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INFLUENCE OF THERMOPLASTIC POLYMER ADDITIVES ON PROPERTIES OF ASPHALT CONCRETE MIXTURES

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In this paper, the mechanical and physical properties of thermoplastic polymer modified asphalt concrete mixtures were investigated. Three different thermoplastic polymer modifiers include; Ethylene vinyl acetate (EVA), Polypropylene (PP) and polyethylene terephthalate (PET) were studied. Constant polymer content of 3% by weight of asphalt cement was used in the studied mixtures. The Physical properties were evaluated in terms of softening point, penetration, kinematic viscosity and ductility tests, while the mechanical properties were evaluated based on Marshall stiffness, indirect tensile strength and unconfined compressive strength. Experimental testing has revealed the enhancement in the physical and mechanical properties of asphalt concrete mixtures when the three studied thermoplastic polymers were added. The EVA modified asphalt had the lowest penetration and highest softening point, kinematic viscosity and ductility. The EVA modified mixture also has experienced the highest Marshall stiffness, fracture energy, indirect tensile strength and unconfined compressive strength. Measurements of the heat dissipation rate of the studied polymer modified mixtures revealed their ability to hold heat longer than conventional mixtures. PP and EVA modified mixtures displayed the lowest rate of heat dissipation.

KEYWORDS: *Asphalt Concrete Mixtures; Thermoplastic Polymers; Physical and Mechanical properties*.

1. INTRODUCTION

Long-term performance of asphalt pavement is a major challenge and ultimate goal of highway agencies. Polymer modification of asphalt concrete mixtures has been considered by many researchers to achieve this goal. When polymers are added to asphalt, the properties of the modified asphaltic mixture depend on the compatibility of the polymer with the asphalt. Therefore, choosing the right polymer modifier is an essential task that can aid in providing better and long lasting roads. Polymer modifiers can be classified into two major groups: elastomeric modifiers, and the plastomeric modifiers. Elastomeric modifiers such as styrene/butadiene polymers, natural rubber and crumb rubbers tend to improve the mixture elasticity and low temperature properties. Plastomeric modifiers such as polyethylene, ethyl-vinyl-acetate and polyvinyl chloride tend to improve the stiffness and high temperature properties of asphaltic mixtures.

Studying the effect of different types of additives on improving the properties of asphalt concrete mixtures is a field of interest for many researchers. An extensive research program sponsored by the Michigan Department of Transportation was performed to evaluate the effect of polymer modification on the micro- and macro structural, morphological, chemical, and engineering properties of asphalt mixtures [1]. The studied polymers include styrene-butadiene-styrene and styrene-ethylene-butylene-styrene. The elastic, fatigue, tensile and permanent deformation properties of asphalt concrete mixtures modified with these polymers were investigated at (60, 25, and -5 deg C). It was indicated that, the fatigue life and the indirect tensile strength of the polymer modified mixtures increased considerably at (25^oC), while the elastic properties at (-5^oC) were not affected by the polymer modification. Another study was performed by Khattak and Baladai [2] to characterize rheological properties of polymer modified asphalts. It was found that the rheological and engineering properties of asphaltic mixtures largely depend on the polymer type and content. It was also reported that the improvements in the fatigue lives and resistance to permanent deformation of polymer modified mixtures are mainly due to the improvements in the rheological properties of the binders.

The effect of thermal cycling on the mechanical and fracture resistance of rubber modified and unmodified asphalt concrete mixtures were conducted by Othman [3]. It was found that the rubber modified mixtures have larger tensile strength and fracture toughness over the entire range of thermal cycles used as compared to unmodified asphaltic mixtures. In a research study performed by Mull et. al, [4] it was indicated that, the fatigue crack growth resistance of asphaltic mixtures was highly improved when modified with crumb rubber. The effect of rubber content on the fracture resistance of the rubber modified mixtures using the fracture mechanics approach was investigated by Othman et. al [5]. Within that investigation, the fracture resistance superiority of the rubber modified asphalt concrete mixtures was evident. The investigation also demonstrated that mixtures modified with 15% rubber content experienced the highest fracture resistance. More recent laboratory studies on the effect of crumb rubber and chemically modified crumb rubber modifiers on the static and fatigue performance of asphalt pavements have been carried out by Mull et. al [6-7]. Out of these studies, it was found that the addition of either crumb rubber or chemically modified crumb rubber enhanced the static and fatigue performance of the asphalt mixtures.

As indicated in the above review, most of the previous work related to evaluation of polymer modified asphalt concrete mixtures was performed using elastomeric modifiers such as styrene/butadiene polymers and crumb rubbers. Very little work has considered using plastomeric modifiers. Therefore, in the present work, focus was placed on studying thermoplastic polymer modifiers. A general testing laboratory program was established in order to assess the physical and mechanical properties of asphalt concrete mixtures modified with three different types of thermoplastic polymer modifiers. The studied polymer modifiers include Ethylene vinyl acetate (EVA), Polypropylene (PP) and polyethylene terephthalate (PET) which is commonly called “Polyester”. Constant polymer content of 3% by weight of asphalt cement was used. Physical properties of modified asphalt were evaluated in terms of softening point, penetration, kinematic viscosity and ductility tests. Mechanical properties of modified mixtures were evaluated based on Marshall stiffness, indirect tensile strength and unconfined compressive strength.

2. SCOPE OF WORK

2.1 Evaluation of Physical Properties

Evaluation of asphalt physical properties is of great importance since they are directly related to the performance of asphalt concrete pavement. Within this work four important physical properties were evaluated for the studied polymer modified asphalts namely; penetration, softening point, kinematic viscosity and ductility. The softening point of asphalt reflects its deformation ability, while penetration reflects its consistency or hardness characteristics. The kinematic viscosity is a measure of flow characteristics of asphalt in the range of temperature used during application. Finally, ductility is a measure of the ductile (ability to stretch) behavior of asphalts.

2.2 Evaluation of Mechanical Properties

The mechanical performance of the studied polymer modified mixtures was evaluated based on the Marshall Stiffness, indirect tensile strength and unconfined compressive strength.

2.2.1 Marshall Stiffness

Marshall stiffness (MS) is widely used to characterize the mechanical performance of asphalt concrete mixtures [8]. It is considered a combined index that reflects both the stability and plastic flow characteristics of the mixtures. It is obtained from Marshall stability testing results as indicated in Equation (1).

$$MS = S_i \,/\, (F_i \times b) \qquad (1)$$

where;
MS = Marshall stiffness
Si = Mixture’s stability at asphalt content (i)
Fi = Mixture’s flow at the same asphalt content (i)
b = Specimen Thickness

2.2.2 Indirect Tensile Strength and Fracture Energy

The indirect tensile strength test is widely used to characterize the mechanical performance of asphaltic mixtures. The experimental procedure used to determine the tensile or splitting strength of a cylindrical specimen is based on loading it diametrically in compression to create a tension zone along the specimen’s loaded diameter. The expression for the maximum tensile strength generated can be stated as;

$$\sigma_t = \frac{2\,P_{\max}}{\pi D H} \qquad (2)$$

where σ_t is the indirect tensile strength, $P_{\max}$ is the maximum applied load and *H, D* are the height and the diameter of the specimen respectively. The fracture energy of the tested mixtures can be calculated during the indirect tensile strength test. The fracture energy is defined as the work to be done to fracture the specimen, and is equal to the area under the load-deflection curve up to the failure load. The fracture energy concept is a fundamental fracture property that is suitable for asphalt concrete materials since it is less dependent on the assumptions of the linear elasticity. The fracture energy (G_f) can be calculated according to RILEM TC 50-FMC specification [9] using the following expression;

$$G_f = \frac{\int_0^{\delta \max} P(\delta)\, d\delta}{H\,D} \qquad (3)$$

where G_f is the Fracture Energy, $P(\delta)$ is the applied load, δ is the resulted deflection and *H, D* are the height and the diameter of the specimen respectively.

2.2.3 Unconfined Compressive Strength

The unconfined compressive strength test is performed to determine the compressive properties of asphalt concrete mixtures. The compressive strength of the mixtures can be obtained through applying a compression load on the circular face of a circular specimen. The load is increased until failure occurs. The compressive strength can be calculated using the following expression;

$$\sigma_c = \frac{4P_{\max}}{\pi D^2} \qquad (4)$$

where σ_c is the unconfined compressive strength, $P_{\max}$ is the maximum applied compressive load and, *D* is the diameter of the specimen.

3. EXPERIMENTAL WORK

3.1 Material Characterization

Asphalt binder 60/70 was used in this research work. Coarse and fine aggregates (Bulk specific gravity of 2.77 and 2.68 respectively) were used in the preparation of the asphalt concrete mixtures. Limestone was used as mineral filler. Table (1) presents the selected mix gradation.

Table (1): Selected mix gradation

Sieve	1”	3/4”	3/8”	3/16”	No.10	No.30	No.50	No.100	No.200
% Pass	100	100	79	50	45	24	22	9	6

Three different thermoplastic polymers include Ethylene vinyl acetate (EVA), Polypropylene (PP), polyethylene terephthalate (PET) were selected for this study. Ethylene-vinyl acetate is the copolymer of ethylene and vinyl acetate. It has good clarity and gloss, barrier properties, low-temperature toughness, stress-crack resistance, hot-melt adhesive and heat sealing properties and resistance to UV radiation. Polypropylene is a thermoplastic polymer, made from the monomer propylene. It is rugged and unusually resistant to many chemical solvents used in a wide variety of applications. Polyethylene terephthalate is a thermoplastic polymer resin of the polyester family that is used in synthetic fibers. It normally exists as an amorphous (transparent) and as a semi-crystalline (opaque and white) material. Table (2) presents the physical properties of thermoplastic polymers under study.

Table (2): Physical Properties of Studied Thermoplastic Polymers

	EVA	PP	PET
Density (g/cm^3)	0.93	0.85	1.37
Water Absorption (*%*)	0.07	0.12	0.16
Young Modulus (*MPa*)	3100	2500	2800
Elongation (*%*)	800	260	150
Melting Point (*°C*)	290	180	260

3.2 Sample Preparation

Asphalt binder content of 5 percent by total mass of the mixture was used based on Marshall stability mix design method. Constant polymer content of 3% by weight of binder was used for all the tested polymers. The used polymers were blended with the asphalt binder at a temperature of 166°C (330°F) using conventional low shear mixer. Marshall specimens were prepared from the studied mixtures in accordance with the standard 75-blow Marshall design method for designing asphalt concrete mixtures, designated as (*ASTM Designation: D 1559-89*) using automatic compaction. To provide adequate data, three samples were prepared from each mixture for each test.

3.3 Experimental Testing

3.3.1 Marshall Stiffness Test

The Marshall stability test (*ASTM Designation: D 1559-82*) was performed to determine the stability and flow values for the studied mixtures. The determined stability and flow results were used for the calculation of Marshall stiffness based on Equation (1), previously presented.

3.3.2 Indirect Tensile Test

Standard Marshall test samples (2.5" in height by 4" in diameter) were used for the indirect tensile strength evaluation. A mechanical displacement control-testing frame was employed to conduct the indirect tensile tests in accordance with *ASTM D4123*.

The load was applied at a vertical deformation rate of 4 mm/min. The indirect tensile strength is the maximum stress developed at the center of the specimen in the radial direction during loading. Load displacement curves were recorded using a x-y plotter.

3.3.3 Unconfined Compressive Strength Test

The unconfined compression tests were performed using a 15-ton capacity universal testing machine. Standard Marshall test samples (2.5" in height by 4" in diameter) were placed on the lower fixed platen of the testing machine. Load was applied with a uniform rate of 2 mm/min on the circular face of the testing samples until failure occurred. The maximum load to failure was recorded and hence the compressive strength was calculated.

3.3.4 Heat Dissipation Test of Asphalt Concrete Mixtures

An experimental program was performed in order to test the ability of the polymer modified mixtures to hold heat as compared to the conventional mixtures. Three different asphalt mixtures were tested, namely, PET, PP and EVA modified mixtures. The results of these mixtures were compared with the result of unmodified mixture. All mixtures were mixed at 160 C^o and then placed at room temperature (32 C^o). The temperature of each mixture was measured every 5 minutes for a period of one hour.

4. RESULTS AND DISCUSSION

4.1 Physical Properties Testing Results

Results of softening point, penetration, kinematic viscosity and ductility tests are presented in Table (3) and Figures (1-4).

Table: (3): Physical properties of polymer modified asphalts

Type of Polymers Modified Asphalt	Penetration (0.1 mm) at 25 ^{o}C	Soft. Point (^{o}C)	Kinematic Viscosity (cstoke) at 135^o C (275^o F)	Ductility (cm)
Unmodified Asphalt	67	51	430	78
PP-Modified Asphalt	59	53	467	84
PET-Modified Asphalt	51	60	612	92
EVA-Modified Asphalt	47	65	783	100

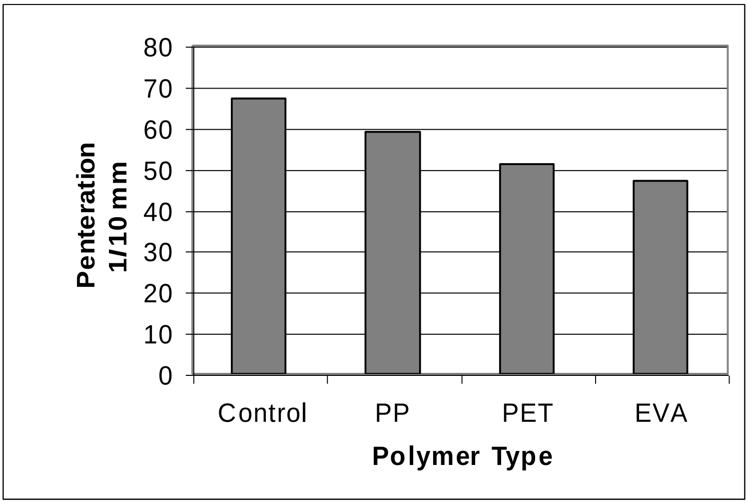

Figure (1): Penetration of polymer modified asphalts

It is indicated from Figure (1) that, the polymer modified asphalts have lower penetration values as compared to the unmodified asphalt. This indicates that, the hardness and stiffness of asphalt have been increased when polymer modifiers were added.

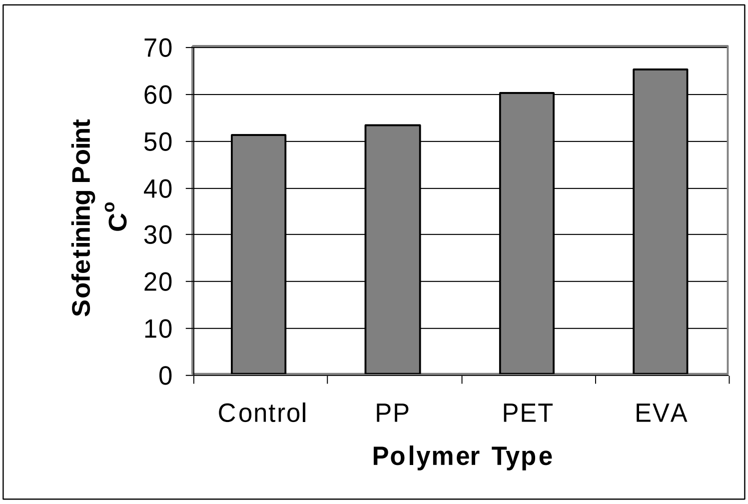

Figure (2): Softening Point of Polymer Modified Asphalts

It can be also concluded from Figures (2-4) that the softening point, viscosity and ductility of the polymer modified asphalts are higher than that for the unmodified asphalt. This means that adding polymers to asphalt has a considerable effect on improving its resistance to flow and deformation. The increase in viscosity when polymers were added is an expected behavior due to the development of a continuous polymer network within the asphalt blend that tends to reduce the interparticle distance between the blend particles, which increases the viscosity of the polymer–asphalt blend. Hence, thermoplastic polymer modified asphalts may perform better in hot climate areas as compared to unmodified asphalt. This opinion is shared by many researchers [10-13].

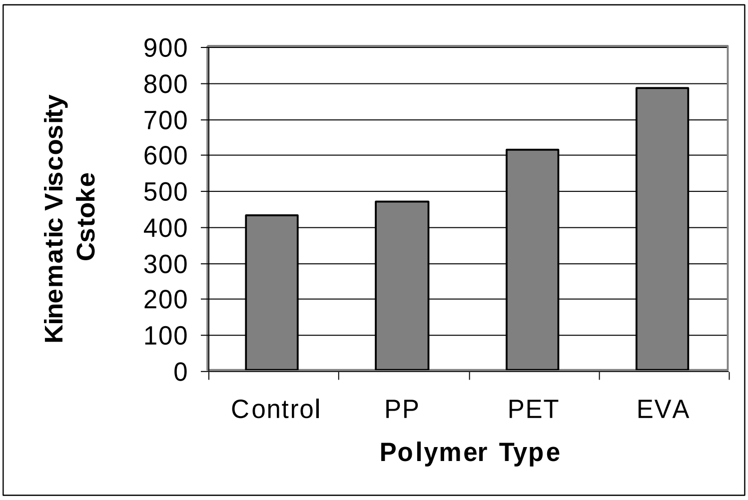

Figure (3): Kinematic viscosity of Polymer Modified Asphalts at 135° C (275° F)

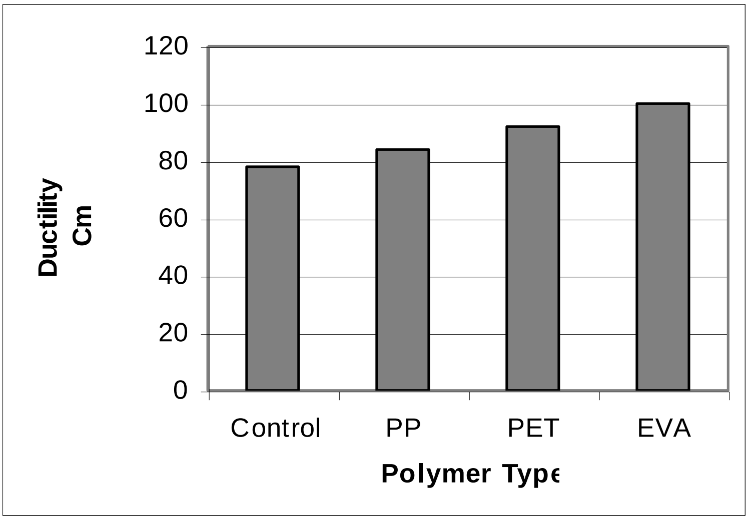

Figure (4): Ductility of polymer modified asphalts

Figures [1-4] indicate also that, the EVA modified asphalt exhibits higher softening point, viscosity, ductility and lower penetration as compared to the other modified asphalts. The PP modified asphalt had the lowest softening point, viscosity, ductility and highest penetration. Therefore, EVA modifier is assumed to be more effective on improving temperature susceptibly of asphalt cement mixtures.

4.2 Mechanical Properties Testing Results

4.2.1 Marshal Test Results

The results of the Marshall stability tests for each of the tested mixtures are summarized in Table (4). All results shown for each specimen are the average value for three tests. It is evident that, the polymer modified asphalt concrete mixtures have higher Marshall stability and lower flow values compared to the unmodified mixtures. The Marshall stiffness value is calculated from Equation (1) and presented in both Table (4) and Figure (5). It is indicated that the values of Marshall stiffness are higher for the polymer modified mixtures than its counterpart for the unmodified mixture. This reflects the enhancement in the mixture stiffness of the asphaltic mixture due to adding the polymer modifiers. It is also indicated that, the mixture modified with EVA has higher Marshall stiffness, higher Marshall Stability and lower flow values when compared to the other modified mixtures studied in this research work.

Table (4): Marshall stability test results

Type of Polymers Modified Mixture			Marshall Stiffness	
			(psi)	(KN/cm^2)
Unmodified Mixture	1795	13.5	5319	3.66
PP- Modified Mixture	2028	11.8	6874	4.73
PET- Modified Mixture	2328	12.6	7390	5.09
EVA- Modified Mixture	2497	12.9	7743	5.33

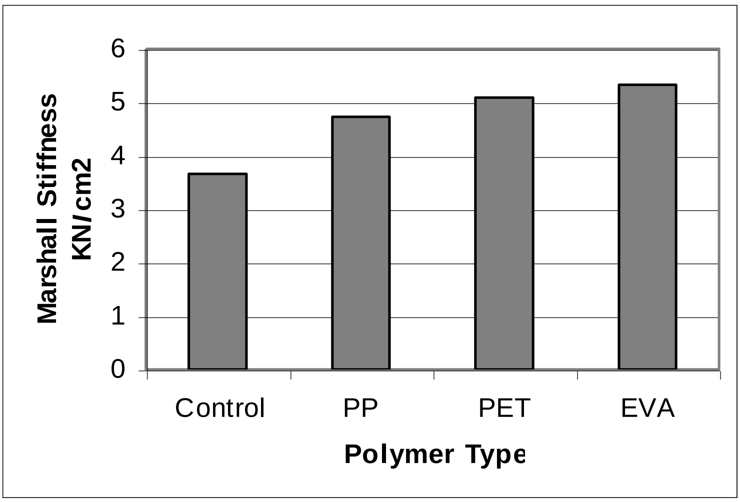

Figure (5): Marshall stiffness of polymer modified asphalt concrete mixtures

4.2 Indirect Tensile Strength Test Results

The load–displacement values measured during the indirect tensile strength test for all the tested mixtures are plotted in Figure (6).

The curves in Figure (6) represent the average values for three samples tested from each mixture. It is evident from that figure that EVA modified mixture has the highest fracture load and displacement among the tested mixtures, while the unmodified mixture has the lowest fracture load and displacement. Also the area under the load-displacement curve for the EVA modified mixtures is higher than that for the other mixtures. This indicates the capability of EVA modified mixture to store more energy. On the other hand the unmodified mixture has the lowest area under the load displacement curve.

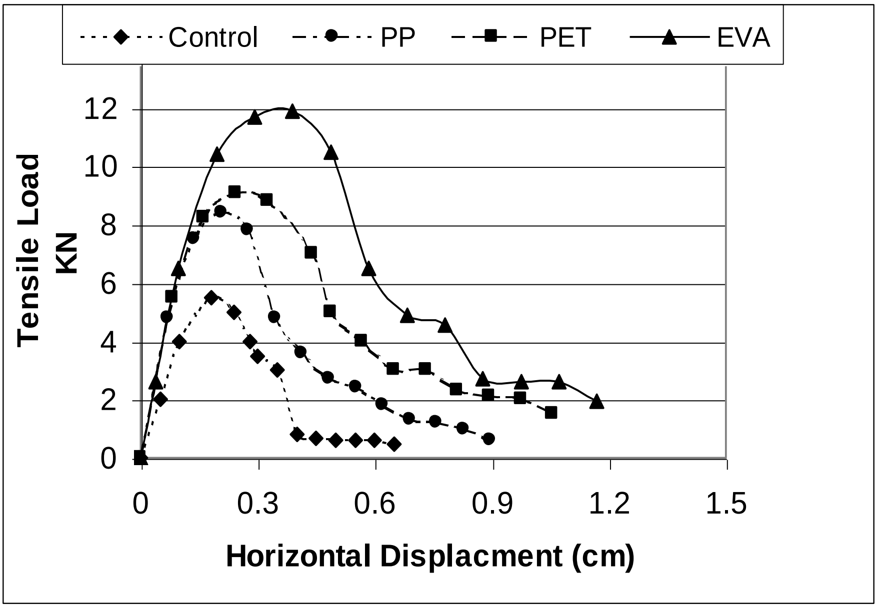

Figure (6): Load – displacement curves based on indirect tensile strength tests for polymer modified asphalt concrete mixtures

Values of indirect tensile strength and fracture energy are calculated based on Equation (2) and (3) and presented in Table (5) and Figures (7) and (8). It is evident that, the value of indirect tensile strength and fracture energy for the polymer modified mixtures are higher than those for the unmodified mixture. This means that less energy is required to split polymer modified samples. This means that polymer modification enhanced the tensile and toughness properties of asphaltic mixtures. The EVA modified mixture exhibited the highest indirect tensile strength and fracture energy. Hence, it can be concluded that the EVA modifier has a potential to increase the toughness of asphalt concrete mixtures and their resistance to tensile stresses.

Table: (5): Tensile failure load, indirect tensile and fracture energy of polymer modified asphalt concrete mixtures

Type of Polymers Modified Mixture	Tensile Failure Load (KN)	Indirect Tensile Strength (KN/cm^2)	Fracture Energy (KN.cm) x 10^{-2}
Unmodified Mixture	5.5	0.056	0.93
PP- Modified Mixture	8.1	0.082	1.67
PET- Modified Mixture	9.2	0.093	2.16
EVA- Modified Mixture	11.7	0.118	4.84

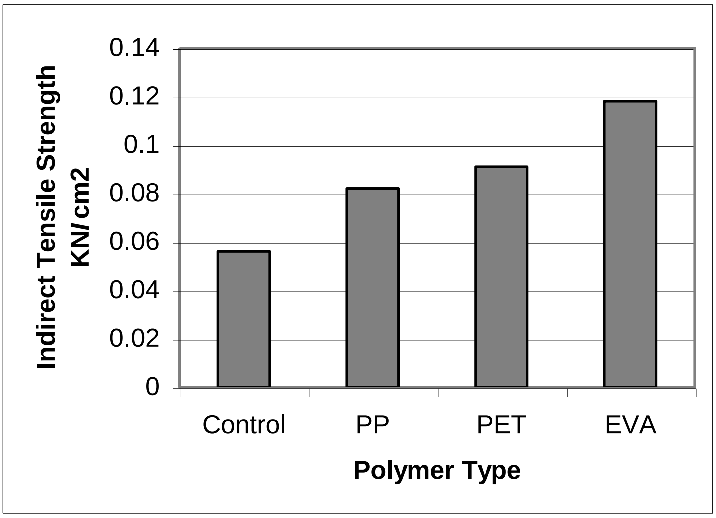

Figure (7): Indirect tensile of polymer modified asphalt concrete mixtures

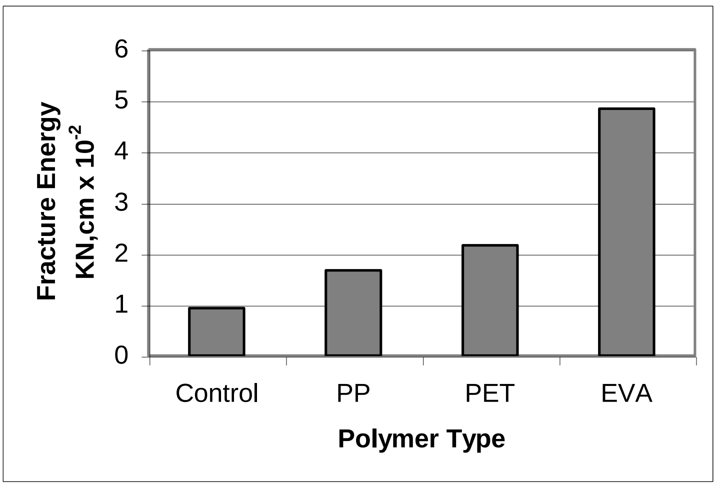

Figure (8): Fracture energy of polymer modified asphalt concrete mixtures

4.3 Unconfined Compressive Strength Test Results

The unconfined compressive strength test was performed to determine the compressive properties of the studied mixtures. The average unconfined compressive strength for various mixtures is calculated based on Equation (4) and presented in Table (6) and Figure (9).

Table (6): Compressive failure load and unconfined compressive strength of polymer modified asphalt concrete mixtures

Type of Polymers Modified Mixture	Compressive Failure Load (KN)	Unconfined Compressive Strength (KN/cm^2)
Unmodified Mixture	19.5	0.248
PP- Modified Mixture	29.2	0.372
PET- Modified Mixture	34.6	0.441
EVA- Modified Mixture	43.4	0.552

As given in Table (6) and Figure (9), the unconfined compressive strength of the polymer modified asphalt concrete mixtures is higher compared to the unmodified mixture. This reflects the enhancement in the mixture resistance to compressive stresses due to adding polymer modifiers. It is also concluded that mixtures modified with EVA displayed the highest compressive strength. Polypropylene (PP) modified mixture displayed the lowest compressive strength among the tested polymers.

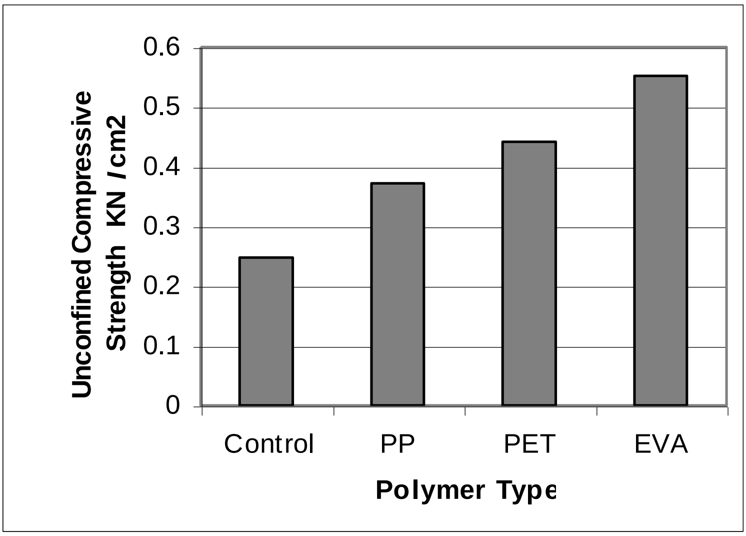

Figure (9): Unconfined compressive strength of polymer modified asphalt concrete mixtures

In view of the above results, it is evident that the mixtures mechanical properties have considerably increased when polymers were added. This is indicative of an improvement in the interfacial strength between the binder and the aggregate.

This can be related to the ability of polymers to increase the adhesive bond between asphalt cement and aggregate particles. The EVA polymer modified mixture displayed the best mechanical properties among the other polymer modified mixtures. The significant improvement in the mechanical properties of the EVA modified mixtures is due to the fact that the EVA is a polymer that approaches elastomeric materials in softness and flexibility, yet can be processed like other thermoplastics. So it can improve both the mixture elasticity and stiffness.

4.4 Heat Dissipation Test Results

Relationships between temperature and time for the four studied mixtures are presented in Figure (10). The starting temperature for all the mixtures was (160 C^o). After ½ hour, the mixture temperature was found to be 93, 100, 117 and 115 C^o for the control, PET, PP and EVA mixtures respectively. After 1 hour the mixture temperature was found to be 66, 70, 80 and 78 C^o for the control, PET, PP and EVA mixtures respectively. It can be stated that, the polymer modified mixtures temperature is always higher than the temperature of the conventional mixture.

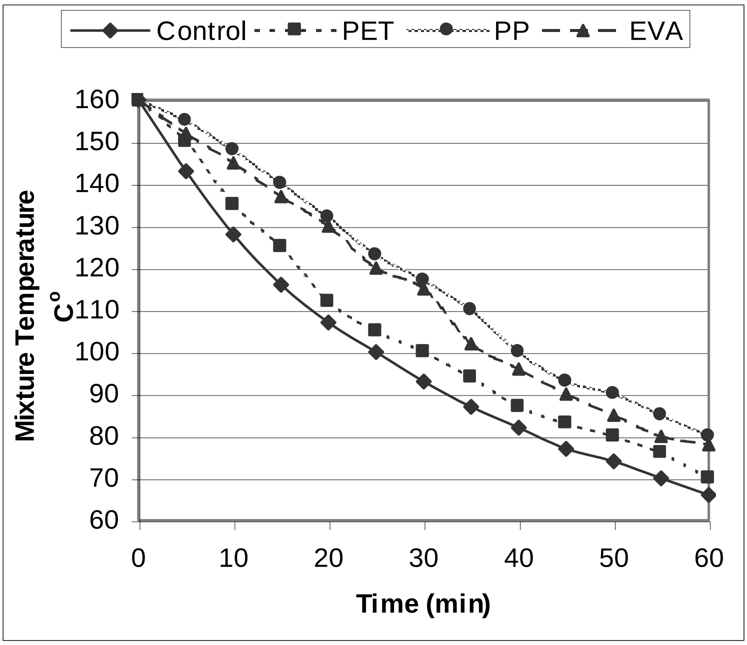

Figure (10): Temperature vs. time for the polymer modified asphalt concrete mixtures

Figure (11) presents the relationship between the drop in temperature in degrees centigrade and time in minutes for the studied mixtures. It is indicated from the figure that, the drop in temperature after ½ hour was found to be 67, 60, 43 and 45 for the control, PET, PP and EVA mixtures respectively. The drop in temperature after 1 hour was found to be 94, 90, 80 and 82 for the control, PET, PP and EVA mixtures respectively.

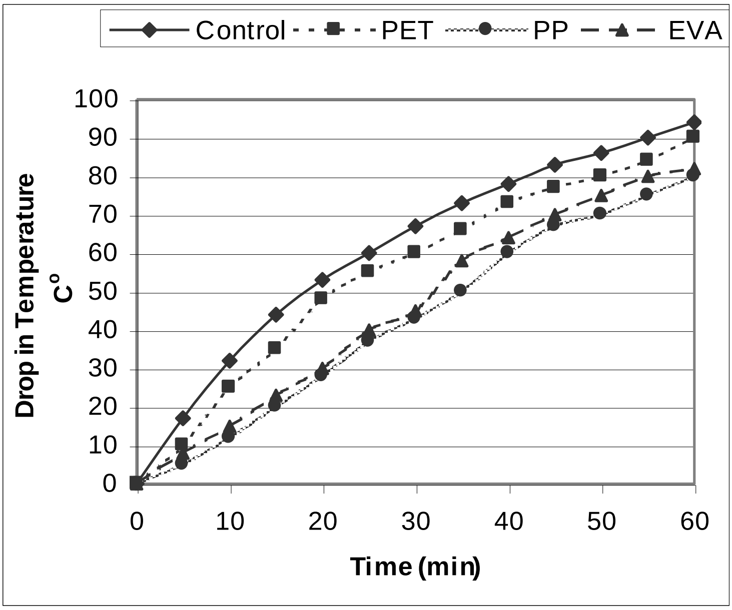

Figure (11): Drop in temperature in degrees centigrade vs. time for the polymer modified asphalt concrete mixtures

It can be concluded from the results of heat dissipation test that, the polymer modified mixtures dissipate less heat as compared to the conventional mixture. This behavior can be attributed to the ability of thermoplastic polymer modified asphalt to hold heat as compared to conventional asphalt. This can have useful application in asphalt paving during cold whether or when long period of post-mix transportation is needed. PP and EVA modified mixtures displayed the lowest rate of heat dissipation among the tested mixtures.

5. CONCLUSION

It would be concluded from this research that polymer modification has enhanced the physical properties of the asphalt cements and the mechanical properties of the polymer modified asphalt concrete mixtures. Comparison between the three studied polymer types has shown that, EVA modified asphalt experienced lower penetration, higher softening point, kinematic viscosity and ductility. EVA modified mixture also exhibited higher values of Marshall stiffness, indirect tensile strength, fracture energy and unconfined compressive strength. The overall improvement on the properties of EVA modified mixture can be related to the increase of the adhesive bonding between asphalt cement and aggregate particles. Measurements of the heat dissipation with time for the studied mixtures indicated that, adding thermoplastic polymers to asphalt concrete mixtures can help in dissipating less heat as compared to conventional mixtures. Further investigations should be carried out to confirm this finding at a wide range of testing temperatures. Further research is also needed to establish the optimum concentration of the polymer to be used.

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تأثير إضافة البوليمرات الثرموبلاستكية على خواص الخلطات الإسفلتية

يتناول هذا البحث دراسة تأثير إضافة البوليمرات الثرموبلاستكية على الخواص الطبيعية والميكانيكية للخلطات الإسفلتية. وقد تم في هذا البحث اختبار ثلاثة انواع من البوليمرات الثرموبلاستكية وهما ايثلين فينيل اسيتات (ETHYLENE VINYL ACETATE (EVA)) و بوليبروبلين (POLYPROPYLENE (PP)) و بولياثيلين تيريفثلات (POLYETHYLENE TEREPHTHALATE (PET)). وقد تمت إضافتهم للخلطة الاسفلتية بنسبة 3% من وزن الأسفلت المستخدم في الخلطة. وقد تم تقييم الخواص الطبيعية للإسفلت المحسن وغير المحسن عن طريق إجراء اختبار درجة التطرية والغرز واللزوجة الكينماتيكية والممطولية، في حين تم تقييم الخواص الميكانيكية للخلطات الاسفلتية المحسنة وغير المحسنة عن طريق تحديد كل من معامل مارشال للصلابة ومقاومتي الشد والضغط .وقد أوضحت نتائج البحث أن إضافة المواد الثلاثة التي تم اختبارها للخلطات الإسفلتية قد ساعد بصفة عامة على تحسين الخواص الطبيعية والميكانيكية لها. كما أوضحت النتائج أيضا انه بمقارنة تأثير كل من تلك المواد على الخواص التي تمت دراستها ,قد ثبت أن الأسفلت المحسن بمادة ايثلين فينيل اسيتات قد حقق قيمة اقل للغرز وقيم أعلى فيما يتعلق بدرجة التطرية واللزوجة الكينماتيكية والممطولية . كما ثبت أيضا أن الخلطات الإسفلتية المحسنة بنفس المادة قد حققت قيم أعلى لمعامل مارشال للصلابة ومقاومتي الشد والضغط كما انها تحتوي على اعلى طاقة لمقاومة الكسر. وأوضحت التجارب المعملية الخاصة بقياس معدل الفقد الحراري للخلطات الإسفلتية المحسنة بانواع من البوليمرات الثرموبلاستكية التي تمت دراستها أن إضافة هذه المواد للخلطات الإسفلتية من شأنه أن يزيد من قدرة الخلطة على الاحتفاظ بالحرارة لمدة أطول بعد الخلط بالمقارنة بالخلطات العادية. وقد لوحظ ان أن الخلطات الإسفلتية المحسنة بمادتي الايثلين فينيل اسيتات و البوليبروبلين لها اعلى قدرة على الأحتفاظ بالحرارة.