Durability assessment of open-graded friction course using a sustainable polymer

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Abstract

Open-graded friction course (OGFC) asphalt mixture, usually used to construct porous pavements, represents one of the materials supporting low-impact development (LID) philosophy due to its use of coarse aggregate gradation. Using such mixtures brings several benefits related to safety, environment and economy. Alas, coarse, open-graded skeleton of OGFC mixtures is prone to failure, particularly raveling and stripping. Continuous traffic loading and the environmental impacts give hand in hand to further increase the potential for failure, hence higher pavement maintenance and rehabilitation costs. Application of different types of modifiers has proved effective in mitigating failure potential. The most common modifiers are polymers, fibers and anti-stripping agents. Aiming at minimizing the costs and maximizing the lifespan while considering sustainability, the study was to investigate the effect of using a recycled stabilizing material as an asphalt modifier on the performance of OGFC asphalt mixtures. Recycled Low-Density Polyethylene (R-LDP) was adopted in this investigation. Changes in mixture air void, porosity, draindown, permeability, rut depth, moisture damage and abrasion loss were observed to evaluate the effect. Compared with unmodified asphalt samples, R-LDP modification increased mixture air void, porosity and permeability by 15%, 10% and at least 40%, respectively. Also, it noticeably contributed to reducing rut depth, moisture damage and abrasion loss (both unaged and aged) by 31%, 20% and at least 40%, respectively. More significantly, it almost eliminated the draindown problem. Incorporating R-LDP proved effective in upgrading OGFC mixture properties to an acceptable level required by most specifications.

Keywords: Porous pavement; Low-density polyethylene; Recycled materials; Modified asphalt binder; OGFC asphalt mixtures

1. Introduction and background

Open-graded friction course (OGFC) asphalt mixture, mainly used to construct porous/pervious pavements, is one of the important materials contributing to the sustainability of transportation infrastructures. It owns characteristics appropriate to support the low-impact development (LID) philosophy [1,2]. Porous structure of the OGFC mixture, owed to its mainly coarse aggregate skeleton, is beneficial towards traffic safety, infrastructure economy and sustainable environment.

Porous asphalt infiltrates surface water and cuts the runoff length short. Less water on the pavement surface reduces spray, splash, hydroplaning and nighttime glares. Traffic safety is improved as a result. Absorbing the sound pressure created by tire/pavement

interaction into the air voids, OGFC asphalt mixture reduces the traffic noise noticeably. Less pollutants carried by runoff water also contributes to reducing the environmental problems [3,4].

Nevertheless, OGFC mixture has demonstrated low durability due to its high air void content. High exposure to air and water weakens the surface by lessening the cohesion within the asphalt binder and the adhesion between aggregate and asphalt binder. In the absence of a thick mastic, consequent stripping and raveling failure is not far from expectation [5,6]. Alvarez et al. [3] stated that the criterion to evaluate the durability of porous asphalt mixtures varies from country to country, as it can depend on the way wheel track, moisture damage or Cantabro loss tests are conducted.

Researchers have tried different solutions to improve the bituminous binders as well as the performance of OGFC mixtures. Further work has been particularly done on those having higher reactivity nature by creating a series of changes in chemical and physical properties of bitumen. Use of different modifiers, such as polymers (e.g. plastomers or elastomers) [7,8], fibers (e.g. cellulose, polyester or mineral fibers) [9,10] and anti-stripping additives (e.g. hydrated lime, quick lime, Portland cement or polyurethane) [11-13], has proved to be promising.

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Due to the high increment in traffic demand leading to further pavement distresses, and in line with addressing sustainability principles in pavement engineering, application of recycled and byproduct materials is strongly advocated to improve the performance of asphalt mixtures and extend pavement lifespan [1,14,15]. Literature shows successful application of different types of recycled polyethylene, polypropylene and their copolymers as well as some ash byproducts, such as rice husk ash, reed fly ash, date seed ash and coal ash [15-18].

In this study, a recycled material from polyethylene group, titled as Recycled Low-Density Polyethylene (R-LDP), is used as an asphalt modifier. R-LDP is produced in the process of recycling carry bags for domestic goods after becoming a solid waste. It is a product of polymerization of ethane forming a long chain of one-monomer ethylene [19-21]. R-LDP is characterized with its non-polar low-crystallized nature. Such a property lowers its immersibility when mixed with asphalt binder, hence, grafting with chemically reactive materials and resulting in a tougher binder [22,23]. Polyethylene is a tough material and its incorporation in bitumen is expected to add a toughness level to the asphalt mixture, its resistance to thermal and fatigue cracking, and its resistance against stripping [24]. Limited researchers, however, have dealt with application of R-LDP as an asphalt modifier. Similar improvements would be a great advantage in the case of OGFC mixture. Therefore, the aim is to study the effect of R-LDP on the durability of OGFC asphalt mixture.

2. Materials

2.1. Aggregate

Crushed limestone aggregate for the study was supplied from a quarry located in Karbala, Iraq. Gradation and the physical properties of the used aggregate are summarized in Table 1.

2.2. Hydrated lime and limestone dust

Hydrated lime (HL) was used as an anti-stripping additive in the composition of OGFC mixture. Limestone dust (LD) worked as the mixture filler; however, HL would perform as the filler too. As recommended by ASTM D7064/D7064M [25], 1.5% HL and 1.5% LD (by weight of dry aggregate) were added. Physical and chemical properties of HL and LD are mentioned in Table 2.

2.3. Bitumen and modifier

The neat 40/60 bitumen used in this study was supplied from a local refinery in Iraq. Six dosages of R-LDP ranged from 1% to 6% (by weight of bitumen) were added to the neat binder. Properties of bitumens before and after modification are illustrated in Table 3. The R-LDP polymer in this investigation was supplied from a recycling plant in Karbala, Iraq. R-LDP was in the form of powder when added to the bitumen. The physical properties of R-LDP polymer are tabulated in Table 4.

Table 1

Aggregate gradation and stone-on-stone contact verification.

Sieve size (mm)	Used gradation/ Percent passing (%)	ASTM D7064/D7064M [25] limits/ Percent passing (%)
19.00	100	100
12.50	92.5	85 – 100
9.500	47.5	35 – 60
4.750	17.5	10 – 25
2.360	7.5	5 – 10
0.075	3	2 – 4
Physical properties		
Bulk specific gravity of coarse aggregate (gm/cm ³)		C127 [26] 2.590
Bulk specific gravity of fine aggregate (gm/cm ³)		C128 [26] 2.640
Water absorption of coarse aggregate (%)		C127 [26] 2.248
Water absorption of fine aggregate (%)		C128 [26] 2.241
Los Angeles abrasion value (%)		C131 [27] 25

Table 2

Chemical and physical properties of fillers.

Element	Concentration	
	LD	HL
SiO ₂ (%)	81.89	0.89
Al ₂ O ₃ (%)	3.78	-----
Fe ₂ O ₃ (%)	1.92	2.25
CaO (%)	7.37	90.58
MgO (%)	3.45	3.6
K ₂ O (%)	0.73	0.58
Na ₂ O (%)	0.19	1
Bulk density (gm/cm ³)	2.65	2.3
Surface area (m ² /kg)	223	1450

Table 3

Physical properties of bitumen before and after modification.

Property	Penetration at 25 °C (mm/10)	Softening point (°C)	Ductility at 25 °C (cm)	Viscosity at 135 °C (Pa.s)	Penetration index (PI)	
ASTM Specification/reference	D 5-5a	D 36-95	D 113-99	D 4402-02	Read et al. [28]	
Modification range	0% R-LDP	43	49	133	0.87	-1.611
	1% R-LDP	38	51	121	1.13	-1.515
	2% R-LDP	32	52	109	1.22	-1.424
	3% R-LDP	29	55	100	1.32	-1.211
	4% R-LDP	25	57	91	1.38	-0.995
	5% R-LDP	21	62	85	1.57	-0.412
	6% R-LDP	17	67	78	1.73	0.193

Table 4
Physical properties of R-LDP.

Properties	Results
Density (g/cm)	0.92
Tensile strength (MPa)	8.6
Tensile elongation (%)	>350
Melting temperature (°C)	111
Flexural modulus (MPa)	7.3
Hardness shore (D)	46

3. Laboratory study

3.1. Preparation of modified bitumen

R-LDP was mixed with bitumen using a shear mixer. Six dosages of R-LDP, 1%, to 6% (by weight of bitumen), were prescribed to create various levels of modification. Initially, bitumen was heated until fluid and then, placed into a pre-heated mixer container. Mixing process began when the temperature of the container reached to 170°C. Measured amounts of R-LDP were added to the heated bitumen and blended for 60 minutes with a rotational speed of 3000 rpm while the container temperature was maintained at 170°C.

3.2. Mixture design and test methods

Cylindrical and slab samples were needed for the study. Two compaction procedures were adopted to design OGFC asphalt mixtures. Marshall test procedure was chosen to produce cylindrical samples where 50 blows on each face is required to compact the samples. Vibratory compactor, as recommended by BS EN 12697-32:2003 [29], was implemented to prepare slab samples. Initially, five asphalt binder contents ranged between 5% and 7% with 0.5% intervals were used according to the limits suggested by D6932/6932M [30]. Then, the mixture with optimum asphalt content (OAC) was selected following the procedure recommended by ASTM D7064/D7064M [25]. That included determination of stone-on-stone contact, air voids, porosity,

draindown, and Cantabro loss for all asphalt binder contents.

3.2.1. Stone-on-stone contact verification

The stone-on-stone contact verification of the aggregate was determined following the calculation of the voids in coarse aggregate (VCA) procedure recommended by ASTM D7064/D7064M [25]. The breaking sieve adopted in this test was 2.36 mm based on the results obtained from other studies [31,32]. The principle of comparison between VCA in dry-rodded condition and VCA in compacted mixture was followed, and the equations shown in Table 5 were used to calculate voids volume.

3.2.2. Air voids and porosity

Air voids (V_a) was determined in accordance with ASTM D7064/D7064M [25] and porosity was determined based on Putman et al. [33]. The equations required to calculate these parameters are given in Table 6.

3.2.3. Draindown

Draindown test gives an indication of the ability of asphalt binder to separate itself from the aggregates during production, transport, placing and compacting. The test was conducted according to the procedure recommended by AASHTO T 305-97 [34]. Four loose samples were used to perform this test. Each two samples were tested under different temperatures, i.e. production temperature and production temperature+15°C. Each sample was placed into a standard basket before being placed over a pan with a known weight. The pan and basket were entered into a forced draft oven. The sample stayed in the oven for 1 hour ± 5 minutes. Then, the basket containing the sample and the pan were removed from the oven. Drained bitumen (left in the pan) was weighed. Eq. (6) was used to calculate the amount of mixture draindown.

$$DR = \frac{D-C}{B-A} \times 100 \quad (6)$$

where, DR is the draindown rate (%), C is the weight of pan (g), D is the weight of pan plus sample after removal from oven (g), A is the weight of empty basket (g) and B is the weight of basket plus sample (g).

Table 5
Equations to determine stone-on-stone contact parameters.

Parameter	Equation/criteria	Parameters
Voids in coarse aggregate in dry condition	$VCA_{DRC} = \frac{G_{CA}\gamma_w - \gamma_s}{G_{CA}\gamma_w} \times 100$ (1)	G_{CA} : bulk specific gravity of the coarse aggregate γ_s : bulk density of the coarse aggregate fraction in the dry-rodded condition (kg/m ³)
Voids in coarse aggregate in compacted mixture	$VCA_{MIX} = 100 - \left(\frac{G_{mb}}{G_{CA}} \times P_{CA} \right)$ (2)	γ_w : density of water (998 kg/m ³) G_{mb} : bulk specific gravity of the compacted mixture, % R_{BS} : percent of aggregate retained on the breaking sieve (%)
Percent of coarse aggregate in total mixture (P_{CA})	$P_{CA} = \frac{\% R_{BS}}{100} \times \left(1 - \frac{\% P_b}{100} \right)$ (3)	% P_b : percent of asphalt content by total weight of mixture (%)

Table 6
Equations to calculate the volumetric properties.

Parameter	Equation/criteria	Parameters	Number of required samples
Air voids	$V_a = \left(1 - \frac{G_{mb}}{G_{mm}} \right) \times 100$ (4)	G_{mb} : bulk specific gravity of compacted specimen G_{mm} : maximum theoretical specific gravity	2
Porosity	$PO = \left(1 - \left(\frac{W_{dry} - W_{sub}}{\rho_w V_T} \right) \right) \times 100$ (5)	W_{dry} , W_{sub} : dry and submerged weight of compacted specimen (g) V_T : total volume of compacted specimen (cm ³) ρ_w : water density (gm/cm ³)	2

3.2.4. Permeability

The evaluation of permeability of OGFC mixture skeleton was done according to the procedure of falling head principle as recommended by ASTM D5084 [35]. ASTM D7064/ D7064M [25] recommend that the initial permeability of OGFC mixture should not be less than 100 m/day. Each testing sample was wrapped on the side only using plastic film to allow a single direction for the flow of water. One sample was then set into permeability test instrument (Fig. 1), tightened and sealed. The upstream pipe was filled with water to the height of 375mm. Then, the water was allowed to flow through the specimen. The time required for the water level to drop from 365 mm to 140 mm was recorded. Four samples were adopted to conduct the test with three replications on each sample. Eq. (7) was used to calculate permeability of each sample.

$$K = \frac{aL}{At} \ln \left(\frac{h_1}{h_2} \right) \quad (7)$$

where, K is permeability (mm/sec), A is the cross-section area of the specimen (mm²), a is the cross-section area of the stand pipe (mm²), L is the height of the specimen (mm), t is the time required for the water to flow through the sample (sec), h_1 is the head above the sample surface (365 mm), h_2 is the head above the sample surface (140 mm).

3.2.5. Moisture damage study using wheel track test

Wheel track test is an indicator of the resistance of a mixture to permanent deformation. In this study, the test was conducted using small size device following the procedure recommended by BS EN 12697 [36]. Two slab samples (300mm×165mm×40mm) with an initial air void content of about 21% were tested. Such air void was chosen after a number of compaction trials to include a serious level of air voids for OGFC mixtures.

The test was conducted at dry and wet conditions to evaluate the mixture resistance to moisture damage. A set of four samples were used for this purpose, following AASHTO T283 [37]. Each couple of samples was tested at dry and wet conditions. Compacted asphalt samples were initially conditioned at 60°C for 16 hours. For dry condition testing, samples were conditioned at 60°C using a forced draft oven for two hours before conducting the test. For wet condition testing, samples were subjected to five cycles of freeze-thaw. Samples were wrapped with plastic film before being placed in a pan filled with 10±0.5ml water, conditioned to -18±3°C

for 16 hours to freeze the samples. Then, the samples were left in an oven set to 60±1°C in a water path for 24±1 hour. At the end of the five cycles when the samples were conditioned at 60±1°C in a water path, dry condition test system was carried out. The outcomes of this test are rut depth after 10000 cycles (RD), rutting rate (RR), and dynamic stability (DS) which were determined after Read et al. [28].

3.2.6. Moisture damage study using indirect tensile strength

AASHTO T283 [37] guidelines were also adopted to perform another moisture damage test with some changes in sample size, shape and condition. Marshall test samples and compaction method (impact compaction with 50 blows to each face) with a testing temperature of 25°C were used. Mixture resistance to moisture damage was evaluated by indirect tensile strength (ITS) test where dry and wet samples were subjected to loading at a constant rate of 50 mm/min on the diametric axis of the sample

until failure. Table 7 provides the information to calculate the tensile strength ratio (TSR).

3.2.7. Cantabro abrasion loss

Laboratory determination of the amount of abrasion loss of Marshall samples gives an indication of the capacity of mixture to resist degradation. A set of six samples were used to perform this test in accordance with procedure recommended by ASTM D7064/ D7064M [25]. Three samples were used to perform the test under unaged condition and three samples for the aged condition.

For unaged Cantabro loss (UCL) test, the compacted samples were placed in a forced draft oven at 25°C for four hours before being placed in the abrasion machine. Weights of the samples before and after abrasion test were recorded.

For aged Cantabro loss (ACL) test, the compacted samples were conditioned at 60°C using a forced draft oven for seven days (168 hours) to simulate the long-term aging. Samples were then extracted and conditioned at room temperature before being conditioned at 25°C in an oven for four hours. Weights of the samples before and after abrasion test were recorded.

Cantabro loss (CL) value is calculated for each sample using Eq. (10).

$$CL = \frac{P_1 - P_2}{P_1} \times 100 \quad (10)$$

where, CL is Cantabro loss, P_1 is the weight of sample before abrasion test and P_2 is the weight of sample after abrasion test.

4. Determination of OAC

Test results tabulated in Tables 8 and 9 were used to find the OAC for mixture comprising neat asphalt. Compiling the results in Tables 8, it is concluded that optimum asphalt content for OGFC

Table 7

Equations to calculate ITS and TSR.

Parameter	Equation/criteria	Parameters
ITS	$S_t = \frac{2000 P}{\pi t D} \quad (8)$	S_t : tensile strength (kPa) P : maximum load (N) t : specimen thickness (mm) D : specimen diameter (mm)
TSR	$TSR = \frac{S_2}{S_1} \quad (9)$	S_1 : average tensile strength at dry condition S_2 : average tensile strength at wet condition.

Fig. 1. Laboratory device used for permeability measurement.

Table 8
Summary of the results of reference mixture evaluation.

Asphalt content (%)	Air voids (%)	Porosity (%)	Draindown (%)	Unaged Cantabro loss (%)	Aged Cantabro loss (%)
5.0	19.90	15.2	1.4	52.2	68.2
5.5	18.89	14.6	2.2	39.9	48.1
6.0	18.01	13.5	3.2	30.5	36.5
6.5	17.95	13.2	3.8	27.3	35.3
7.0	18.20	13.3	4.7	35.2	55.2

Table 9
Stone-on-stone contact verification for aggregate gradation.

Asphalt contents (%)	G_{CA}^*	P_{CA}	BD^{**}	V_a	VCA_{DRC}	VCA_{mix}	VCA_{mix}/VCA_{DRC}
5	2.59	87.88	1.92	19.9	39.3	35.08	0.893
5.5	2.59	87.41	1.931	18.89	39.3	35.04	0.892
6	2.59	86.95	1.941	18.01	39.3	35.12	0.894
6.5	2.59	86.49	1.927	17.95	39.3	35.88	0.913
7	2.59	86.03	1.926	18.2	39.3	36.3	0.924

* G_{CA} : bulk specific gravity of coarse aggregates

** BD : bulk density of compacted mixture

mixture to fulfill the specification (ASTM D7064/D7064M [25]) is 6.2%. Considering stone-on-stone contact verification, result of which is shown in Table 9, 6.2% is an acceptable OAC for the mixture. It is evident that the voids in coarse aggregate in compacted mixture are lower than those in dry rodded condition for all asphalt contents as required in ASTM D7064/D7064M [25], which explains that the selected gradation is appropriate for an OGFC mixture. Therefore, asphalt content of 6.2% was selected for all the OGFC mixtures in the investigation. This is denoted as the reference mixture (RM), and the performance of OGFC mixtures containing R-LDP additive is compared to the performance of the RM.

5. Discussion

5.1. Air voids and porosity

Fig. 2 shows the results of air voids and porosity of OGFC asphalt mixture modified with different contents of R-LDP. The more the asphalt binder of OGFC mixture is modified with R-LDP, the higher both the air voids and the porosity of the OGFC mixtures. All the air voids fall in the range required by the specification (ASTM D7064/D7064M [25]), i.e. 18% to 22%. Adding up to 6% R-LDP shifted the air voids for 15% and the porosity for 10%. Such behavior is attributed to a set of chemical and physical alterations of asphalt binder, as a result of adding R-LDP [38]. The chemical modification takes place across a biphasic

Fig. 2. Air voids and porosity of RM and R-LDP modified OGFC mixtures.

reaction. In phase one, asphaltene-rich substances are created, and in the other, polymer-rich substances are formed as a result of the absorption of the light-weight molecules of asphalt by R-LDP molecules. Physically, comprising R-LDP resulted in higher viscosity of asphalt binder following the chemical reactions [8]. When hardness of R-LDP polymer plays its role, asphalt binder thickens and raises the asphalt film thickness, hence, better aggregate coating. Less binder will then be available to fill the air voids. Therefore, porosity of OGFC mixture will increase with increase in the added R-LDP. Shirini et al. [39] and El-Naga et al. [40] have concluded similar trends when they modified asphalt binder of OGFC mixtures with other additives.

5.2. Draindown

The results of draindown of OGFC mixtures with and without R-LDP polymer at two temperatures are displaced in Fig. 3. ASTM D7064/D7064M [25] specifies a maximum level of 0.3% draindown for OGFC mixtures. Use of R-LDP appears to be effective in mitigating draindown problems particularly for contents having more than 4% R-LDP. Higher dosages of R-LDP polymer reduces draindown to as low as 0.15%. It appears that binder became more adhesive and viscous. In addition, development of a polymer-rich substance improves the integrity of asphalt binder. Large surface area of the additives paves the ground for more light molecular absorption. A combination of these factors explains why higher cohesion in asphalt binder and better binder-aggregate adhesion is concluded. The trend of binder

Fig. 3. Draindown of RM and R-LDP modified OGFC mixtures.

draindown appears similar to that observed by Al-Hadidy et al. [24] working on stone mastic asphalt mixtures containing polyethylene polymer. Lyons et al. [41] have also achieved relatively similar results when using SBS polymer in their study on porous asphalt.

5.3. Permeability

The results of permeability tests for all samples of OGFC mixtures are presented in Fig. 4. Results indicate that modifying the asphalt binder used in the OGFC mixtures containing R-LDP polymer enhances the ability of OGFC porous structure to infiltrate water by up to 50% in comparison to the performance of RM. All types of OGFC mixtures after incorporating R-LDP demonstrated an initial permeability of higher than 100 m/day which is a requirement by ASTM D7064/D7064M [25].

As the dosage of R-LDP increased within the asphalt binder, higher permeability was observed from the modified OGFC mixture. Such a performance is built upon the higher viscosity of the R-LDP modified asphalt binder following the alteration of the bitumen structure to a gel-type structure [28]. Development of a polymer network within the modified asphalt binder and the hardness R-LDP brought in tend to turn the mixture to behave less flexibly. In such a structure pores are further interconnected and permit larger volumes of water to flow through the mixture structure. The trend of permeability of OGFC asphalt mixture is understood to be similar to those observed by Shen et al. [42] and Qian et al. [43].

5.4. Wheel track and moisture damage

The results for resistance to permanent deformation and dynamic stability of all types of OGFC mixture are summarized in Figs. 5 to 8. Figs. 5 and 6 display that OGFC mixture resistance to permanent deformation is a direct function of the level of modification but differs under dry and wet conditions. Higher dosages of R-LDP additive have reduced the potential of the OGFC mixtures for rutting; however, the effect of R-LDP in strengthening OGFC mixture is less pronounced as the dosage level rises. R-LDP additive has shown its highest influence in controlling permanent deformation of OGFC mixtures at 1% and 2% for both dry and wet conditions. Figs. 5 and 6 also depict that all test samples have almost approached their deformation stability stage at 10000 cycles, and the interlocking forces within the coarse aggregates are reaching a balance.

Fig. 7, showing the final rut depths (RD) after the completion of the tests, confirms the conclusions above. Comparing the results under dry and wet conditions, it is evident that the OGFC mixtures of the study have a degree of sensitivity to the presence of water. The rut depth of the reference mix (RM) under wet condition was nearly twice as that in dry condition. Although use of R-LDP has reduced water susceptibility of the OGFC mixtures under dry condition, the influence has been more for the sample under wet condition. Therefore, it is concluded that not only use of R-LDP increases mixture resistance against repeated loading, it also mitigates OGFC mixture susceptibility to water significantly.

This is believed to be related to the reduction in the chemical aging of the mixture and turning the binder to behave more viscously. Formation of polymer network directed by R-LDP causes development of crosslinks within the asphalt binder. As a result, stone-on-stone contact of the aggregate is maintained further and leads to better mechanical performance of the modified OGFC mixtures.

Fig. 4. Permeability of RM and R-LDP modified OGFC mixtures.

Fig. 5. Variation in rut depth against the number of cycles for RM and R-LDP modified OGFC mixtures at dry condition.

Fig. 6. Variation in rut depth against the of cycles for RM and R-LDP modified OGFC mixtures at wet condition.

Fig. 7. Variation in final rut depth of RM and R-LDP modified OGFC mixtures at dry and wet conditions.

As seen in Fig. 8, utilization of R-LDP polymer returned higher dynamic stability. Comparing the dynamic stability values shows up to 50% improvement which is believed to be directly related to the thickness of the asphalt film coating the aggregates. Higher

dynamic stability results in enhancement in the resistance of mixture to permanent deformation. The deformation behavior of OGFC mixtures in this study appear to be similar to that in the research conducted by Dalhat et al. [21] (use of waste plastic polymer as additive) and the stability trend was similar to that in Zhao et al. [31] (SBS and SBR modified asphalt mixtures). Dynamic stability test results reconfirmed that OGFC mixtures are susceptible to the presence of water and that adding R-LDP improves the situation for both dry and wet samples.

5.5. Mixture tensile performance and moisture damage

Fig. 9 illustrates the resistance of OGFC mixtures to tensile cracking and moisture sensitivity. Results indicate that the resistance of mixture to tensile cracking enhanced by more than 18% at both dry and wet conditions after incorporating R-LDP polymer as asphalt modifier. Sensitivity of the mixture to moisture (i.e. TSR limits of more than 80% according ASTM D7064/D7064M [25]) is improved by about 20% after five freeze-thaw cycles when using 6% R-LDP.

Resistance of mixture to stripping is strengthened by the presence of hydrated lime. Chemical composition of HL contains calcium and sodium ions. Such strong basic ions in the presence of the acids of bitumen tend to form salts covering the aggregate surface. The higher roughness on the aggregate surface increases the adhesion between aggregate and asphalt binder and reduces the likelihood of stripping. In the other hand, oxygen atoms in the chemical composition of HL react with the aliphatic chains within asphalt molecules leading to the creation of a weak carboxylic acid which can react with the strong ions of Ca^{++} and Na^+ [44,45]. Therefore, a combined modification by R-LDP and HL developed resistance against moisture for OGFC mixtures. A similar development was observed by Kok and Yilmaz [46] where SBS combined with HL improved the resistance of asphalt mixture against moisture.

5.6. Cantabro loss

Cantabro test was conducted to evaluate OGFC mixtures resistance to degradation. ASTM D7064/D7064M [25] recommend that the amount of loss should not be more than 20% and 30% for unaged and aged conditions, respectively. Results, shown in Fig. 10, display that the resistance of OGFC mixtures to degradation improved after incorporating R-LDP polymer. Adding more R-LDP reduced the degradation to a certain point after which a slightly more loss was observed. Nevertheless, Fig. 10 shows that all mixtures modified with R-LDP fulfill the specification requirements (ASTM D7064/ D7064M [25]) at both conditions. For instance, 3% R-LDP reduced 45% and 60% of the potential to abrasion of unaged and aged samples, respectively.

It is, therefore, concluded that the R-LDP modification improved OGFC mixtures's durability, as it reduced the loss in a larger scale for aged condition than for unaged condition. It is understood that the polymer network and the physical and chemical reactions elaborated previously are responsible for the enhancement in reducing the degradation, but it appears that higher R-LDP dosages disadvantages the mixture integrity, increasing the abrasion loss. This can be seen in viscosity measures in Table 3 where increasing R-LDP grows viscosity, however, with a larger gradient for more than 3% R-LDP.

Fig. 8. Dynamic stability and rate of rutting development for RM and R-LDP modified OGFC mixtures at dry and wet conditions.

Fig. 9. Indirect tensile strength and TSR of RM and R-LDP modified OGFC mixtures.

As the trends present in Fig. 10, UCL samples have suffered less than ACL samples under Cantabro test because ACL samples were subjected to the harsh conditioning system of the test (aging at 60°C for 168 hours). Aging caused further oxidization which turned the mixtures behaviors to be more brittle [48]. The oxidation phenomena appear in the form of a number of oxides such as carboxyl, hydroxyl, sulfoxide, and ketones. Previous research suggests that carboxyl has the highest concentration of oxidized material affecting the properties of asphalt binder largely [47]. Utilization of R-LDP could hinder formation of carboxyl due to the crosslinking properties of polymer [28]. However, it is difficult to evaluate the effect fully, as HL plays a role in reducing the effect of aging in asphalt mixtures [45]. Shirini et al. [39] concluded similarly when the binder was rubberized.

Fig. 10. Cantabro abrasion loss of RM and R-LDP modified OGFC mixtures.

6. Conclusion

The study aimed to investigate modification of asphalt binder with R-LDP, a recycled polymer, and gauging the effect on the durability performance of OGFC mixtures. Test results revealed that the modification changed the asphalt binder, hence, the performance of OGFC mixture, significantly. The following is the summary of the outcomes:

1. Considerable improvement in the permeability of OGFC mixture (at least 40%) following higher air voids and porosity by about 15% and 10%, respectively.
2. Significant reduction in the draindown property of modified OGFC mixtures.
3. Improvement in mixture dynamic stability, therefore, reduction in the rutting potential of modified OGFC mixtures.
4. Mitigating mixture susceptibility to the presence of water by considerably decreasing the rut depth.
5. Higher tensile strength, in terms of both ITS (dry and wet) and TSR.
6. Greater resistance of OGFC mixtures to abrasion loss measured by Aged and Unaged Cantabro Loss test with larger effect on the aged samples, showing the potential to further material durability.

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