Using Metakaolin Material As Additive For Hot Asphalt Mixtures

Islam Abo El-Naga[1] **Akram Elsaied Mostafa**[2] **Mohamed Ragab**[3]

[1] *Associate Prof., Dept. of Public Works Eng., Faculty of Engineering, Tanta University, Egypt*
e-mail: islam_aboelnaga@f-eng.tanta.edu.eg

[2] *Assistant Lecturer, Dept. of Public Works Eng., Faculty of Engineering, Tanta University, Egypt*
e-mail: akram.elsaied@f-eng.tanta.edu.eg

[3] *Assistant Prof., Dept. of Civil Eng., Faculty of Engineering, Suez University, Egypt (Corresponding Author)*
e-mail: mohamed.ragab@suezuni.edu.eg

ABSTRACT

In recent years, the using of modifiers was used to improve the performance of asphalt binder and asphalt mixtures. In this research, metakaolin material is investigated as an additive to modify asphalt cement properties. A comparative test program was conducted on asphalt binders and asphalt mixtures to assess the effects of nano metakaolin (NMK) material on pavement performance. The NMK material was used instead of part of the asphalt binder with different percentages (0%, 2%, 4%, 6%, 8%, and 10%) by weight. A number of basic tests were conducted on asphalt binder such as the penetration, softening point, flash point, and absolute viscosity tests. Furthermore, standard Marshall, loss of stability, and rutting tests were carried out on asphalt mixtures. The results indicated that the physical properties of the modified asphalt binder with NMK material were improved. Moreover, the use of NMK material has greatly affected the pavement resistance to deformation. Finally, using the NMK material with a percentage of 6% by weight of asphalt binder achieved a greater improvement in the mechanical properties of the modified mixtures.

Keywords

Asphalt Binder, Asphalt Mixtures, Marshall Test, Metakaolin Material.

1. INTRODUCTION AND BACKGROUND

Asphalt pavement is exposed to many distresses caused by the deficiencies in construction, materials, and maintenance [1]. The mixture and adhesion of bitumen and aggregate surfaces under various situations may also lead to the low serviceability and durability of asphalt pavements [2]. Maintenance of such distresses is expensive and preventing the occurrence of these distresses requires more cost effective approaches [3].

Changing in asphalt mix design, material characteristics, material types, construction quality control, and using additives can improve the physical and mechanical properties of asphalt mixtures [4]. From this point of view, several attempts have been performed to enhance the performance, durability, and resistance of asphalt mixes, as well as the production of high-quality bitumen. Actually, various bitumen modifications have been made to achieve the desirable pavement properties by adding different additive materials to the asphalt mixtures [5]. To improve the performance of the asphalt mixtures, there are several types of additives such as mineral fillers, polymers, and waste materials [6]. The use of additives has gained popularity due to their high quality, versatility, and long-term performance [7]. Mostafa [8] investigated the effect of using nano materials such as nano silica and nano carbon on the physical and mechanical properties of hot asphalt mixtures. It was found that 7% and 0.5% of nano-silica and nano-carbon respectively are the optimum percentages for improving the properties of asphalt binder and asphalt mixtures.

Metakaolin material is considered one of the most important natural sources. It has many uses in different industry fields such as making ceramic and pottery pots, water treatment filters, as well as in medicine for treating the skin and removing toxins [9]. It is produced by the calcination method at a temperature of about 600-800 °C for two hours to allow the material to be used as a filler material [10]. In recent years, metakaolin material is used as a pozzolanic addition for mortar and concrete to provide enhanced strength [11,12]. Therefore, in this research, the impact of using metakaolin material on improving the performance of both asphalt binder and asphalt mixtures was investigated.

It should be noted that most of the previous studies demonstrated the effect of different types of additives on the performance of asphalt mixtures. Some research works have been done to the investigation the impact of metakaolin material on pavement performance. In a study conducted by Murano et al. [11], the authors used the metakaolin material as a modifier in asphalt mixtures. They used this material as a partial replacement for cement in asphalt mixtures. The study concluded that the mechanical properties and the volumetric properties of the investigated mixtures meet the standard specifications at an optimum bitumen content of 5.5%. Zghair et al. [6] investigated the impact of using nano metakaolin filler on the rheological properties of asphalt binder. The results of this study indicated that the use of nano metakaolin filler as a modifier enhanced the rheological properties of the asphalt binder. Moreover, 5% nano metakaolin by asphalt weight was an optimum percentage for achieving the better performance of the asphalt binder. Qasim et al. [13] evaluated the impact of using the metakaolin material in asphalt mixtures. They used this material instead of a part of cement mineral filler. The study concluded that using 50% metakaolin content with asphalt content of 5.2% is an appropriate choice for enhancing the mechanical properties of the asphalt mixtures.

2. TESTED MATERIALS AND THEIR PROPERTIES

2.1 Metakaolin Material

The used metakaolin (NMK) material in this research has an off-white-gray to buff color as shown in Figure 1. It was obtained from the Shak El-Thoban zone, Cairo, Egypt. Table 1 presents the physical properties of the used NMK material.

Figure 1: The NMK Material

Table 1: Physical Characteristics of MKF Material

Property	Description
Color	Off white-gray to buff
Brightness	81-83 Hunter L
Specific gravity	2.44 gm/cm^3
Average size	40 nm

2.2 Bitumen

One type of bituminous materials used in this research. The used type is asphalt cement (60/70) with a specific gravity of 1.02. It was obtained from Suez Petroleum Company. Table 2 presents the properties of the used asphalt binder.

Table 2: The Properties of the Used AC 60/70 Asphalt Cement

Test	**AASHTO Specs. No.**	**Results**	**Specification Limits**
Softening Point, ^{o}C	T-53	49	45-55
Penetration (25 ^{o}C , 0.1 mm)	T- 49	62	60-70
Flash Point, ^{o}C	T- 48	276	≥ 250
Kinematic Viscosity (135 ^{o}C, Cst)	T-201	339	≥ 320
Absolute Viscosity, Poise	T-201	4067	≥ 4000

2.3 Aggregates

The suitability of aggregates used in asphalt mixtures is assessed in terms of many properties. These properties include size, specific gravity, grading, durability, and particle shape and texture. It is important to note that all aggregate properties should be meeting the standard specifications to insure good pavement performance.

All used aggregates were obtained from ATAKA quarry, Suez Governorate, Egypt. They include coarse aggregates, fine aggregates, and mineral filler. The coarse aggregates used in this research are crushed siliceous dolomite with sizes (1.0 and 2.0 inch). While the fine aggregates are siliceous sand, the mineral filler is lime stone powder with a bulk specific gravity of 2.85. The physical properties of the used coarse aggregates, fine aggregates, and mineral filler are presented in Tables 3 and 4. The gradation and specification limits of the used aggregates are given in Table 5.

Table 3: Characteristics of the Used Coarse Aggregates

Test	AASHTO Specs.	Results	Specification Limits
% Water absorption	T-85	2.44	≤ 5%
% Disintegration	T-112	0.52	≤ 1%
% Stripping	T-182	92	≤ 95%
%Los Angeles Abrasion after 100 rev.	T-96	5.5	≤ 10%
%Los Angeles Abrasion after 500 rev.	T-96	28	≤ 40%
Bulk specific gravity	T-85	2.534	-
Apparent specific gravity	T-85	2.673	-
Saturated surface dry specific gravity	T-85	2.541	-

Table 4: Characteristics of the Used Fine Aggregates

Test	AASHTO Specs.	Results	Specification Limits
% Water absorption	T-85	2.10	≤ 5%
% Disintegration	T-112	0.35	≤ 1%
% Stripping	T-182	89	≤ 95%
%Los Angeles Abrasion after 100 rev.	T-96	4.9	≤ 10%
%Los Angeles Abrasion after 500 rev.	T-96	18	≤ 40%
Bulk specific gravity	T-85	2.531	-
Apparent specific gravity	T-85	2.662	-
Saturated surface dry specific gravity	T-85	2.532	-

Table 5: Gradation of the Used Aggregates

Sieve Size (mm)	Percent Passing, %			
	Coarse Aggregates		Fine Aggregates	Mineral Filler
	Size 1.0 inch	Size 2 inch		
25	100	100	100	100
19	98.9	100	100	100
9.52	53.4	86.5	100	100
4.75	9.6	2.8	96.3	100
2.36	1.2	0.3	85.9	100
0.60	0.7	-	46.8	100
0.30	0.3	-	23.1	97
0.15	0.16	-	2.9	91
0.075	0.11	-	1.6	89

2.4 Asphalt Mixtures

The selected gradation of the investigated asphalt mixtures in this research is the 4-C gradation according to the Egyptian standard specifications for wearing surface layer [14]. Table 6 represents the used mixture gradation and the corresponding specification limits.

Table 6: The Gradation of the Investigated Asphalt Mixtures

Sieve Size (mm)	Percent Passing, %	Specifications Limits of 4-C
25	100	100
19	92	80 - 100
9.52	71	60 - 80
4.75	53	48 - 65
2.36	43	35 - 50
0.60	25	19 - 30
0.30	19	13 - 23
0.15	12	7 - 15
0.075	5	3 - 8

3. EXPERMENTAL PROGRAM

3.1 Sample Preparation

3.3.1 Modified asphalt binder

For preparing the modified asphalt binder, NMK material was heated to 140°C in a particular pan with standard and specific dimensions and gently added to the heated asphalt cement that had been heated to 140°C. They were mixed for an extended length of time to obtain a homogenous blend. The homogeneity of the blend was evaluated by visual examination.

3.3.2 Modified asphalt mixture

For preparing the investigated specimens of asphalt mixtures, designed aggregates were batched and heated to 140°C according to gradation. Separately, modified asphalt binder was heated to 140°C and applied to the aggregate at a predetermined pace. The used aggregate and the modified asphalt binder were mixed until the aggregate particles are thoroughly covered with asphalt.

3.2 Testing on Asphalt Binder

Several experiments were performed on both original asphalt bitumen and produced adjusted asphalt samples to evaluate asphalt cement characteristics. The modified specimens are made by varying the percentages of NMK material (0%, 2%, 4%, 6%, 8%, and 10%) by the weight of asphalt. The laboratory tests including penetration, softening point, flash point, and absolute viscosity tests were carried out to assess the properties of the modified asphalt binder. While the penetration test was performed according to ASTM D5 [15] to measure the consistency of the binder, the softening point test was performed according to ASTM D36 [16] to determine the temperature at which the binder reaches certain softness. Furthermore, the flash point test ASTM D92-05a [17] was used to determine the temperature to which binder can be safely heated in the presence of an open flame. The absolute viscosity test was carried out to measure the flow of the binder [18].

3.3 Testing on Asphalt Mixtures

The binders modified with 2%, 4%, 6%, 8%, and 10% of NMK were selected to prepare the investigated modified mixtures. Many tests were conducted on the investigated specimens of asphalt mixtures including Marshall test, loss of stability test, and wheel tracking test. While the standard Marshall test was performed according to ASTM D6927 [19] to determine the optimum asphalt contents, the corresponding physical and mechanical properties, the loss of stability test was carried out according to AASHTO T-165 [20] to evaluate the moisture durability for asphalt mixtures. Moreover, the wheel tracking test was described by British Road Research Laboratory [21] to simulate the rutting test.

4. RESULTS AND DISCUSSION

4.1 Effect of MKF Material on the Properties of Asphalt Binder

Table 7 presents a summary of results of the tests conducted to investigate the effect of NMK material on the proprieties of asphalt binder. Figure 2 depicts the influence of the NMK percentages on both the penetration values and softening point of the binder. It can be noticed that the penetration values decreased with increasing the NMK percentage. On the other hand, the softening point values increased with increasing the NMK percentage. Furthermore, the effect of the MKF percentages on both the flash point values and absolute viscosity of the binder is shown in Figure 3. It is notable that the increase of NMK percentage always exhibited higher values for both flash point and absolute viscosity.

Table 6: Prosperities of the Modified Asphalt Binder Prepared with Different Percentages of NMK

Percentages of NMK %	0	2	4	6	8	10
Penetration (0.1 mm)	68	42.2	41.9	41.1	40.6	39.8
Softening Point (C°)	47	51.3	52.2	53.4	53.9	54.3
Flash Point (C°)	240	265	280	295	305	312
Absolute Viscosity (Poise)	4045	4355	4580	4810	4920	5044

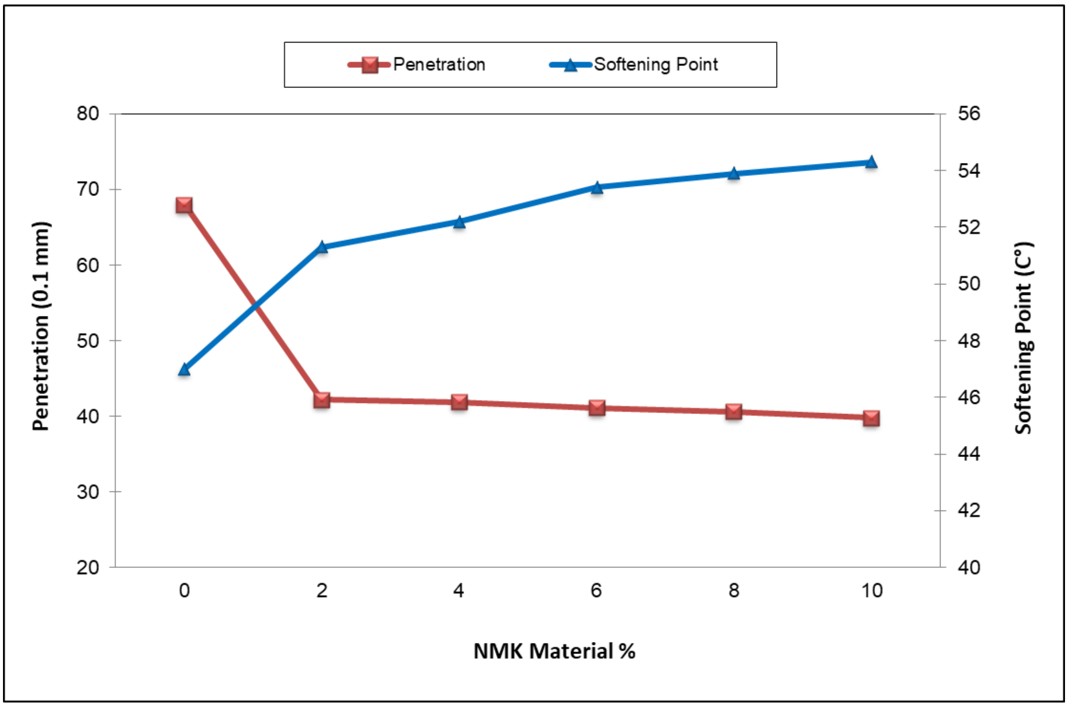

Figure 2: Penetration and Softening Point versus the Percentage of NMK

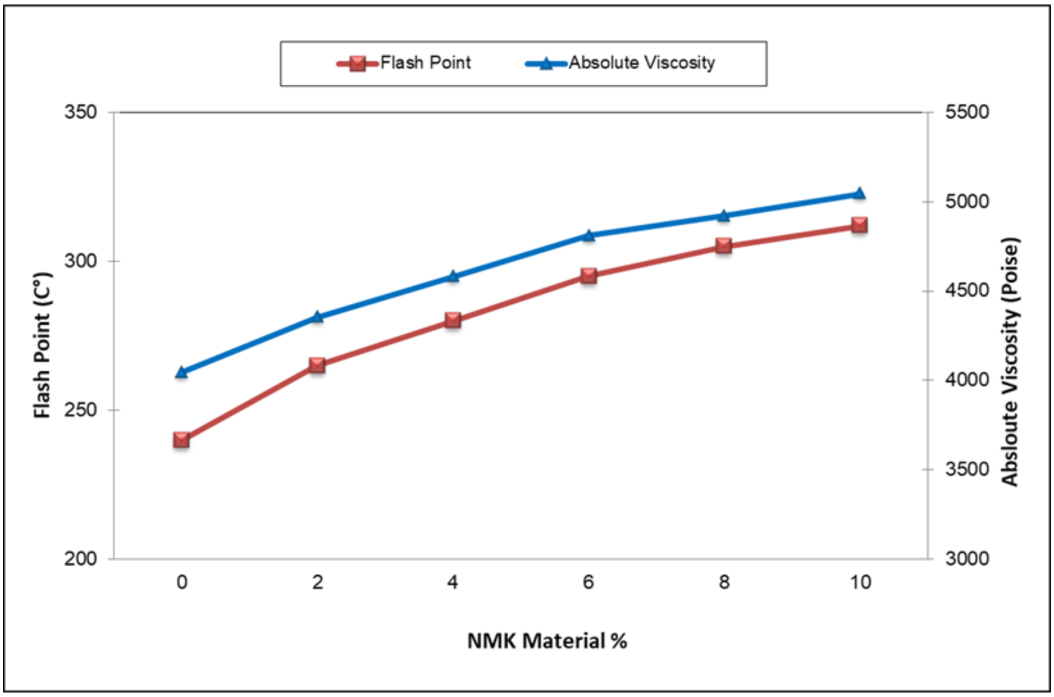

Figure 3: Flash Point and Absolute Viscosity versus the Percentage of NMK

4.2 Effect of MKF Material on the Performance of Asphalt Mixtures

4.2.1 Marshall test results

Table 7 summarizes the results of the Marshall test for the modified hot mix asphalt (HMA) mixtures. It presents the Marshall stability, flow, Marshall Stiffness Modulus (M_s), Marshall Quotient (MQ), unit weight (γ), and optimum asphalt content (AC%) of the modified HMA mixtures as well as the volumetric properties including air voids percentage (AV%), voids percentage in the mineral aggregate (VMA%), and voids percentage filled with asphalt (VFA%).

Table (7): Marshall Test Results for the Investigated Asphalt Concrete Mixtures

NMK Material %	AC %	γ gm/cm^3	Stability kg	Flow 0.25 mm	AV%	VMA%	VFA%	M_s* Kg/mm^2	MQ** kg/mm
0	4.8	2.208	604	10.9	3.8	14.2	72.1	3.49	221.65
2	4.5	2.276	624	9.2	4.1	13.9	68.7	4.27	271.30
4	4.5	2.281	658	9.0	4.1	13.3	68.3	4.61	292.45
6	4.4	2.296	696	8.6	4.3	12.8	67.9	5.10	323.72
8	4.4	2.275	664	8.9	4.3	12.6	67.5	4.70	298.43
10	4.3	2.269	647	9.1	4.4	12.4	67.1	4.48	284.40

*$\mathbf{M_s}$: Marshall Stiffness Modulus = Stability/(Flow × Specimen Thickness)
MQ: Marshall Quotient = Stability/Flow

The Marshall test results of the modified HMA mixtures are shown in Figures (4 to 7**).** Unit weight and optimum asphalt content (AC) versus the percentage of MKF were shown in Figure 4. From this figure, it can be noticed that an increase in unit weight with the increase in percentage of NMK up to 6%, then it decreases gradually. A 6 % NMK material percent in HMA mixtures increases the unit weight by 3.99%. Moreover, it is found that optimum asphalt content decreases by an increase of percentage of NMK. A reduction of 8.33% of the asphalt content was found when using 6 % NMK material percent in HMA mixtures. Figure 5 illustrates Marshall stability and flow of the modified HMA mixtures having different percentages of the NMK material. It is notable that

Marshall stability increased by increasing the NMK material percentage up to 6%. The maximum value of stability occurred at 6% percentage of NMK. It can be also noted that increasing of Marshall stability of about 15.23% was found when using 6 % NMK material percent in HMA mixtures. On the other hand, a greater decrease in flow occurred by using NMK material. The minimum value of flow occurred at 6% percentage of NMK. A reduction of 21.10% of Marshall flow was found when using 6 % NMK material percent in HMA mixtures. This indicates that the modified HMA mixtures with NMK material are capable of resist the tendency to deformation under traffic loads.

The volumetric properties of the modified HMA mixtures having different percentages of the NMK material were depicted in Figure 6. It can be noticed that an increase in the air voids percentage (AV%) with the increase in percentage of NMK. All AV% values of the modified mixtures are within the accepted range (3 to 5%) set by ECP [22]. On the other hand, a slight decrease in the voids percentage in the mineral aggregate (VMA%) and voids percentage filled with asphalt (VFA%) occurred by using NMK material. Marshall stiffness modulus and Marshall quotient versus the percentage of NMK were shown in Figure 7. They are an indicator of the resistance of HMA mixtures to permanent deformation [23]. From Figure 7, it can be noticed that an increase in Marshall stiffness modulus and Marshall quotient with the increase in percentage of NMK up to 6%, then it decreases gradually. A 6 % NMK material percent in HMA mixtures increases Marshall stiffness modulus and Marshall quotient by 46.10%.

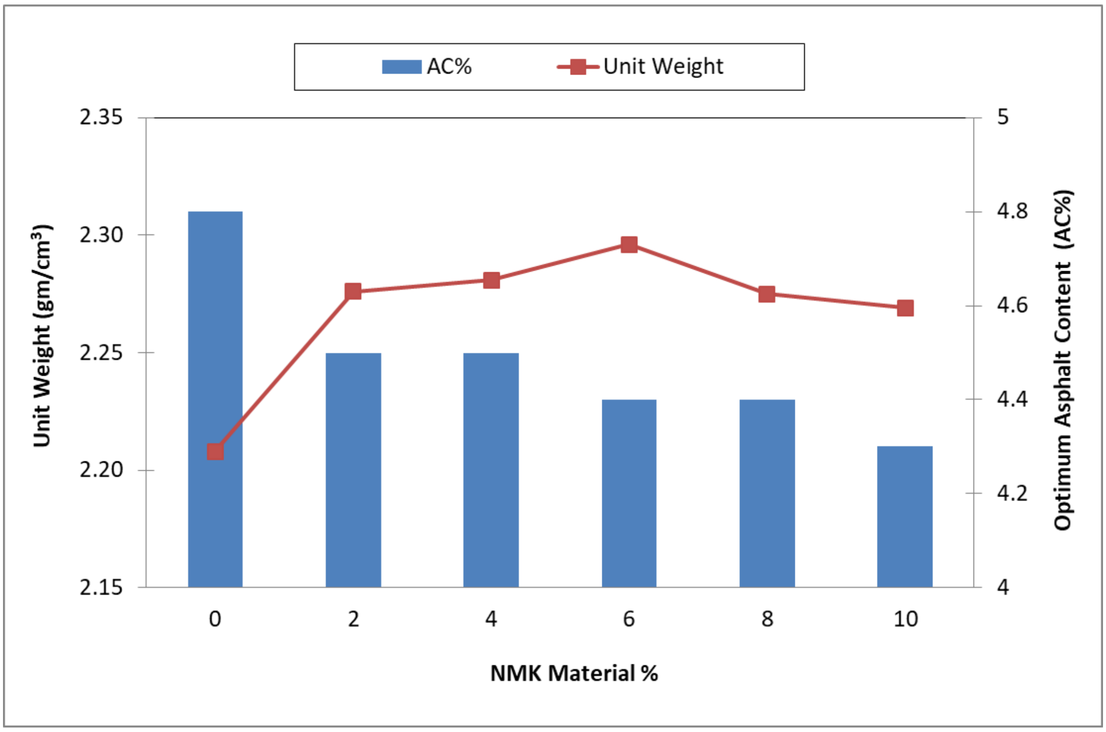

Figure 4: Unit weight and Optimum Asphalt Content versus the Percentage of NMK

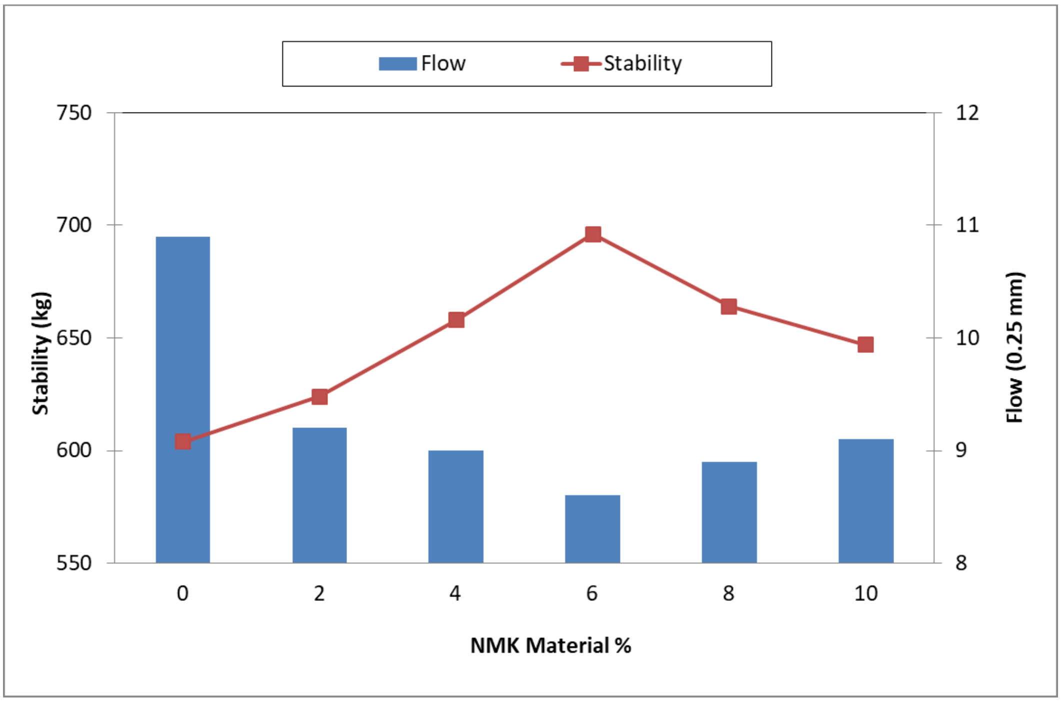

Figure 5: Marshall Stability and Flow Values versus the Percentage of NMK

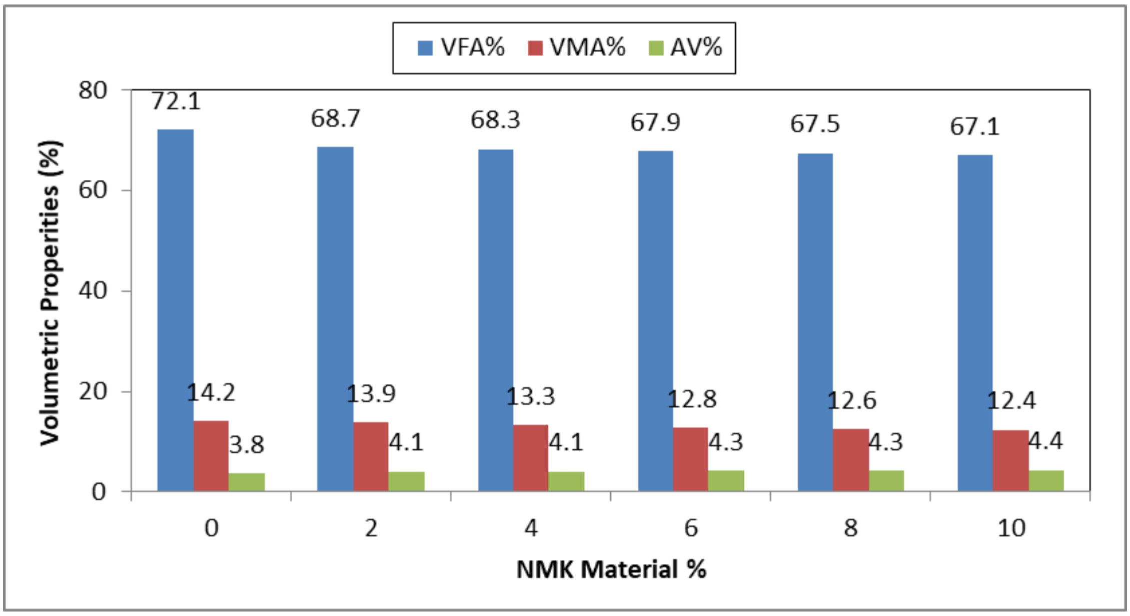

Figure 6: Volumetric Properties the Modified HMA Mixtures versus the Percentage of NMK

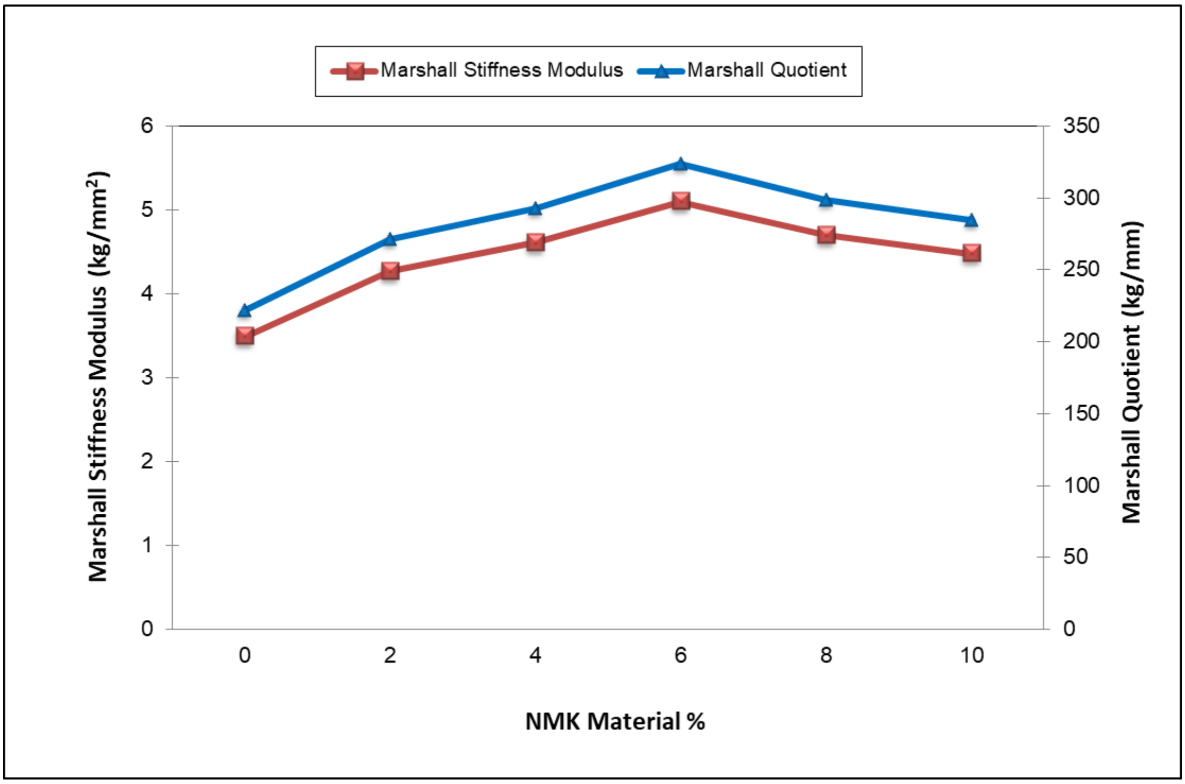

Figure 7: Marshall Stiffness Modulus and Marshall Quotient versus the Percentage of NMK

4.2.2 Loss of stability test results

Figure 8 depicts the relationship between loss of stability percent and the percentage of NMK. Noteworthy is that, the loss of stability increases with the increase of immersion time. Furthermore, the values of loss of stability values are within the acceptable range (< 20%) when the percentage of NMK is less than 8%. [20].

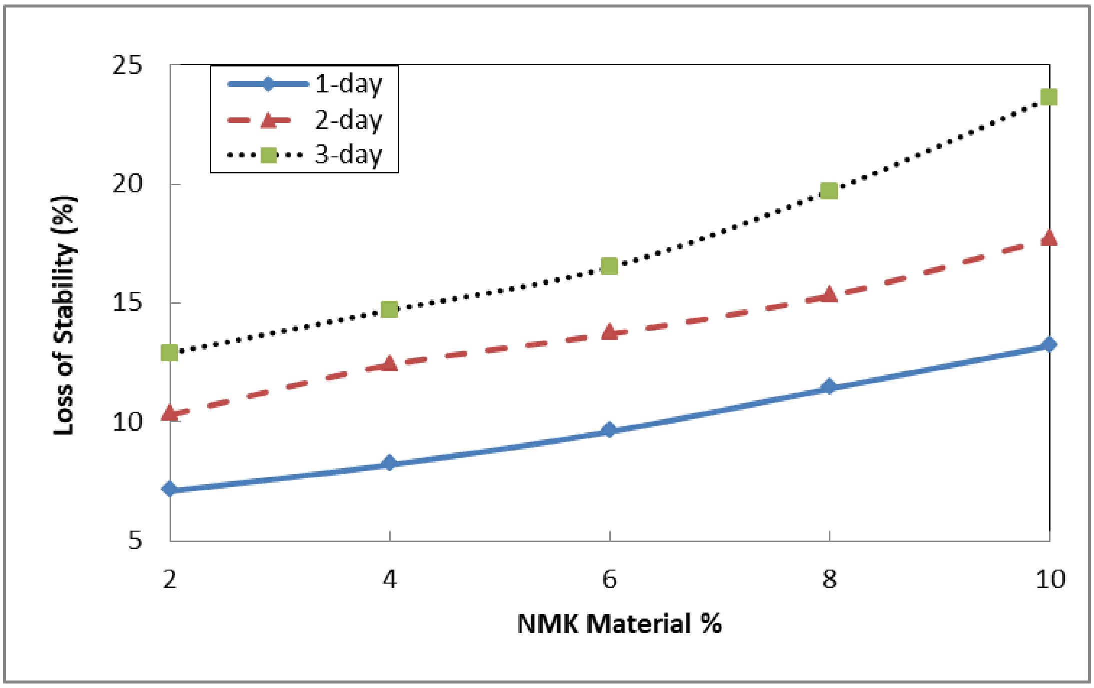

Figure 8: Loss of Stability Percent versus the Percentage of NMK

4.2.3 Rutting test results

Figure (9) depicts relationship between rut depth and time of the investigated mixtures. From this figure, it was clear that the rut depth increases with time. Moreover, the rut depths for the modified HMA mixtures are generally lower than those for the asphalt mixture without NMK material. Consequently, the use of NMK material has greatly affected the pavement resistance to deformation.

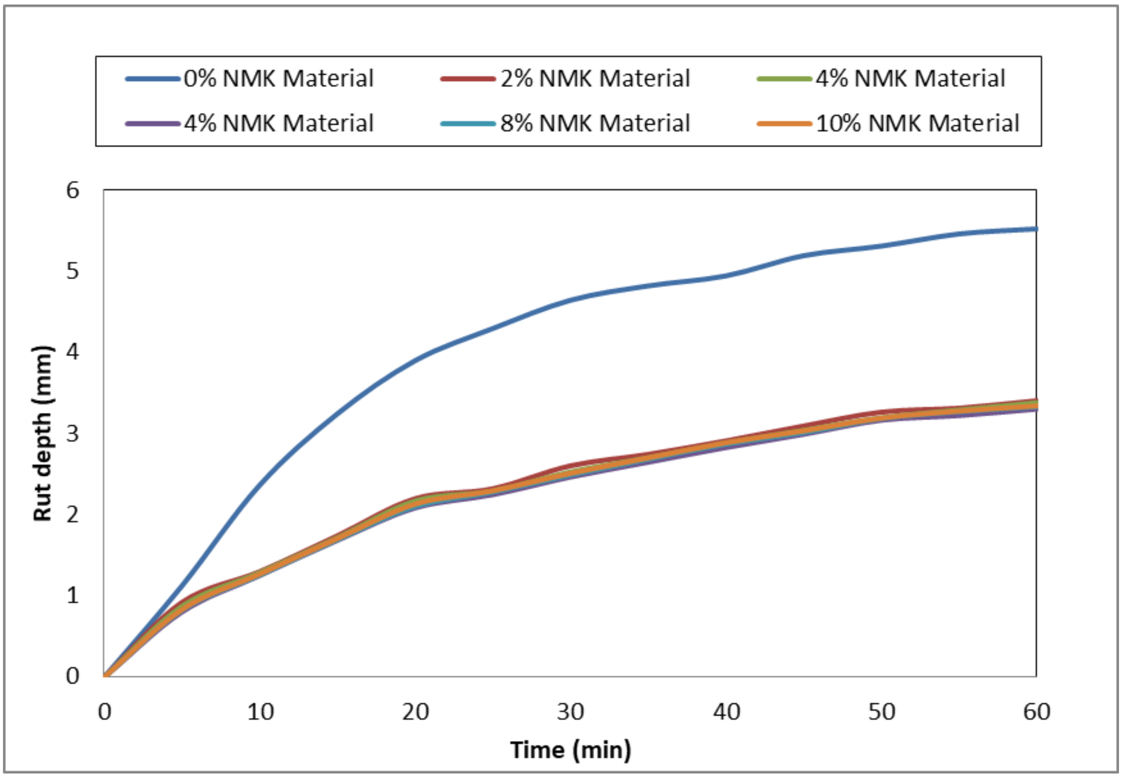

Figure 9: Observed Rut Depth for the Modified HMA Mixtures

5. CONCLUSIONS

This paper investigated the effect of using the NMK materials on the physical properties of asphalt binder and the mechanical properties of hot asphalt mixtures. Based on the obtained results, the following conclusions were drawn:

1. The physical properties of the modified asphalt binder with NMK material were improved with a decrease in its penetration and an increase in its softening point, flash point, and viscosity compared to the unmodified asphalt binder.
2. The values of unit weight, Marshall stability, Marshall stiffness modulus, and Marshall quotient increases by increasing the NMK percentage up to 6%, then these values decrease gradually.
3. A 6 % NMK material percent in HMA mixtures increases the unit weight, Marshall stability, Marshall stiffness modulus, and Marshall quotient by 3.99%, 15.23%, 46.10%, and 46.10% respectively.

4. A reduction of 8.33% of the asphalt content was found when using 6 % NMK material percent in HMA mixtures. Consequently, the NMK material can be used to reduce the asphalt content of HMA mixtures.
5. For the modified HMA mixtures, the air voids percentage increases with the increase of NMK percentages. On the other hand, the voids percentage in the mineral aggregate and voids percentage filled with asphalt decrease slightly with the increasing of NMK percentages.
6. The value of Marshall flow decreases by increasing the NMK percentage up to 6%, and then this value increases gradually. A reduction of 21.10% of Marshall flow was found when using 6 % NMK material percent in HMA mixtures.
7. The loss of stability of the modified HMA mixtures is in the acceptable range of < 20% when the percentage of NMK is less than 8%.
8. The rut depths for the modified HMA mixtures are generally lower than those for the asphalt mixture without NMK material.

The modified asphalt binder with NMK material is more applicable in hot weather conditions and heavy traffic areas. Moreover, using the NMK material as a modifier in HMA mixtures with a percentage of 6% by weight of asphalt binder is a reasonable selection to improve the mechanical properties of these mixtures. A future extension of this work should be extended to performing the other binder tests that are not conducted in the present study such as superpave binder tests.

REFERENCES

1. Huang, Y., (2004). "Pavement Analysis and Design". Pearson Prentice Hall is a trademark of Pearson Education, Inc, Second Edition, USA.
2. Crucho J., Santos L., and Neves J. and Capitao S. (2019). A review of nanomaterials' effect on mechanical performance and aging of asphalt mixtures. Applied sciences, 9, 3657, MDPI.

3. Raufi H., Topal A., Sengoz B. and Kaya D. (2020). Assessment of asphalt binders and hot mix asphalt modified with nanomaterials. Periodica Polytechnica Civil Engineering, Vol. 64, No. 1, pp:1–13.
4. Ragab, M., Abo El-Naga, I. (2022). Performance assessment of cold asphalt concrete mixtures containing recycled paving materials. Arabian Journal for Science and Engineering, Vol. 47, pp: 4351-4360.
5. Zghair H., Joni H. and Mohammed A. (2020). Assessment of the influence of nano metakaolin filler on asphalt binder rheological properties. 3rd International Conference on Engineering Sciences, IOP Conference Series: Materials Science and Engineering 671.
6. El-Naga I. and Ragab M. (2019). Benefits of utilization the recycle polyethylene terephthalate waste plastic materials as a modifier to asphalt mixtures. Construction and Building Materials, Vol. 219, pp:81–90.
7. Keshu R., Yadav J., Meenu C. and Shanker U. (2021). An updated review on synthetic approaches of green nanomaterials and their application for removal of water pollutants: Current challenges, assessment and future perspectives. Journal of Environmental Chemical Engineering, Vol. 9, No. 6.
8. Mostafa A. (2016). Examining the performance of hot mix asphalt using nano-materials. IOSR Journal of Engineering, Vol. 06, No. 2, pp: 25-34.
9. Bracamonte A. (2022). Sensing and Bio-Sensing Research Microarrays towards nanoarrays and the future next generation of sequencing methodologies (NGS), 37.
10. Alaa M. Rashad (2013). Metakaolin as cementitious material: History, scours, production, and composition – A comprehensive overview. Construction and Building Materials, Vol. 41, pp: 303–318.
11. Murana A., Olowosulu A. and Ahiwa S. (2014). Performance of metakaolin as partial replacement of cement in hot mix asphalt. Nigerian Journal of Technology, Vol. 33, No. 3.
12. Alrashedi1 B. and Hassan M. (2018). Effects of nano and micro size of clay particles on the compressive and tensile strength properties of self-consolidating concrete, Matec Web of Conferences, 162.
13. Qasim G., Hussein Z., Banyhussan Q. (2020). Evaluating the mechanical performance of hot asphalt mixtures modified with metakaolin as filler.Periodicals of Engineering and Natural Sciences, Vol. 8, No. 1, pp.113-124.
14. Egyptian standard specifications (1995), published by Roads and Bridges Authority, Cairo, Egypt.
15. ASTM D5 (2013). Standard test method for penetration of bituminous materials, USA, ASTM Int.
16. ASTM D36 (2014). Standard test method for softening point of bitumen (ring-and-ball apparatus), American Association of State and Highway Transportation Officials, Washington, DC.

17. ASTM D92-05a (2015). Standard method of test for flash and fire points by cleveland open cup, USA, ASTM Int.
18. Fwa T (2006). The handbook of highway engineering. CRC Press, Taylor& Francis Group.
19. ASTM D6927 (2006), Standard Test Method for Marshall Stability and Flow of Bituminous Mixtures, Annual Book of ASTM Standards, West Conshohocken.
20. Standard method of test for effect of water on compressive strength of compacted bituminous mixtures (2002). American Association of State Highway and Transportation Officials (AASHTO); T 165.
21. Please A. (1962). A wheel-tracking test to compare the resistance to deformation of rolled and mastic asphalt. 4th International Asphalt Congress, London.
22. Egyptian Code of Practice for Urban and Rural Roads (2020). Housing and Building National Research Center, Cairo, Egypt.
23. Moussa G., Abdel-Raheem A., and Abdel-Wahed T., (2020). "Investigating the moisture susceptibility of asphalt mixtures modified with high-density polyethylene," JES Journal of Engineering Sciences, Vol. 48, pp. 765-782.