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SUSTAINABLE RECYCLING OF POLYETHYLENE WASTE THROUGH UTILIZATION IN ASPHALT PAVING APPLICATIONS

Mohammed G. Jamel*, Oday A. Salih, Ayman Talib Hameed, Al-Hadidy A.I.

Department of Civil Engineering, College of Engineering, University of Mosul, Mosul 41002, Iraq

** mohammed_g72@uomosul.edu.iq*

One the enormous amount of waste polyethylene (PE) materials amassing in Iraq is posing an expensive landfill and disposal issue. The current study examines the potential for employing PE as a partial replacement for environmentally friendly pavement construction. Different amounts of PE were used to partially replace asphalt cement (3 %, 6 %, 9 %, and 12 % by weight). The PE-substituted asphalt (PESA) binders were subjected to the rheological and compatibility properties. Additionally, two asphalt concrete (AC) mixtures—one control and one PEAC—were created for the mechanical and durability experiments. Among the parameters assessed during the tests are the following: adhesion to a variety of substrates and substrate surfaces; elongation at room temperature (aging index); flexibility at elevated temperatures (cracking index); temperature susceptibility; compatibility; and the extensional viscosity of the PESA binder as well as the extensional viscosity of the PESA-mixture (PESAM). Furthermore, the mechanical and durability properties of AC and PEAC mixes were examined using the Marshall stability, Marshall quotient, static indirect tensile strength at 25 and 60°C, tensile strength ratio, and resilient modulus 25°C tests. Results show that PESA binder outperforms virgin asphalt binder in terms of cracking and temperature resistance. PEAC mixture exhibits higher stability, indirect tensile strength, moisture resistance and resilient modulus than AC mixture. According to standard and durability testing, replacing virgin binder with six percent PE can be recyclable and suitable for use as sustainable material for paving applications.

Keywords: polyethylene waste, rheological properties, cracking resistance, mechanical tests, durability tests

1 INTRODUCTION

It is common to see asphalt pavement cracking in northern Iraq due to non-load-related low-temperature cracking. Because of the spalling, heaving, or settling that occurs at the cracks as a result of this stress, the pavement's useful life is reduced. When a new overlay is applied, these fissures show through. Finding the rehological features of the asphalt binder that cause this kind of suffering is critical.

Techniques for reducing the detrimental impacts of asphalt binders, additives, modifiers, and aggregate were provided in FHWA-HIF-16-012. One of these options is to improve the asphalt material by mixture design, building techniques, and, in some situations, modern substances like warm mix asphalt (WMA) or the addition of polymers, rubber, and other modifiers when traffic, climate, and present conditions warrant it [1].

The introduction of polymers to asphalt mixtures in a variety of doses and types appears to offer the most potential for success in the construction of flexible pavements [2]. Among these attempts, the use of polymer-modified asphalt binders has shown promise in decreasing early pavement failures, especially in provinces with substantial seasonal climate differences and large truck traffic volumes.

Asphalt binder/mix modification is a common use of plastomeric polymers, such as high-density polyethylene (HDPE). As a result, polyethylene (PE) in the form of low-density polyethylene (LDPE) or linear low-density polyethylene (LLDPE) appears to improve asphalt concrete mixes when used at 3-5 % bitumen [3].

Numerous research conducted over the past few decades have found that polymers can alter and enhance the characteristics of asphaltic pavements [4–14]. The use of polymer as an asphalt binder is a practical way to reduce or completely get rid of pavement distress. Pyrolisis LDPE's potential application as a modifier for asphalt paving materials is examined by Al-Hadidy and Tan [4]. Five distinct mixes, including conventional mix, were put through a variety of homogeneity tests and binder testing, including rheological tests. According to research findings, modified binders displayed higher softening points, maintaining ductility values at the minimum range of specification of (100+ cm), and reducing the percentage of weight loss due to heat and air (i.e., increasing the durability of original asphalt).

Reclaimed PE was employed by Punith and Veeraragavan [5] as asphalt modifiers. They discovered that the basic test results showed that adding PE modifier increased the softening point and specific gravity values while decreasing penetration and ductility values of neat asphalt. For the performance of asphalt cement to be improved, a PE concentration of 5% by weight of asphalt is advised.

Sinan and Emine [6] looked at the possibilities of adding polymer additives to asphalt concrete using different plastic wastes that contained high density polyethylene (HDPE). The impact of HDPE-modified binder on Marshall Stability, Flow, and Marshall Quotient (MQ) (Stability to Flow Ratio) was examined.

HDPE-modified binder was produced by altering mixing periods, mixing temperatures, and HDPE percentage. The AC-20 with 4-6 % and 8 % HDPE (by the weight of the optimal bitumen content) were mixed for 5–15 and 30 minutes at 145°C –155°C and 165°C, respectively, to create the binders used in HMA. They came to the conclusion that the

Marshall Stability (strength) value and a MQ value were significantly increased by the HDPE-modified asphalt concrete (resistance to deformation). Marshall Stability, flow, and MQ were all found to function best under the following conditions: 4 % HDPE, 165 °C mixing temperature, and 30 minutes of mixing. Compared to the control mix, MQ went up by 50%. Due to their high stability and high MQ, it can be argued that waste HDPE-modified bituminous binders offer superior resistance against permanent deformations, which helps with both the recycling of plastic waste and environmental protection.

The laboratory design of continuously graded asphalt concrete mixtures with recyclable plastic aggregate substitution was covered by Zoorob and Suparma [7]. In dense graded bituminous mixes, recycled waste plastics, primarily made of LDPE in pellet form, were utilized to partially (by volume) replace the mineral aggregates of the same size, i.e., 5.00-2.36mm. They claimed that the compacted Plastiphalt mix has a lower bulk density than the traditional control mix at the same air-void content. With the LDPE replacing 30% of the aggregate by volume, the bulk compacted mix density is reduced by 16%. In terms of hauling expenses, this decrease in density is beneficial. The Marshall stability (strength) value and MQ value both rise by 250 % with LDPE partial aggregate substitution. After one hour of loading at 60 °C, it is discovered that the Plastiphalt mix's creep stiffness value is marginally lower than the control mix's. However, the Plastiphalt provides 1 hour of unloading time with a recovery rate of 14% as opposed to the control mix's 0.64%. While the static indirect tensile strength values of the Plastiphalt compacted mix were substantially higher than those of the control mix, the indirect tensile stiffness modulus values were found to be lower. They also looked into the Plastiphalt's potential for recycling in the future. It was discovered that the mechanical qualities of the recycled mix were superior to those of the control mix and equal to those of the original Plastiphalt.

For a high-durability asphalt binder (HDAB) and a high-durability asphalt mixture (HDAM) appropriate to the wearing course of a bridge deck system, Hee et al. [8] detailed the findings of laboratory and full-scale performance tests. The HDAB was created utilizing a hydrocarbon and an SBS-modifier to increase construction workability and fatigue fracture resistance. The HDAB was subjected to a number of binder tests, and the findings revealed that, when compared to the PG 64-22 and PG 76-22 binders, the HDAB greatly increased its resistance to fatigue and low temperature cracking. The HDAM has three times longer fatigue life than the SBS-modified asphalt mixture, according to the findings of the fatigue tests. Additionally, it was discovered that the HDAM had a stronger resilience to damage brought on by moisture. The bridge deck pavement system underwent full-scale expedited testing, and the results showed that the HDAM can greatly enhance pavement performance. Moatasim et al. [9] investigated the moisture and temperature susceptibility of polyethylene-modified bitumen mixes (HP/BM). When it came to resistance to moisture and temperature, HP/BM blends fared better than control mixes. An HP concentration of 5% weight of asphalt can enhance asphalt performance. Mansour and Amin [10] examined the fracture strength of recycled asphalt (RA) and steel slag as aggregate (SSA) under thaw and freeze cycles and LTA. It is discovered that RA/SSA mix fracture strength increases with aging.

In his investigation of the physical characteristics of asphalt-PE mixtures, Al-Gannam [11] discovered that PE improved the rheological qualities of virgin asphalt. According to Milkowski [12], adding PE in a minor amount to asphalt decreased penetration while increasing shear strength of asphalt joints.

Al-Dubabe et al[13] attempt to assess the efficiency of Arab asphalt treated with polymers. Four refineries in Gulf nations provided the asphalt binders that they collected. It was discovered that adding low density polyethylene (LDPE) raised the original asphalt's softening point by 3%. They concluded that polymer modification works well to enhance the rheological characteristics of neat Arab asphalt binders.

By using a third point beam test, Nolan et al. [14] investigated the impact of PE and chlorinated PE on the low temperature (-15 to -40°C) fracturing of the modified asphalt concrete mixtures. They came to the conclusion that adding 8 % by weight of unstabilized PE to Bow River Binder significantly reduced the failure temperature (-20°C at 6 % wt. VS, -35°C at 8 % wt.PE). A binder amended with 8% weight PE did not exhibit such a drastic decrease, maybe as a result of the asphalt's higher temperature susceptibility.

Finally, more study is required to determine how PE affects the asphalt binder and mixture. To calculate the PE content of the asphalt mix and binder, more research is required. The goal of the current study is to minimize the price of road maintenance while also advancing our knowledge of how PE-substituted asphalt (PESA) binders behave during the construction of road infrastructure.

A thorough understanding of how PE affects binders is essential. This topic has been studied for decades, but there is still room for further investigation. The following are the study's goals: (1) Testing was conducted on PE-substituted asphalt (PESA) binder to compare its softening point, penetration, ductility, elastic modulus, and absolute viscosity to that of 40/50 grade asphalt cement; (2) to measure temperature susceptibility; (3) to determine PESA binders' aging (durability); (4) to determine the cracking index of PESA binder and mixture; and (5) to determine the mechanical and durability tests of PE-asphalt concrete (PEAC) mixture in terms of Marshall stability (MS), Marshall quotient (MQ), indirect tensile strength (ITS) at 25 and 60 °C, tensile strength ratio (TSR), and resilient modulus (MR); and (6) to compare the PEAC mixtures results with those of AC reference mixtures.

2 EXPERIMENTAL DESIGN

To conduct the investigation, four PESA binders and one asphalt cement binder were created. For the purpose of testing, four PESA binders were created, each with 3%, 6%, 9%, and 12% PE content. Among the parameters assessed during the tests are the following: adhesion to a variety of substrates and substrate surfaces; elongation at room temperature (aging index); flexibility at elevated temperatures (cracking index); temperature susceptibility; compatibility; and the extensional viscosity of the PESA binder as well as the extensional viscosity of the PESA-mixture (PESAM). Furthermore, the mechanical and durability properties of AC and PEAC mixes were examined using the Marshall stability, Marshall quotient, static indirect tensile strength at 25 and 60°C, tensile strength ratio, and resilient modulus 25°C tests. Fig. 1 illustrates the work methodology.

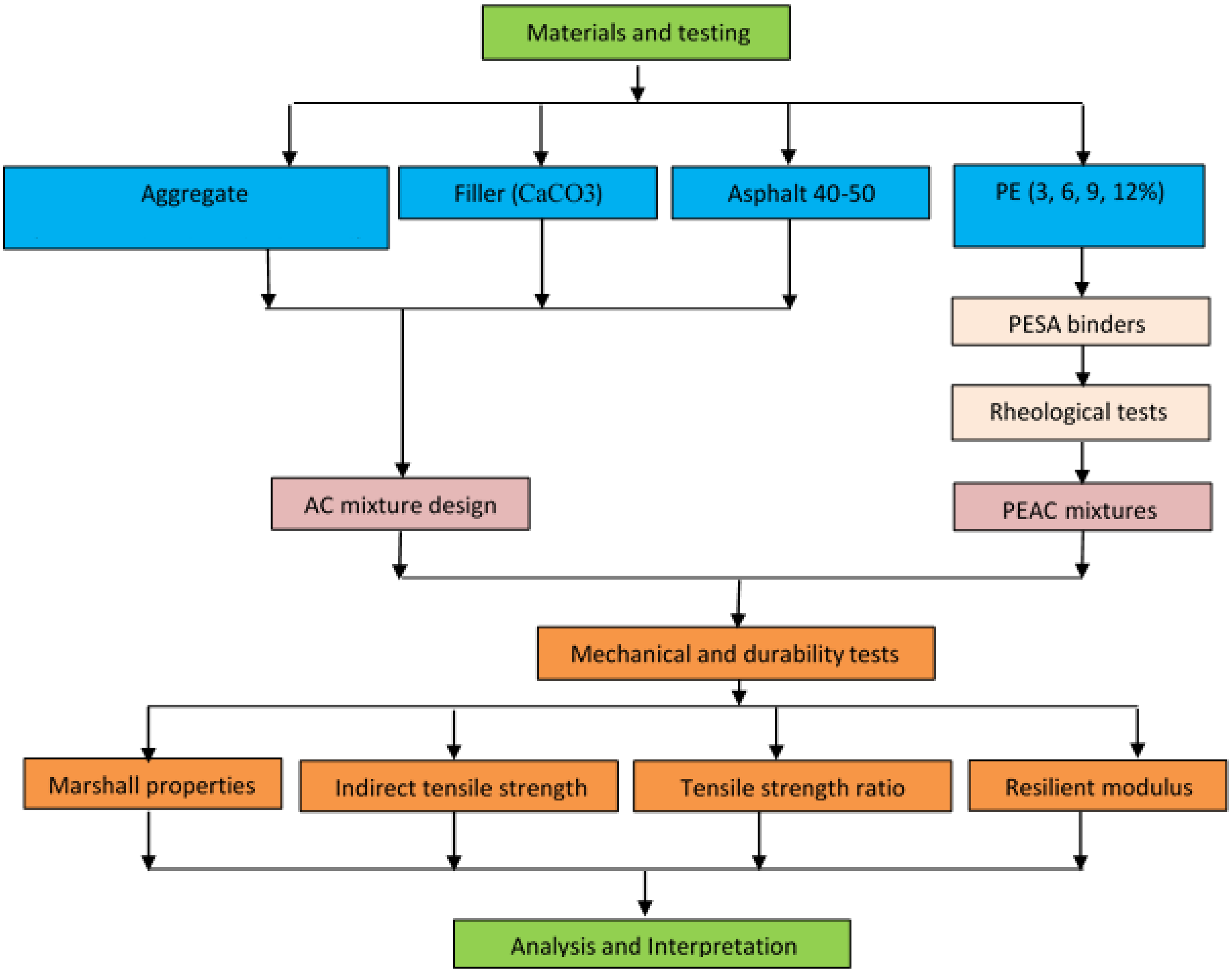


Fig. 1. Flow chart of experimental work of the study

3 MATERIALS

The oil refinery in Baiji provided the 40/50 penetration grade asphalt cement employed in this study (200 km north of Baghdad). The Nineveh government has frequently employed this asphalt in its highway development projects. Table 1 shows the asphalt's physicochemical parameters. The results showed that this asphalt conforms to penetration graded asphalt cement ASTM [15] and SCRB [16] requirements.

In this study, waste PE plastomeric polymer was collected from a private plant in Nineveh Governorate for the fabrication of bags. The PE has a density of 0.94 grams per cubic centimeter and a thermal deterioration temperature of 407 °C. PE was chosen because it is ideal for the Iraqi continental climate, has greater than 90% reliability, and has reasonable pricing [11].

In the northern region of Iraq, in the Nineveh Governorate, aggregate was acquired from a single asphalt plant. The gradation chosen for this research was in the center of the ASTM D3515 [15] suggested gradation limits for AC mixtures (Fig. 2).

The aggregates' characteristics, including their angularity, toughness, soundness, water absorption, and specific gravities, were identified; the test results are shown in Table 2.

Calcium carbonate ($CaCO_3$), a filler, was employed and it was brought from one asphalt plant. A 200-sieve was used to filter calcium carbonate, which had a specific gravity of 2.734.

Table 1. Asphalt cement's physical and chemical qualities.

Property	Units and testing conditions	The ASTM designation number	Result	Limits set by ASTM [15]	SCRB limitations [16]
Ductility value	25 °C, 50 mm/min, cm	D113	150+	100 min.	>100

Property	Units and testing conditions	The ASTM designation number	Result	Limits set by ASTM [15]	SCRB limitations [16]
Softening degree	R&B, °C	D36	54	50-58	51-62
Penetration value	25°C,100g,5 ,1/10mm	D5	42	40-50	50-60
Flash temperature	COC, °C	D92	263	>240	-
Loss on heat	5hrs, I63 °C, %	D1754	0.25	0.2 max	-
Sp. gr	25 °C/ 25 °C	D70	1.053	1.01-1.06	-
Asphaltenes	%	D2006	32.65	-	-

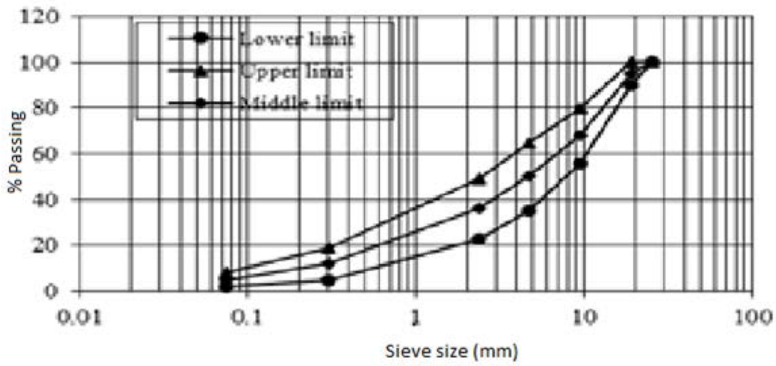


Fig. 2. Aggregate gradation

Table 2. Aggregates' source and consensus qualities

Property	Value	
	Coarse	Fine
Bulk sp.gr.	2.71	2.64
Apparent sp.gr	2.77	2.69
Toughness, %	23.4	---
Angularity, %	97	46
Soundness, Na2SO4	1.48	1.08

4 PESA SAMPLE PREPARATION AND TESTS

By substituting the asphalt binders with different percentages of PE, the mixing was adopted as follows: (1) In an oven, asphalt binder was baked to 155±5°C temperature; (2) The stainless steel container that was utilized for blending was washed and maintained at 170±5°C in the oven; (3) The correct quantity of asphalt and the amount of PE required to produce the right PE-to-asphalt ratio were weighed into a stainless steel container; (4) By total weight of binder, four mixes were made with 3.0 %, 6.0 %, 9.0 %, and 12 % PE, respectively; (5) For a minimum of 20 minutes, the stainless steel container was put on a hot plate to obtain a 170±5°C blending temperature. The laboratory mixer's propeller was then positioned about 15 mm from the beaker bottom; (6) the mixer was turned on, and while swirling, the prepared PE was gradually substituted for the stainless steel. The rotating speed of the mixer was increased to 3000 rpm.

The PESA binder was homogenized after another 2 hours of continuous blending [17]; and (7) for laboratory testing, the PESA was poured into tiny containers, cooled to a lab temperature, and wrapped in aluminum foil. The effects of the preparation and construction of the asphalt mix were simulated using a variety of techniques, such as short-term oxidative aging using thin film oven tests and penetration (T-49), softening point, TR&B (T-53), ductility (T-51), absolute viscosity, elastic modulus, and temperature susceptibility.

Using Eq. (1), which was mentioned by [18, 19], the PESA's elastic modulus, or "binder stiffness." was calculated based on the binder's properties.

$$E_b = 1.157 \times 10^{-7} \times \tau^{-0.368} \times 2.178^{-PI} \left(T_{R\&B} - T_{asp.}\right)^5 \quad (1)$$

Where:

E_b: binder elastic modulus (N/sq.mm),

$T_{R\&B}$: Binder softening point after recovery (R&B) (°C),

$T_{asp.}$: temperature of the subsurface of the asphalt (25°C),

$P.I.$: recovery in binder's penetration index and

τ: loading times (seconds). It assumed a speed of 50 kph, or 0.02 seconds.

Using Equation 1 is only appropriate if the following conditions are met:

-1.0 < P.I. < 1.0, 0.01sec < τ < 0.1sec, 20°C < ($T_{R\&B}$ - $T_{asp.}$) < 60°C.

The penetration assay can be combined with the softening point degree to assess asphalt's temperature susceptibility. The characteristic of asphalt that makes it temperature susceptible is often represented as (Eq. (2)):

$$A = \left[\left(\log \ P1 - \log \ P2 \right) / \left(T1 - T2 \right) \right] \quad (2)$$

Where: T1, T2= temperatures in °C; P1= penetration at T1; P2= penetration at T2.

Because the asphalt has an approximate penetration of 800 at the softening point, the temperature susceptibility may be calculated using the softening point and the penetration at 25 °C, as shown in Eq. (3):

$$A = \left[\left(\log \ pen. \ at \ 25\ °\text{C} - \log 800 \right) / \left(25 - Softenng \ point \ temp. \right) \right] \quad (3)$$

This value of A can then be utilized to calculate a penetration index (P.I) value as shown in Equ. (4) [20].

$$Penetration \ Index \ \left(P.I. \right) = \left[\left(20 - 500A \right) / \left(1.0 + 50A \right) \right] \quad (4)$$

Normal asphalt cement has a P.I. value between -2 and +2. Asphalts are high resistant to temperature when their P.I. is greater than +2.0 and low resistant to temperatures when their P.I. is less than -2.0. Low P.I. asphalt mixtures are more vulnerable to extreme heat, whereas high P.I. asphalt mixtures imply lower temperature cracking and plastic deformation, according to Lu and Isacsson [21].

Asphalt cracking caused by thermal impacts is a substantial and expensive pavement degradation mechanism in many areas with extremely cold winters. The problem is primarily brought on by the cold weather, which results in fractured pavement components due to tensile strains [22].

The degree of transverse cracking distress has been expressed in the literature using a variety of methods. The idea of a cracking index is one of the most popular techniques (*CI*). Al-ani [23] established an excellent association (R2 = 0.843) for estimating low temperature cracking based on binding qualities before and after TFOT. The CI is defined as follows in equation 5:

$$CI = 0.334 \ \log(P) + 10.033 \ (AI)^{0.5} + 3.3148(SP) - 166.204 \quad (5)$$

Where

P = penetration at 25°C,

AI = aging index (as defined above),

SP = softening point in degrees Celsius of TFOT-aged asphalt,

CI = cracking index.

Using equations 6 and 7 given by Collop et al. [24], based on the parameters of the binder and the volume concentration of the aggregate, the extensional viscosity of PESA and PESAM was calculated.

$$\lambda_b = 3 \times 10^{-6} \ \left[1.3 \times 10^{\left[3 + \left(T_{R\&B} - T_{asp.} \right) / 10 \right]} \right] \quad (6)$$

Where:

λ_b : is the extensional viscosity of the bituminous binder (MPa.s.),

$T_{R\&B}$: is the softening temperature of recovered bitumen 'Ring and Ball' (°C), and

$T_{asp.}$: is the asphalt layer's temperature (°C).

$$\log(\lambda_a) = \phi 2(VMA) \ \log(\lambda_b) + \phi 1(VMA) \quad (7)$$

$$\phi 1(VMA) = 1.86\times10^{-3}(VMA)^2 \; -1.65\times10^{-1}\; VMA + 6.98$$

$$\phi 2(VMA) = -2.2\times10^{-4} VMA + 7.5\times10^{-1}$$

λ_a : is the asphalt mixture's extensional viscosity (N/mm2. s.), and (*VMA*) is percentage of voids in mixed aggregate.

5 MIXTURES AND DESIGN TESTS

The asphalt concrete (AC) mixtures in Iraq are typically optimized using the Marshall mix design (ASTM D-1559) [15] process. The Marshall method of mix design is typically used in the design of AC mixtures to confirm that the voids are sufficient. In order to create the AC mixtures, five asphalt percentages (6.0 %, 5.5 %, 5.0 %, 4.5 %, and 4.0 %) were used. The needed asphalt content was discovered to be 5.2 % at 4.0 % air voids. To ensure uniformity throughout the investigation, 6 % PE-modified mixes were prepared using this optimal asphalt content. Using a mechanical mixer, the modified samples are blended for 2 minutes at this asphalt ratio and the recommended mixing temperature of 160 °C to 170 °C [5]. Using a Marshall mechanical compactor, the samples were then heated to a compaction temperature that was 10°C lower than the equivalent mixing temperature. A tire pressure of 1379 kPa was used to crush the specimens for heavy-duty use at a rate of 75 Marshall blows for each face. After being taken out of the mold, the specimens were air-cured for 24 hours.

Then, the tests performed were Marshall properties, indirect tensile strength at 25 °C and 60 °C, tensile strength ratio (durability), and resilient modulus at 25°C (mechanical) tests. On the AC and 6% PEAC mixes, which were compacted to an average air void content of 7.0%, the moisture susceptibility test in accordance with ASTM D6931 [25] method was carried out. For the unconditioned group, three Marshall specimens and three for the conditioned group were created. The indirect tensile strength test findings at 25°C were used to calculate a tensile strength ratio (TSR) of the conditioned group to the unconditioned group. The strength should be less affected by the water soaking condition or more water-resistant the higher the TSR number. Normal AC specifications call for a TSR value of 85% or above.

One of the most significant mechanical qualities of AC is its resilient modulus (MR). The modulus of AC is a fundamental design parameter when asphalt pavement constructions are designed using elastic-layered system theory. The modulus is a crucial material property used in the current models for predicting the performance of asphalt pavements. To optimize performance prediction and pavement mixture design, therefore, it is advisable to determine the modulus of AC while designing the AC mixture.

The ratio of an applied stress to the recoverable strain that results once the applied stress is removed is represented by the MR. Tests on cylindrical specimens for each mixture at the intended asphalt concentration in the indirect tension mode were used to determine the MR. For conventional and 6 % PE-modified specimens, the vertical diameter received about 15% of the indirect tensile strength of each mixture.

In order to conduct an indirect tensile test with repeated loads, Marshall specimens with a special binder were repeatedly crushed on equipment built just for this test. 1 Hz of load application frequency was used with a load length of 0.1 seconds to simulate field conditions and a resting time of 0.9 seconds.

The tests were performed at a temperature of 25°C, and the test protocol used was ASTM 4123 [15]. An ambient air chamber was used to maintain a constant test temperature. Prior to testing, each specimen was kept in the chamber for three hours at the predetermined temperature. The average of the three samples was used to represent the MR for each of the five types of combinations being considered.

6 RESULTS AND DISCUSSION

6.6 Properties of ductility, softening point, and penetration

Different percentages of PE have been used in this study to replace asphalt. The performance of PESA binders has been assessed using traditional assay techniques such softening degree, penetration feature, and ductility feature. Table 3 displays the physical characteristics of the binders.

The table shows that when PE concentration rises, penetration at 25°C decreases while softening point rises. PESAM is more resistant to shear deformation if it has a higher softening point. This result is in line with what was seen in other studies [5, 11, 13].

According to Table 3, PESA specimens with a PESA content of up to 9 % have a ductility value that is higher than the 100+ cm minimum requirement for ASTM [15] and SCRB [16]. This demonstrates that PESA binders offer sufficient adhesive qualities and, hence, sufficient field behavior. Additionally, earlier studies [4, 11, 13] have revealed that a 9 % PESA binder must have a minimum ductility value of 100 cm. Additionally, the ductility value of PESA at 12 % is less than 100 cm.

Table 3. PESA binders' characteristics.

PE, %	Penetration	Ductility	TR&B degrees Celsius	AV, 21 °C (poise)
0.0	42.0	150+	54.0	5.0×10^6
3.0	39.0	148	61	16.5×10^6

PE, %	Penetration	Ductility	TR&B degrees Celsius	AV, 21 °C (poise)
6.0	31.5	141	64	22×10^6
9.0	23.7	127.5	69	30.7×10^6
12	21.5	85	71	39.6×10^6

6.2 Absolute viscosity

The Shell nomogram [26] at 21°C is used to calculate PESA's absolute viscosity (AV). Table 3 demonstrates that the absolute viscosity rises at 21°C when the PE concentration is increased. In terms of AV, binders with 3% PESA, 6% PESA, 9% PESA, and 12% PESA are shown to have an AV of 3.3, 4.4, 6.2%, and 8% greater than those with virgin asphalt, respectively. As the AV value rises, so does the adhesion between the binder and the particles, resulting in less asphalt mixture peeling. As a result, PESA binders reduce the cost of maintaining asphalt paving while maintaining the structural integrity of the asphalt concrete features.

Similar findings on the impact of PE material on viscosity and asphalt binder penetration have been published in the literature [4].

6.3 Elastic modulus

Fig.3 demonstrates that raising the PE content raises the elastic modulus (binder stiffness). A higher elastic modulus indicates that PESAM is more resistant to deformation. The hardness of PESA binders can be used to explain this.

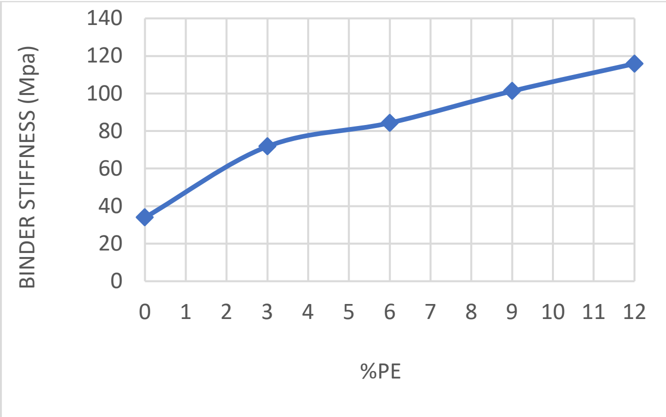


Fig. 3. PESA stiffness

6.4 Temperature Susceptibility Feature

Fig.4 displays the PE concentration and Penetration Index (PI). As can be shown, compared to the PE-modified binders, virgin asphalt cement is more susceptible to temperature changes. All PE contents were found to keep the virgin asphalt's original and recovered P.I. value within a desirable range (-1.0 P.I. -0.5) [26].

PESA binders are less susceptible to temperature changes than raw asphalt, as seen in Fig. 4. Regarding resistance to low-temperature thermal cracking and heightened plastic deformation at high temperatures, this suggests that PESA outperforms virgin asphalt. This result agrees with earlier research [4]. The results show that the PESA specimens have a P.I. ranging from -2 to +2. All PE contents preserved tidy asphalt's initial and recovered P.I values in the desired range (-1 P.I -0.5), like the KSLA nomograph [26] illustrates.

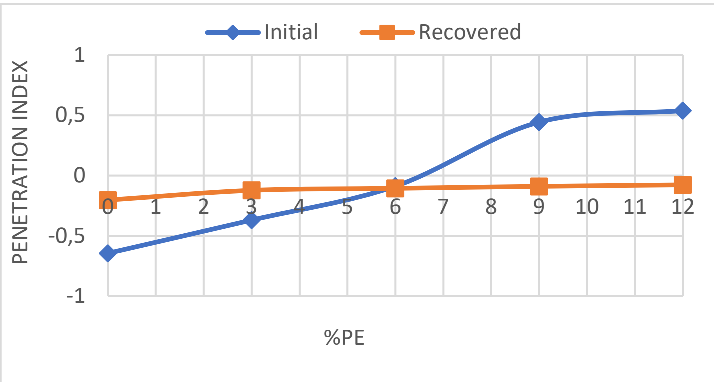


Fig. 4. Penetration index of PESA

6.5 Compatibility test

The compatibility of PE and asphalt was examined by passing the binder through an ASTM 0.075mm sieve at165°C. It was found that PESA made in this way might be saved for later use [8].

6.6 Durability (ageing) Factors

The short-term aging characteristics of PESA binders were evaluated using the penetration, softening point, and ductility tests. Asphalt frequently ages quickly while being heated, mixed, and constructed. The original asphalt was used for the penetration test, while the thin film oven test (TFOT) used an older batch of asphalt residue. Assessments of asphalt consistency were made using the AI (Aging Index). Assays were also conducted on the original and TFOT-aged asphalt specimens for ductility. The experiment was conducted at a temperature of 25°C. PESA binder aging properties can be detected simply, directly, and sensitively by testing its ductility at 25°C. The low temperature cracking index was calculated by measuring the residue's softening point upon exposure to heat and air (CI). The penetration of residue revealed that PESA binders stiffened after being exposed to heat and air. The following equation is used by artificial intelligence (AI) to calculate the rate of aging: AI = (original penetration at 25°C/residue penetration after ageing at 25°C). The results of the tests carried out on PESA samples, including AI, aged softening point, and TFOT-aged ductility values, are displayed in Table 4. Increases in PE dosage reduce the brittleness of resulting binders due to stronger bonds between PE and asphalt, as can be seen from the rising AI (improved short-term aging characteristics). Aged asphalt's ductility shows that asphalt can be molded at moderate temperatures (i.e., the resistance to deformation). The D25, a measure of polymer ductility at 25°C, varied depending on the polymer. The ductility was reduced with increasing PE dosage in the aged PESA samples, which showed the largest loss of ductility. It was shown that the PESA binders' ductility was lowest when the PE dosage was 9%. PE polymer was shown to sustain the aging ductility properties of 100+ to a degree of up to 9%.

Table 4 shows that as the PE level rises, the percentage loss of PESA binders decreases. This is due to the fact that PE takes up space in the entire mix and reduces asphalt volume, resulting in less asphalt loss due to dehydrogenation and oxidation (i.e., durability is raised slightly with the substitution of PE content in PESA). It was shown that virgin asphalt's durability enhanced by 24% when 6% PE was added in its place.

6.7 Low-temperature cracking properties

Fig. 5 depicts the CI for untreated and PESA binders. The CI of PESA binder increases as the PE dose increases, according to this graph. The CI of specimens containing 3.0 % PESA, 6.0 % PESA, 9.0 % PESA, and 12.0 % PESA is 162% higher, 228.5% higher, 294.7% higher, and 328% higher than the CI of virgin asphalt. Because PESA has reduced temperature susceptibility, PESAM is more resistant to cracking than control mixtures.

Table 4. TFOT Characteristics of PESA binders.

PE, %	Residue penetration	Loss of heat and air, %	A.I.	Residue ductility	TR&B,°C
0	37	0.25	0.88	142	56
1	21.4	0.22	0.891	135	63
3	18.8	0.19	0.895	120	67
6	16.2	0.17	0.9	103	71
9	14.6	0.13	0.913	49	73

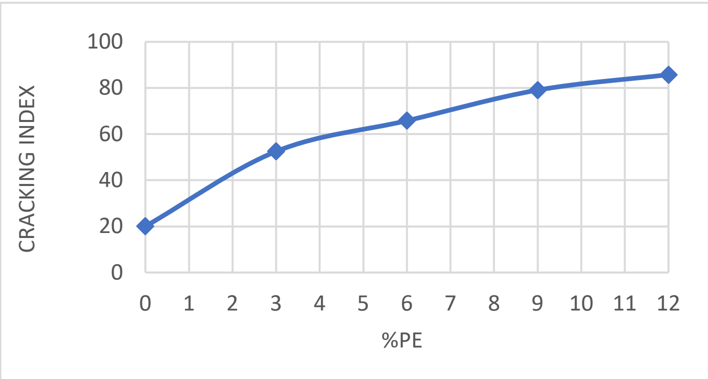


Fig. 5. PESA cracking index

6.8 Extensional viscosity

Figs. 6 and 7 illustrate the extensional viscosity of the PESA and the PESAM content. The extensional viscosity of PESA binders was discovered to rise as the PE percentage increased. The extensional viscosity of specimens containing 3.0% PESA, 6.0% PESA, 9.0% PESA, and 12.0% PESA is 3.5 % higher, 5.4 % higher, 8.3% higher, and 12 % higher, respectively, than the extensional viscosity of virgin asphalt. Furthermore, it can be seen that substituting PE into the control mixture raises the extensional viscosity. In addition, as demonstrated in Figs. 8 and 9, a decrease in temperature causes an increase in asphalt and extensional viscosity of the mixture for all PE concentrations.

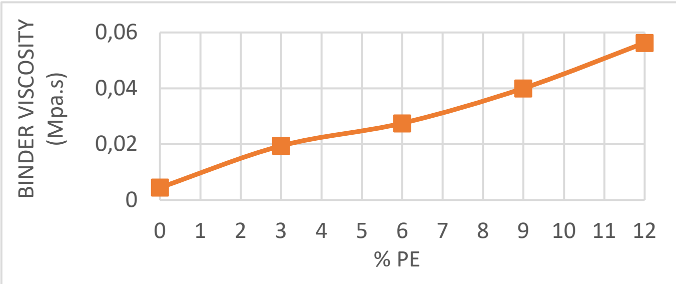


Fig. 6. PESA extensional viscosity at 60°C

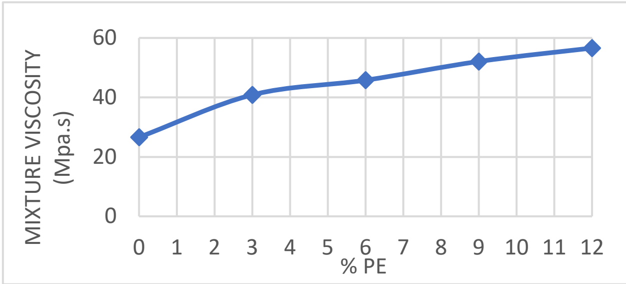


Fig. 7. PESAM extensional viscosity.

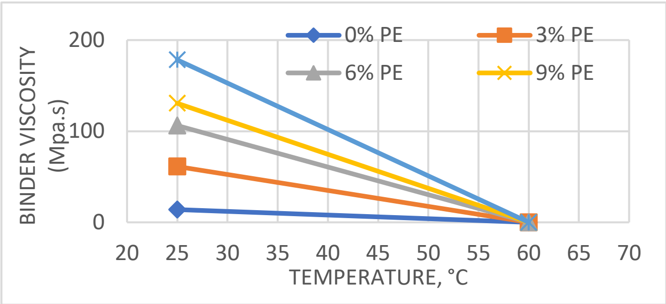


Fig. 8. PESA Viscosity at extension at 25 and 60 °C

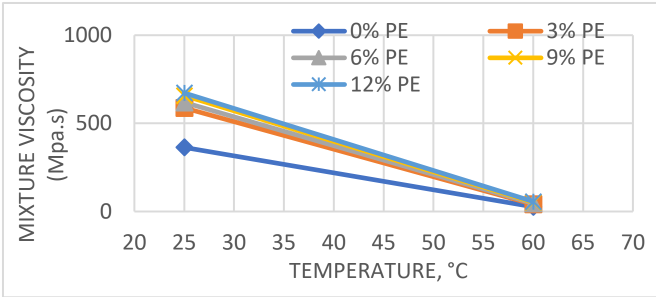


Fig. 9. PESAM Viscosity at extension at 25 and 60 °C

6.9 Marshall Properties

Fig. 10 shows the results of the measurements of the Marshall stability, flow, Marshall quotient, and voids in mineral aggregates characteristics of the AC and 6 % PEAC mixtures. As compared to the control AC mixtures, the PEAC mixture demonstrates higher values for the Marshall stability and quotient, as seen in the figure. While the Marshall quotient increased by 82.83 %, the stability of the 6 % PEAC increased by 16.3 %. The decrease in the % air void level brought on by the PE substitution is what caused the increase in Marshall stability and Marshall quotient. Results from PEAC combinations have somewhat lower flow values than those from the AC mixture, showing that specimens with 6 % PEAC are more rut-resistant than specimens with AC. Because of their high stability and high MQ, the results in Figure 9d show that PEAC mixtures at 6 % offer better resistance against permanent deformations than AC mixes do. Given the need for stiff asphalt mixtures with low asphalt composition in military airfield pavements, it is possible that PEAC mixtures might be used. Similar findings were observed by earlier studies [6].

The void in mineral aggregates (VMA) content of the PEAC mixture is higher than that of the AC specimens at the same optimal binder level. Overall, it can be said that specimens of 6% PEAC combination meet the minimal ASTM standards of 14% VMA, 2-4 mm flow, and 8kN stability.

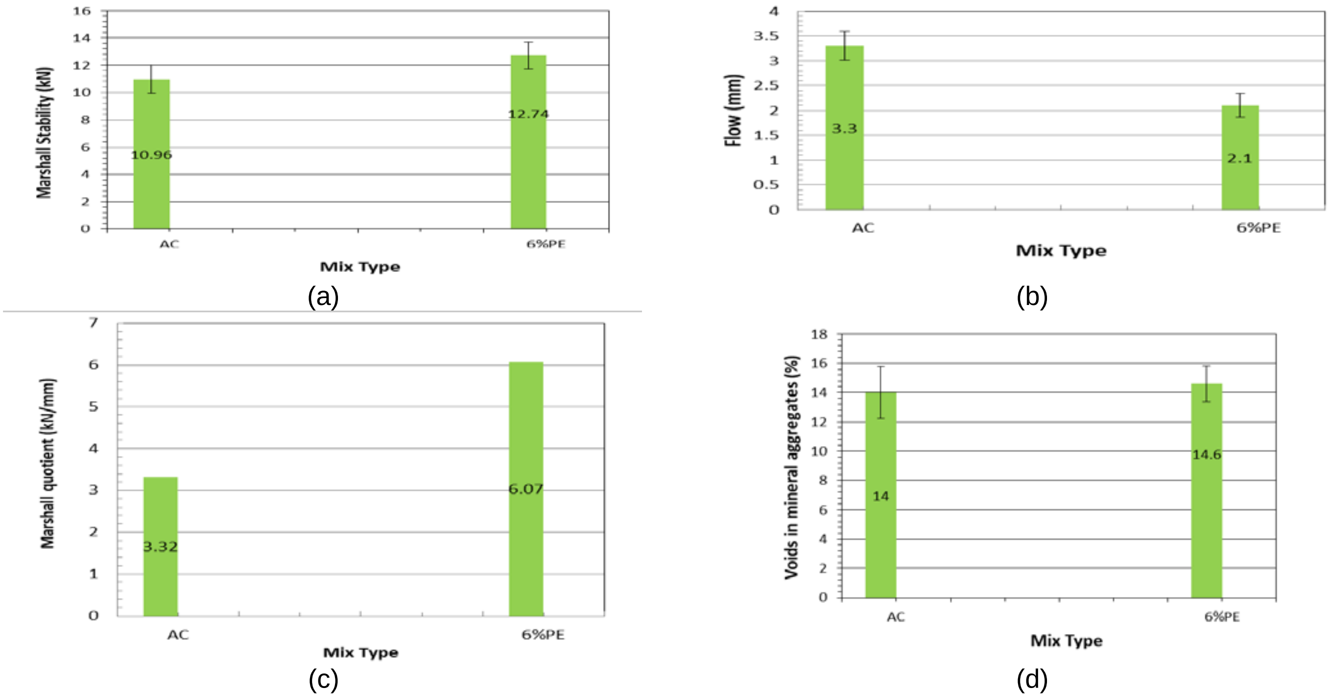


Fig. 10 Marshall properties of AC and PEAC mixtures (a- Stability, b- Flow, c- Marshall quotient, and d- Voids in mineral aggregates)

6.10 Moisture susceptibility

By carrying out the ITS test, it was possible to determine how temperature and moisture affected the tensile strength of mixtures containing AC and 6 % PEAC. Fig. 11a provides a graphic representation of the findings for the AC and PEAC combinations' unconditioned and conditioned tensile strengths. The figure reveals that the magnitudes of ITS for both conditioned and conditioned PEAC specimens are higher than those obtained from the control AC mixtures. Because PESA binder is used in asphalt mixtures, the ITS levels of unconditioned specimens have increased. Previous investigations [5] reported similar results.

Results obtained from the 6 % PEAC mixture demonstrate an increase of roughly 18.4% in the ITS values of unconditioned specimens as compared to the AC mixture. The average ITS values of the conditioned samples of the 6 % PEAC combinations also increased by 35.2%. The increased stiffness of the PEAC mixtures may be the cause of the rise in ITS. This shows that PEAC combinations have greater crack resistance than AC mixtures

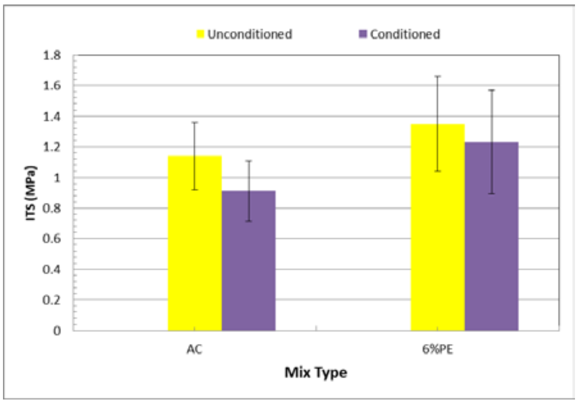
Additionally, as shown in Fig. 11b, the tensile strength ratio (TSR) of the conditioned to unconditioned group was used to assess the moisture susceptibility of AC and PEAC combinations. The graph demonstrates that samples of 6% PEAC combinations have better TSR than AC samples, indicating greater resistance to moisture damage. When compared to the AC combination, the TSR values of the 6 % PEAC mixture rose by 14.2 %. This finding is verified by the earlier study reported by [4, 5].

The results of a 6 % PEAC mixture demonstrate a TSR score of 0.91, which indicates adequate moisture resistance (Fig. 11b), whereas the TSR of an AC mixture is less than 0.85, a value where the moisture vulnerable mixes are anticipated, if TSR of 0.85 is accepted as a minimum acceptable ratio [27]. These comparisons collectively show that the 6 % PEAC mixture offers greater ITS and TSR. The conditioning procedures do not weaken the PESA binder. The amount of air spaces in the mixture decreases when PE is present, which increases the PEAC combination's susceptibility to moisture.

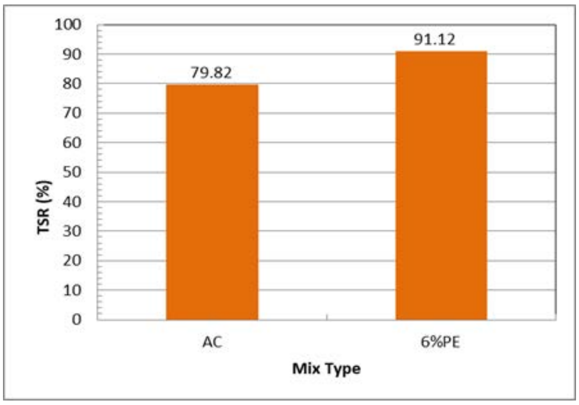
6.11 Resilient Modulus

Fig.12 displays the MR test outcomes. Fig.12 shows that the MR values for AC and PEAC samples with a 6 % concentration are 1515 MPa and 2290 MPa, respectively. The average MR's percentage increase is discovered to be rather considerable. According to the study, adding 6% PE to asphalt increased its MR value by 51.2%. Previous investigations [5] reported similar results.

Based on the findings of the PESA tests, 6 % PE is chosen as the ideal additive content. PE is less economically viable at larger additive contents, and it may also give rise to other worries about the future of the material.



(a)



(b)

Fig. 11. Properties of indirect tensile strength in mixes of AC and PEAC

Indirect tensile strength & b- Tensile strength ratio)

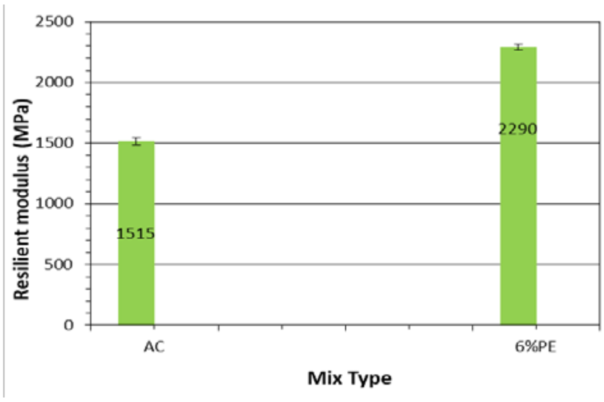


Fig. 12. Resilient modulus of AC and PEAC mixtures.

7 CONCLUSIONS

This study evaluated the use of waste polyethylene as a partial replacement in asphalt mixtures. Polyethylene waste made up 3 %, 6 %, 9 %, and 12 % of the asphalt binder. In-depth laboratory tests were conducted to determine the impact of partial asphalt cement substitution on the mechanical and durability characteristics of the asphalt cement and AC combination. While the effects of the PESA on the mechanical and durability properties of the AC mixture were investigated through the use of indirect tensile strength, moisture damage, and resilient modulus tests, the rheological and durability parameters of PESA were examined in terms of ductility, penetration, softening point, loss of heat and air (aging), absolute viscosity, temperature susceptibility, cracking index, and extensional viscosity. The conclusions drawn from the findings of this inquiry can be summed up as follows:

1. The PESA binders have a lower penetration and a higher softening point, aging resistance, absolute and extensional viscosity, elastic modulus and cracking index.
2. Results obtained from Marshall studies, indirect tensile strength, and resilient modulus tests show that PEAC mixtures provide higher resistance to permanent deformation, moisture damage, and loading effects when compared with AC mixtures.
3. Utilizing the waste polyethylene at 6% in asphalt concrete mixtures would potentially be more cost effective and valuable landfill space would be spared at the same time.

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