% Epoxy and 10% Stearic acid to MCM with 10% NP9 increase the stability of CM by around 652%.

5. By adding 5% Epoxy and 10% Stearic acid to MCM with 0.4% Natural Zeolite increase the stability of MCM by around 627%.

6. By adding 5% Epoxy and 10% Stearic acid to MCM with 0.5% Synthetic Zeolite increase the stability of MCM by around 658%.

7. By adding 5% Epoxy and 10% Zinc to MCM with 0.35% Advera increase the stability of CM by around 402%.

8. By adding 5% Epoxy and 10% Zinc to MCM with 10% NP9 increase the stability of CM by around 556%.

9. By adding 5% Epoxy and 10% Zinc to MCM with 0.4% Natural Zeolite increase the stability of MCM by around 545%.

10. By adding 5% Epoxy and 10% Zinc to MCM with 0.5% Synthetic Zeolite increase the stability of MCM by around 561%.

- **Recommendations**

Based on the results obtained from this research and the conclusion, the following recommendations are provided:

1. Synthetic Zeolite is the best nanocomposite materials to enhance the stability of asphalt mixture and produce an eco-friendly half warm asphalt pavement mix.

2. Adding of 0.5% Synthetic Zeolite, 5% Epoxy and 10% Stearic acid to produce an eco-friendly HWMA with maximum stability (around 658% of CM stability).

3. It is recommended to achieve stripping susceptibility, wheel track, indirect tensile strength and tensile strength ratio tests.

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