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Performance Evaluation of Hybrid Fibers and Nano-zeolite Modified Asphalt Micro-surfacing

Reference

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ABSTRACT

Micro-surfacing is a cationic mixture for reparation and maintenance of asphalt pavement and contains polymer-modified bitumen emulsion, 100 % manufactured well-graded fine aggregate, mineral filler, water, and chemical additives. The object of this study was to extend the lifespan of a Micro-surfacing mixture against traffic loads to obtain a higher performance asphalt mixture using different additives, including Diatomite filler, nano-zeolite, styrene butadiene rubber, and glass fiber. To evaluate the performance of the mixtures, a variety of experimental tests, including the abrasion test (International Slurry Surfacing Association [ISSA] TB 100), adhesion test (ISSA TB109), and Wet Cohesion test (ISSA TB139) and Scanning Electron Microscopy, were conducted to classify Micro-surfacing quality control against traffic loads. Cohesion test results showed that adding 2 % nano-zeolite and 4 % polypropylene increased loading resistance up to 25 % (Quick Set and Quick Traffic). In addition, using 10 % of Diatomite improved abrasion resistance. It is worth noting that with an increasing dosage of asphalt emulsion, the effect of the additives will also increase. Moreover, adding 0.26 % of glass fiber in the mixtures increased bleeding resistance around 14 %.

Keywords

asphalt emulsion, Micro-surfacing, nano-zeolite, glass fiber, Diatomite filler, cohesion test, wet track abrasion

Introduction

Asphalt pavements have been widely used and account for approximately 90 % of highways, which play an important role in pavement industry because of the unique advantages.[1,2] Increasing traffic volume together with the high price of crude oil cost the governments a huge amount of money to build and preserve the roads.[3] Pavement preservation enhances pavement durability at the lowest cost. Environmental conditions and wheel load–related parameters are among deteriorating factors that affect asphalt pavements. Load-related stresses develop fatigue cracking and rutting, whereas environmental factors induce thermal cracking, block cracking, and weathering and raveling.[4,5] One of the preventive maintenance technologies is Micro-surfacing, which is widely accepted in asphalt pavement maintenance.[6] Micro-surfacing materials are a sort of cold fine-grained asphalt mixtures that are usually obtained from aggregates (cationic), asphalt emulsion, water and filler (i.e., cement powder), and additives in some cases. Based on the material properties and the circumstances of the project, a proper mix design should be selected in order to prevent low-temperature cracking as well as high temperature bleeding. Micro-surfacing has several advantages, including friction enhancement, rutting restoration, and cracking resistivity, in addition to preventing the pavement from aging, oxidation, penetration of water, and bleeding. However, in the case of alligator cracking, as rutting occurs due to the weakness of the pavement structure, Micro-surfacing is not effective enough.[7]

Micro-surfacing mixtures create a microscopic polymer network, which can increase the performance of the mixture against permanent deformations as well as improve performance against aging.[8] In research by Zalnezhad and Hesami on Micro-surfacing mixtures, they evaluated the effect of adding steel slag and found that because of the alkali properties of steel slag, enhanced rutting performance resulted under a Loaded Wheel Test (LWT).[9] In another study done by Hafezzadeh and Kavussi, they demonstrated that adding 5 % latex styrene butadiene rubber (SBR) could improve abrasion resistance up to 50 %.[10]

It has been approved that utilizing Micro-surfacing is also cost beneficial. For instance, in a study carried out by Bashar et al., they performed several tests in 27 field sections. They concluded that Micro-surfacing is one of the most cost-effective methods to improve rutting resistance of the asphalt mixes, while it extended the lifetime of the studied sections.[11]

Nanotechnology is highly dealt with atomic and molecular interactions. In this respect, nano-materials are three-dimensional materials that have at least one dimension between 1–100 nm. The surface impact of nano-materials on the performance improvement of asphalt mixtures has been in the center of attention recently. Applying nano-materials can also improve the viscoelasticity of the blends, enhance high temperature performance, and increase the resistance of the mix against aging, fatigue, and moisture damage.[12]

Because of some deficiencies of current Micro-surfacing (i.e., low crack resistance), efforts have been made in order to improve the performance. You et al. investigated the application of nano-materials through mixing montmorillonite nano-clay at two different percentages (i.e., 2 %, 4 % by weight of the mix) with asphalt binder at high temperature (e.g., 185°C). Subsequently, the prepared mixtures were subjected to rotational viscosity test, dynamic shear modulus, and direct tensile test using Superpave standard methods. The results of the study indicated that nano-clay can be used to improve the rheological properties of asphalt binder.[13] In other research, Yang and Tighe evaluated the use of nanotechnology in asphalt mixtures. For this purpose, the application of several types of nano-materials, including nano-clay and nano-silica, was investigated. The experimental results showed that employing nano-materials in asphalt mixes resulted in a better resistance against rutting and thermal cracking. In addition, aging and fatigue cracking performance, rutting resistance, and the anti-stripping property of nano-silica modified asphalt binders and mixtures were improved. Meanwhile, the addition of nano-silica did not greatly enhance the low-temperature properties of asphalt binders and mixtures.[13] Considering the use of nano-materials in asphalt mixtures, Shafabakhsh, Mirabdolazimi, and Sadeghnejad examined the effect of nano-titanium dioxide (TiO_2) on the performance of Hot Mix Asphalt. Nano-TiO_2 was added for preparation of the samples with an aggregate size of 20 nm and a purity of 99.5 % at four different percentages (i.e., 1 %, 3 %, 5 %, and 7 % by weight of asphalt binder). The results demonstrated that the addition of 5 % nano-TiO_2 (optimum content) to the asphalt binder improved the performance of asphalt binder at high temperatures and pressures significantly. Furthermore, nano-TiO_2 prevented the tensile and horizontal cracks from propagating.[14]

Four main design methods recommended by the International Slurry Surfacing Association (ISSA) were compared in another study done by Robati, Carter, and Perraton to obtain a possible optimum mix design for the preparation and testing of emulsified asphalt. The aggregates used in this study included granite aggregate of Raycar, Graham Pitt, and Rive-Sud limestone with a particle size of 0–5 mm, which were then mixed with emulsified asphalt at different percentages of 11.75 %, 12.5 %, and 13.25 %, respectively. They found that an improved optimized mix design could be achieved by adding residual binder at various percentages of 7.6 %, 8.1 %, 8.6 %, and 1 % of the cement for preparation of the specimens.[15] Wu and Fu used the "graph method" to obtain the optimum emulsified asphalt content. The emulsified asphalt used in this study included modified emulsified asphalt with SBR latex and cationic emulsifier, hydrochloric acid, water, stabilizer, and calcium chlorine. The fillers used in this study were typical portland cement grade 325, limestone, and mineral powder. The optimal percentages of materials were determined as 7.7 weight percent (wt.%), 2 wt.%, 6.8 wt.%, 0.2 wt.%, and 7.7 wt.% for optimal percentage of aggregate, cement, water content, fibers, and asphalt emulsion, respectively.[16] Tanzadeh and Otadi developed a mix design of Micro-surfacing by adding 4 wt.% nano-silica, 3 wt.% nano-clay, and 0.4 wt.% polyethylene fibers, which yielded acceptable results according to the cohesion test, LWT, and Wet Track Abrasion Test (WTAT). It was found that the effect of nano-materials on increasing the stability of the mixture and accelerating the setting for a quick crossing of traffic flow was achieved by far more than adding residual asphalt and fiber to the mixture. Since cationic emulsifiers act as anti-stripping agents after breaking the emulsion, adhesion was improved by 8 % by adding nano-silica. In addition, the results showed that nano-silica caused a 5 % increase in the cohesion of the asphalt emulsion. Nano-clay caused a 12 % increase in abrasion resistance. However, adding nano-silica and fiber led to an emulsion break occurring faster. Furthermore, considering the role of fibers in crack prevention, the results obtained from the low-temperature flexural creep test showed an increase in the flexural tensile strength by 17%.[17]

Zeolite is a porous aluminosilicate with either natural or artificial origin. A restricted amount of water in their structure (i.e., zeolite water) could be removed because of heating and replaced or absorbed by other substances. This has several chemical and physical advantages that have made nano-zeolites popular in industries such as the asphalt industry. Using nano-zeolites can significantly improve the performance of asphalt binders including the penetration index, softening point, and complex modulus as well as enhancing the rutting resistance of the asphalt mixtures.[18]

Employing zeolite in the blend decreases the viscosity of the asphalt binder, which leads to a lower mixing and compaction temperature. Similarly, increased indirect tensile stiffness modulus, increased complex modulus, and consequently improved rutting resistance are among the advantages of adding zeolite to the asphalt mixture. In addition, utilizing zeolite will improve the performance of the mixture at both low and high loading frequencies.[19–21]

On the contrary with other mineral fillers, it has been demonstrated that utilizing Diatomite as filler in the asphalt mixtures will not lead to a decreased tensile strength at low temperatures.[22] Similarly, using fibers in asphalt mixtures will lead to an improved performance of the mixtures, including life cycle and rut performance. For instance, glass fibers increase stability, decrease penetration, and increase the softening point of the asphalt binders, in addition to what was mentioned earlier.[23,24] In a study, Tanzadeh and Shahrezagamasaei investigated the effect of using glass fibers and polypropylene (PP) fibers in asphalt mixtures. In this study, drain down, rutting, and Indirect Tensile Strength of the specimens containing additives were evaluated. According to this study, the use of glass fibers and PP fibers can reduce drain down by about 80 % and increase the Indirect Tensile Strength of the specimens by about 65 %.[25]

Proper abrasion resistance is one of the most important features of a desired asphalt mixture. Employing modifiers is one of the most effective ways to improve the performance of the mixtures. The Micro-surfacing mixture is well known because of the promising advantages, including longer life cycle and easier maintenance. However, lower cracking and rutting resistance are among the negatives that should be treated. As mentioned earlier, utilizing modifiers would significantly help to achieve this goal. The materials mentioned so far can be used to enhance different properties of Micro-surfacing. However, the differences between various combinations of these materials have not been well studied. As the aggregate type and gradation and additive type and content as well as the ratio of asphalt-aggregate vary, the impact of different materials in the mix design cannot be directly compared. Therefore, in order to enhance the performance of Micro-surfacing, four additives (namely, nano-zeolite, SBR polymer, polypropylene, and glass fibers) together with two filler types (namely, Diatomite powder and cement) were employed at different percentages and combinations in this study, and the optimum combinations were determined. With this regard, several tests, including the LWT, cohesion test, Scanning Electron Microscopy (SEM) test, and WTAT, were conducted to analyze the effect of the aforementioned additives. The obtained results can pave the way for the further development and application of fiber Micro-surfacing.

Materials

AGGREGATES

According to previous researchers, to obtain maximum abrasion resistance and improve durability of the mixture against heavy traffic, aggregates of 0–5 mm were used in accordance with ISSA A-143 type III gradation. Also, aggregates were broken 100 % in order to get a rough surface. Tables 1 and 2 indicate the characteristics of aggregates based on the ISSA A-143 standard and the characteristics of the aggregates used in this study, respectively.[26]

ASPHALT EMULSION

The asphalt emulsion used in this mixture was cationic slow setting (CSS-1 h). According to the research conducted by Robati, Carter, and Perraton, 11 %, 13 %, and 15 % of the dry weight of the aggregate was used in preparation of the samples.[14,15] The characteristics of the asphalt emulsion are shown in Table 3.

NANO-MATERIALS

In order to improve asphalt binder performance, nano-materials were used in this research. Considering the few applications of nano-zeolite in past research and the similarities between nano-zeolite and nano-silica, the utilized percentage of nano-zeolite was obtained based on research in which nano-silica was used.[27,28] Woszuk and Franus

TABLE 1
Specifications of aggregate gradation according to ISSA A-143

Sieve Size (mm)	Gradation Limits, %	Passing by Weight, %
3/8 (9.5)	100	100
No. 4 (4.75)	70–100	88
No. 8 (2.36)	45–70	62
No. 16 (1.18)	28–50	45
No. 30 (0.6)	19–34	32
No. 50 (0.3)	12–25	22
No. 100 (0.15)	7–18	15
No. 200 (0.074)	5–15	9

TABLE 2
Specifications of aggregates used

Aggregates Size	Property	Test Value
Coarse aggregate (ASTM C127-04)	Bulk specific gravity, gr/cm^3	2.703
	Apparent specific gravity, gr/cm^3	2.73
	Water absorption, %	0.385
Fine aggregate (ASTM C128-04)	Bulk specific gravity, gr/cm^3	2.695
	Apparent specific gravity, gr/cm^3	2.742
	Water absorption, %	0.73

TABLE 3
Specifications of emulsified asphalt binder

Test	Emulsion Results
Viscosity, saybolt furol seconds @ 25°C	86
Sieve, retained on no. 20, %	0.02
Residue by distillation	66
Particle charge	Positive
Settlement and storage stability, %, 24 h	0.2
Softening point by (R&B), °C on residue (asphalt binder)	62.3
Penetration @ 25°C, 100 g, 5 s on residue (asphalt binder)	76

Note: R&B = ring and bail.

TABLE 4
Specifications of nano-zeolite filler

Type	Quantity, gr	Purity, wt.%	SiO_2/Al_2O_3	Cation Form	Form	Shape	Crystal Size, μm	Pore Size, Ao	Surface Area, m3/gr	Bulk Density, gr/ml
ZSM-5	100	>99	40	Na	White Powder	Sphere	0.5	5.5	300	8.6

demonstrated that utilizing synthetic zeolite had a better impact on the performance of the asphalt mixtures compared to natural zeolite. For example, Indirect Tensile Strength of the mixtures prepared by synthetic zeolite was better than that of natural zeolite by about 12 %.[29] The percentage of nano-zeolite content was 1 % and 2 % by weight of dry aggregates combined with asphalt binder by a mechanical mixture machine.[30] The synthetic nano-zeolite used in this study was provided from the Pouyan Exir industrial company in Tehran, Iran. The characteristics of nano-zeolite are shown in Table 4.

FILLER

Considering that cement powder has been used as filler in most studies and considering the promising results of using Diatomite filler in Cong et al.'s study, the use of both mentioned filler types was considered in this study. It should be noted that the Diatomite was prepared from the Cain plant.[3] Tables 5 and 6 present the physical and chemical characteristics of the Diatomite used. Portland cement was also used as filler to enhance the coating of wet aggregates with the binder.

Diatomite powder increases special surface area, because of its honeycomb structure and inclusion of sedimentary rocks, which leads to a larger contact between particles and improvement of the mixture functional

TABLE 5
Chemical components of Diatomite powder

Chemical Composition	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	CaO	TiO_2
Content, %	73.2	10.6	1.5	1.5	1	0.5	1.3	0.4

TABLE 6
Physical properties of Diatomite powder

Test	Standard Test Method	Results	Approval
Moisture content, %	ASTM D2216-05	6–8	OK
Granulation (mesh)	ISIRI 8199-1	400	OK
Bulk density, gr/cm^3	…	0.55–0.65	OK

properties. The effect of cement on the moisture susceptibility of the mixtures has been investigated by Oruc, Celik and Akpinar. It was found that the addition of cement filler reduced the failure pace of asphalt emulsion.[31] In this study, the portland cement filler was used at 1.5 % by weight of dry aggregates based on the specification of the cement components in the emulsion mixture curing time.

POLYMER

Another additive that has been used in many cases to modify the properties of asphalt mixtures is polymer.[32,33] According to Yao, Dai, and You, the proper usage of polymer is between 2 % and 8 % by weight of aggregates in the polymer mixture.[34] In this study, SBR polymer with 3 % weight of aggregates was used. This SBR polymer was utilized with products provided from the Takht Jamshid Petrochemical Company in Tehran, Iran (see Table 7).

FIBERS

The results obtained from studies showed that the application of glass fiber at 0.1 % to 0.3 % by weight of aggregate could strengthen the properties of the mixture.[35,36] In this study, the percentage of 0.4 (by weight of aggregates) was selected for the total fiber used. The polypropylene and glass fiber properties can be seen in Tables 8 and 9, respectively. PP fibers and glass fibers are produced by Afzir Construction Company in Tehran, Iran.

WATER

The amount of water was selected as 6 %–8 % by weight of aggregates according to Wu and Fu.[16] The used materials and corresponding utilized percentage for the production of each sample are presented in Table 9. It should be noted that three experiments were tested in order to obtain the results for each sample, and the average value is reported.

TABLE 7
SBR specifications

SBR	Results
Standard	Q/320205 GLFF01 2010
Solid, %	50.0±1
Density, g/cm^3 25°C	0.99–0.98
pH value (25°C)	10–11
Mechanical stability, %	5≥
Chemical stability, %	0.33≥

TABLE 8
Introduction of the PP properties

Property	Specific Gravity, gr/cm^3	Diameter, μm	Cross Section	Length, mm	Melting Point, °C	Tensile Strength, MPa	Failure Strain, %	Modulus of Elasticity, MPa
Standard	ASTM D792	…	…	…	…	ASTM D638	ASTM D638	ASTM D638
Value	0.91	22	Round	12	163	225	118.5	3,000

TABLE 9
Introduction of the glass fiber properties

Property	Specific Gravity, gr/cm^3	Diameter, μm	Cross Section	Length, mm	Melting Point, °C	Tensile Strength, MPa	Failure Strain, %	Modulus of Elasticity, MPa
Standard	ASTM D792	…	…	…	…	ASTM D638	ASTM D638	ASTM D638
Value	2.52	0.010	Rectangular	12	>300	1,400	2.88	70,000

MIX DESIGN METHODS

The fiber-reinforced Micro-surfacing mix design method was conducted in five stages:

1. The water phase was prepared by combining warm water, acid, and emulsifier material.
2. The asphalt binder was heated up and passed through the filter and weighed and the achieved water phase was added to the binder in the mix tank.
3. Latex was added to the materials and stirred for few minutes at 950 rpm in the mix tank.
4. The remaining binder, using a combination of nano-zeolite, was mixed and modified in a high-speed shearing device. After complete incorporation of the material into the amulobic system, the achieved mixture was removed from the outlet valve and passed through the filter to be combined with the nano-materials.
5. The fiber-reinforced Micro-surfacing asphalt mixtures at 24°C of room temperature and a relative humidity of 50 % were produced within one minute at the pug mill with the addition of aggregates and filler from one side, as well as fibers from the other side in the asphalt emulsion. Moreover, ten different specimens were made by combining different weights of nano-material, fiber, and residual asphalt as presented in Table 10. In this study, the samples were classified into three groups: A (including 11 % asphalt emulsion), B (including 13 % asphalt emulsion), and C (including 15 % asphalt emulsion), according to the

TABLE 10

The combination of materials used for the mixing of specimens of Micro-surfacing

Group	Samples	Asphalt Emulsion, wt.%	Cement Filler, wt.%	Diatomite Filler, wt.%	Glass Fiber, wt.%	Polypropylene, wt.%	SBR Latex, wt.%	Water, wt.%	Nano-zeolite, wt.%
A	ACC	11	1.5	0	0	0	3	6	0
	ACP	11	1.5	0	0	0.4	3	6	1
	ADP	11	0	10	0	0.4	3	6	1
	ACGPW	11	1.5	0	0.2	0.2	3	8	1
	ADPG	11	0	10	0.2	0.2	3	6	1
	ACPG	11	1.5	0	0.13	0.26	3	6	1
	ACPN	11	1.5	0	0	0.4	3	6	2
	ADGP	11	0	10	0.26	0.13	3	6	1
	ADPGW	11	0	10	0.13	0.26	3	8	1
	ACGP	11	1.5	0	0.26	0.13	3	6	1
B	BCC	13	1.5	0	0	0	3	6	0
	BCP	13	1.5	0	0	0.4	3	6	1
	BDP	13	0	10	0	0.4	3	6	1
	BCGPW	13	1.5	0	0.2	0.2	3	8	1
	BDPG	13	0	10	0.2	0.2	3	6	1
	BCPG	13	1.5	0	0.13	0.26	3	6	1
	BCPN	13	1.5	0	0	0.4	3	6	2
	BDGP	13	0	10	0.26	0.13	3	6	1
	BDPGW	13	0	10	0.13	0.26	3	8	1
	BCGP	13	1.5	0	0.26	0.13	3	6	1
C	CCC	15	1.5	0	0	0	3	6	0
	CBCP	15	1.5	0	0	0.4	3	6	1
	CDP	15	0	10	0	0.4	3	6	1
	CCGPW	15	1.5	0	0.2	0.2	3	8	1
	CDPG	15	0	10	0.2	0.2	3	6	1
	CCPG	15	1.5	0	0.13	0.26	3	6	1
	CCPN	15	1.5	0	0	0.4	3	6	2
	CDGP	15	0	10	0.26	0.13	3	6	1
	CDPGW	15	0	10	0.13	0.26	3	8	1
	CCGP	15	1.5	0	0.26	0.13	3	6	1

TABLE 11
Test specifications and standards

Property			Application	Test	Requirement
Mixing time			Design test	ISSA TB 102	125 s @ 25°C
Cohesion test	Quick Traffic		Performance test	ISSA TB139	>2 N.m @ 60 min
	Quick Set		Design test		>1.2 N.m @ 30 min
WTAT			Design test	ISSA TB 100	≤538 g/m^2
LWT	Sand adhesion test		Design test	ISSA TB109	1 hr @ ≤538 g/m^2@ 60°C
	Adhesion test	Vertical deformation	Performance test	ISSA TB 147	1,000 & 2,000 cycles
		Horizontal deformation	Performance test		1,000 cycles
SEM			Design test	…	15 kv

percentage of emulsified asphalt binder. Tests for the surface treatment of asphalt mixtures were conducted separately for each group.

EXPERIMENTAL PROGRAM

In this research, the experiments were carried out in two groups of performance testing and mixed design according to the ISSA standard method, which is demonstrated in **Table 11**.

MIXING TIME TEST

Several component combinations and the allowable mixing time were determined according to the mixing time test (ISSA TB 102-Mixing Test). The foaming of mixture and coating of aggregates were observed at the allowed time. The proportion of components must be determined during at least 120 s at a temperature of 25°C. Simultaneously, the amount of water and additives was assessed to produce a high-quality mixture.

WTAT

An abrasion test (WTAT-ISSA TB100) was used to determine the abrasion resistance of the mixtures at different asphalt binder percentages. Specimens of 6 and 280 mm in thickness and diameter were immersed for 1 h in water at 25°C. Then, the abrasion test was applied on a wet sample under the weight of a rotating rubber rod weighing 2.3 kg for a period of 5 min. The abrasion sample was then dried and weighed at 60°C. The allowed weight loss of a one-hour immersed sample should not exceed 538 g/m^2.

LWT

The adhesion test (LWT-ISSA TB109) was used to assess the maximum binder content as well as the bleeding potential of the specimens. In this test, a specimen with a width of 50 mm and length of 375 mm and a desired thickness (usually 1.25 times the nominal maximum aggregate size) was compressed under the weight of 56.5 kg with 1,000 cycles. The specimen was then rinsed and dried at 60°C and weighed. In the next step, sand was poured on the specimen, it was loaded again under 1,000 cycles, and the amount of sand absorbed by the specimen was determined (ISSA recommends a maximum adhesion of 538 g/m^2 for heavy traffic loading).

COHESION TEST

The wet cohesion test was conducted to classify Micro-surfacing based on the set time and initial time of the traffic flow in accordance with ISSA TB139. The device measures the cohesion of torque required to break the mixture into specified dimensions, which is loaded up to 200 kPa. The amount of this torque was measured at different time intervals, which should meet the relevant specification ranges. In this test, a mixture disk with a thickness of 6 to 8 mm and diameter of 60 mm was used and a rubber base with a diameter of 32 mm and pressure of 200 kPa was placed on it. The required torsional couple was then recorded at time intervals of 20–30, 60, 90, 150, 210, and 270 min. If the required couple (two parallel forces in the opposite direction) over the period of 20 to

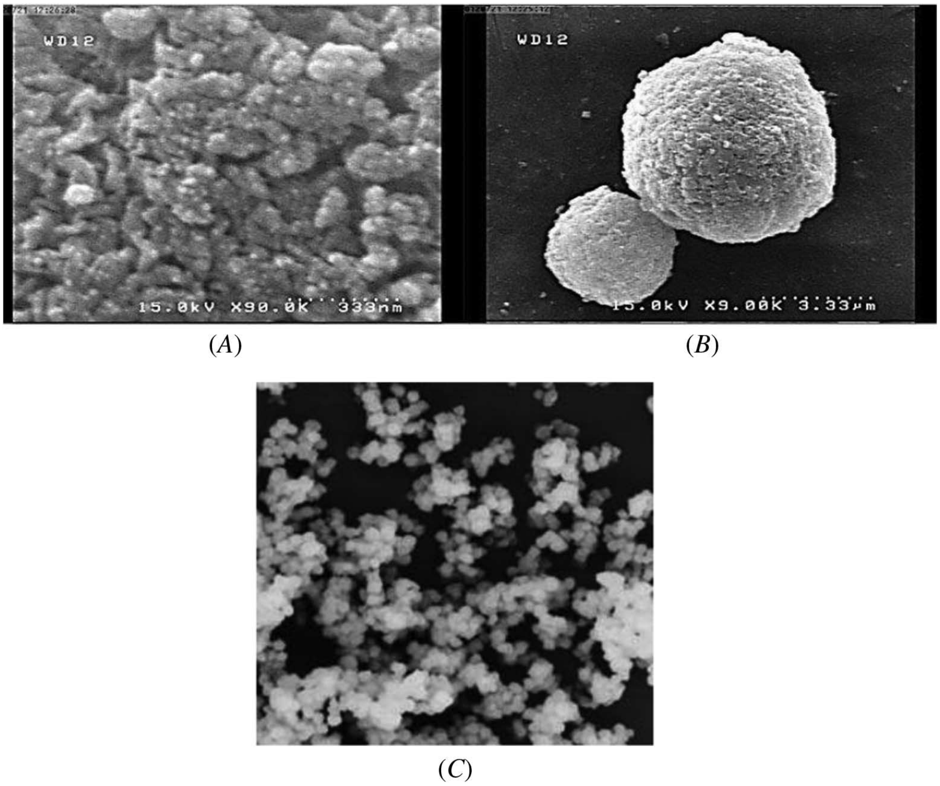
30 min is 1.2 Nm, the mixture is called Quick Set, and this couple means that the mixture gained enough set. If the required couple at less than 60 min reaches 1.96 Nm, it is called Quick Traffic System, indicating the mixture can withstand passing traffic. According to ISSA, the minimum cohesion of 12 kg-cm for set time of 30 min is determined, and for the passage of traffic (60 min), this value is 20 kg-cm.[6]

Results and Discussion

MIXING TIME TEST AND MICROSTRUCTURE CHARACTERIZATION

Mixing time testing was performed according to ISSA TB-102. The result of mixing time was observed to be in the range of 150 to 200 s. Observations confirmed the homogeneity of the mixture and the created cover on aggregates due to adding the additives, as well as employing different percentages of water in the mix. In addition, it was observed that nano-zeolite was uniformly distributed into the mixture and prevented the mixture from being massed. SEM images of the samples are presented in **figure 1** in order to investigate the structure and shape as well as dispersion of nano-zeolite. As can be seen, nano-zeolite particles seemed to be spherical and porous. Porous nano-zeolite could be considered as a catalyst in the mixture with storage and cationic capabilities, because of porosity and cavities.[37] It could be inferred from **figure 1*C*** that crystalline nano-zeolite particles are dispersed evenly in the mixture and resulted in a homogenous blend. Generally, SEM images verify that nano-zeolite could participate as a porous catalyst, which absorbs asphalt binder. In addition, adding nano-zeolite enhanced the performance of emulsified asphalt through resisting against imposed tensions.[38] This phenomenon occurred because of the fact that the cavities in nano-zeolite were saturated in the binder mass and simultaneously glass fibers were mixed with the other additives in the mixture in the given time period.[39] It is highly possible that the lighter

FIG. 1 SEM images of (*A*) nano-zeolite pore, (*B*) appearance from the nano-zeolite, and (*C*) distribution of nano-zeolite.



compounds in the binder mass were absorbed by fibers which resulted in an increase in the portion of asphaltenes in the binder which led to a more ductile binder.[33]

WTAT RESULTS

A WTAT was conducted in this study in order to determine optimum binder content and abrasion resistance. The results of WTAT are presented in figures 2–4. As can be observed from figure 2, ADP showed a higher resistance against abrasion compared to that of ACP, which confirms the better performance of Diatomite rather thancement powder. In addition, the sample ADPGW resisted abrasion more than ADPG, which implies adding 8 % water to ADPG led to a 12 % increase in abrasion strength. With reference to figure 1, it could be observed that

FIG. 2

WTAT results of Group A with 11 % emulsified asphalt binder.

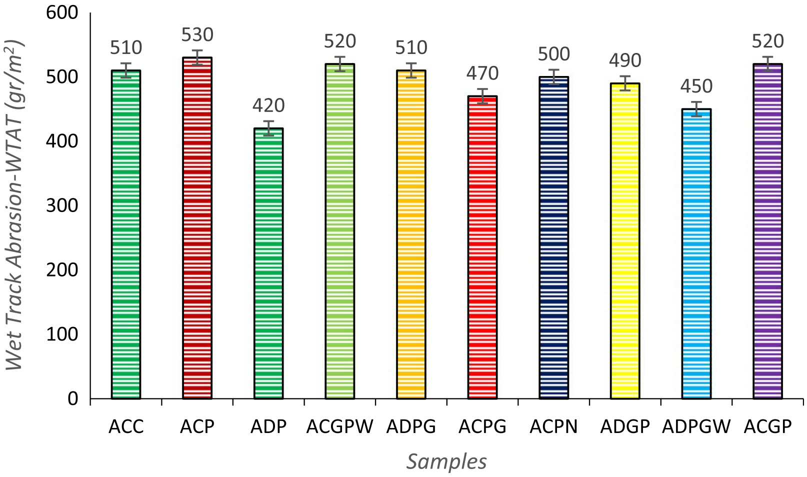


FIG. 3

WTAT testing results of Group B with 13 % emulsified asphalt binder.

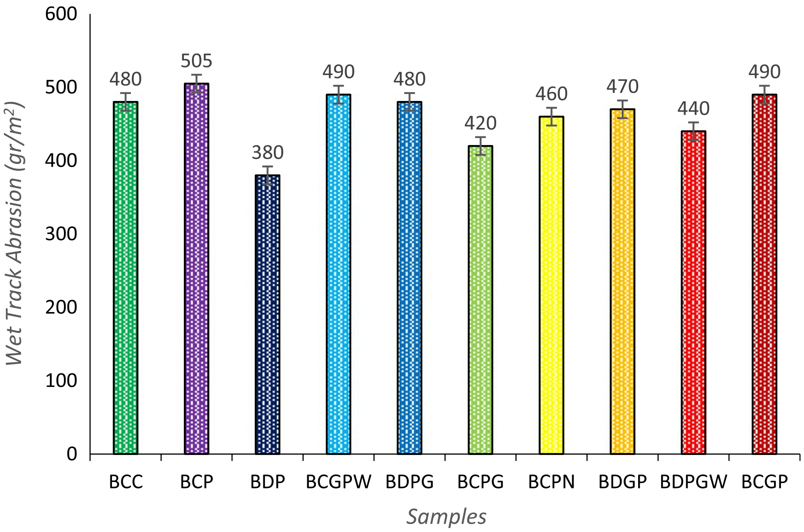
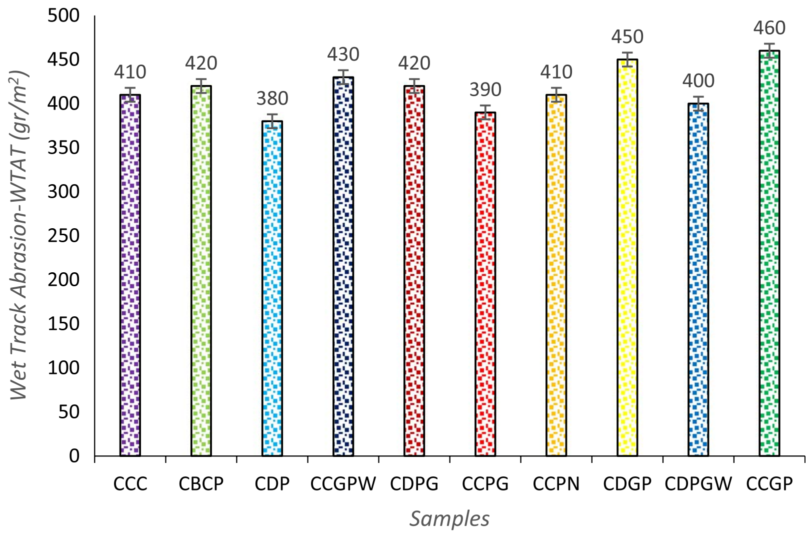


FIG. 4

WTAT testing results of Group C with 15 % emulsified asphalt binder.



ACPN had a better resistance to abrasion compared to that of ACP, which indicates that adding 2 % of nano-zeolite could improve abrasion resistance considerably. This might have happened because of the storage capability of nano-zeolite, which resulted in covered aggregates with asphalt binder and performed better against abrasion. Regarding ACPG and ACPGW, 2 % increment in water amount, 0.06 % increment in glass fiber, and 0.07 % reduction in polypropylene did not have a significant change in abrasion resistance. The value of abrasion resistance for both samples was recorded as 520 gr/m^2. Figure 2 confirms that all the samples have had abrasion resistance in the allowable range.

Figure 3 demonstrates that Group B samples performed better against abrasion than Group A. With this regard, adding 10 % Diatomite led to a decrease in weight and 21 % increase in abrasion resistance in BDP. Moreover, it can be concluded that increasing the amount of emulsion by 2 % led to 6 % increase in abrasion resistance averagely. As illustrated in figure 3, the abrasion resistance of sample BCPG was approximately 14 % higher than that of BCGP due to having 0.06 % more and 0.07 % less polypropylene and glass fiber, respectively. With more absorption of asphalt binder by BCGP, the portion of emulsified asphalt on aggregates lessens, and this will increase the probability of stripping. Nonetheless, BDP performed the best against abrasion among the specimens.

With regard to figure 4, it could be inferred that Group C samples had the best performance among the whole groups of samples. Adding 2 % of nano-zeolite (e.g., CCPN) compared to other samples (e.g., CCGP and CDGP) led to a significant improvement against abrasion deteriorations such as abrasion on the surface of pavement because of braking. Similarly, it can be observed that adding 2 % of water resulted in a 7 % increase in abrasion resistance. Moreover, having 1 % more nano-zeolite and 0.14 % polypropylene led to an 11 % increase in abrasion resistance. Among the specimens with glass fiber, CCPG with 0.26 % polypropylene and 0.13 % glass fiber was observed to perform better than the others in the same type against abrasion. The abrasion resistance of CCPG was approximately 15 % higher than that of the weakest specimen CCGP.

Generally, it could be concluded from the WTAT results that with an increase in emulsified asphalt, the impact of nano-zeolite and glass fibers on improving the abrasion resistance increases. The probable reason for this would be that additives absorbed a portion of asphalt binder, which was supposed to fill the cavities. This absorbed binder with additives will create a cover on aggregates that can help them stick together. As a result, the binder–aggregate bond strengthens, and it can prevent the surface of the pavement from deformation.[40]

SAND ADHESION TEST RESULTS

A sand adhesion test was carried out in this study in order to determine optimum binder content and adhesion. Figure 5 depicts Group A specimens, in which Diatomite was replaced with cement powder as filler. As seen, ACP and ADP performed better compared to other samples, which indicates the better performance against bleeding. For example, the performance of ADP against bleeding was 25 % better than that of the control specimen. In addition, cement powder together with polypropylene and glass fibers would perform more properly compared to the specimens containing Diatomite filler. This implies that Diatomite would not be considered a suitable catalyzer to accelerate the interaction of polypropylene and glass fibers.

Comparing the columns in figures 5 and 6 verifies the mixes containing cement powder as filler seemed to have a weaker bond between aggregates than the mixes that contained Diatomite as filler. In this regard, Group A samples (e.g., ACGP and ACPG) behaved better against bleeding than Group B samples (e.g., BCPG and BCGP). In addition, in the case of BCPN, it is demonstrated that adding 1 % more nano-zeolite led to a strengthened bond between aggregates, which also helped the mix to resist 15 % more against loading.

Figure 7 indicates that among all group samples, Group C samples showed weaker performance against loading and bleeding. For example, specimen CDP could not meet the criteria ($\leq$540 gr/m^2). Generally, it can be concluded from sand adhesion testing results that with an increase in optimum emulsified asphalt content, the aggregate interlock weakened. Besides, adding 2 % emulsified asphalt to ACPN led to more absorbed asphalt binder because of relatively more cavities in the structure of nano-zeolite. This resulted in more adhesion between the aggregates, which could improve skid resistance and rutting performance. Moreover, less probable bleeding and hydroplaning might be expected as a result of absorbed emulsified asphalt.

DETERMINATION OF THE OPTIMUM ASPHALT EMULSION CONTENT RESULTS

By plotting the results of abrasion and adhesion tests (ISSA TB 139 and TB 109), the optimal asphalt binder content was obtained at different asphalt binder percentages. According to figure 8, the optimal asphalt binder content at the intersection of abrasion and adhesion curves was determined to be 13 %.

DEFORMATION TEST

Another test that was carried out in this study was the lateral and vertical displacement test, which expresses the performance of the mixtures against permanent deformation. According to the optimum asphalt binder

FIG. 5

Sand Adhesion test results of Group A with 11 % emulsified asphalt binder.

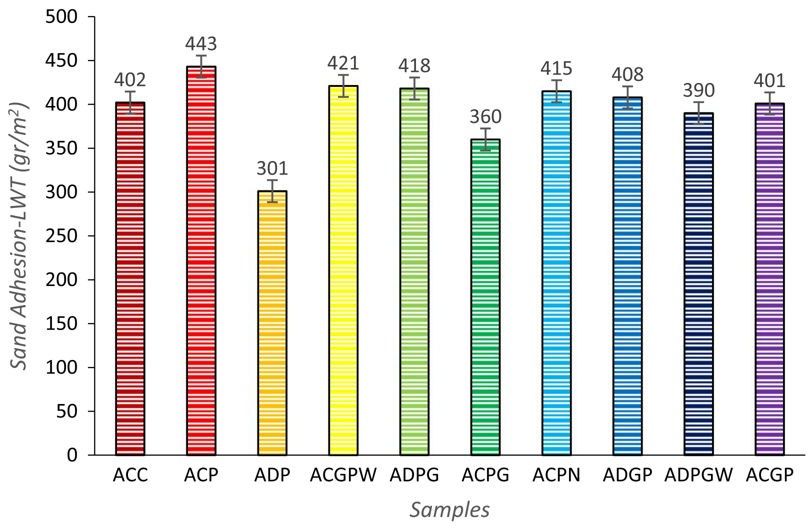


FIG. 6

Sand Adhesion test results of Group B with 13 % emulsified asphalt binder.

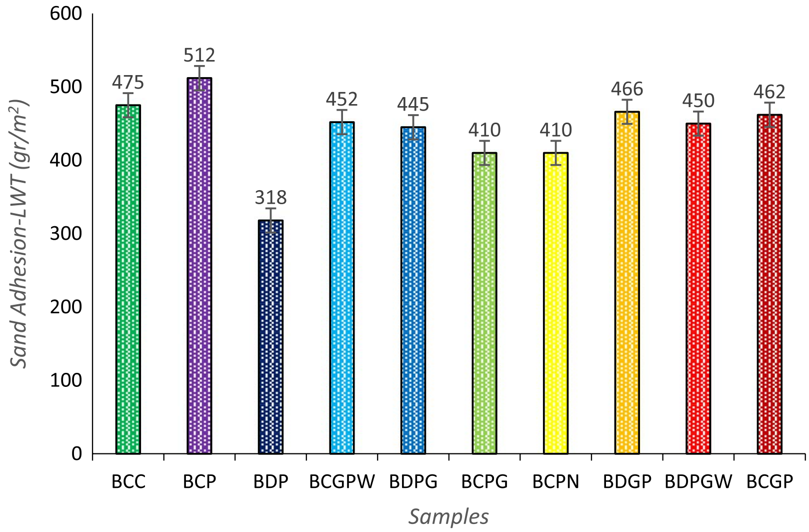
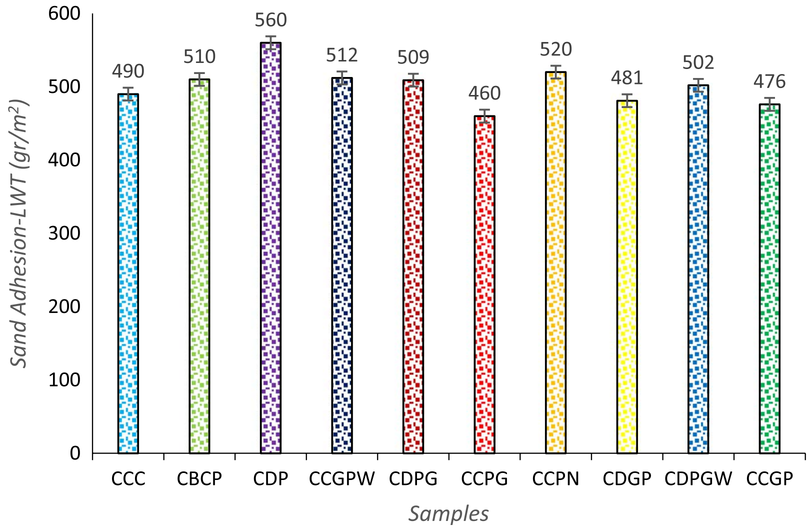


FIG. 7

Sand Adhesion test results of Group C with 15 % emulsified asphalt binder.



percentage, lateral and vertical displacement tests were performed at optimal asphalt binder percentage (13 %) and the results are shown as follows.

HORIZONTAL DEFORMATION TEST

With reference to figure 9 it could be inferred that the recorded horizontal deformation for BDP was the lowest among the tested specimens. Besides, adding fibers and nano-zeolite significantly affected the horizontal deformation. With this regard, adding 2 % nano-zeolite in BCPN resulted in 10 % reduced horizontal deformation. Likewise, the addition of 0.2 % glass fibers and polypropylene in BCPG decreased the horizontal deformation up to 22 %. This implies that adding 0.2 % glass fiber and 0.2 % polypropylene as well as 2 % nano-zeolite to emulsified asphalt mixtures can greatly affect the strength of the mixture and reduces the horizontal deformation to an acceptable extent, which results in a better performance against permanent deformations. An increase in horizontal

FIG. 8

Determining optimum asphalt emulsion content based on abrasion and adhesion tests.

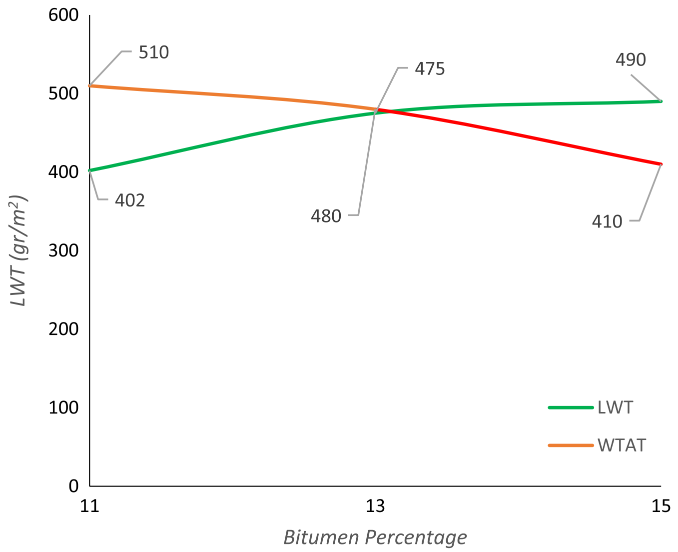
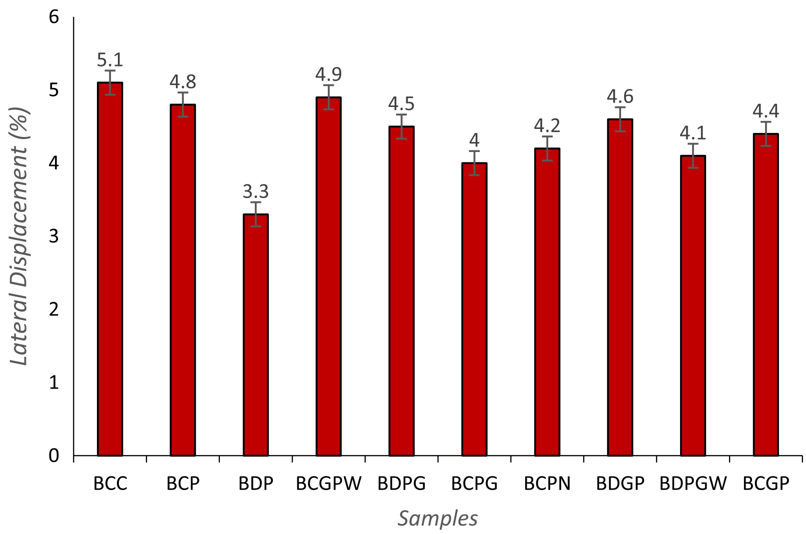


FIG. 9

Horizontal deformation at optimal asphalt binder percentage.



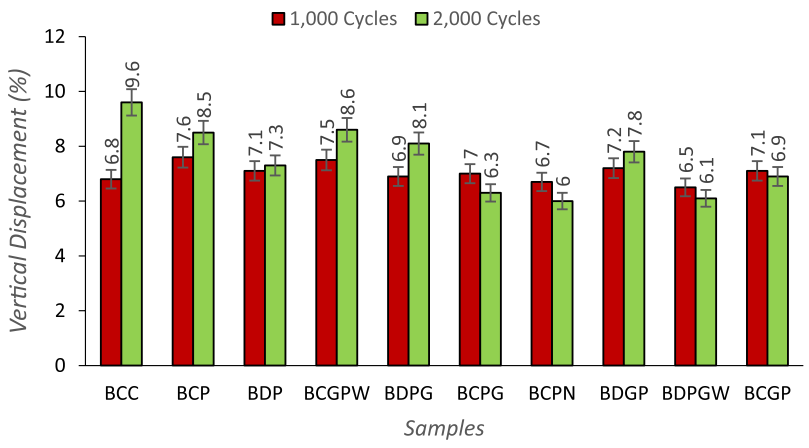
displacement could potentially contribute to shear failures at intersections due to turning traffic.[39] A comparison of the two BDPGW and BDPGW samples demonstrates that adding 8 % water to the BDPG mixture will increase resistance, thereby increasing stiffness and improving the asphalt performance against damage such as shear failures.

VERTICAL DEFORMATION TEST

The results of the vertical loading test at two distinct loading cycles (i.e., 1,000 and 2,000) are illustrated in figure 10. It can be deduced that adding 2 % nano-zeolite in BCPN had greatly reduced vertical deformation at 2,000 loading cycles. Asphaltene portion has an important effect on the rheological properties of asphalt binder. The longer the asphaltene chains, the stronger and stiffer the asphalt binder. Adding water to the mixture

FIG. 10

Vertical deformation at optimal asphalt binder percentage.



strengthens the asphaltene chains in the asphalt emulsion and creates hydroxyl bonds between the water and bitumen molecules. Water could be the most dominant factor affecting the bond of adhesion between the asphalt binder and aggregates as water molecules are always prone to replace asphalt binder molecules on the aggregate surface. In addition, in the breaking behavior of binder-in-water emulsions, an important factor to realize is the water push out and wetting of the stone surface by the asphalt binder.[18,33,35,40] Regarding BDPGW, adding 2 % more water improved the performance at 1,000 loading cycles considerably. This increase in performance may be due to stronger asphaltene chains caused by increasing the water content in this sample. With reference to **figure 10**, it could be observed that three samples of BDPGW, BCPN, and BCPG were determined to have the lowest values for horizontal deformation at 2,000 loading cycles with 36 %, 37 %, and 32 % of deformation, respectively.

COHESION TEST RESULTS

Figure 11 presents the results of the cohesion test for Group A samples. Regarding specimen ACP, it could be observed that adding 4 % polypropylene fibers plus 1 % nano-zeolite in a mixture containing 11 % emulsified asphalt led the torsional couple to be increased from 1.2 $N.m$ to 1.25 $N.m$ in 30 minutes, which indicates the occurrence of Quick Set. Besides, the samples ACP and ACPN were determined to have the highest torsional

FIG. 11

Cohesion test results of Group A with 11 % emulsified asphalt binder.

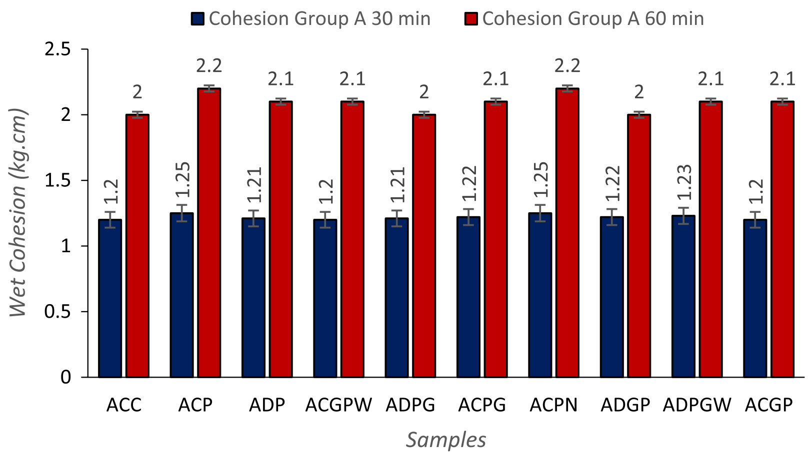
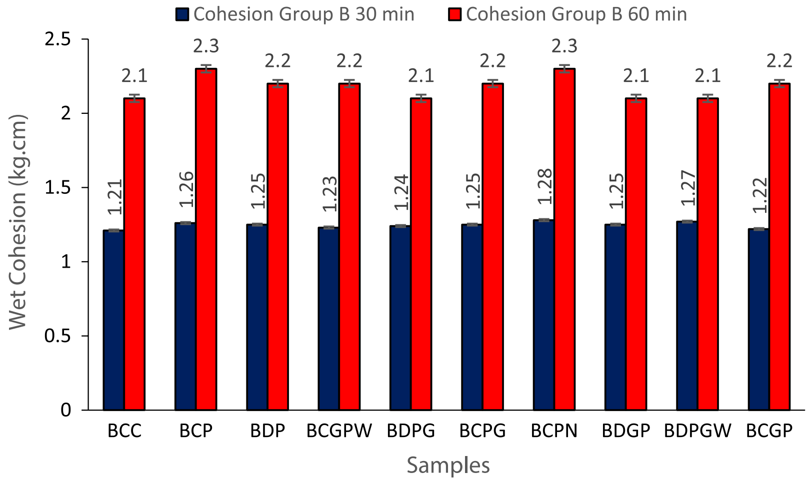


FIG. 12

Cohesion test results of Group B with 13 % emulsified asphalt binder.



couple among other samples in 60 minutes, which means that ACPN (including 4 % polypropylene and 4 % nano-zeolite) had an appropriate loading capacity compared to the control specimen ACC and was suitable for a Quick Traffic System. It can be concluded from figure 10 that although ACP and ACPN were recorded to have the highest torsional couple, ACP would be selected as the ideal specimen in this group regarding the lowest percentage of additives.

The results of the cohesion test for Group B samples are illustrated in figure 12. Generally, it can be seen that Group B samples had more cohesiveness than Group A. Regarding BCPN, it could be observed that adding polypropylene and nano-zeolite resulted in an increased torsional couple to 1.28 $N.m$ and 2.3 $N.m$ in 30 and 60 minutes, respectively. This indicates BCPN will provide better resistance against traffic loading. With reference to figure 12, it can be inferred that while BCP and BCPN performed better than other specimens of Groups A and B, BCPN containing 1 % more nano-zeolite was shown to have a better setting in 30 minutes than BCP. This improvement in setting led to an increase in cohesion and better interlocking between the aggregates.

With respect to figure 13, it could be realized that generally, Group C samples performed better than other groups regarding cohesion testing results. As seen, adding 4 % polypropylene and 2 % nano-zeolite resulted in

FIG. 13

Cohesion test results of Group C with 15 % emulsified asphalt binder.

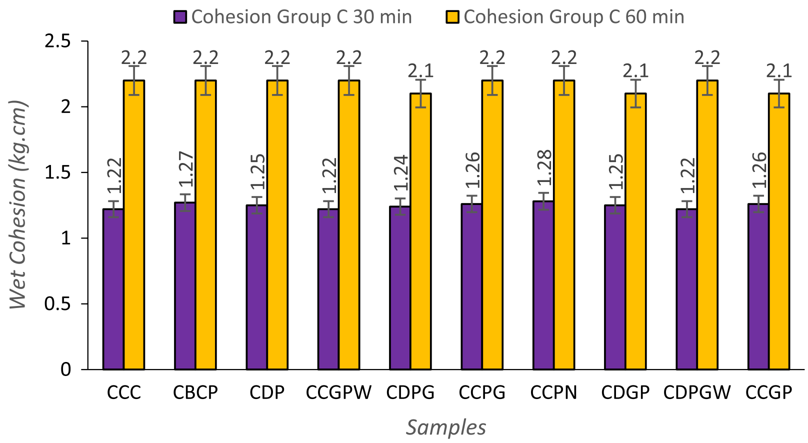


TABLE 12
Structural specifications of the best sample of each group

The Effect of Materials on	Wet Track Abrasion	Loaded Wheel: Sand Adhesion	Loaded Wheel: Horizontal Deformation	Loaded Wheel: Vertical Deformation	Cohesion
Percentage of asphalt emulsion	11 (ADP) 13 (BDP) 15 (CDP)	11 (ADP) 13 (BDP) 15 (CCPG)	13 (BDP)	13 (BDPGW)	11 (ACPN) 13 (BCPN) 15 (CCPN)
Percentage of cement filler	0 (ADP, BDP, & CDP)	0 (ADP, BDP) 1.5 (CCPG)	0 (BDP)	0 (BDPGW)	1.5 (ACPN, BCPN, CCPN)
Percentage of Diatomite	10 (ADP, BDP, & CDP)	10 (ADP, BDP) 0 (CCPG)	10 (BDP)	10 (BDPGW)	0 (ACPN, BCPN, CCPN)
Percentage of glass fiber	0 (ADP, BDP, & CDP)	0 (ADP, BDP) 0.13 (CCPG)	0 (BDP)	0.13 (BDPGW)	0 (ACPN, BCPN, CCPN)
Percentage of polypropylene	0.4 (ADP, BDP, & CDP)	0.4 (ADP, BDP) 0.26 (CCPG)	0.4 (BDP)	0.26 (BDPGW)	0.4 (ACPN, BCPN, CCPN)
Percentage of SBR	3 (ADP, BDP, & CDP)	3 (ADP, BDP, CCPG)	3 (BDP)	3 (BDPGW)	3 (ACPN, BCPN, CCPN)
Percentage of water	6 (ADP, BDP, & CDP)	6 (ADP, BDP, CCPG)	6 (BDP)	8 (BDPGW)	6 (ACPN, BCPN, CCPN)
Percentage of nano-zeolite	1 (ADP, BDP, & CDP)	1 (ADP, BDP, CCPG)	1 (BDP)	1 (BDPGW)	2 (ACPN, BCPN, CCPN)
Percentage of improvement	17.65 (ADP) 20.83 (BDP) 7.32 (CDP)	25.12 (ADP) 33 (BDP) 6.12 (CCPG)	35.29 (BDP)	36.46 (BDPGW)	10 (ACPN) 9.5 (BCPN) 4.92 (CCPN)

better cohesiveness and faster setting and led to a desirable behavior for a Quick Traffic System. The addition of polypropylene and nano-zeolite in CCPN led to a better setting and cohesiveness. Furthermore, with comparing CCGP and CCPG, it could be realized that adding glass fiber led to a smaller increase in the torsional couple in 60 minutes rather than polypropylene fibers.

Generally, it can be concluded from the cohesion testing results that nano-zeolite had a significant impact to provide adhesion between the particles and a proper cohesiveness for the whole mixture. This might be due to the catalyst property of nano-zeolite, which accelerates the interactions inside the mass, improves cracking resistance of the binder, and forms a homogenous structure.[41,42] Moreover, the existence of SBR, which includes styrene thermoplastic monomers in between elastic Butadiene monomers, initiates the interaction that leads to enhanced cohesiveness and adhesion.[33] Improved fatigue cracking resistance and rutting performance together with increased viscosity could also be mentioned as other outcomes of the existence of SBR in the mass.[43]

Table 12 shows the most appropriate amount of use of each additive in each group. Also, their effect on improving the performance of the samples compared to the control sample has been determined.

Conclusion

The impact of utilizing cement powder and Diatomite (as filler) as well as glass fibers, polypropylene, SBR, and nano-zeolite on the performance of asphalt mixtures was evaluated in this study. In order to assess the effect of different additives, a WTAT, LWT, and cohesion test were performed. The obtained results demonstrated that using the mentioned additives had a positive impact on the performance of the Micro-surfacing mixtures.

- Increasing the percentage of the emulsifier from 11 % to 13 % led to a 6 % improvement in the abrasion resistance of the asphalt mixtures. In addition, Diatomite was observed to have a better impact on the abrasion resistance of the mixtures compared to cement powder. Based on the results, employing 1 % nano-zeolite in Micro-surfacing mixtures could lead to an 11 % increase in the abrasion resistance of the mixtures.

- The results of the mixing time test showed that 6 % and 8 % of the water content at time of 120 s and temperature of 25°C could meet the requirements of the standard.
- The abrasion resistance of Group B was 6 % greater than Group A because of the 2 % increase in the emulsified asphalt content. Moreover, a 1 % increase in the content of nano-zeolite could increase the resistance of the mixture against abrasion by 11 %.
- The mixture with 11 % emulsified asphalt binder showed the best performance in terms of resistance against bleeding and prevention of adhesion loss. In addition, the test results for the determination of optimum emulsion asphalt content revealed that bleeding of the mixture at optimum emulsion asphalt content (e.g., 13 %) was compensated by the addition of 2 % nano-zeolite.
- Using 8 % water in the mixtures increased the strength between the components of the Micro-surfacing, which led to an improved rutting resistance. The addition of 2 % nano-zeolite reduced the permanent deformation considerably. Besides, the addition of 0.2 % fiber glass reduced the horizontal deformation of the mixture by about 22 %.
- The adhesion testing results exhibited that the addition of 4 % polypropylene and 2 % nano-zeolite increased the rotation couple, which might demonstrate that nano-zeolite increased the viscosity and stiffness of the asphalt binder. Nano-zeolite was able to form a bond between water and other additives, which increased the adhesion between aggregates.

Based on the obtained results, adding additives to asphalt Micro-surfacing could not only improve the performance of the mixtures but also reduce the maintenance costs during the life cycle of the pavement. Moreover, because of the reduced pace of aging of binder blends containing additives, it seems a novel idea to evaluate the effect of these additives on reclaimed asphalt (RAP) blended mixes. As a result, adding RAP into the tested mixtures could be a novel idea for future studies.

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Corrigendum

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