Contributory Factors related to the Tensile Strength of Hot Mix Asphalt Concrete

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ABSTRACT

Tensile strength is a critical property of Hot Mix Asphalt (HMA) pavements and is closely related to distresses such as fatigue cracking. This study aims to evaluate methods for assessing fatigue cracking in Asphalt Concrete (AC) mixes. In order to achieve optimum density at different binder contents, the mixes were compressed using a gyratory compactor. Tensile strength was assessed using the Indirect Tensile (IDT) and Semi-Circular Bend (SCB) tests. The results showed that the tensile strength measured by the SCB test was consistently higher than that measured by the IDT test at 25 °C. In addition, the SCB test showed a stronger correlation between increasing binder content and tensile strength. For binder contents ranging from 4.2% to 5.2%, the IDT test results increased from 541% to 678.7%, while the SCB test results increased from 630.3% to 743.7%. These results suggest that the SCB test provides a more accurate representation of the tensile strength of AC mixes than the IDT test.

Keywords-Marshall mix design; Indirect Tensile (IDT) test; strength test; Semi-Circular Bending (SCB) test; Hot-Mix Asphalt (HMA)

I. INTRODUCTION

Bituminous mixes used in road construction are subject to cyclic loading, as a result of the continuous movement of vehicles. If the loads are sufficiently high, they can cause loss of the material's stiffness, resulting in cracking due to stresses accumulated over a longer period of time. Several studies have been carried out on this subject [1-5]. In general, the superstructure has the following three different functions:

- It prevents soil deformation by reducing the stresses transmitted to the soil to a level commensurate with its bearing capacity.
- It forms a durable and rigid framework, resistant to deformation and able to withstand repeated vehicle loads. This architecture is precisely designed to provide the driver with optimum driving comfort.
- It ensures road safety by solving the problems of tire/pavement adhesion in weather conditions such as rain, mud, snow, ice and rubber deposits.

This study examines the variation in tensile strength measured by the IDT test and the SCB test. The deformation observed in the grips during the IDT test is not ideal for assessing the cracking potential of AC mixes [6]. However, the SCB test can reduce the deformation induced by the loading strips and is more suitable for evaluating the tensile strength of AC mixes. Results from the IDT and SCB tests were found to be compatible and equivalent [7]. The SCB test is widely recognized as a suitable method for assessing fracture toughness, which defines the strength properties of an AC mix [8]. The effectiveness of the SCB test in quantifying the tensile and fracture resistance of AC mixes, determines that the fracture properties of AC correlate with the results of laboratory tests, particularly the flexural behavior of (SCB) beams. Fracture properties of two AC mixes were conducted, using 3-point bending tests on specimens with notches and the SCB method. A strong correlation was found between the stress intensity values obtained from the two different sample geometries [9]. In addition, both geometries are suitable for evaluating mixed mode fracture of AC materials. The SCB test effectively assesses the fracture resistance of fine aggregate mixtures, with the total energy consummation, serving as a reliable indicator to separate different combinations [10]. Fatigue testing of AC mixtures using different asphalt binders has highlighted the important role of bitumen composition and properties in determining the quality and performance of the asphalt mix. Studies have also considered the effect of temperature and bitumen content on the ability of the mix to withstand loads, and have found that bitumen content has a significant effect on the performance of the mix [11-13]. In addition, aging time affects the performance of asphalt mixtures, with longer aging times resulting in harder mixtures and improved stability, which increases resistance to permanent deformation [15, 16, 30]. Various laboratory cracking tests, including regression analysis, have been developed to evaluate (AC) mix failure.

This study examines the tensile properties of asphalt concrete mixes with different binder contents using the IDT and SCB tests and analyses the correlation between the test results. Table I provides a short overview of the advantages and disadvantages of the IDT and SCB tests and contains valuable information for optimizing mix designs for improved pavement performance.

TABLE I. ADVANTAGES AND DISADVANTAGES OF IDT

Advantages	**Disadvantages**
Simple to conduct	Permanent deformation under the loading strip is undesirable
Specimens can be easily obtained from a σuperpave gyratory compactor or field cores	Only controlled stress testing may be performed
Existing equipment, such as the Marshall testing system, can be utilized	Strain distribution in the middle of the specimen is quite non-uniform
Failure is not seriously affected by sample surface conditions	The stress state during the diametrical test on a specimen under loading is complicated and not a realistic representation of the stress state in the whole pavement structure
The stress state in the vicinity of the center is similar to that at the bottom of the asphalt layer	If the compressive strength of the material under loading is lower than three times the tensile strength, specimen fracture will be initiated by compressive failure. High stresses at the supports in IDT may cause local failure at these points

II. MATERIALS

A bituminous mix is usually made up of coarse aggregates, fine aggregates, mineral fillers and binders. In the current research, penetration grade 40-50 was used as the binder, while cement was used as the mineral filler.

A. Asphalt Cement

A conventional 40-50 penetration grade asphalt cement was selected, which is widely used in Iraq for typical HMA compositions. Table II provides a comprehensive overview of the physical parameters of the asphalt cement. An initial evaluation of the asphalt samples collected was carried out to confirm that the essential properties met the requirements of [17].

B. Coarse and Fine Aggregates

As part of this research, work was carried out on the wearing course. As a result, the coarse aggregate, that was crushed and passed through a 19 mm sieve, was retained on sieve no. 4. The mixture of crushed sand and natural sand was used as the fine aggregate (it was able to pass through sieve no. 4 but was retained on sieve no. 200). After washing, the aggregate was allowed to air dry before being sieved into different sizes as required by SCRB specifications [17]. The physical properties of the aggregate are given in Table III and the results and specification limits as set out by the SCRB are summarized in Table IV. The test results show that the selected aggregate meets the SCRB specifications.

TABLE II. PROPERTIE OF ASPHALT CEMENT

Test	**Unit**	**Result**	**Specification limit (SCRB 2003/R9)**
Penetration at 25 °C, 100 gm, and 5 s (ASTM D5)	0.1 mm	44	40–50
S softening point R&B (ASTM D36)	°C	52	—
Specific gravity at 25 °C (ASTM D70)	—	1.02	—
Flashpoint (ASTM D92)	°C	280	Min. 232
Ductility (ASTM D113)	cm	129	Min. 100
Residue from thin film oven test (ASTM D1754), retained penetration % of original (ASTM D5)	%	56	Min. 55
Ductility at 25 °C, 5 cm/min, (cm) (ASTM D113)	cm	86	Min. 25

TABLE III. PHYSICAL PROPERTIES OF AGGREGATE

Property	**Coarse aggregate**	**Fine aggregate**	**Specification limit (SCRB 2003/R9)**
Bulk specific gravity (ASTM C127 and C128)	2.636	2.62	—
Apparent specific gravity (ASTM C127 and C128)	2.646	2.65	—
Percent water absorption (ASTM C127 and C128)	0.139	0.52	—
Percent wear (Los Angeles abrasion) (ASTM C131)	18.89	—	30 max
Fractured pieces,% (ASTM D5821)	96	—	90 max
Sand Equivalent (ASTM D2419)	—	53	45 min
Soundness loss by sodium sulfate solution,% (ASTM C88)	3.5	—	12 max

TABLE IV. SELECTED GRADATION FOR WEARING COURSE

Wearing course sieve size		**Selected gradation Specification limit (SCRB 2003/R9)**
Inch	mm	Wearing course
3/4	19	100
1/2	12.5	100–90
3/8	9.5	76-90
No. 4	4.75	44–74
No. 8	2.36	28-58
No. 50	0.3	5–21
No. 200	0.075	4–10

C. Mineral Filler

The research activity utilized local ordinary Portland cement that met the specifications indicated in the SCRB. Table V shows the physical parameters of cement made with Portland cement, a non-plastic substance that can pass through filter No. 200 (0.075 mm).

TABLE V. PHYSICAL PROPERTIES OF FILLER

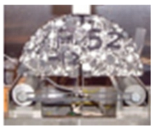
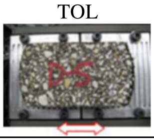
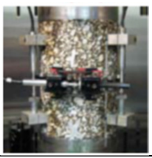
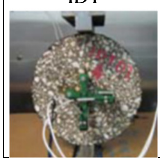
Property	**Result**
Bulk Specific Gravity	3.20
Passing sieve No. 200 (0.075 mm)	97%

III. EXPERIMENTAL WORK

This section provides a detailed overview of the tests conducted to produce the asphalt mixtures and assess their resistance to wear, as shown in Figure 1. The AC mixture, along with the fine and coarse aggregate samples, was prepared by combining them with the mineral filler in order to achieve the desired gradation on specific sieves (3/4, 1/2, 3/8, No. 4, No. 8, No. 50, and No. 200). The mineral filler was employed in the wear cycle of the asphalt concrete. The aggregate was batched to weigh 1150 g in accordance with the grading specifications stated in the SCRB standards. For aggregate preparation, the coarse aggregates were crushed and passed through a sieve with a size of 19 mm and retained on sieve No. 4. A blend of crushed sand and natural sand was used as fine aggregate, passing through sieve No. 4 but retained on sieve No. 200.

Prior to the mixing process, the aggregate was heated to 160 °C. This was done in order to facilitate the combination of the aggregate with the asphalt cement. The asphalt cement binder was heated to 150 °C in accordance with the recommendations set forth by the SCRB [18]. Table VI presents a summary of the laboratory cracking test methods. Subsequently, the heated binder was incorporated into the hot aggregate in the specified quantity and manually mixed until all aggregate particles were coated with a thin layer of binder. The Marshall properties of AC are presented in Table VII. The binder content was adjusted to be 0.5% above and below the optimal standard. Once the mixture reached the appropriate consistency, it was transferred to an oven set at a specific compaction temperature of 146 °C, corresponding to a viscosity of 280 °C. The material was then compacted into cylindrical samples measuring 101.6 mm in diameter and 63.5 mm in height, using a static load of 5 kN until the desired bulk density was achieved. Subsequently, samples with a diameter of 150 mm and a height of 120 mm were prepared and cut into semicircular shapes using a saw, as depicted in Figure 2 [19, 20].

TABLE VI. LABORATORY CRACKING TEST METHODS

Test type	Purpose	Specimen dimensions	Specimen preparation	Test output	Pros/Cons
SCB 	Fracture resistance	15.240 cm (6 in) (Ø) 7.620 cm (3 in) (H) 5.080 cm (2 in) (T)	Notching required = 1.524 cm (0.6 in); External LVDTs optional	Fracture energy from load-displacement curve, peak load, critical displacement	Relatively easy specimen fabrication; Easily-obtained field specimens; Two specimens per core or slice; Simple three-point bending load, better-representing field conditions
I-FIT 	Fracture resistance at intermediate temperature	15.240 cm (6 in) (Ø) 7.620 cm (3in) (H) 5.080 cm (2in) (T)	Notching required = 1.524 cm (0.6 in); External LVDTs optional	Flexibility index, load-displacement curve, secant modulus, peak load, critical displacement	In addition to SCB Pros, IFIT has the following advantages: Less cost (no need for environmental chamber); High practicality and repeatability; High ability to discriminate cracking potential of AC mixes
DCT 	Fracture resistance	15.240 cm (6 in) (Ø) 14.478 cm (5.7in) (H) 5.080 cm (2in) (T)	Notching required = 6.248 cm (2.46 in); Extensometer required	Fracture energy from load-displacement curve, peak load, critical displacement	Direct tensile mode; Possible breakage close to loading holes at an intermediate-temperature application
TOL 	Cracking (reflective) potential	15.240 cm (6 in) (L) 7.620 cm (3 in) (W) 3.810 cm (1.5) in (T)	Gluing required; curing time needed; External LVDTs optional	No. of cycles used as a measure of crack resistance	Higher variability; Cyclic loading application; No fundamental property related
DT 	Tensile strength, cracking resistance, ductility potential	10.160 cm(4 in) (Ø) 10.160 cm(4 in) (H)	Gluing required; curing time; external LVDTs required	Tensile strain at max load used as an indicator of ductility & cracking resistance potential	Simple stress state; Pure Mode I loading; Possibility of load eccentricity because of end fixtures; Difficult to obtain field specimens; Closed-loop CMOD control is difficult
IDT 	Tensile strength (indirect)	6 in (Ø) 2 in (T)	External LVDTs required	Max horizontal strain at max load & strength used as an indicator of ductility & cracking resistance potential	Relatively easy specimen fabrication; Easily-obtained field specimens; Tensile strength potentially related to cracking resistance

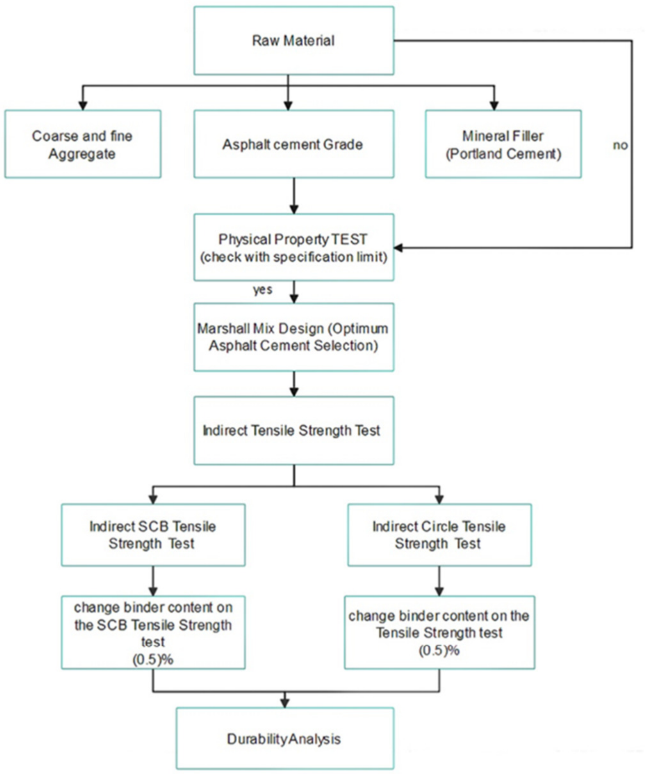


Fig. 1. Flow chart of the experimental work.

TABLE VII. MARSHALL PROPERTIES OF AC

Property	Test result
Optimum binder content %	4.7
Marshall stability kN	17
Marshall flow mm	3.6
Bulk density gm/cm³	2.237
Volume of voids %	4.13
Voids in mineral aggregates %	14.8
Voids filled with binder %	71

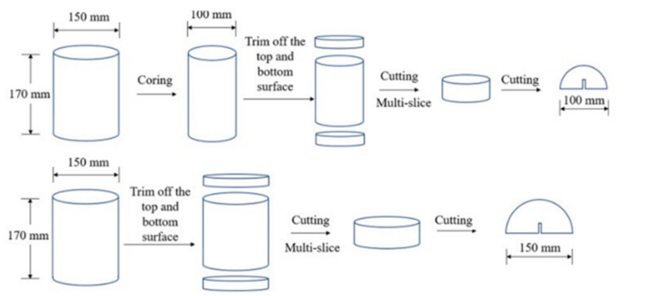


Fig. 2. Methods for preparing samples with diameters of 100 mm and 150 mm.

A. IDT Test

The IDT test was conducted using a servo-hydraulic closed-loop testing apparatus, as illustrated in Figure 3. This apparatus applies axial compression to generate horizontal tensile stresses, which ultimately result in fracture, as presented in Figure 4 [21-24]. The IDT test measured vertical strain at the center of the specimen, with data collected on the time, applied load, and horizontal and vertical deformations [19, 25-28]. The tensile strength (S_t) was calculated by:

$$S_t = \frac{200 \times P}{\pi \times t \times D} \qquad (1)$$

where S_t is the IDT strength (kPa), P is the maximum load (N), T is the specimen height immediately before the test (mm), and D is the specimen diameter (mm).

Fig. 3. The gyratory compactor.

B. SCB Test

The SCB test involved the application of a three-point flexural device to a circular disk specimen [29]. The specimen was notched to ensure crack initiation at the center. The loading equipment — which is also compatible with the IDT test — was utilized to generate the three-point bending mode, with the additional apparatus shown in Figure 5. A groove was made at the bottom of the sample in order to guarantee that the crack initiates in the middle of the specimen [24, 30, 31]. For analytical reasons, the distance between the supports is usually 0.8 times the diameter of the specimen. The literature review revealed that the standard test temperatures for the SCB test range from 10°C (50°F) to 25°C (77°F) [27, 29]. The data collected during SCB testing consists of the following parameters: time, applied force, and horizontal displacement at the crack, or vertical deflection in the specimen [27, 32]. Figure 6 depicts the SCB test arrangement and a representative testing result. The following equation is determining the SCB bending:

$$CTIndex = \frac{t}{62} \times \frac{l75}{D} \times \frac{Gf}{|m75|} \times 106$$

where *CTIndex* is the cracking tolerance index, *Gf* is the failure energy (Joules/m^2), $|m75|$ is the absolute value of the post-peak slope m75 (N/m), *l75* is the displacement at 75% of the peak load, *D* is the specimen's diameter (mm), and *t* is its thickness (mm).

Fig. 4. Indirect tensile test.

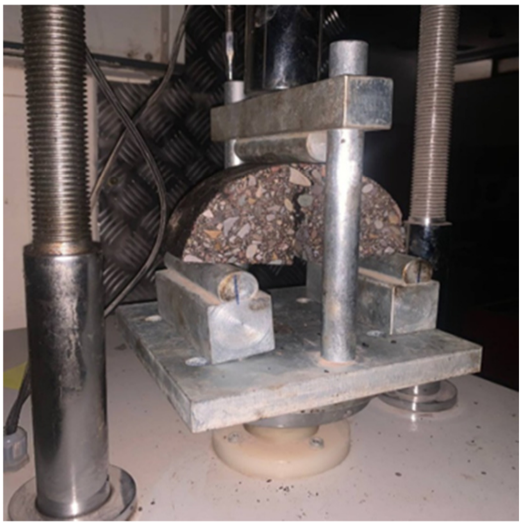


Fig. 5. SCB test.

IV. RESULTS AND DISCUSSION

A. *Relationship between IDT and SCB Test Results*

Figure 7 explains the impact of binder content on the correlation between indirect tensile strength and the SCB test for semicircular bending. Both tests were conducted at a temperature of 25 °C. It is evident that there is a positive correlation between the quantity of binder and its propensity which is becoming increasingly adverse.

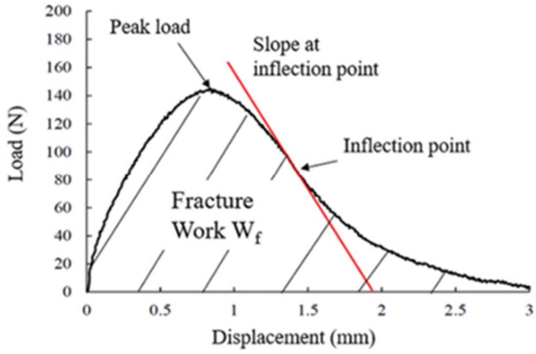


Fig. 6. A typical load-displacement curve in the SCB test and fracture parameter definitions.

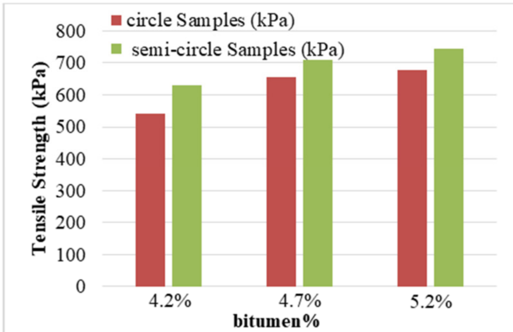


Fig. 7. IDT - SCB test results relationship.

The tensile strength derived from the SCB bending test exhibits a positive correlation with the binder content. A comparison was made between the results obtained from indirect tensile strength testing IDT and those derived from the bending test. Equations (1) and (2) were applied to determine the tensile strength of the SCB sample, which was found to be 8% greater than the tensile strength of the ITS sample when tested at 25 °C with a binder concentration of 4.7%. The tensile strength can be determined through the use of the ITS test. This pertains to the tensile strength acquired by the SCB test. The reason for this is that the two-point loading in the case of IDT causes deformation in the test strips and initiates micro-cracks, while the three-point loading in the case of SCB demonstrates greater flexion rather than distortion [1]. An assessment of the SCB test for determining the tensile and fracture strength of AC mixtures, affirmed that the outcomes of SCB, as well as IDT, were completely transferable. The discrepancy in tensile strength between ITS and SCB testing was attributed to variations in stress states during loading [8, 33].

B. *Influence of Binder Content on Tensile Strength*

Figure 8 demonstrates the influence of binder content on IDT strength. The experiment was conducted at a temperature of 25 °C and a direct correlation can be observed between the quantity of binder present and the magnitude of the IDT strength. The resistance is exerted on the sample during the test to measure the tensile strength of the mixture. This is determined by the adhesion between the binder and the aggregate, as well as the cohesion of the binder that binds the aggregate together in the mixture.

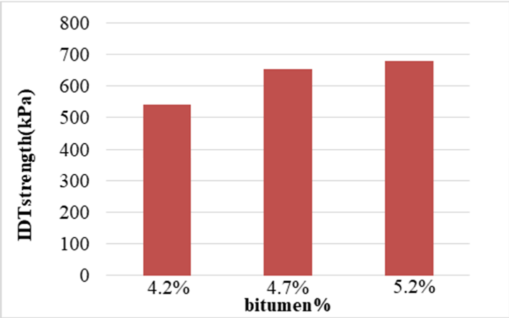


Fig. 8. Influence of binder content on tensile strength.

C. Influence of Binder Content on SCB Tensile Strength

Figure 9 shows the influence of binder content on the tensile strength of the SCB. The experiments were conducted at a temperature of 25 °C and the binder content increased by 0.5%, from 4.2% to 4.7% and to 5.2%. A direct relationship between the binder content and the tensile strength value of the SCB is obvious, which indicates that the SCB test is sensitive to changes in the binder content and bonding of mixture components, and can be observed when a load is applied during the test [7, 8, 33].

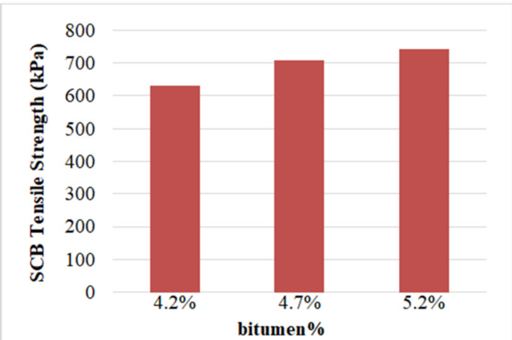


Fig. 9. Influence of binder content on SCB tensile strength.

V. CONCLUSIONS

There is a notable absence of comparative evaluations of tensile strength testing methodologies for Hot Mix Asphalt (HMA) pavements. Previous research has often concentrated on individual tests without providing a comprehensive comparison of the Indirect Tensile (IDT) test and the Semi-Circular Bend (SCB) test under standardized conditions. This has resulted in inconsistencies and uncertainties in determining the most accurate and reliable method for evaluating tensile strength and fatigue resistance in asphalt mixtures. This study addresses this gap by conducting a systematic comparison of the two methods and examining the influence of varying binder content on tensile strength and some of the insights gained are:

- The SCB test consistently indicated higher tensile strength values compared to the IDT test at the standard testing temperature of 25 °C.
- Increased binder content in the mixtures resulted in higher tensile strength, with SCB test results demonstrating greater sensitivity to variations in binder content compared to IDT test results.
- The tensile strength of the SCB rose from 630.3 to 743.7 when samples were tested at a temperature of 25 °C, when the binder concentration increased by 4.2% to 5.2%, respectively.
- The IDT strength of samples was evaluated at a temperature of 25°C and increased by 541 to 678.7 with binder concentrations of 4.2% to 5.2%, respectively.
- Regardless of the testing conditions and binder levels, the mathematical models are capable of accurately evaluating the tensile strength of asphalt concrete.
- Both IDT and SCB testing methods were validated as reliable measures for evaluating the tensile strength of Asphalt Concrete (AC).

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