Assessing the Mechanical Properties of Open-Graded Asphalt Mixtures

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ABSTRACT

In consideration of the escalating vehicular intensity and the substandard material properties of pavements in Iraq, particularly with regard to their impact on wet-weather accident rates and noise pollution in urban areas, there is an urgent need for an analysis of Open-Graded Asphalt (OGA) mixes to address the environmental and safety concerns. While OGA mixtures offer the dual advantages of reducing stormwater runoff and enhancing wet skid resistance, they are also more prone to raveling due to their high porosity. To enhance the performance of OGA mixes, various methods have been employed, including the incorporation of recycled polymers. The primary objective of this research is to evaluate the durability and strength properties of OGA mixes through laboratory testing using the Recycled Polyvinyl Chloride (RPVC) polymer. Laboratory tests were conducted on OGA mixes to ascertain the Marshall stability, resistance to abrasion, permeability, tensile strength, and moisture-induced damage. The mix designs were executed in accordance with the design procedure proposed by the National Cooperative Highway Research Program (NCHRP) for a range of 5.5%–7.0% asphalt content. RPVC was used in various proportions (2%, 4%, 6%, and 8%) by the weight of the base binder. The experimental findings demonstrated that the incorporation of RPVC led to enhanced Marshall stability and Indirect Tensile Strength (ITS) in porous asphalt concrete, surpassing the performance of conventional asphalt mixes. Additionally, the OGA mixture exhibited significant improvements in raveling resistance and moisture susceptibility. The study concluded that the Optimal Binder Content (OBC) of RPVC could enhance the pertinent engineering properties of OGA mixtures without compromising their permeability.

Keywords-open-grade friction course; fibers; porous asphalt concrete; recycled polymer; permeability; indirect tensile strength

I. INTRODUCTION

The objective of Porous Asphalt Mixtures (PAMs), also referred to as Open-Graded Friction Courses (OGFC), is to enhance surface frictional resistance, mitigate hydroplaning, splash, and spray, improve visibility at night, and reduce pavement noise levels. These specialized mixtures are recommended for both newly constructed and existing high-speed, high-volume roadways and expressways [1-4]. Authors in [5, 6] showed that the functionality of these materials is primarily achieved through the drainage of water from pavement surfaces during precipitation events. PAMs are engineered to have an air void that ranges from approximately 15% to 25% during compaction, allowing water to be absorbed by the pavement [4, 7]. By implementing a uniform grading of aggregate, predominantly comprising a single aggregate size, OGA mixes aim to attain a substantial proportion of internal air voids. The majority of aggregate particles (approximately 50%-60%) tend to be of uniform size [8]. Conversely, a PAM typically contains a low percentage of filler, typically ranging from 2% to 5%, as determined by the 0.075 mm sieve size, to ensure the presence of a substantial amount of internal air voids

[5, 9]. In comparison to dense graded mixes, PAMs generally exhibit a slightly higher asphalt composition [6]. In 1950, the United States initiated the usage of the OGFC asphalt mixture, superseding the previous standard of Dense-Graded Asphalt Mixture (DGAM). Its primary use commenced in Australia in 1973 and in Japan in 1987 [10-12]. This asphalt mixture has been proven to be superior to its alternatives in terms of noise reduction, anti-skidding properties, environmental impact, and safety [13, 14]. Additionally, its high air void content contributes to reduced aquaplaning risks by allowing water to permeate through its porous skeleton and limiting water hazards, such as splash and spray [15]. The mixture's sensitivity to water and oxygen, attributable to its high air void content and neat binder, can be exploited through raveling. This, in turn, can lead to reduced adhesion between the aggregate and binder in the paving layer [16, 17]. To ensure sufficient strength and prevent drain-back, these mixtures necessitate a modified binder composed of polymers or fibers, which, in turn, results in an increase in cost [18]. The enhancement of the strength and durability of porous asphalt has been the subject of numerous scientific studies. Authors in [19] proposed the incorporation of a binder modified with rubber, crumb, or polymer to extend the lifespan of OGA mixes in hot and wet regions subject to high traffic volume. Authors in [5] found that fibers may be employed to enhance the asphalt binder content of PAMs. This, in turn, resulted in increased film thickness and, consequently, enhanced durability. The usage of recycled and byproduct materials is strongly recommended to enhance the performance of asphalt mixtures and extend the lifespan of pavements [3, 20].

Authors in [21] investigated the effects of several blends of asphalt binder types and additives on the durability and noise reduction properties of an OGA mixture with a small aggregate size. The findings indicated that the utilization of polymer-modified or rubberized binders in lieu of an unmodified binder OGA mixture led to a reduction in permeability, while concurrently augmenting the acoustic absorption and enhancing the mixture's resistance to moisture damage, raveling, and rutting. Authors in [5] evaluated the durability and strength of the porous asphalt through laboratory testing using different types of additives, such as fiber, hydrated lime, and DBS polymer. The incorporation of DBS polymer enhanced its performance at elevated temperatures, but diminished its durability and cracking resistance at low temperatures. The findings indicate that the incorporation of DBS enhances the performance of porous asphalt in hot and wet climates. Authors in [8] employed digital image analysis to assess the stone-on-stone contact properties of OGA mixtures. Permeable Friction Course (PFC) mixtures were fabricated with both asphalt rubber and polymer-modified asphalt. The research emphasized the importance of verifying and balancing the properties of open asphalt mixtures, such as Cantabro loss, coarse aggregate ratio, drain-down, and compaction control, in addition to the air void ratio, to achieve the best contact between the aggregate particles used in making the open mix. The impact of two asphalt modifier types, namely Styrene Butadiene Styrene (SBS) and Propylene Polypropylene (PP), on the characteristics of OGA mixtures was examined in [22]. The findings of this study indicated the necessity of incorporating modifiers into OGA mixtures to enhance their durability, stability, and reduce abrasion loss. The blends that demonstrated the most optimal corrosion resistance and stability properties were those modified with 4% SBS polymers and 4% PP polymers. The primary objective of this study is to evaluate the engineering properties of an open asphalt mixture modified by using RPVC polymer and to examine the effect of this additive on the durability and stability of the designed asphalt mixtures. The selection of optimal aggregate gradation and acceptable AC percentage was conducted to formulate a suitable OGA mixture, characterized by desirable permeability, stability, and air void percentage. The performance of the modified OGA mixtures was subsequently evaluated and compared with that of the control OGA mixtures. The OGA mixture was modified with varying proportions of RPVC polymer (2%, 4%, 6%, and 8%) and its performance was evaluated. The performance metrics included Marshall properties, binder drain-down, Cantabro mass loss, strength, moisture sensitivity, and permeability.

II. MATERIALS

A. Asphalt

The asphalt binder that was selected for this study was a penetration grade (40–50) obtained from the Dourah refinery. This asphalt binder is a prevalent component in road construction in Iraq. The physical attributes of the asphalt binder used are presented in Table I.

TABLE I. PHYSICAL ATTRIBUTES OF THE ASPHALT BINDER USED

Test	Result	Specification	
		Min.	Max.
Penetration (25 °C, 100 gm, 5 s) ASTMD5	44	40	50
Ring and ball softening point (°C) ASTM D36	52	50	60
Ductility (25 °C), ASTM D 113 (cm)	117	100	
Specific gravity	1.02	1.01	1.06
Rotational Viscosity at 135 ˚C (Pas.S) Rotational Viscosity at 165 ˚C (Pas.S) Rotational Viscosity at 185 ˚C (Pas.S)	0.437 0.132 0.08		
Flash point ˚C	253	> 232	
Fire point ˚C	274		

B. Aggregate

Mineral aggregate, comprising both fine and coarse crushed materials, was obtained from the Al-Nabai quarry in Taji, Baghdad. The coarse aggregate contains durable, strong, and hard particles, and the physical properties of the used mineral aggregate are outlined in Table II. The filler is composed of common Portland cement.

TABLE II. PHYSICAL PROPERTIES OF AL-NIBAEE AGGREGATES

Property	Specification	Coarse Aggregate	Fine Aggregate
Percent Wear (Los-Angeles Abrasion)	(ASTM C131-14)	21.72	
Bulk Specific Gravity	(ASTM C127-128-15)	2.651	2.53
Apparent Specific Gravity	(ASTM C127-128-15)	2.667	2.568
Percent Water Absorption	(ASTM C127-128-15)	0.37	0.36
Pieces fractured %	(ASTM D5821-18)	98	
Flatness and elongation %	(ASTM D4791-10)	1.1	

C. Recycled Polyvinyl Chloride (RPVC)

Polyvinyl Chloride (PVC) is a thermoplastic that has seen extensive use in the construction industry due to its relatively lower cost, high durability, and high workability. The PVC material is typically collected from wastewater drainage pipes in demolished houses [23]. The discarded PVC is then subjected to a shredding process, whereby it is fragmented into minute particles. The characteristics of the used RPVC are presented in Table III.

TABLE III. PHYSICAL PROPERTIES OF WASTE PVC

Properties	Results
Density	1.3-1.6 (g/cm^3)
Tensile strength	40-50 (MPa)
Flexural modulus	2.1-3.4 (GPa)
Thermal coefficient expansion	80×10^{-6}

D. Natural Fiber

In the context of OGA, the employment of fiber stabilizers is a common practice, with the objective of minimizing the probability of asphalt mastic drain-down. The cellulose fibers used in this study were derived from palm fronds sourced in the immediate vicinity. The fibers were sliced utilizing a cutter with a range of 5–10 mm [24]. Table IV presents the physical properties of the cellulose fibers used in this study. According to NAPA [25], 0.3% of the total mass of the mixture was allocated to the natural fiber stabilizing portion.

TABLE IV. THE PHYSICAL CHARACTERISTICS OF DATE PALM FIBERS

Property	Value
Average length (mm)	(5-10)
Bulk density (gm/cm^3)	0.5
Breaking Elongation %	2.25
Thickness (mm)	0.1
Tensile strength (MPa)	758
Moisture content (%)	2.97
Max tensile force (N)	8.1

III. METHOD AND EXPERIMENTS

A. Preparation of Modified Asphalt Binder

The modified asphalt binder was manufactured using varying addition ratios of RPVC (2%, 4%, 6%, and 8%) by weight of the base asphalt [26, 27]. The base asphalt employed in this study was classified as grade 40-50. The mixture was heated to 170°C to initiate the mixing process. Subsequently, the requisite amount of polymer is incorporated at a rate of 10 g/min, concurrently with the mixing of the mixture at 3,000 rpm for a duration of 1 hour [22, 28].

B. Optimum Aggregate Gradation Selection

The gradation for the mixes was developed using a band from the NCHRP [29], with a maximum nominal particle size of 12.5 mm. Testing for stone-on-stone contact concerning air voids was conducted on three gradations: the upper, mid, and lower gradations within the chosen gradation band, as shown in Figure 1. The stability of the mixture is ensured by stone contact. For the compacted samples, the Voids Coarse Aggregate (VCA_{mix}) are compared to the Voids Coarse Aggregate in a dry-rodded condition sample (VCA_{drc}), as specified in AASHTO T19 [30]. This comparison ensures that the criteria are met. The presence of stone-on-stone contact is contingent upon a VCAmix/VCAdrc ratio below 1 [31]. The three gradation levels were evaluated in accordance with this criterion. The asphalt cement percentage in the trial mixes was 6.0% by weight.

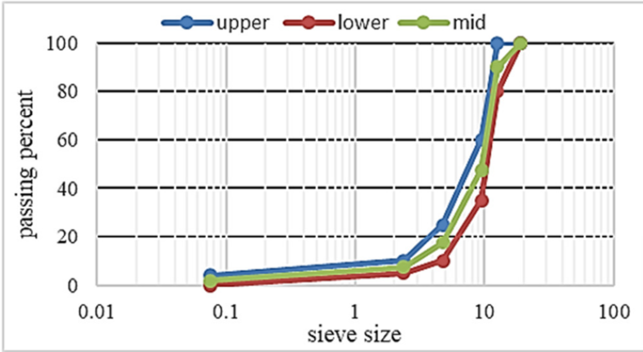

Fig. 1. The gradation of aggregate for the open graded asphalt mix used.

C. OGA Mixture Preparation

Subsequent to the definition of the design gradation, the prepared specimens with varying asphalt contents are used to ascertain the optimal asphalt content for the control and RPVC-modified asphalt mixtures. Four asphalt contents were assessed: 5.5%, 6%, 6.5%, and 7%. To this end, Marshall's procedure was adopted to design the OGA mixtures, with the objective of producing cylindrical samples. Each specimen was subjected to 50 blows on each side using the Marshall hammer to ensure compaction. Subsequently, the method outlined in ASTM D7064 was employed to select the combination with the OBC. The evaluation criteria for the samples included the drain-down, air void content, and Cantabro abrasion testing.

1) Air Void Content

The determination of the air void content (V_a) was conducted in accordance with the standard method outlined in ASTM D7064 [32], as shown in (1). A minimum air void value of 18% is considered typical [25, 29]:

$$V_a = \left(1 - \frac{G_{mb}}{G_{mm}}\right) \times 100 \qquad (1)$$

where G_{mb} is the bulk specific gravity of the mix, and G_{mm} is the theoretical maximum specific gravity.

2) Drain-Down

The drain-down test is a method of assessing the potential separation of the asphalt binder from the aggregates during the mixing, transportation, placement, and compaction processes [33]. The method described in AASHTO T 305 [34] was meticulously followed throughout the duration of the test. The test was conducted using loose samples at production temperature. The acceptable limit of the drain-down has been established as less than 0.30% [35, 36]. The amount of the mastic drain-down was calculated using:

$$DD\% = 100 \times \left(\frac{D-C}{B-A}\right) \quad (2)$$

where *DD* is the drain-down rate (%), *C* is the weight of the empty pan in g, *D* is the weight of the pan and sample after being removed from the oven in g, *A* is the weight of the empty basket in g and *B* is the weight of the basket and sample in g.

3) Cantabro Loss Test

In accordance with the approach employed by numerous other investigations, the Cantabro loss was used to assess the mixture's disintegration resistance [3, 8]. In compliance with the guidelines established by the ASTM C131 specification [37], a standard Marshall sample was prepared and subsequently exposed to a rotational velocity of 33 revolutions per minute for a total of 300 revolutions within a Los Angeles abrasion tester. The Cantabro loss of the mixture was then determined by calculating the difference in weight before and after the test:

$$CL\% = 100 \times \left(\frac{M_0 - M_1}{M_0}\right) \quad (3)$$

where *CL* is the Cantabro loss value, M_0 is the mass of the sample before the Cantabro test, and M_1 is the mass of the sample after the Cantabro test.

D. Permeability

One of the most critical characteristics of the OGA mixes is their permeability, which demonstrates the extent to which the mixture facilitates the drainage of water from the system. In accordance with the protocol specified in ASTM D5084 [38], the permeability of the OGA mixture was evaluated through the implementation of the falling head technique. The apparatus used for the falling head permeability test was fabricated on a local scale, as depicted in Figure 2. For each mix type, cylindrical OGA specimens measuring an average of 63 mm in height and 100 mm in diameter were subjected to the permeability test, with the binder content having been adjusted to its optimal level for that particular mix type. The permeability coefficient was then calculated using (4) and according to [32], the OGA mixture's initial permeability should not be lower than 100 m/day.

$$K = \left(\frac{aL}{At}\right) ln\left(\frac{h_1}{h_2}\right) \quad (4)$$

where *K* is the permeability coefficient in mm/sec, *L* is the height of the sample in mm, h_1 is the initial head in mm, h_2 is the final head in mm, *a* is the inside cross-sectional area of the standpipe in mm^2, *t* is the elapsed time between h_1 and h_2 in sec, and *A* is the sample's cross-sectional in mm^2.

E. Moisture Damage Using Tensile Strength Ratio (TSR)

The moisture resistance of the asphalt mix was evaluated using the TSR test according to the AASHTO T283 [39]. For each type of mix, a total of six standard specimens were prepared for the TSR test: three dry specimens for the control group and three wet specimens for the conditioned group. The TSR value is calculated by dividing the average ITS of the specimens in the conditioned group by the average strength of the specimens in the unconditioned group. A higher *TSR* value for the asphalt mix indicated that it was more resistant to moisture. The ITS was determined using (5) and the TSR was determined using (6). Combinations with values below 80% may be more susceptible to moisture damage and need to be adjusted for optimum performance:

$$ITS = \frac{2000 \times P}{\pi \times t \times D} \quad (5)$$

$$TSR\% = 100 \times \left(\frac{S_w}{S_d}\right) \quad (6)$$

where *P* is the ultimate applied force in N, *D* is the sample's diameter in mm, *t* is the sample's thickness in mm, and the *ITS* is the indirect tensile strength of the sample in kPa. The mean *ITS* (in kPa) for the unconditioned specimen group is represented by S_d, whereas for the conditioned specimen group, it is represented by S_w.

Fig. 2. Laboratory device used for permeability measurement.

IV. RESULTS AND DISCUSSION

A. Aggregate Gradation Selection

Table V presents the outcomes for each of the three categories. It is evident that both the upper-grade and intermediate-grade combinations attain the stone-to-stone contact condition. However, the intermediate grade mixture was selected for the mixture design trials due to its ability to meet the minimum air void content requirement of 18%, which is a prerequisite for an OGA mixture to function effectively in water drainage applications.

B. Optimum Asphalt Content Selection

The outcomes of the OGAM mechanical properties assessment for the asphalt specimens are presented in Figure 3, contingent upon the test method ASTM D 7064 [32]. Using these data as a reference point, it is recommended to select a binder content that possesses an air void content of more than 18%, a loss in the Cantabro test that is less than 20%, and a drain-down that is less than 0.3%. The determination of the binder content can be facilitated by the graphical representations provided in Figure 3. These graphs allow for the determination of the binder content by intersecting the limit values for the three criteria with the corresponding asphalt content. The mean value was then employed as the OBC. The OBC of various OGA specimens based on the experiments conducted is displayed in Table VI. Subsequent evaluations of asphalt mixes at OBC will involve additional tests, including ITS, TSR, and permeability analysis. Referring to Figure 3, the Cantabro loss and drained-down asphalt for the modified OGA mixtures were lower compared to the control OGA mixture, which means an increase in the durability of the mixture.

TABLE V. STONE-ON-STONE CONTACT VERIFICATION

Criteria	Gradation		
	Upper limit	Mid limit	Lower limit
G_{mb}	2.01	1.96	1.93
Pca%	90	82.5	75
G_{ca}	2.647	2.647	2.647
VCA_{mix}	31.66	38.91	45.32
VCA_{drc}	43.85	41.91	42.65
G_{mm}	2.39	2.40	2.35
AV%	15.90	18.33	17.87

C. Marshall Stability

As presented in Figure 4, the Marshall stability results demonstrate that the incorporation of the RPVC polymer additive significantly enhances the Marshall stability in comparison to the unmodified OGA mixture. At a percentage of 6%, the addition of RPVC results in an increase of the Marshall stability value to 38%, in contrast to the control mix. It is noteworthy that any further augmentation in the RPVC content will result in a reduction of the stability value. This enhancement in Marshall stability values can be ascribed to the enhancement in the asphalt binder viscosity and stiffness, which in turn leads to an improved resistance to permanent deformation and stability of the asphalt mixture as a whole [16].

D. Durability Test Using Cantabro Abrasion Loss

As illustrated in Figure 5, the incorporation of RPVC into the OGA mixture resulted in a reduction in Cantabro loss. This loss exhibited a progressive decrease as the concentration of RPVC in the asphalt binder increased. It was found that, up to a certain extent, the addition of more RPVC led to a reduction in the rate of deterioration. However, beyond a certain threshold, a slight loss became evident. The Cantabro loss of a/the mixture was reduced to approximately 17% when the RPVC concentration was at 6%, indicating that the mixture exhibited relatively adequate anti-raveling performance [16, 26].

E. Permeability Test

As displayed in Figure 6, the results of the permeability tests conducted on all of the OGA mixture samples indicate that the OGA mix's capacity for water infiltration was enhanced when the asphalt binder was modified with a polymer of RPVC. The findings reveal that the modified OGA mix exhibited enhanced permeability when the dosage of the RPVC polymer within the asphalt binder was augmented.

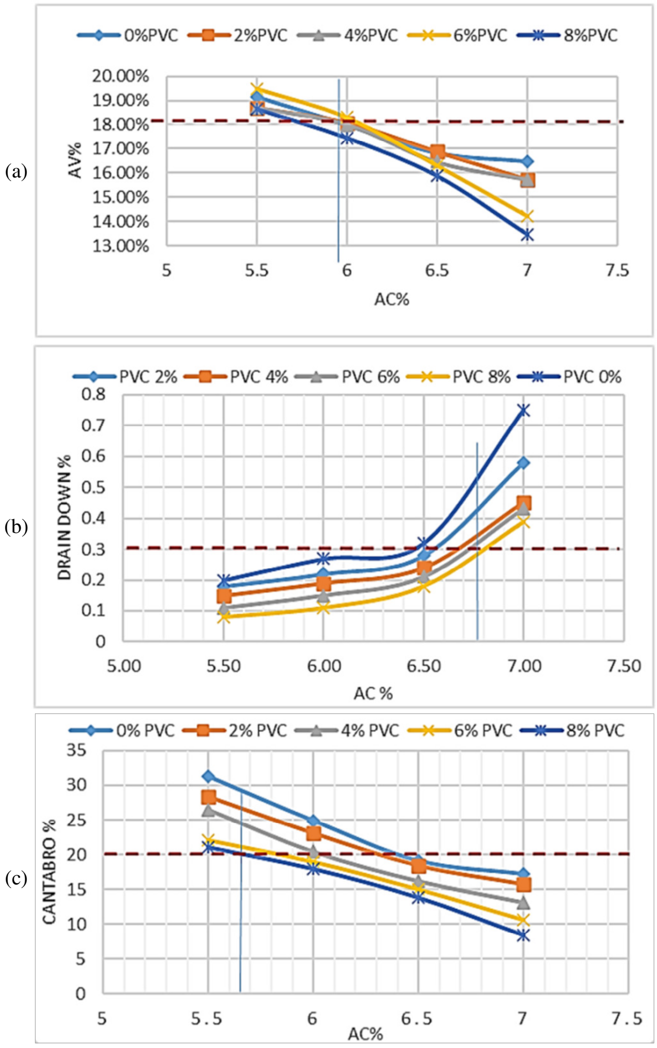

Fig. 3. Properties of OGA mixes to determine OBC: (a) AV%, (b) DD%, (c) Cantabro%.

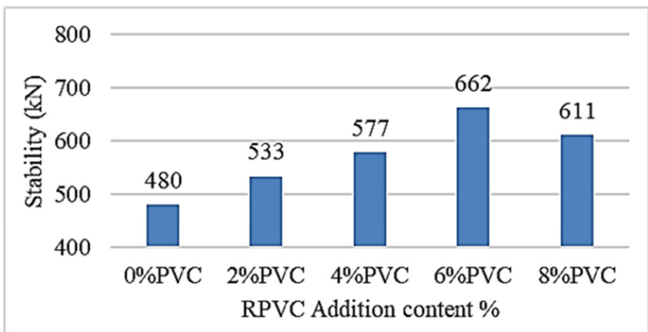

Fig. 4. Marshal stability of RPVC modified OGA mixtures.

The permeability coefficient exhibited an enhancement of 53% at an addition rate of 8%, in comparison to the control mix. It is noteworthy that all specimens exhibited an initial permeability greater than 100 m/day, which aligns with the recommended standard of ASTM D7064 [32]. This behavior is attributed to the effect of the RPVC polymer on increasing the viscosity of the asphalt binder, which increased its bonding with the aggregate particles and reduced the leakage of the binder to collect within the sample. This process created more connected open pores that allow larger amounts of water to flow through the open asphalt mixture structure [16, 40].

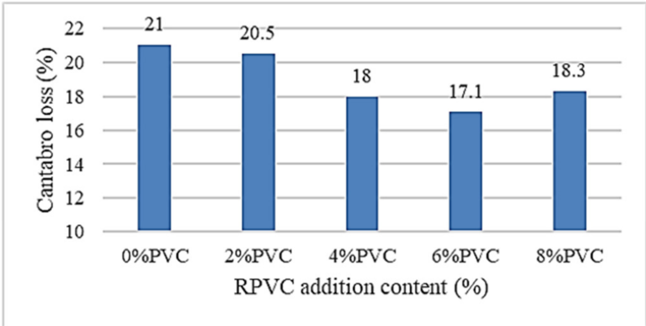

Fig. 5. Cantabro loss of the RPVC-modified OGA mixes at OBC.

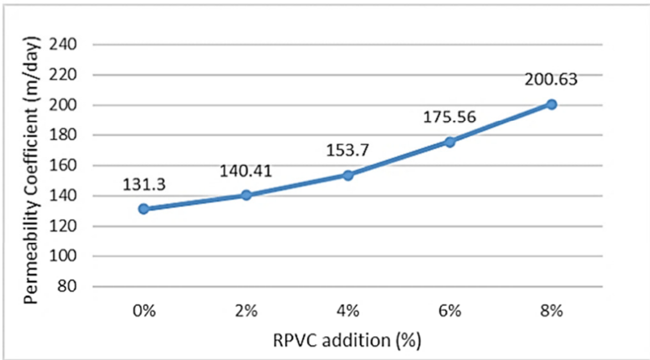

Fig. 6. Permeability of RPVC-modified OGA mixes at OBC.

F. Moisture Damage by TSR

The test generates two metrics: the TSR and the ITS. The findings from the ITS test for the OGA mixes are presented in Figure 7. The tensile strength of the unconditioned and conditioned OGA mixture was found to be indirectly enhanced by the incorporation of the RPVC polymer, with this effect being proportional to the increase in RPVC concentration. This phenomenon could be attributed to the enhanced elasticity and durability of the asphalt mix, which was achieved through the incorporation of viscosity from the RPVC-modified binder. Consequently, the mixture's deformation resistance was increased, and its total strength was improved. While all mixes met the mix design criterion of exceeding 80%, the moisture susceptibility data revealed that the mix using RPVC polymer exhibited higher moisture resistance performance. The TSR value for the base asphalt satisfied the criteria to a minor extent. As the concentration of the RPVC polymer in the OGA mixture increased, the TSR values exhibited a progressive rise, indicating an enhancement in the mixture's moisture susceptibility. Notably, the TSR value for the mixture containing 6% RPVC-modified asphalt reached its maximum at 83.75%, which was a notable increase compared to the control mix (4.2%) [16, 41].

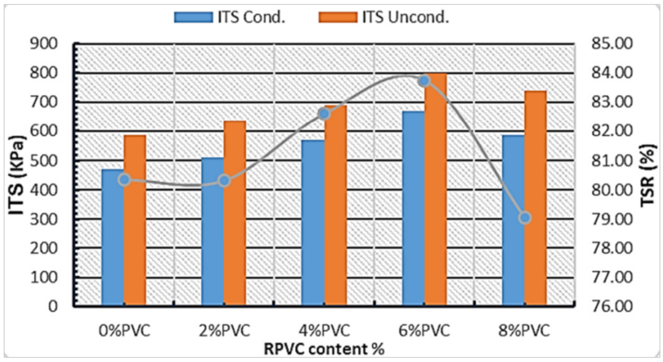

Fig. 7. Results of ITS ratio test.

V. CONCLUSIONS

The objective of this study was to examine the modification of an Open-Graded Asphalt (OGA) mix with Recycled Polyvinyl Chloride (RPVC) at varying contents. The research focused on the mechanical and functional characteristics of OGA mixes. The ensuing conclusions, derived from a thorough examination of the experimental results and their analysis revealed that:

- The incorporation of the RPVC polymer has been shown to enhance the rigidity of the OGA mixture, as evidenced by an augmentation in Marshall stability and Indirect Tensile Strength (ITS). The highest observed rigidity was recorded at a 6% addition content, exhibiting an increase in ITS of 43% compared to the control mix. This observation naturally suggests the positive impact of this additive in enhancing the tolerance to traffic loads at both normal and high service temperatures.
- In the corrosion test, employing the Cantabro method, optimal outcomes were attained for the mixtures with a polymer addition ratio of 6%, exhibiting an enhancement in corrosion loss of approximately 17%. This outcome led to an augmentation in the durability of the open asphalt mixtures.
- Regarding the impact of augmenting the RPVC additive ratio, there is a general enhancement in mechanical properties up to a certain percentage of the additive (6%) after which point the specifications begin to deteriorate. This observation may be indicative of the fact that the high addition ratio may compromise the internal structure of the binder, thereby weakening the strength of the asphalt mixture as a whole. Consequently, it is advised to restrict the incorporation of the RPVC polymer content to a maximum of 6% in the fabrication of OGA mixtures.
- The incorporation of the RPVC polymer led to a substantial alteration in the functional properties of OGA mixtures, resulting in a notable enhancement in the permeability of OGA mixtures with an increasing RPVC addition [42], accompanied by higher air voids and porosity. It is

noteworthy that the permeability value was found to be satisfactory across all the series of samples. The permeability exhibited an incremental rise of 53% with the incorporation of 8% of RPVC. This outcome suggests that the incorporation of RPVC has led to the formation of a greater number of interconnected open pores, which in turn facilitates an enhanced water flow through the open asphalt mixture structure.

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