The Effect of Waste Low-Density Polyethylene on the Mechanical Properties of Thin Asphalt Overlay

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Abstract

In recent years, there has been a huge demand for innovative methods to upcycle waste materials. This study aims to explore and evaluate the effect of using waste low-density polyethylene (w-LDPE), collected from waste plastic bags for domestic purposes, on the mechanical properties of dense Thin Asphalt Overlay (TAO). Waste materials have been deemed appropriate in the development of asphalt pavement mixtures, due to the expected enhancement in mixture properties further to the reduction in cost and saving natural resources. Three dosages of w-LDPE were incorporated with asphalt binder: 2%, 4%, and 6%. Marshall stability and flow test, indirect tensile strength, creep compliance, skid resistance, wheel track, Cantabro abrasion loss and tensile strength ratio tests were carried out on both control and modified asphalt mixes to achieve the aim of the study. The results show a substantial enhancement in the performance of TAO modified with w-LDPE when compared to the control mix. The pre-eminent improvement was obtained in the creep compliance test, in which the creep compliance value decreased by 83% compared to the control mixture when using 6% of w-LDPE. This study indicated that using waste material is an effective method of asphalt modification that also contributes to promoting environmental sustainability.

Keywords:

Creep compliance; indirect tensile strength; low-density polyethylene; thin asphalt overlay; wheel tracking.

1. Introduction

The rise in traffic and traffic load, alongside the environmental impacts, play a significant role in increasing the rate of deterioration of asphalt pavements especially the thicker traditional ones. Consequently, maintenance of such pavement is rendered costly, this highlight benefits of Thin Asphalt Overlay (TAO) as a more economic alternative. Alongside reducing maintenance cost [1], TAO also increases pavement lifespan through decreasing minor distresses endured by pavement such as raveling, bleeding, shallow rutting etc. [2]. However, the use of modified TAO mixtures instead of traditional TAO can increase the resistance of these pavements to external impacts and delay the appearance of distresses [3]. The incorporation of polymeric materials into asphalt binder is a common additive used to improve the Physico-chemical properties of asphalt [4]. Chemically, the addition of polymer to asphalt achieves the bi-phasic interaction, where a part of it tends to react with the functional groups found into asphaltene and forming what means by "asphaltene rich phase". On top of this, the remaining part is swollen in maltenes and forming a "polymer-rich phase" as represented by Figure 1. This behaviour enhances the physical properties of the asphalt binder through increasing the cross-linking between asphalt molecules by the formation of a polymer network. In addition to this, the Physico-chemical properties of the polymer itself play an important role in improving the ability of asphalt to withstand the various distress problems, whilst also extending the pavement lifespan [5, 6]. There are various types of polymers such as virgin elastomers (styrene-butadiene-rubber, styrene-butadiene-styrene, styrene-isoprene-styrene) and virgin plastomers (polypropylene, polyethylene, and their copolymers [7, 8], both with differing properties and abilities to modify asphalt.

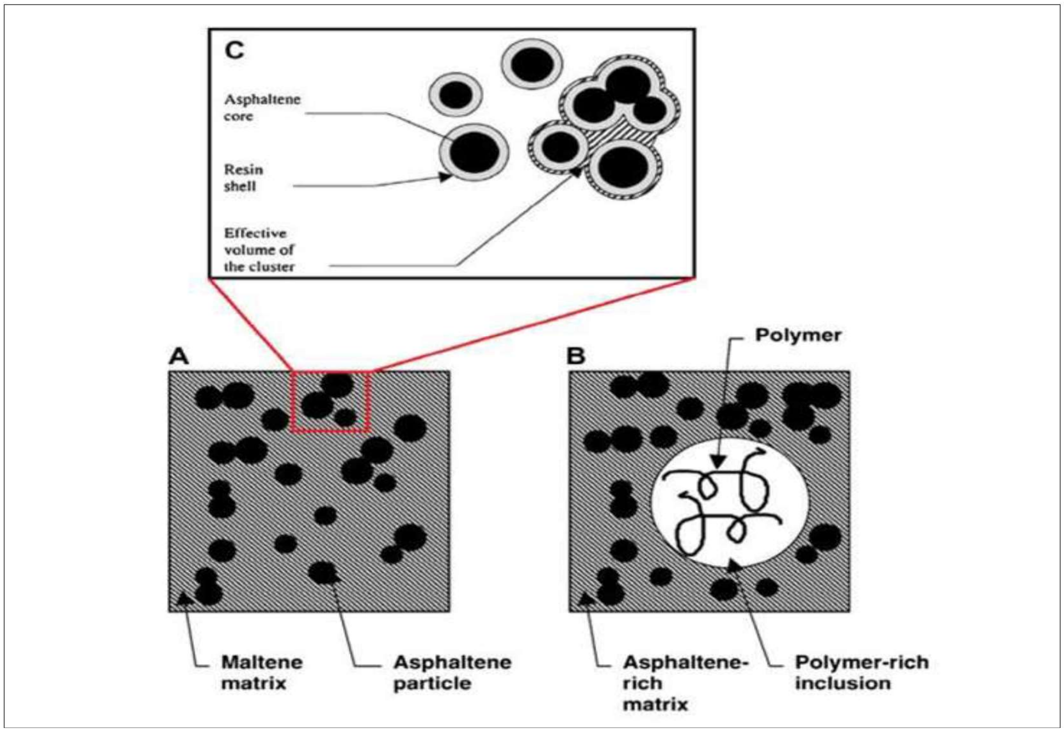

Figure 1. Schematic illustration of the colloidal structure of bitumen and the effect of polymer modification. (A) Base bitumen. (B) The corresponding PMB with increased asphaltenes content in the matrix. (C) Asphaltenes micelles. Adapted from [6].

However, recent global trends urge the employment of other types of polymers sourced from waste materials to reap the bi-benefits to pavement performance and the environment [9-11]. Global dependence on plastics is undeniable and seemingly increasing. Solid plastic production is projected to reach 2.2 billion tonnes from 2018 level of 1.3 billion tonnes [12]. This surge in plastic production will certainly have a detrimental effect on the environment, wildlife and human health, emphasizing the need to upcycle waste plastics. Utilizing such waste plastics would not only curb pollution and landfill usage but also reduce costs through reducing disposal expenses. As a result, researchers were incentivized to incorporate these wastes, and especially the recycled ones as an additive with the construction materials, as one of the sustainability principles. Consequently, disposal costs are reduced, pavement service life is increased and the impact of plastic production on the environment is curbed [13-16]. Commonly used recycled materials are Polypropylenes (PP) and materials that are derived from ethylene like High-Density-Polyethylene (HDPE) and Low-Density- Polyethylene (LDPE). LDPE represents a lightweight material having a density ranged between (0.91-0.94) g/cm^3, derived under high-pressure polymerization of ethylene [17], and it is considered as a source of the solid wastes of domestic goods.

A study conducted by Al-Hadidy and Yi-qiu [18] stated that LDPE could increase the modulus of rupture of the asphalt mixes and stiffness at low temperature (-10 ^oC), which lead to reducing the cracking potential of pavements. Also, the strain values for the mixture developed by LDPE were lower than the strain of conventional asphalt mixtures. Shbeeb [19] founds that using plastic polyethylene in the modification of the asphalt mixture increases the resistance to fatigue failure and reduces pavement deformation in addition to achieving better adhesion between the asphalt and the aggregate. Others like Ahmad [20] and Eme and Nwaobakata [21] also show that the utilization of LDPE has a significant impact on the mechanical properties of the mix and the physical properties of the asphalt binder.

This study aimed to examine the influence of the utilization of waste LDPE (w-LDPE) as an asphalt modifier on the performance of the TAO mix. The effect of it offered in terms of mechanical and durability properties of asphalt mix: Marshall stability, Marshall flow, indirect tensile strength, thermal cracking resistance, skid resistance, rut resistance in addition to Cantabro abrasion loss and tensile strength ratio. The majority of the previous literature studies have focused on characterising LDPE polymer modified binders, while relatively limited research has studied LDPE polymer modified asphalt mixes with small nominal max aggregate size (NMAS). It is worth mentioning that amount of research dealing with waste or recycled polymer modified asphalt is comparatively limited. Moreover, the majority of such studies recommended further research (which is in high demand) for comparison between the behaviour of waste and virgin incorporated polymer materials. The current research focuses on a comprehensive methodology (including characterising volumetric, mechanical, functional and durability properties) for more understanding of a specific type of asphalt mix i.e. TAO. The authors believe that such type is still not comprehensively covered in the previous studies.

2. Materials

2.1. Aggregate

The coarse and fine aggregates used in this research were produced from crushed limestone with densities equal to 2.600 g/cm^3 and 2.640 g/cm^3 for each one respectively. The gradation adopted for these aggregates was selected according to the suggestion by General Specification for Roads and Bridges, section R9 [22], as represented by Table 1. In the case of mineral powders, two types were used, Limestone Dust (LD) and Hydrated Lime (HL) 5.5% and 1.5% amounts respectively. Physical properties of both coarse and fine aggregate are presented in Table 2, while the properties of these powders are presented in Table 3.

Table 1. Designed aggregate gradation.

Sieve size, mm	% of the passing of aggregate gradation	
	GSRB Limits	Designed gradation
12.5	100	100
9.5	90-100	95
4.75	55-85	70
2.36	32-67	49.5
0.3	7-23	15
0.075	4-10	7

Table 2. Physical properties of fine and coarse aggregates

property	ASTM designation	GSRB limitations	Obtained value
Physical Properties of Fine Aggregates			
Bulk specific gravity, gm/cm^3	C128 [23]	-	2.64
Passing sieve No.200, %	C117 [24]	-	3.52%
Clay lumps, %	C142 [25]	-	1.9%
Water absorption, %	C128 [23]	-	0.7
Sand equivalent, %	D2419 [26]	45% min	49%
Physical properties of coarse aggregates			
Bulk specific gravity, gm/cm^3	C127 [27]	-	2.6
Clay lumps, %	C142 [25]	-	0.05%
Percent wear by Los Angeles abrasion, %	C131 [28]	30% max	9.1
Water absorption, %	C127 [27]	-	1.36
Passing sieve No.200, %	C117 [24]	-	0.91%

Table 3. Properties of fillers

Property	LD	HL
CaO	7.37	90.58
SiO_2	81.89	0.89
Al_2O_3	3.78	-
Fe_2O_3	1.92	2.25
MgO	3.45	3.6
K_2O	0.73	0.58
Na_2O	0.19	1.00
SiO_2	81.89	0.89
$Al2O_3$	3.78	-
Specific surface area (m^2/kg)	225	1240
Density (gm/cm^3)	2.62	2.3

2.2. Bitumen

The neat bitumen adopted in this research was supplied from Al- Nasseriya Refinery, Iraq, with a penetration grade of 40-50. Table 4 presents the properties of this bitumen.

Table 4. Properties of asphalt binder

Property	ASTM designation	Test results	GSRB requirements
Penetration,100gm., 25 °C, 5 sec (1/10 mm)	D5 [29]	45.5	40-50
Ductility, 25 °C, 5 cm/min (cm)	D113 [30]	140	>100
Softening point, °C	D36-95 [31]	48.5	-
Viscosity, cts	D4402 [32]	836	-

2.3. Additives

w-LDPE in the powder form was used as a modifier for asphalt cement. It was brought from the recycled materials factory in Karbala city. Table 5 displays the properties of w-LDPE and Figure 2 shows the particle shape of this material.

Table 5. Physical properties of the waste-Low-Density-Polyethylene polymer

Property	Value
Density, gm/cm^3	0.91
Tensile strength, MPa	8.5
Tensile elongation, %	>350
Melting temperature, °C	110
Flexural modulus, MPa	7.2
Hardness shore D	45

Figure 2. The particle shape of the waste-Low-Density-Polyethylene polymer

3. Experimental plan

3.1. Asphalt mixture preparation

Two compaction procedures were adopted to achieve the requirements of this study. The one using the Marshall Design procedure followed ASTM D6926 [33], where the samples were designed using 75 blows of Marshall hammer on each face, and the amount of effort was varied depending on the test requirements. The other procedure is done by using the vibration compaction procedure recommended by BS EN 12697-22 [34] to prepare the slab samples. The control mixture denoted by (M0) having the optimum asphalt content (OAC) of about 5.3% was selected from the range of asphalt contents (4, 4.5, 5, 5.5, and 6) % by weight of the total mix. Thereafter, the modification process was conducted on it.

3.2. Asphalt Cement Modification

Asphalt cement was heated to 160 °C then placed in a mechanical shear mixer shown in Figure (3). After operating the mixer at a rotation speed of 1500 rpm, w-LDPE was added slowly into the shear mixer tank. The duration of mixing was 30 min at a temperature of 170 °C to obtain a homogeneous blend. Blends were produced in proportions of 2%, 4% and 6% w-LDPE, denoted by 2L, 4L and 6L respectively. w-LDPE dosages were selected as used by other researchers such as; Al-Hadidy and Yi-qiu [18], Eme and Nwaobakata [21], Ahmadinia et al. [35], Ahmadinia et al. [36]. Table 6 displays the mixture's designation according to the w-LDPE content. Figure 3 shows the mechanical shear mixer which was locally manufactured in the asphalt lab of the University of Kerbala.

Figure 3. Shear mixer device used

3.3. Testing methods

3.3.1. Air Voids

The quality of asphalt mixes can be assessed by the volumetric properties of compacted paving mixes. It was reported that the volumetric properties provided a valuable indication of the performance of the mixture's during its service life [37]. Volumetric properties were evaluated by determining the air void content in the total mix following ASTM D2041(ASTM, 2015b) and ASTM D2726 (ASTM, 2011a).

3.3.2. Marshall Stability and Flow Test (MS & MF)

The resistance of the mixture to plastic deformation was evaluated according to ASTM D6927 [38] by depending on measuring the maximum compression load and the amount of flow that accompanied it. The test was conducted on Marshall samples cured in a water bath at 60 °C for two hours to simulate the exposure of the TAO surface to high ambient temperature.

3.3.3. Indirect Tensile Strength Test (IDT)

The indirect tensile strength test measures the strength of asphalt mixes to tension, the test procedure recommended by AASHTO T283 AASHTO [39] was followed here. A constant rate of 50 mm/min was applied on the diametrical axes of the Marshall sample, the effect of load on the sample was measured using two LVDT: horizontal and vertical. A set of three samples were used to evaluate the purpose of this test. Initially, each sample was conditioned for 16 hours at 60 °C in an oven, then compacted using 35 blows of Marshall Hammer to achieve 7 ± 0.5% air voids following AASHTO T 283 [40]. Thereafter, samples were conditioned in an oven at 25°C for two hours before conducting the test. Equation (1) was used to calculate the tensile strength of each sample.

$$S_t = \frac{2000\,P}{\pi\,t\,D} \qquad \textit{Equation (1)}$$

Where: S_t: tensile strength, Kpa, P: maximum load, N t: specimen thickness, mm, and D: specimen diameter, mm.

3.3.4. Creep Compliance Test (CC)

AASHTO T322-03 [41] was followed to perform this test, which is a time-dependent strain divided by stress. The CC test is usually used for assessing the rate of accumulated damage in the asphalt mixture. The specification above recommended that the air voids ratio should be 7 ± 0.5%. The thermally controlled sample (0 °C) is subjected to a static load along diametrical axes, for a specified time of 1000 seconds. During the loading period, vertical and horizontal deformations are measured by using an LVDT sensor. Equation (2, 3, and 4) was used to determine the amount of creep compliance of Marshall samples:

$$D(t) = \frac{\Delta X \times D_{avg} \times b_{avg}}{GL \times P_{avg}} \times C_{Cmpl} \qquad \textit{Equation (2)}$$

Where:

D(t) = creep compliance at time t ,1/kPa.

ΔX = trimmed mean of the horizontal deformations, mm.

Davg = average specimen diameter, mm.

bavg = average specimen thickness, mm.

Pavg = average force during the test, kN.

GL = gage length, mm.

Ccmpl = creep compliance parameter at any given time, computed as:

$$C_{Cmpl} = 0.6345 \times \left(\frac{X}{Y}\right)^{-1} - 0.332 \qquad \textit{Equation (3)}$$

Where:

X/Y is the ratio of horizontal to vertical deformation, taken at mid-testing time.

The limitations of the Ccmpl value as shown in the following equations:

$$\left[0.704 - 0.213\left(\frac{b_{avg}}{D_{avg}}\right)\right] \leq C_{Cmpl} \leq \left[1.566 - 0.195\left(\frac{b_{avg}}{D_{avg}}\right)\right] \qquad \textit{Equation (4)}$$

3.3.5. Skid Resistance Test

The skid resistance test indicates the resistance of the pavement surface to sliding, the test procedure recommended by ASTM E303 [42] was adopted in this investigation. A set of two samples with dimensions of 300×165×25 mm was used to perform this test; each sample was tested at dry and wet conditions by using a British Pendulum tester. This device consists of an arm with a slider rubber and a drag pointer which indicates the British Pendulum Number (BPN). The pendulum arm is fixed and released to touch the surface of the specimen. When the sliding rubber passing a distance ranged between (124-127) mm on the surface of the slab sample, then the reading is recorded.

3.3.6. Wheel Tracking Test (WTT)

Rutting is a common sign of pavement failure that occurs under repeated traffic loads. The mechanism of this failure lies in that when the pavement surface is subjected to loading then a part of it is recovered after removing the load, but the other accumulated so that it cannot be recovered again. The procedure of the Wheel Track Test (WTT) based on BS EN 12697-22 [43] was adopted to display the resistance of the mixture to rut. Two slab samples with dimensions of 300×165×25 mm were used and subjected to 700 N wheel load after conditioning it at 60°C. The final rut depth was recorded after 10, 000 repetitions by using a vertical LVDT.

3.5.7. Cantabro Abrasion Loss Test (CAL)

It was reported by Doyle and Howard [44] that although the CAL test is sensitive to changes in the binder properties after aging, it is more susceptible to changes in mix properties. This test is achieved following the ASTM-D7064 [45]. The test temperature was performed at 25°C ± 5. Six samples were tested, three of them before aging and others after aging. The Marshall samples were placed in the drum of the Los Angeles Abrasion testing machine after weighing them. No iron balls were used in performing the test. The samples were extracted after the machine running 300 cycles (around 10 min) and they were cleaned lightly and then the weight of the samples was recorded. Cantabro abrasion loss can be calculated by the equation below as stated in D7064 [45]:

$$P = \frac{\text{P1} - \text{P2}}{\text{P1}} * 100 \qquad \text{Equation (5)}$$

where:

P = Cantabro abrasion loss.
P1 = initial weight of the sample.
P2 = final weight of the sample.

A separate group of samples was placed in an oven at 60°C for 7 days for conditioning to simulate the aging process in the site, they were then cooled to 25°C and stored for 4 hours before the Cantabro test.

3.5.8. Tensile Strength Ratio (TSR)

The procedure mentioned in AASHTO-T283 [39] was adopted to obtain the TSR results with two groups with three samples in each group. The samples in the first group were conditioned while the samples in the other group were not conditioned. The conditioning samples were subjected to a vacuum saturation of 13-67 kPa absolute pressure, for (5-10) min, after that they were saturated in water. Next, they were kept at -18 °C for 16 hours after which they were immersed in a water bath at 60 °C for 24 hrs. The specimens were positioned in a water bath at 25 °C for two hours prior to the test. IDT values of the dry condition can be divided over the wet condition samples in order to calculate the tensile strength ratio (TSR) following the AASHTO-T283 [46] as below:

$$TSR = \frac{S2}{S1} \qquad \text{Equation (6)}$$

where:

TSR= Tensile Strength Ratio.
S1=Average tensile strength of the dry subset kPa.
S2=Average tensile strength of the conditioned subset kPa.
The accepted values ranged between (0.7 - 0.9).

4. Results and Discussion

4.1. Air Voids

The percentage of air voids reduce to 3.1% by adding 2% R-LDPE as can be seen in Figure 4. Although within specification limits, increasing polymer content from 4% to 6% causes a slight increase in air void content. All the modified mixes with 2%, 4% and 6% of w-LDPE have air voids that are less than the reference mix, this can be attributed to the increase in mixing and compaction temperature. The oxidation of bitumen and moisture absorption by entrapped air can be prevented by the reduction in air voids. The Marshall Stability value can also be improved as stated by Ahmad [20].

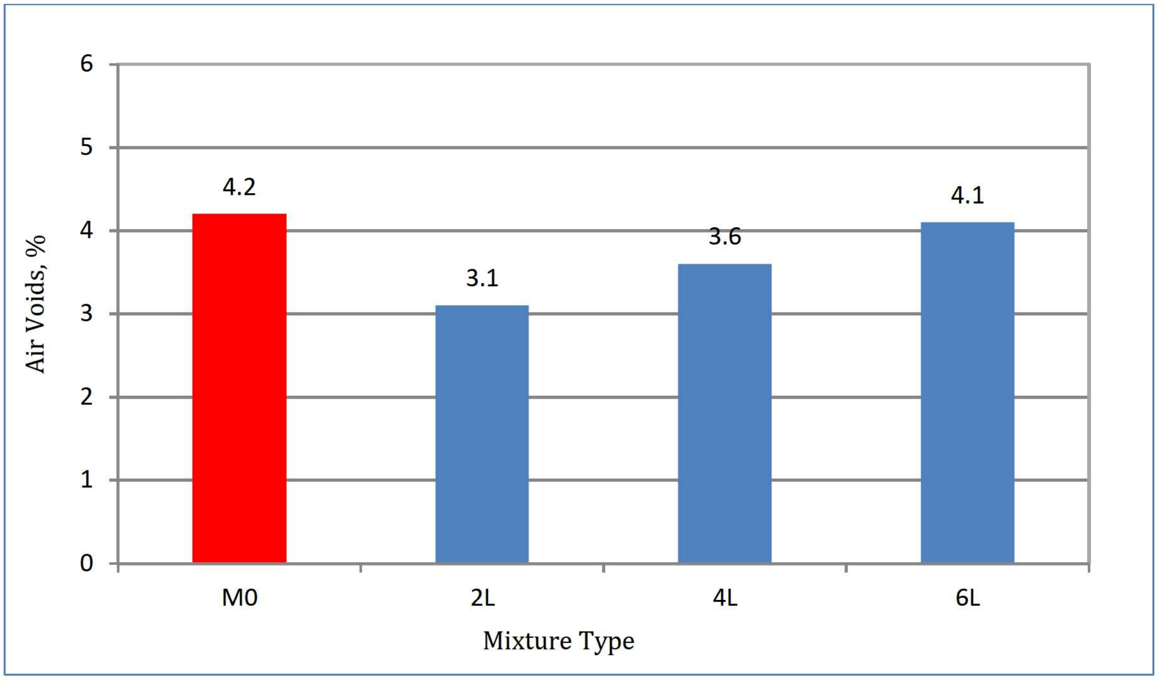

Figure 4. Air voids for reference and modified TAO mixes.

4.2. Marshall Stability and Flow (MS & MF)

Figures 5 and 6 show Marshall Stability and Marshall Flow levels of control and modified TAO mixtures. Results in Figure 4 indicate that as w-LDPE increases, MS increased higher than 40%, for the 6L mixture in contrast with M0. This behaviour is related to, that after adding w-LDPE polymer to asphalt, a series of reactions will occur with the fractions found in it. Chemically, when the w-LDPE polymer is comprised then a part of it is absorbed by the lightweight asphalt molecules "maltenes" and forming the "polymer-rich phase". At the same time, the other part of the polymer tends to react with the functional groups found into the asphaltene polar adhesive part and gained some rigidity by forming an "asphaltene rich phase". The increment in the latter one leads to make asphalt harder because of the asphaltene responsible for gaining the asphalt its rigidity properties. In the end, these chemical reactions are responsible for the physical variations of asphalt binder, as it leads to increase asphalt viscosity, the formation of polymer network increase both adhesion and cohesion properties. All these factors work side by side to increase the asphalt mixtures stiffness, and then, the amount of stability under the applied load will be enhanced.

Moreover, results in Figure 5 display that the limits of flow decrease as w-LDPE increases until an amount of variation above 30% for the 6L mixture is achieved. Also, it can be seen that the usage of w-LDPE polymer helps in maintaining the flow limits within the specified ranged that is ranged between (2-4) mm as recommended by GSRB [22]. The reason returns the same to the mentioned above, as the polymer network works on reinforcing the asphalt, whilst toughening the mixture. This then helps in minimizing the ability of the mixture to respond to the applied load and flow done.

These results are in agreement with those of Ahmad [20], Al-Hadidy and Yi-qiu [47], and Sadeque et al. [48]. However, both MS and MF results confirm the potential to increase the resistance of plastic deformation of TAO comprising w-LDPE, Furthermore, the enhancement follows nonlinear relation with increasing polymer content.

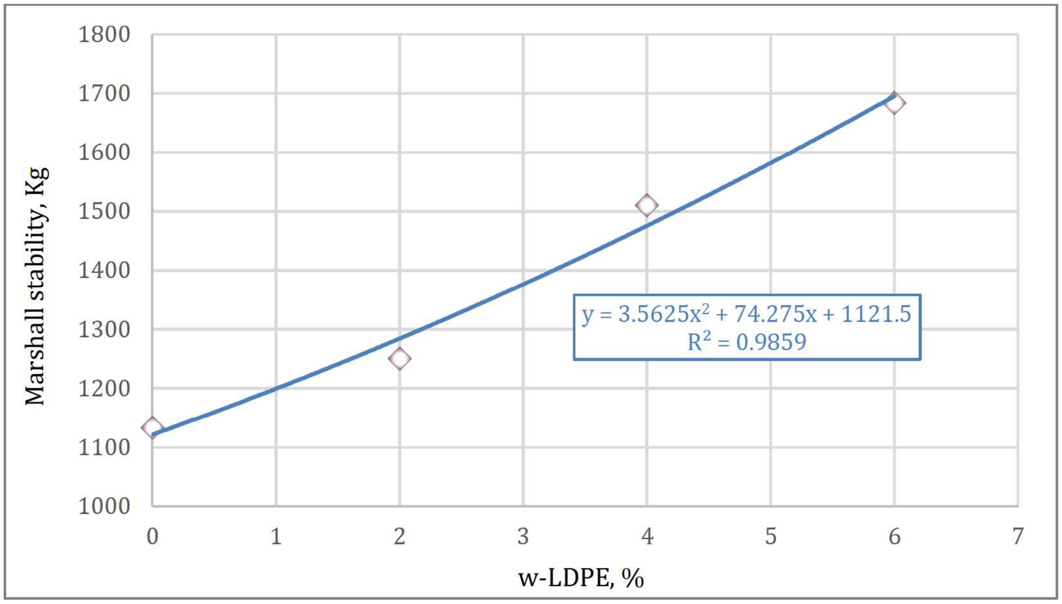

Figure 5. Marshall stability for control and modified TAO mixtures

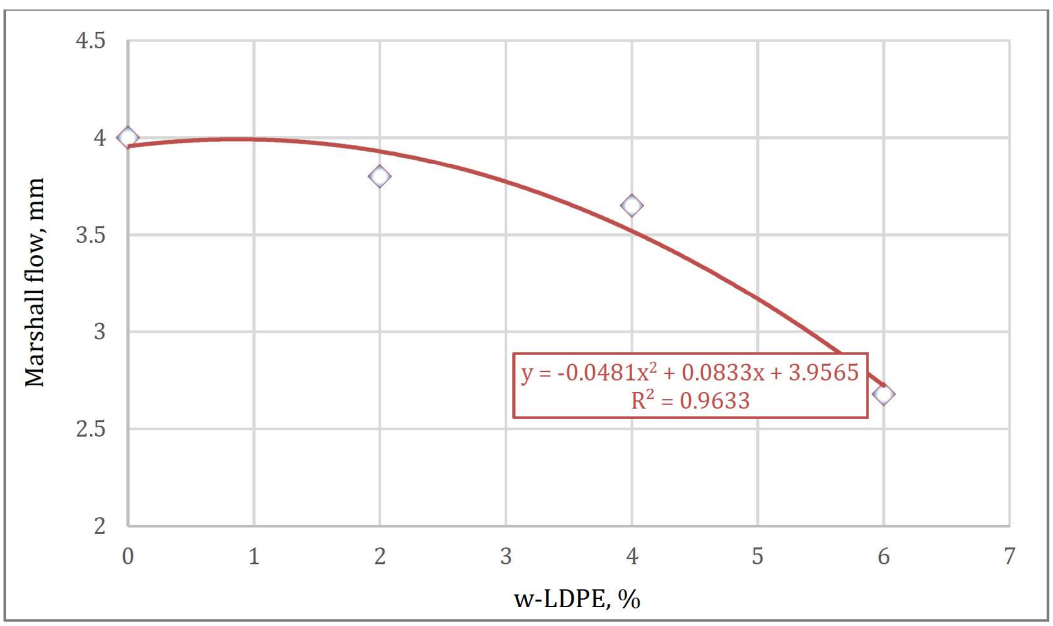

Figure 6. Marshall flow of control and modified TAO mixtures

4.3. Indirect Tensile Strength (IDT)

The results of the indirect tensile strength (IDT) for all mixture types are represented in Figure 7. Results show that IDT is generally enhanced after comprising w-LDPE as an asphalt modifier, and the optimum resistance was achieved at 2% w-LDPE by higher than 50% compared to M0. This behaviour is attributed to the formation of polymer-rich phase and asphaltene-rich phase after incorporation of w-LDPE with asphalt, this behaviour leads to reinforcing the asphalt binder. As well as helping to increase the rigidity and flexibility of it mainly, and then control the initiation of TAO mixture to cracking. Nevertheless, the continuous increment into w-LDPE content higher than 2% shows lower IDT levels. This is due to the rigidity properties of w-LDPE polymer that renders asphalt binder hard and brittle with the continuous increment into its content thus making the mixture suffer from cracking. Punith and Veeraragavan [8] show results that reconcile with those observed in this investigation. It is worth mentioning that the higher dosage of w-LDPE affecting the continuous phenomena of the asphalt binder results in reduced binder cohesion. This phenomenon is a result of the absorption of light molecule weight fractions of asphalt by polymer [49]. Moreover, the higher dosage of the polymer has been approved by previous studies as an inferior factor for polymer modified asphalt characteristics, for example [50-52].

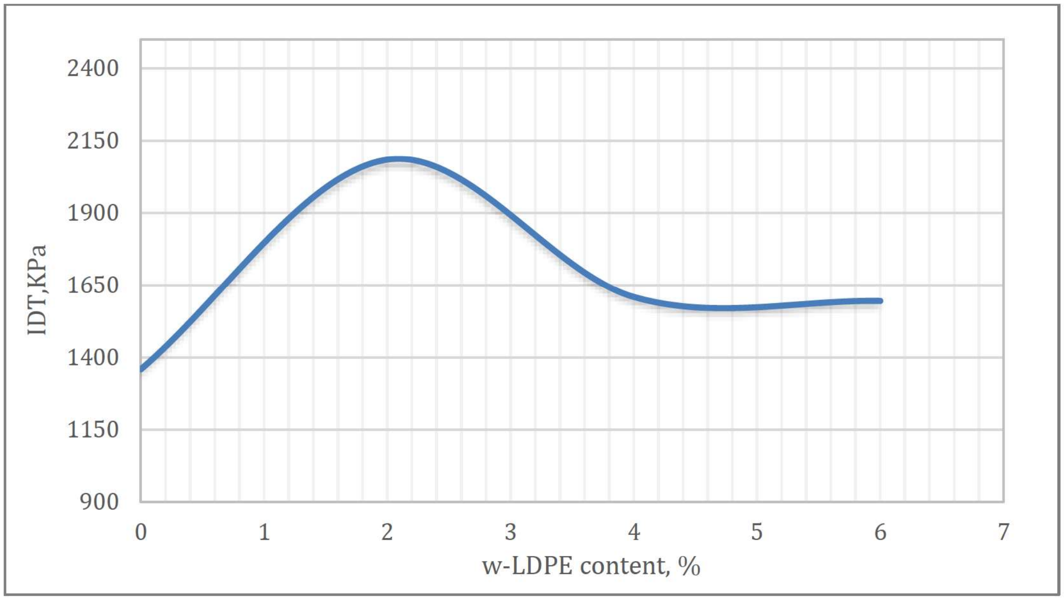

Figure 7. IDT for control and modified TAO mixtures

4.4. Creep Compliance (CC)

A comparison between creep compliance results of modified and unmodified TAO mixtures at 0 °C (following AASHTO T 322 [53]) is presented in Figure 8. It can be seen that the creep values increased with time and decreased with the increase in w-LDPE ratios. This reduction indicates the high stiffness obtained by using the modified asphalt cement. Creep compliance values decreased by higher than 30% after comprising the w-LDPE modifier. Angelone et al. [54] revealed that using 2%, 4% and 6% of waste plastic materials can decrease the values of creep compliance. However, the results confirm that increased w-LDPE enhance the resistance of TAO to crack progression and crack initiation at low temperatures. The behaviour of the mixture returns to the increment of mixture flexibility after comprising w-LDPE due to the rigidity properties of this modifier. As well as, due to the increment into mixture stiffness as a result of the increment of asphaltene fraction and the formation of the polymer network. This is in high demand for TAO as it normally serves from such type of failure [55].

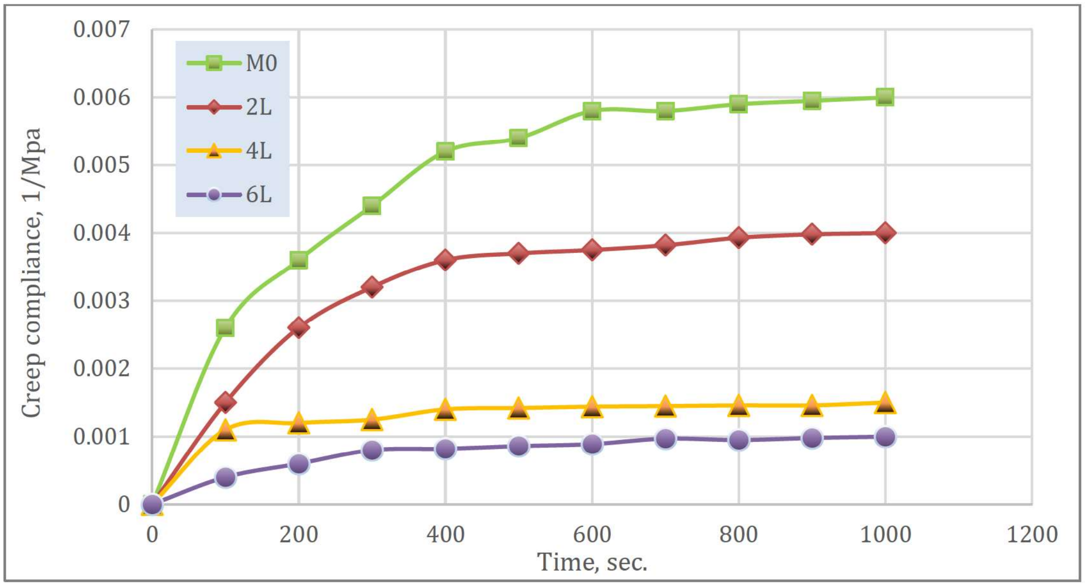

Figure 8. Creep compliance of control and modified TAO mixtures

4.5. Skid Resistance

Figure 9 illustrates the effect of using w-LDPE on skid resistance in both dry and wet conditions. As expected, the skid resistance for the wet surface is lower than that of the dry surface, due to the reduction in the friction between the slider rubber of the British pendulum tester and the sample surface. This refers to the impact of water, which works on the lubrication of the asphalt surface as mentioned by Dan et al. [56]. The mixture 4L recorded the highest reduction in skid resistance in wet conditions by around 14%, compared to dry conditions followed by 6L and 2L mixtures. Results also show that the resistance of TAO mix to skid improved by 36% and 38% at dry and wet conditions, respectively for the 6L mixture compared with the M0 mixture.

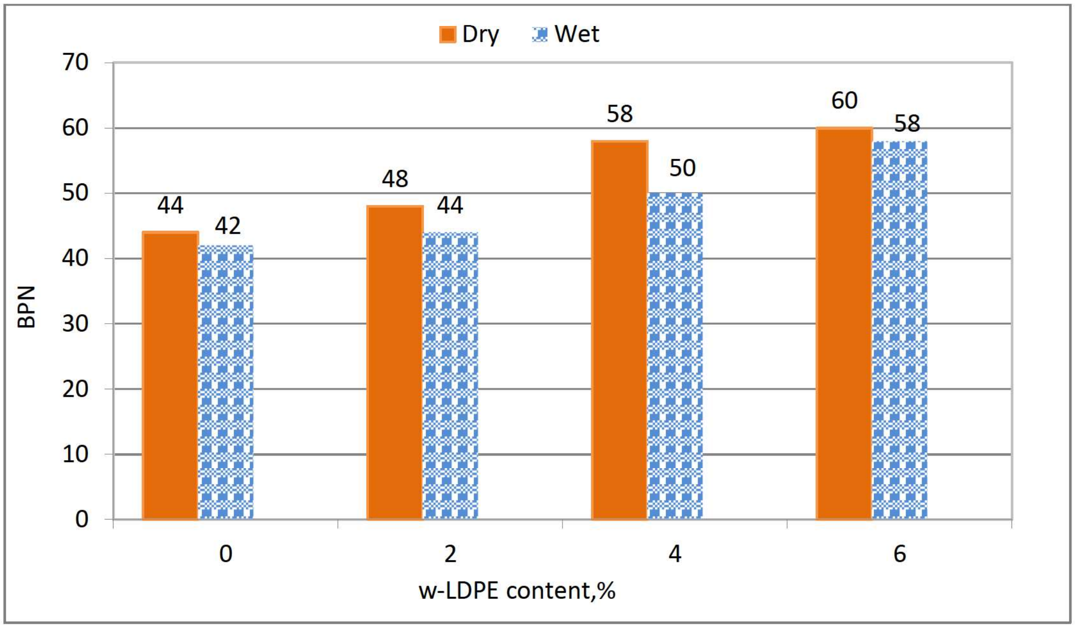

Figure 9. BPN for control and modified TAO mixes

The trend of results attributed to the increment into asphalt binder viscosities due to the formation of asphaltene-rich phase and polymer-rich phase, as well as, the rigidity properties of w-LDPE. That is work on enhancing the micro-texture properties of asphalt mixture, consequently, the roughness of the slab surface the skid resistance of the mixture improved. The addition of w-LDPE to the asphalt binder contributes to increasing the stiffness of the binder, simultaneously, increasing the asphalt film thickness that coats the aggregate which is a result of polymer role acting as a stabilizer. This in turn will minimize the compliance of the asphalt film due to tire stress and increase the grabbing between the tire and the coated aggregate, consequently reducing pavement problems against skid resistance.

4.6. Wheel Track (WTT)

Figure 10 displays the results of the wheel track test. The graph demonstrates the influence of comprising w-LDPE with asphalt cement on the resistance of the mixture to rutting. It can be observed that the rut depth increased with the increment in the number of cycles and decreased with increasing w-LDPE content. Where rut depth decreased by about 71% for the mixture with higher w-LDPE dosage (i.e. 6L), compared to the M0 mixture. This behaviour related to the increment of asphaltene polar adhesive as w-LDPE increased, as well as, the formation of polymer-rich phase. That works on reinforcing asphalt binder, increase its viscosity, as well as, stiffness. This was in turn reflected on the TAO mixture properties, and helped in minimizing the possibility of exposure of it to rutting. A similar result has been recorded by Angelone et al. [57]. Results show that the utilization of w-LDPE polymer as a modifier is a sound alternative to the other virgin polymers.

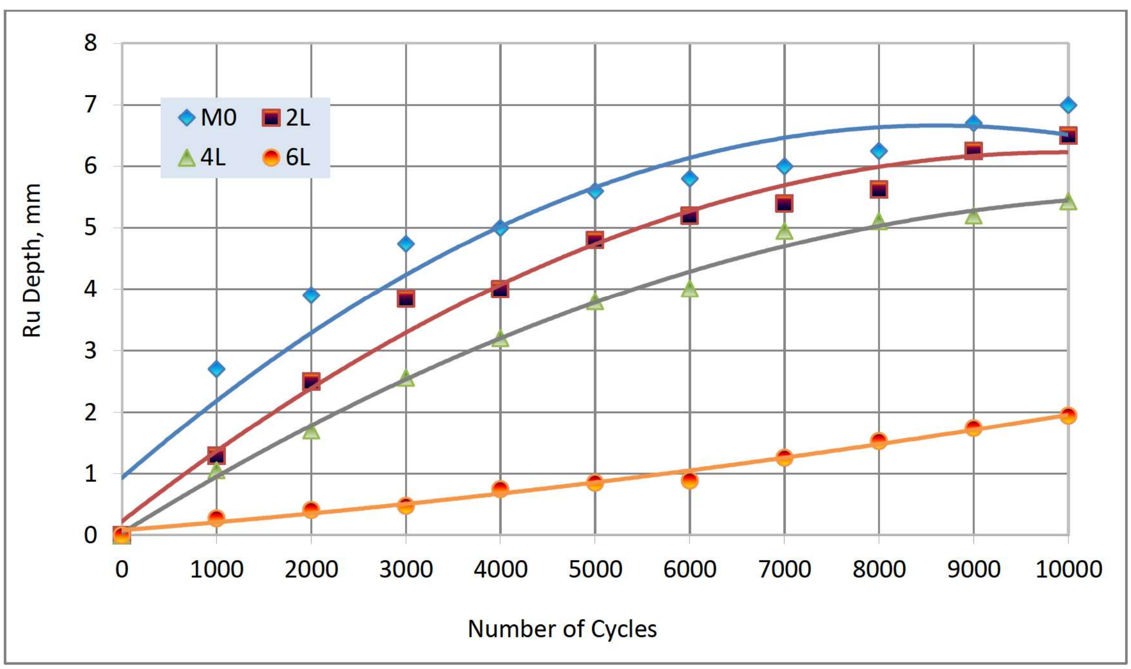

Figure 10. Rut depth for control and modified TAO mixes.

4.7. Cantabro Abrasion Loss Test (CAL)

Figure 11 displays a comparison between the proportion of Cantabro loss for mixes with various proportions of w-LDPE for both aged and unaged specimens. CAL values for mixes modified with w-LDPE are lower in comparison to the control mixes. It can be also observed that the abrasion loss of the aged samples is higher in comparison to the unaged samples due to the increase in brittleness. A thicker and more durable asphalt binder film that surrounds the aggregate particles generated by the addition of w-LDPE, improves the cohesion within the mix. In addition, the polymer network increases the stiffness of the asphalt binder. It is observed that mix 2L exhibits a substantial reduction in CAL by around 30%, whereas mixes 4L and 6L display a lower reduction in CAL. The increase in viscosity of asphalt binder generates a less compressible mix and this led to an increase in the air void content. Figure 12 shows the samples after the Cantabro test before and after aging.

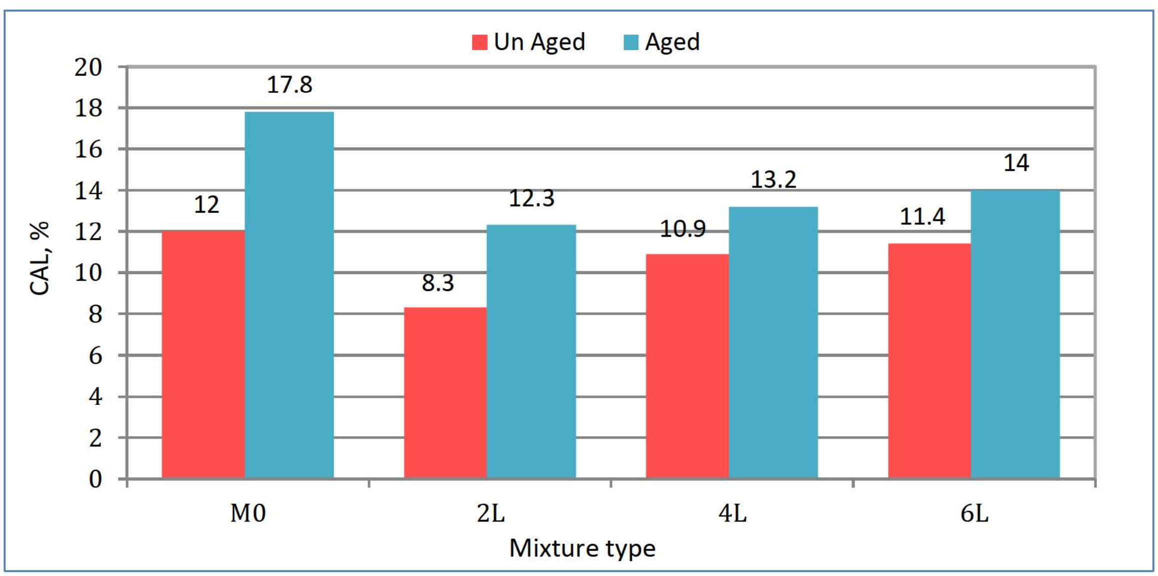

Figure 11. Cantabro abrasion loss test results for control and modified TAO mixes before and after aging.

Figure 12. The specimens after the Cantabro test before and after aging.

4.8. Tensile Strength Ratio (TSR)

Figure 13 shows the TSR for both reference and the modified mixes. The TSR increased as the R-LDPE content increased, thus w-LDPE has a positive influence on resistance to water damage. The highest value of w-LDPE (6L) has substantially improved TSR due to the enhancement in binder stiffness and resistance against stripping generated by the improvement in adhesivity and cohesion. It is worth mentioning that the reference mix has an accepted resistance to water damage due to the use of HL as an anti-stripping agent. Figure 14 illustrates the unconditioned and conditioned samples after the TSR test.

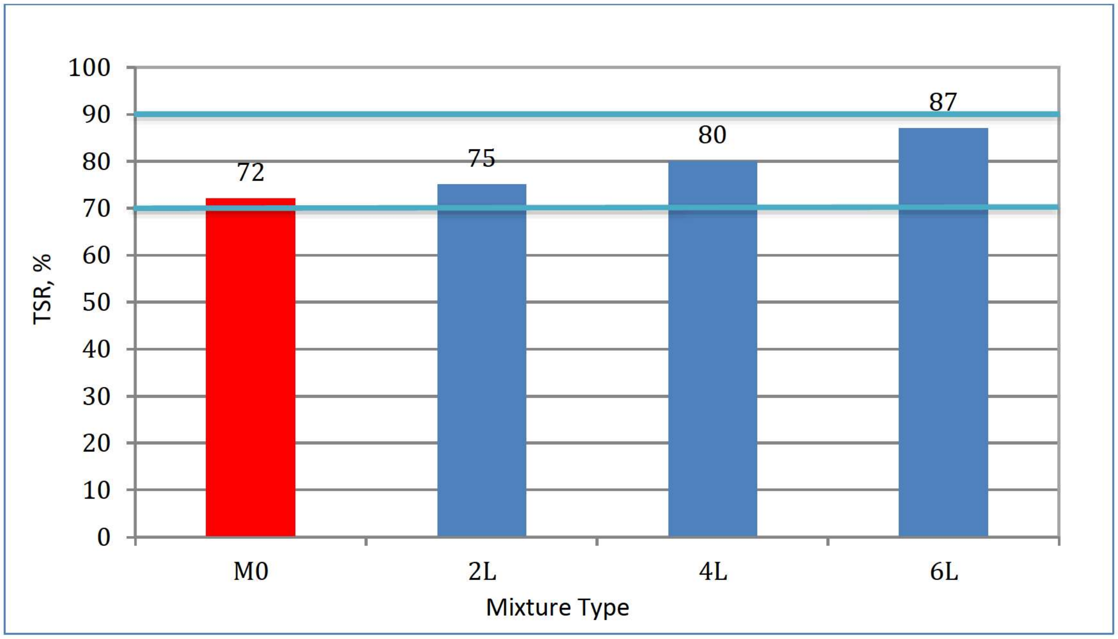

Figure 13. TSR for control and modified TAO mix.

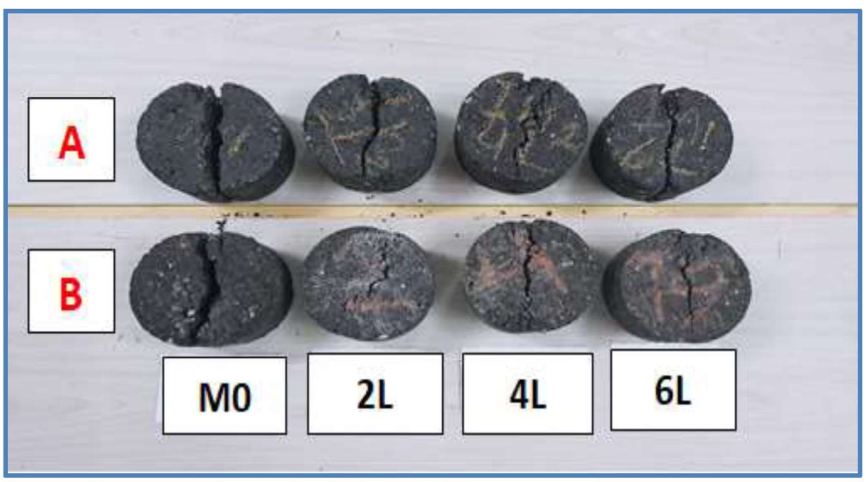

Figure 14. The specimens after IDT, group (A) represents the dry subset, group (B) represents the wet conditioned subset.

5. Conclusions

According to the laboratory test results of the mechanical properties for the modified and unmodified TAO mixes with w-LDPE, it can be concluded the following:

1. Resistance to plastic deformation is heightened by an increase in w-LDPE content. The addition of w-LDPE to asphalt binder increases mixture stability and flow by 48% and 33%, respectively, compared with the control mixture.
2. Although Indirect tensile strength improved significantly at an intermediate temperature. The addition of w-LDPE improved IDT by higher than 50%.
3. w-LDPE enhances resistance to low temperature-crack and cracks progression, where creep compliance improved by 83% in comparison to the control mix.
4. Skid resistance is enhanced by modified binder with w-LDPE, British pendulum number is increased in dry and wet conditions by 36% and 38%, respectively compared to control TAO mix.
5. Rut depth is decreased noticeably as w-LDPE content increases, it decreases by 71% after incorporation of w-LDPE, compared to the control TAO mix.
6. The incorporating of w-LDPE significantly improves the abrasion resistance for the aged and unaged TAO mixes. However, the 2% w-LDPE is the optimum proportion as it provides the best abrasion resistance.
7. The durability in terms of water sensitivity is noticeably enhanced as a result of incorporating w-LDPE. The higher water damage resistance is associated with an increase in the dosage of w-LDPE up to 6%.

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