Appraisal of Asphalt Mixtures' Cracking Resistance Modified with Waste Aluminum Scrap Powder (WASP) at Intermediate Temperatures

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Abstract. Considering that most asphalt concrete pavement distresses are fracture-related, evaluating and quantifying mix fracture properties is essential to improved pavement design. Therefore, the first step of the study, a pre-development phase, determines the optimal value for adding waste aluminum scrap powder (WASP) with a fraction size of 2.36-0.075 mm to mixes. Based on previous digital image analysis (DIA), AlDoz and AlNibaa'e aggregates were selected from seven central, northern, and southern Iraq sources. The second post-development phase studies the testing factors of a reliable and practical semi-circular bending (SCB) test for assessing asphalt concrete mixture fracture properties at intermediate service temperatures. The development and calibration of the Marshall System into the SCB-Tester, which switched from analog to digital and computerized control, accurately predicted reference and modified mix fracture characteristics at 50.8 mm/min. Three notch lengths (25, 32, and 38) mm were selected to be studied. Five percentages of WASP (0.5, 1.0, 1.5, 2.0, and 2.5) percent were added by weight to the entire mix and compared to the reference mixture. Results indicate that 1.5% WASP decreases fracture severity and stiffen AlNibaa'e and AlDoz mixes. Increased fracture strength and toughness of modified mixes relative to the reference may dramatically increase asphalt concrete fracture resistance. Even though a higher evaluation for AlNibaa'e mixes than AlDoz with an expected difference, the impact of modifying appears to be an effective influence for AlDoz mixes with determination factors (R^2) of 0.9788 and 0.9889 than that of AlNibaa'e modified coarse and fine mixes, which have R2 of 0.8535 and 0.8461, respectively.

Keywords: SCB-tester; fracture toughness; Marshall stiffness; WASP; roller compaction.

1. INTRODUCTION

Cracking is one of the most effective forms of deterioration to asphalt pavements that reduce their durability. Surface-level pavement failure often begins with microscopic fractures in the asphalt pavement. Fracture behavior in asphalt concrete is determined by its internal composition and mesostructured since it is a composite heterogeneous material formed of asphalt mastic and mineral aggregate [1,2]. For the objective of developing sustainable and long-lasting pavements, it is vital to have a friendly and reliable correlation between the internal structure of asphalt concrete and its fracture behavior [3]. Several macro-scale practical tests have been carried out to satisfactorily comprehend the fracture behavior of asphalt concrete. The three-point bending test is widely used to determine whether or not a fracture has occurred. The semi-circular bending (SCB) test is well-known as a straightforward but reliable method of quantifying asphalt concrete fracture resistance [4, 5]. Many more SCB tests at moderate temperatures have examined asphalt concrete's cracking behavior. These approaches were used to analyze asphalt mixture fracture behavior and develop asphalt concrete mixes for cracking-related loads, aggregate gradation, and modifier addition or improvement. [6-9]. Authors have performed SCB fracture tests at temperatures ranging from -30°C to 30°C and displacement speeds varying from 5 mm/min to 100 mm/min. The study hypothesized that a more significant disparity between mixes would result from a higher peak value of fracture toughness, so they suggested conducting the SCB fracture test at an intermediate temperature (25°C) and a rapid displacement rate (50 mm/min), which yielded the highest overall fracture toughness values. Assuming the room temperature could be kept at 25°C, this temperature was also chosen to avoid requiring a separate environmental conditioning chamber [10].

Theoretically, the examination of the relationship between Elastic-Plastic Fracture Mechanics (EPFM) and Linear Elastic Fracture Mechanics (LEFM) should be a part of the performance testing of asphalt mixtures using the SCB technique [11]. To investigate the composition of alternative and control fillers, milled filler fractions ($d < 0.063$ mm) were employed for microstructural analyses. Performance-based and performance-related asphalt mechanical tests using conventional criteria explored how replacing limestone filler with aluminum dross filler affected asphalt mix performance [12]. In another study, laboratory tests of modified asphalt concrete with aluminum and polymer waste composite affect pavement mixtures. Waste powder largely replaced fine aggregate fraction in the dry process [13]. Another study indicated that recycled concrete aggregate could replace coarse aggregate, and aluminum filings can partly replace fine aggregate in hot asphalt mixes. Marshall Properties' hot asphalt mixes using recycled concrete aggregate (RCA) and aluminum filings (AF) waste performed comparably to regular hot asphalt [14].

This study assessed the fracture characteristics of reference and modified mixtures compacted using a roller to determine the effects and optimal quantities of WASP (fraction size 2.36 - 0.075 mm) corporation.

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Coarse and fine mixes for AlNibaa'e and AlDoz sources via SCB geometry were tested after a series of development.

This study focused on analyzing the SCB test and then using the data to assess the resistance to cracking failure of various asphalt mixes. To achieve this goal, a selection of coarse (CM) and fine (FM) asphalt mixes was evaluated, including compositions modified with an optimum amount of waste aluminum scrap powder (CM-WASP and FM-WASP, respectively). This study compares crack propagation approaches modified mixtures to the reference to identify the effects and ideal quantities of WASP addition and evaluate the maximum stress at failure, strain at maximum force, and fracture toughness after pre and post developments.

2. MATERIALS AND EXPERIMENTAL METHODOLOGY

2.1 Coarse and Fine Aggregate (CA and FA)

AlDoz and AlNibaa'e crushed coarse and fine aggregates (CA and FA, respectively) were chosen, and evaluated the selection method via the analysis of digital images (DIA). Table 1 shows the measured physical characteristics. It was taken per the guidelines established by the ASTM and the State Corporation of Roads and Bridges [15].

Table 1: CA and FA's physical characteristics.

Coarse Aggregate				
Character	**AlDoz**	**AlNibaa'e**	**Limits [15]**	**ASTM Specification and References**
Bulk Specific Gravity	2.624	2.584	≥ 2.5	C127 [16]
Apparent Specific Gravity	2.639	2.608	≥ 2.6	C127 [16]
Water Absorption, %	0. 51	0.57	≤ 2 %	C127 [16]
Los Angeles Abrasion, %	12.16	13.08	≤ 28 %	C131 [17]
Fine Aggregate				
Bulk Specific Gravity	2.635	2.604	≥ 2.4	C128 [18]
Apparent Specific Gravity	2.645	2.664	≥ 2.5	C128 [18]
Water Absorption, %	2.667	1.419	≤ 3 %	C128 [18]

2.2 Neat Asphalt Cement (AC)

The AlDaurah refinery produced AC with a penetration grade of 40-50, which was then used as a binder in the various mixtures. After a series of tests, it was determined to comply with the requirements outlined by the State Corporation of Roads and Bridges, SCRB (2003/R9). The properties of AC's physical characteristics are summarized in Table 2.

Table 2: Physical characteristics of neat AC.

The character with Test Condition	**Results**	**SCRB Limits**	**ASTM Specification and References**
Penetration/25°C, 100 gm, 5 sec, 0.1 mm	45	40-50	D5 [19]
Softening Point/5°C/min	49	-	D36 [20]
Ductility, cm/25°C, 5 cm/min	+ 150	≥ 100	D113 [21]
Specific Gravity/25 °C	1.04	-	D70 [22]
Flash Point	290	≥ 232	D92 [23]
Rotational Viscometer, Pa.sec/135°C	0.6	≤ 3	D4402 [24]
Rotational Viscometer, Pa.sec/165°C	0.144	-	D4402 [24]
After Thin Film Oven Test (TFOT), Characteristics			
Retained Penetration of Residue, %/25°C, 100 gm, 5 sec, 0.1 mm	60	≥ 55	D5 [19]
Ductility of Residue, cm/25°C, 5 cm/min	85	≥ 25	D113 [21]
Loss on Weight/163°C, 50 gm, 5 hrs.	0.3	-	-

2.3 Filler

The Karbala cement factory, a French cement producer Lafarge subsidiary, provided Cement Kiln Dust (CKD) as filler for the project. In the Karbala plant, they experimented with using the dry process. The source was responsible for producing physical data that can be identified in Table 3.

Table 3: CKD's physical characteristics.

Character	**Results**	**Limits [16]**	**ASTM Specification and References**
Bulk Specific Gravity	3.14	≥ 2.6	D854 [25]
Passing Sieve No.200, %,	96	≥ 90	C117 [26]

2.4 Additive

The scrap is separated into two categories, virgin scrap from the aluminum industry and used scrap from final products (old scrap). Depending on its source and collecting methods, old scrap is typically polluted to varying degrees after a few consumers cycle times. For this study, WASP gathered samples from Baghdad's scrap metal and processed them via the aluminum industry's filing and sizing processes. A Waste Aluminium Scrap Powder (WASP) (fraction size 2.36 - 0.075 mm) was utilized as an additive to modify the resistance behavior of asphalt mixes. Table 4 lists the physical features.

Table 4: WASP additive physical characteristics.

Character	Results
Bulk Specific Gravity	2.68
Melting Point Temperature, °C	658

2.5 Pre-Development Phase

During the pre-development phase, the optimal asphalt content for AlNebaa'e and Aldoz aggregate sources is 4.8% ± 3. Thus, two mixes were compacted, one with a fine gradation and the other with a coarse gradation, with 5.1 and 4.5% by weight of aggregate, respectively. The trial specimens were manufactured per ASTM D1559 [27] with a typical air void of 7% ± 0.5%. After placing 1150 kg of aggregates and filler in the pan, the temperature was raised to 160 ºC. Before mixing, the asphalt was brought to a temperature of 150 ºC and then poured into a pan placed on a hot plate. Mixing and heating were produced using a dry process to apply WASP as an additive. WASP would be added to the mixture at a rate of 0.5, 1.0, 1.5, 2.0, and 2.5%. After a rapid mixing process that ensured that all of the mixes were coated with asphalt cement and reached a viscosity of 170 to 20 cSt, it was finally ready to be compacted. 8 Marshall references and 20 modified samples have been prepared. Reference fine mixes from AlNibaa'e and AlDoz aggregate sources are N-FM and D-FM, whereas coarse mixes from the same sources are N-CM and D-CM. Modified samples labeled as N-FM-WASP and D-FM-WASP for fine mixtures and N-CM-WASP and D-CM-WASP for coarse mixes of the two aggregates indicated. In this phase, Marshall stability systems were provided with analog apparatus to measure, display, and record the load and flow of reference and modified asphalt specimens. It is supplied with a set loading speed of (50.8 mm/min).

The Marshall stiffness, used to determine the ideal percentage of addition, was determined by dividing the Marshall stability in (kN) by the Marshall flow in (mm) for each specimen. On the other hand, it is used as a benchmark to reassess the function of certain factors in the microstructure mechanism of fracture. The Pneumatic Roller Compactor is a new pneumatically powered system for compacting asphalt slabs. The appropriate mixture weight was heated to 165°C based on Marshall specimens' desired density and asphalt content for the two types of aggregate sources, then transferred to the roller compaction mold of (300x400x50) mm dimension and compacted. The applied force was 5 kN, and the number of roller cycles was regulated necessary to reach the desired target density and air void of 7 ± 0.5%, attained after several experiments following EN 12697-33, [28]. After 24 hours, the slab samples were removed from the mold. As seen in Figure 1, 8 coarse and fine reference and modified slabs were produced via the combination of AlNibaa'e and AlDoz aggregates with 1.5% WASP. As shown in Figure 1, a mechanical core device was utilized on each slab to obtain two cylindrical samples of 150 mm in diameter and a height of 50 mm.

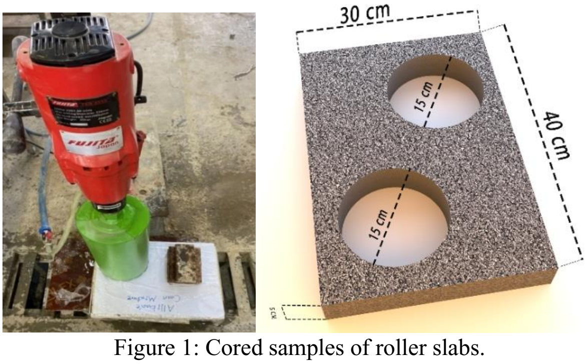

Figure 1: Cored samples of roller slabs.

3.2.2 Post-Development Phase

In the Post-development phase, Marshall Stability-Flow System has been improved in the Transportation Laboratory of the Department of Civil Engineering at Al-Nahrain University from analog to digital elements to use as an SCB Tester. The produced apparatus has comprehensive testing capabilities that permit assessing asphalt mix fracture resistance in long-term pavement performance at intermediate temperatures and calculating strain energy for a given notch depth. The SCB test approach, as illustrated in Figure 2, has been identified as a starting crack propagation option for assessing asphalt mixture fracture characteristics of all reference and modified samples at intermediate temperatures of 25°C in the laboratory. After compacting the asphalt into slabs using a roller compactor per EN 12697-33 [28], two cylindrical samples with dimensions of (150 ± 1) mm diameter by (50 ± 3) mm were cored. Cut each core into two equal semi-circular specimens through the middle using the mechanical saw. Each semi-circular specimen has a straight vertical notch cut along its symmetrical axis and is in the middle of the specimen. The typical notch depths are 25 mm, 32 mm, and 38 mm, respectively. The notch's breadth must be 3.5 mm. A sample with a 10 mm notch has been tested to ensure the validity of the SCB findings. A valid test is performed if the crack terminates in a zone 15 mm (= 10% of the specimen's diameter) from the loading strip's center.

a. Semi-Circular Cored Samples b. Limits of the Sample Notches

c. A straight Vertical Noches d. The Four Tested Fractured Samples per Slab

Figure 2: The Methodology of SCB-Test.

4. RESULTS ASSESSMENT AND DISCUSSION

4.1 Evaluation of the Pre-Development Phase

In this phase, Marshall Samples for AlNibaa'e and AlDoz aggregates were cured for 30 minutes in a water bath at 60 °C before conducting the test. Marshall Stability ($\mathrm{M_{Stability}}$) is the greatest allowed load at the fracture point, and flow ($\mathrm{M_{Flow}}$) is the deformation at the fracture's moment. Marshall Stiffness ($\mathrm{M_{Stiffness}}$) is mainly assessed in Equation (1):

$$\mathrm{M_{Stiffness}} = \frac{\mathrm{M_{Stability}}}{\mathrm{M_{Flow}}} \tag{1}$$

Enhanced Marshall Stiffness indicates enhanced mixture stiffness, implying that the whole mixture is more resistant to persistent deformation. As shown in Figure 3, the Marshall characteristics of reference and modified asphalt concrete reveal that increasing WASP content raised stability to the optimum of 1.5% of the total mix and, after that, dropped. At the same time, the flow correspondingly increased. Furthermore, the results show that. $\mathrm{M_{Stiffness}}$ increased slightly up to 1.5% WASP, then declined sharply. It has been concluded that adding 1.5% WASP to the mix greatly influenced Marshall's properties. Due to that, fracture parameters of the post-development phase were evaluated based on this optimal percentage.

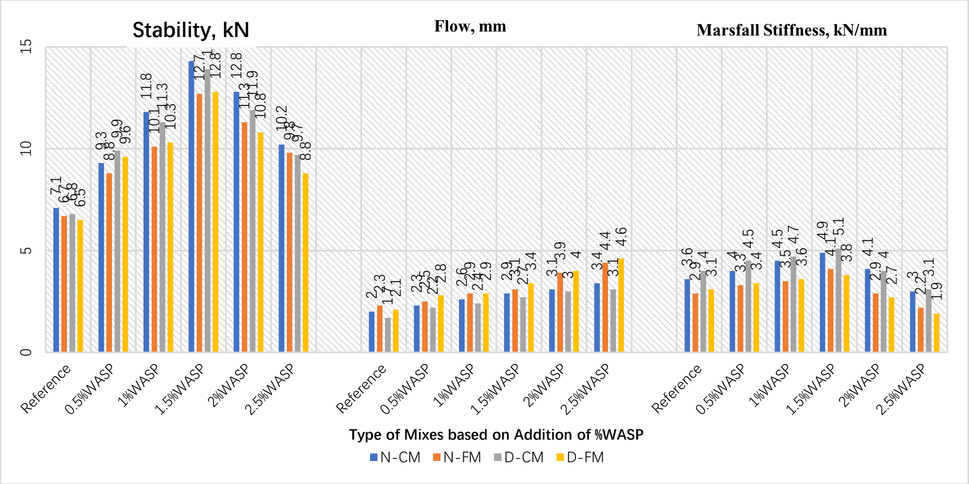

Figure 3: Marshall properties for AlNibaa'e and AlDoz samples.

4.2 Evaluation of the Post-Development Phase

Throughout this stage, at an intermediate temperature of 25 °C, numerical and practical analysis has been conducted on the damaging and fracture performances of SCB specimens with various notch sizes. One sample with a notch depth of 10 mm was used to validate the test, and three samples with notch depths of (25, 32, and 38) mm were used to analyze the results. Coarse and fine aggregate gradations are simulated for AlNibaa'e and AlDoz mixes. According to the results of the pre-development phase study (Marshall Stiffness), the modified mixes were produced by adding an optimum of 1.5% WASP. The effects of aggregate gradation and WASP content have been dryly combined in the experiment results. It can determine how aggregate distribution and notch orientation affect a crack. The crack propagation techniques were simulated after a series of mathematical calculations were completed to determine the maximum stress at failure, the strain at maximum force, and the fracture toughness. Table 5 shows the maximum load, F_{max}, and vertical deformation, ΔW, for the two aggregate source mixtures.

The findings demonstrate that AlNibaa'e coarse and fine mix increased by around 0.5 to 25% from AlDoz mixes for the reference and modified condition across all depths of notches, according to the peak load Fmax and the vertical deformation ΔW. On the other hand, the findings indicate that they considerably impact the modified mixes relative to reference when comparing the mixes from the same source. For all notch depths, the impact of modification is raised to above 100%.

Table 5: F_{max} and ΔW parameters of SCB test.

Notch Depth, mm	25 mm		32 mm		38 mm	
Parameters	$F_{max, N}$	ΔW, mm	$F_{max, N}$	ΔW, mm	$F_{max, N}$	ΔW, mm
Mix Type	AlNibaa'e Aggregate Source					
N-CM	6023	2.51	4392	1.34	2635	0.14
N-FM	5609	2.46	4026	1.29	2120	0.11
N-CM-1.5%WASP	9031	2.36	7085	1.29	5666	0.09
N-FM-1.5%WASP	8987	2.29	6905	1.18	4989	0.04
Mix Type	AlDoz Aggregate Source					
D-CM	5034	2.48	3467	1.31	2103	0.12
D-FM	4691	2.41	3284	1.28	1931	0.09
D-CM-1.5%WASP	8982	2.35	6399	1.27	5233	0.09
D-FM-1.5%WASP	7890	2.23	5934	1.22	4978	0.03

4.3 The Maximum Stress at Failure and Corresponding Strain

Maximum stress ($б_{max}$) at failure load can be determined employing Equation (2), and the percentage of strain (ε_{max}) at failure can be obtained by applying Equation (3) [29]. For linear elastic materials (LEFM) until failure, the stress intensity factor (K) explains the stress distribution nearer to a fracture tip. When the SCB sample is loaded, a notch develops a tensile stress that causes a crack to start at the tip of the notch.

$$\text{б}_{\max} = \frac{4.263\ \mathrm{F}_{\max}}{\mathrm{D\,t}} \tag{2}$$

$$\varepsilon_{\max} = \frac{\Delta \mathrm{w}}{\mathrm{w}} * 100\% \tag{3}$$

Where the $\text{б}_{\max}$ in N/mm², D and t are the diameter and thickness of the sample in mm, and $\varepsilon_{\max}$ are the maximum percentage of corresponding strain in %.

As a consequence, shown in Figures 4 and 5, for AlNibaa'e mixes, the failure $\text{б}_{\max}$ at the notch depth (25, 32, 38) mm is raised by (50, 61, 116) % for the modified N-CM-1.5%WASP compared to N-CM, and (60, 72, 158) % for the modified N-FM-1.5%WASP compared to N-FM. Similarly, $\varepsilon_{\max}$ decreases by (6, 4, 36) % and (7, 9, 64) %, respectively. For AlDoz mixes, the failure $\text{б}_{\max}$ at the notch depth (25, 32, 38) mm is raised by (78, 85, 149) % for the modified D-CM-1.5%WASP compared to D-CM, and (68, 81, 158) % for the modified D-FM-1.5%WASP compared to D-FM. Similarly, $\varepsilon_{\max}$ decreases by (5, 3, 25) % and (7, 5, 67) %, respectively. The bar charts show that WASP significantly affects the stress of fracture propagation of mixes, and when 1.5% WASP is applied, all mixtures have virtually substantial crack propagation resistances.

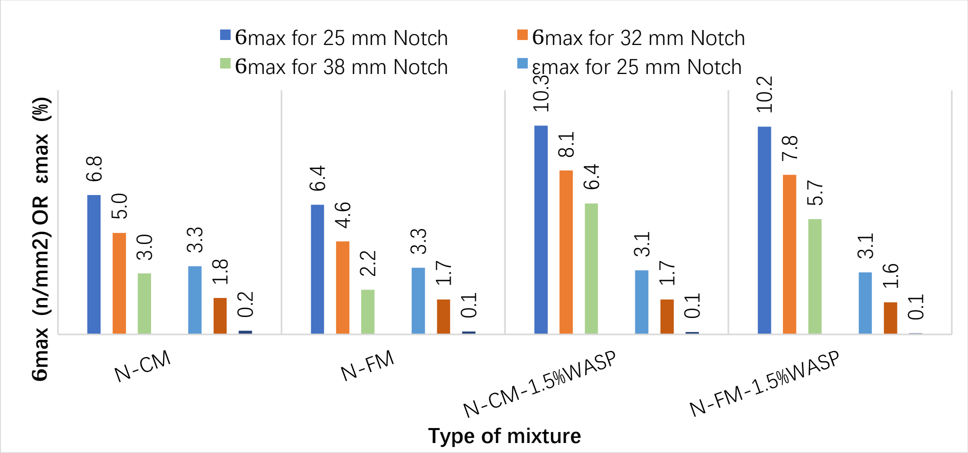

Figure 4: $\text{б}_{\max}$ and $\varepsilon_{\max}$ for AlNibaa'e Reference and Modified Samples.

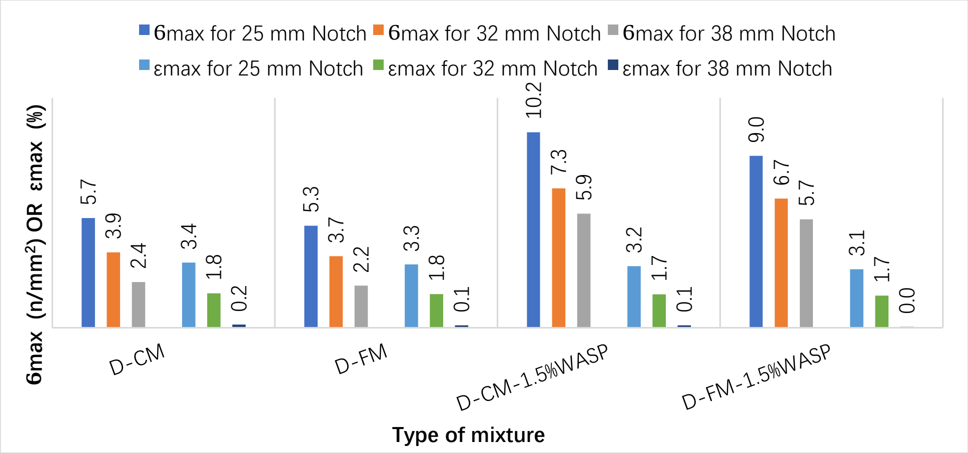

Figure 5: $\text{б}_{\max}$ and $\varepsilon_{\max}$ for AlDoz Reference and Modified Samples.

4.4 The Fracture Toughness (K_{Ic}) Until failure

The resistance of a material to fracture can be quantified by measuring its critical value for the stress intensity factor, also known as fracture toughness (K_{Ic}). The fracture toughness has been widely used in linear elastic fracture mechanics (LEFM) studies. It depends on the tension being applied and the specimen's Geometric factor (GF). Its value grows as stress increases, reaching a maximum just before failure. According to Equation (4), K values can be determined, while GF stands based on Equation (5) [29].

$$K_{Ic} = б_{max} * GF \tag{4}$$

$$GF = -4.9965 + 155.58\left(\frac{a}{w}\right) - 799.94\left(\frac{a}{w}\right)^2 + 2141.9\left(\frac{a}{w}\right)^3 - 2709.1\left(\frac{a}{w}\right)^4 + 1398.6\left(\frac{a}{w}\right)^5 \tag{5}$$

Where K_{Ic} in N/mm$^{2/3}$, a and w is the notch depth and width of the sample in mm.

The results of the fracture toughness (K_{Ic}) tests need to have a reasonable correlation with the results of the stiffness tests to ensure that the tensile strength obtained from the SCB test can be used to investigate the influence of asphalt-aggregate interaction on the mechanical behavior of bituminous mixtures. This step is necessary to ensure that the tensile strength is adequate. These results from the significance of Marshall Stiffness identified previously to modify the specimens with 15% WASP. The fracture toughness (K_{Ic}) values measured on the SCB specimen versus the notch depth match well with the values of determination factors 'R^2', as shown in Figures 6 and 7 by a fitting curve. Modified WASP mixes exhibit significant toughness values compared to reference mixes for the two aggregate sources. Although a higher assessment for AlNibaa'e mixes than AlDoz with an expected difference, the effect of modifying is very well and seems to be a valuable influence for AlDoz mixes with R^2 of 0.9788 and 0.9889 than that of AlNibaa'e modified coarse and fine mixes, which have R^2 of 0.8535 and 0.8461, respectively. The aggregate gradation (coarse or fine mixes) has a significant role in addition to the WASP physical, chemical, and morphological characteristics and contents effect. The fracture toughness of coarse mixtures is often greater than fine mixes. As a result, the proportion of coarse aggregates increases, with coarse WASP corresponding to greater stiffness in the resulting mixture. Fine mixes are less resistant to cracking than coarse mixes since they have a composition with greater asphalt binder content.

Further clarification will be included in the analysis. According to the findings, a 1.5% WASP presence in a mixture increased the load-bearing ability of the specimen at an intermediate temperature. This is because of the rough texture and angular form of WASP, which improved interlock and resistance.

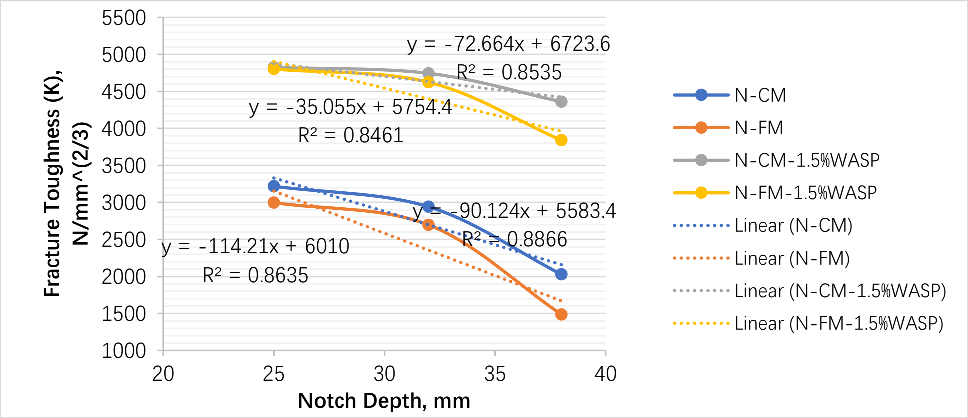

Figure 6: Notch Depth versus K_{Ic} Plot Used For AlNibaa'e Reference and Modified Mixes.

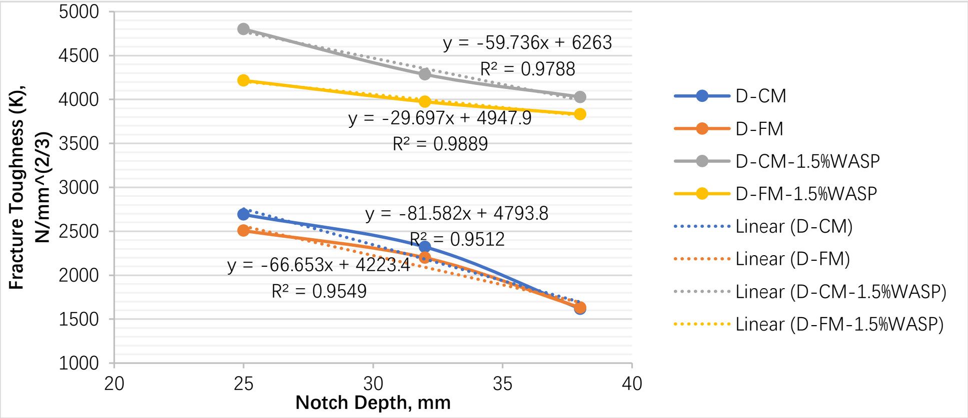

Figure 7: Notch Depth versus K_{Ic} Plot Used for AlDoz Reference and Modified Mixes.

5. CONCLUSIONS

On the basis of the findings, the following conclusions could be drawn:

- With an average rate of 50.8 mm/min at intermediate temperatures (25 °C), the development and calibration of the Marshall System into the SCB-Tester, resulting in the transition from analog operation to digital and computerized control, produces accurate predictions on the characteristics of fractures of reference and modified mixes, when compared to previous studies.
- The study investigated the viability of using WASP as an additive in asphalt mixtures and its fracture characteristics at an intermediate temperature. It found that the addition of 1.5% WASP (fraction size 2.36 - 0.075 mm) increases stiffness for AlNibaa'e and AlDoz aggregate sources and reduces fracture severity. In addition, powder's physical, chemical, and morphological characteristics affect asphalt mixtures, particularly coarse types.
- The fracture resistance of asphalt concrete may be greatly improved by significantly increasing the fracture strength and fracture toughness of the modified mixes compared to the reference. The higher the fracture strength, the larger the peak load produced. However, the higher the fracture toughness, the slower the damage process will be since the crack will need more force to propagate.
- According to peak load F_{max} and vertical deformation Δw, AlNibaa'e coarse and fine mix increased by 0.5 to 25% from AlDoz mixes for the reference and modified condition throughout all notches. However, comparing mixes from the same source significantly affects improved mixes. The modification affects all notch depths over 100%. In addition, it shows that the $б_{\max}$ and fracture toughness K_{Ic} values obtained on the SCB specimen versus the notch depth match the values of determination factors "R^2" with decreasing$\varepsilon_{\max}$. Modified mixes have higher $б_{\max}$ and K_{Ic} than reference mixes for the two aggregate sources. Although a higher assessment for AlNibaa'e mixes than AlDoz with an expected difference, the effect of modifying is very well and seems to be a valuable influence for AlDoz mixes with R^2 of 0.9788 and 0.9889 than that of AlNibaa'e modified coarse and fine mixes, which have R^2 of 0.8535 and 0.8461, respectively.

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