Prediction of fracture parameters for asphalt mixtures using semi-circular bending test

Qais Sahib Banyhussan1*, Gofran J. Qasim1, Ali M Al-Dahawi2, Yaser H. Jabar1
1Highway and Transportation Engineering Department, Mustansiriyah University, Iraq.
2Civil Engineering Department, University of Technology- Iraq
*Corresponding author email: qaisalmusawi@uomustansiriyah.edu.iq

Abstract: fracture due to brittleness of asphalt concrete mixtures at low and/or intermediate temperatures is considered as the main unsightly distresses of pavements. A dependable value for fracture properties of AC mixtures is required which is considered as a significant design parameter. The aim of this research is to investigate the contribution of different variables on the fracture properties; fracture energy and fracture toughness using semi-circular bending (SCB) test. Routine tests were achieved as Marshall Test, where the optimum asphalt content (OAC) was 5.2% with air voids 4%. At this OAC, the number of blows (B) was lowered from 75 to 50 to assess the increase in the air voids on the fracture properties. Three variables were adopted to evaluate the fracture properties; temperature (0, 10 and 20 °C), loading rate (0.25, 0.5, and 1 in/min) and compaction effort (50 and 75 blow). The results showed that, a fracture energy (Gf) trend to increase due to increasing in energy effort, loading rate, and temperature. Regarding fracture toughness (Kj), it increased with an increase energy effort and loading rate. On the other hand, the fracture toughness shows a different trend in terms of the changing in temperature where it decreased when the temperature raised from 0 to 20 °C. Furthermore, a good correlation between the adopted variables and fracture properties were found through statistical models, where the correlation coefficients R² for all models were greater than 0.90.

Keywords: Semi-circular bending test; Fracture toughness; Fracture energy; Response Surface Methodology.

1. Introduction
The daily and seasonal environmental change, inappropriate construction methods and traffic loading may lead to developing different types of deteriorations in asphalt pavement or overlay. These may cause appearing of crack’s initiation and propagation in the pavement courses which their characteristics in the material are identified by fracture mechanics [1]. Fracture in notched materials taking place when the energy found at the vicinity of a crack is amounting to the energy wanted for the building of new surfaces. It is noticeable that this hypothesis needs a pre-existing crack/notch to be applicable. If the rate of strain energy is equal to the fracture toughness, then the crack growth occurs under steady-state and the failure lately happens. Several fracture testing techniques have been adopted to assess the fatigue-fracture in AC mixtures to investigate the mechanical and structural behavior of AC pavement. A semi-circular bending (SCB) test is broadly used in the flexible (AC) pavement organizations. This test is adopted by several researchers because of its many advantages such as its easiness to fabricate specimens, its appropriateness for field cores and its repeatability in testing results [2-5].
Wu et al. [6] studied fracture properties with different asphalt content, nominal maximum aggregate size (NMAS), and notch length. One loading rate (0.5mm/min) and a temperature of 25 oC were used. The results showed that the maximum load is sensitive to the asphalt type and content besides the compaction level.

Li and Marasteanu [2] evaluated the fracture behavior of AC mixtures by using the SCB test at low temperature fracture with different aggregates (limestone and granite). The compacted level was variable, where they adopted two design air voids 4% and 7%. The results indicated that higher air voids led to lower fracture properties regarding to fracture energy.

Aragão and Kim [3] evaluated the characteristics of asphalt mixtures subjected to different loading rates at intermediate temperature conditions using SCB test geometry. They found that, a clear dependence of fracture energy and cohesive strength to loading rates above 5mm/min.

2. Study aim and objectives
The aim of this study to investigate the effect of temperature, loading rate and compaction effort on the fracture parameters which are fracture energy and fracture toughness by using a semi-circular bending (SCB) test using AASHTO specifications [7]. The objectives of this research are:
1. To investigate the influence of individual SCB testing variables on asphalt concrete fracture behavior at different temperatures.
2. To investigate the influence of different loading rates on asphalt concrete fracture behavior.
3. To investigate the impact of different compaction effort on asphalt concrete fracture behavior.

3. Experimental work
3.1. Materials
The needed materials to prepare the AC mixture are asphalt, aggregate and fillers. They were characterized using conventional tests to check their fitting to the State Corporation for Roads and Bridges’ (SCRB) specifications [8]. Asphalt cements 40/50 brought from ALDAURAH refinery which has the physical properties shown in Table 1 were used in the experimental work of this study. The aggregate was crushed quartz got from Al-Nibaie quarry. The coarse and fine aggregates were sieved and recombined in the proper proportions to be fitted with the specification of type IIIA mixes of wearing course gradation [8] as shown in Table 2. Routine tests were performed to evaluate the physical properties of the used aggregate. The gradation of fine aggregates is between 4.75mm (No.4) sieve and 0.075mm (No.200) sieve. It contains tough grains and it is free from clay, loam and other deleterious substances. The physical and chemical properties of the coarse and fine aggregates are shown in Tables 3 and 4, respectively.

| Test                  | Test condition                        | ASTM designation | Units       | Asphalt binder 40-50 (%) |
|-----------------------|---------------------------------------|------------------|-------------|--------------------------|
| Penetration           | 100gm,25c,5sec, (0.1mm).              | D-5              | 1/10mm      | 47                       |
| Viscosity             | 135C                                  | D-4402           | Pas. sec    | 0.478                    |
|                       | 165C                                  |                  |             | 0.145                    |
| Specific gravity      | 24C                                   | D-70             |             | 1.03                     |
| Flash point           | ----------                            | D-92             | C           | 300                      |
| Ductility             | 25C,5cm/min                           | D-113            | cm          | >100                     |
| Softening point       | (4±1)C/min                            | D-36             | C           | 50                       |

After thin-Film oven ASTM D1754

| Test                  | Units | Asphalt binder 40-50 (%) |
|-----------------------|-------|--------------------------|
| Penetration of         | 1/10mm| 38                       |
| Residue               | mm    |                          |
| Ductility of residue   | cm    | 109                      |
| Loss in weight         | 163C,50gm,5h | %                       |
|                       |       | 0.3                      |
Table 2. Selected gradation of type IIIA mixes of wearing course

| Sieve | mm 19 | mm 12.5 | mm 9.5 | No.4 | No.8 | No.50 | No.200 |
|-------|-------|---------|--------|------|------|-------|--------|
| % Passing | 100  | 99      | 90     | 65.5 | 49.1 | 16    | 6.5    |

Table 3. Physical properties of the used aggregates

| Property | Coarse aggregate | Fine aggregate |
|----------|------------------|----------------|
| Bulk specific gravity (ASTM C-127 AND C128) | 2.610 | 2.631 |
| Apparent specific gravity (ASTM C127 AND C128) | 2.641 | 2.6802 |
| Percent water absorption (ASTM C-127 AND C128) | 0.423 | 0.542 |
| Percent wear (Loss Angeles abrasion) (ASTM C-131) | 20.10 | - - - |

Table 4. Chemical composition of the used aggregates

| Chemical composition | %Content |
|----------------------|---------|
| Silica, SiO2         | 82.50   |
| Lime, CaO            | 5.37    |
| Magnesia, MgO        | 0.78    |
| Sulfuric anhydride, SO3 | 2.7    |
| Alumina, Al2O3       | 0.48    |
| Ferric oxide, Fe2O3 | 0.69    |
| Loss on ignition     | 6.55    |
| Total                | 99.09   |

Mineral composition

| Mineral | %Content |
|---------|---------|
| Quartz  | 80.3    |
| Calcite | 10.92   |

Portland cement is used as mineral filler. It is dry and free from aggregations of fine particles. Table 5 shows the chemical and physical properties of the mineral filler.

3.2. Sample preparation For Marshall test

The graded aggregate was stored in buckets. To prepare the asphalt mixture, they were heated at the temperature of 145 °C for 2 hours. The asphalt grade 40/50 was prepared for the mixture by keeping in the oven for 2 hours at 150 °C. The prepared materials were mixed to prepare three Marshall Specimens of 100mm (4in) diameter and 63mm (2.5in) height which then compacted at temperature 145°C. The asphalt concrete AC mixture was prepared according to the ASTM -D 1559-89 [9] with the standard 75-blow Marshall Design method.

Table 5. Chemical composition and physical properties of mineral filler

| Chemical composition | %content |
|----------------------|---------|
| Silica, SiO2         | 21.51   |
| Lime, CaO            | 62.52   |
| Magnesia, MgO        | 1.58    |
| Sulfuric anhydride, SO3 | 5.64   |
| Alumina, Al2O3       | 3.77    |
| Ferric oxide, Fe2O3 | 3.35    |
| Loss on Ignition     | 1.34    |
| Total                | 99.44   |

| Physical properties |
|---------------------|
| %passing sieve No.200(0.075mm) | 98   |
| Apparent specific gravity | 3.1  |
| Specific surface area (M²/kg) | 355  |
3.3 Marshall and Volumetric Properties

The Marshall test was performed according to the ASTM Designation: D 1559-89 (ASTM, 2004) at a deformation rate of 51mm/min (2 inch/min) and a temperature of 60 ºC to obtain the Marshall stability and flow. The Marshall stability, in KN, is the peak load recorded in the Marshall machine while the Marshall flow, in mm, is the deformation of the specimen recorded when the load begins to decrease. It should be noted that to evaluate the impact of reducing the compaction energy on the fracture properties at the same optimum asphalt content (OAC), the standard blow that shown above (75-blow) was lowered to 50-blow. Marshall Properties at OAC by weight of the whole mixture with 75 and 50 blows are shown in Table 6.

| Optimum Asphalt Content (% | Marshall Stability (KN) | Marshall flow (mm) | Voids in total mix (%) | Bulk Density (gm/cm³) |
|---------------------------|-------------------------|--------------------|-----------------------|-----------------------|
| 75-blow                   | 5.2                     | 12                 | 3.5                   | 4                     | 2.335                 |
| 50-blow                   | 5.2                     | 7                  | 4.5                   | 7                     | 2.05                  |

3.4 Sample preparation for (SCB) test

The optimum asphalt content and the densities which are corresponding to 75 and 50 blows were used to prepare SCB samples. The samples’ dimension were 150mm diameter and 50mm height, which meets the European Standards for the notched SCB test [10]. They were compacted using manufactured vibrating compactor machine with two values of densities (2.335 and 2.05 g/cm³) that corresponding to the energy compaction of 75 and 50 blows, respectively. The specimens were cut into two semi-circular halves with a notch depth of 15mm. The process of preparing the SCB samples is shown in Figure 1.

3.5. Notched SCB test method for Fracture properties

Figure 2(a) shows the setup of SCB test, and Figure 2(b) shows its schematic. The test was conducted at three temperatures, 0, 10, and 20 ºC, and three deformation rates 0.25, 0.5, and 1 in/min. The specimens were retained in an environmental chamber at the testing temperature for 15 hours before testing which is more than the minimum of 12 hours that recommended as curing time [11].

The SCB samples were manufactured for intermediate temperature fracture toughness testing under symmetric three-point bend loading. The different loading rates were applied to each specimen compression test machine to record the load-line displacement values using the digital data logger for each loading rate. Then, the fracture energy is computed using a conventional formula [12]:

![Asphalt mix added into mold(a)](image)

![Sample compaction by vibrating(b)](image)
The maximum value of KI (KIC), which is a fracture toughness parameter, was calculated using equation (2). This parameter is usually calculated as a secondary parameter when conducting fracture energy tests, since the maximum load (Pmax) is recorded. When substituting Pmax in Equation 2, the fracture toughness obtained will be the estimated fracture toughness at the onset of crack extension [13,12].

$$K_I = \frac{P}{2\pi t} \sqrt{\pi a} \left( 4.782 + 1.219 \left( \frac{a}{r} \right) + 0.063 \exp \left[ 7.045 \left( \frac{a}{r} \right) \right] \right)$$  \hspace{1cm} (2)
Where:
P = applied load (N),
r = specimen radius (m),
t = specimen thickness (m), and
a = notch length (m)

4. Experimental Results

As mentioned before, three variables: loading rate, temperature, and no. of blows were adopted to state their effects on the fracture parameters, toughness and energy and the maximum load response. The summary results of the above variables, which are obtained from the data of load-deflection curves that obtained from SCB test and Equations 1 and 2, are stated in Table 7.

| Mixture No.(*) | Loading rate (in/min) | Temperature (°C) | No. of blows | Max. Load (N) | Fracture Toughness (Mpa.m²) | Fracture Energy (J/m²) |
|----------------|----------------------|-----------------|--------------|--------------|----------------------------|-----------------------|
| 1              | 1.00                 | 20              | 75           | 2432.88      | 0.3719                     | 2183.80               |
| 2              | 0.50                 | 20              | 75           | 1795.23      | 0.2740                     | 1694.09               |
| 3              | 0.25                 | 20              | 75           | 1584.31      | 0.2422                     | 1625.55               |
| 4              | 1.00                 | 20              | 50           | 1206.63      | 0.1844                     | 1618.13               |
| 5              | 0.50                 | 20              | 50           | 1088.91      | 0.1664                     | 1293.62               |
| 6              | 0.25                 | 20              | 50           | 588.600      | 0.0899                     | 767.430               |
| 7              | 1.00                 | 10              | 75           | 4993.29      | 0.7634                     | 1916.93               |
| 8              | 0.50                 | 10              | 75           | 4010.11      | 0.6636                     | 1631.77               |
| 9              | 0.25                 | 10              | 75           | 3844.17      | 0.6183                     | 1347.33               |
| 10             | 1.00                 | 10              | 50           | 2427.97      | 0.3712                     | 1209.47               |
| 11             | 0.50                 | 10              | 50           | 2015.95      | 0.3082                     | 903.400               |
| 12             | 0.25                 | 10              | 50           | 919.300      | 0.2054                     | 599.710               |
| 13             | 1.00                 | 0               | 75           | 7553.70      | 1.1548                     | 1650.00               |
| 14             | 0.50                 | 0               | 75           | 6225.00      | 1.0528                     | 1569.46               |
| 15             | 0.25                 | 0               | 75           | 6104.03      | 0.9943                     | 1069.11               |
| 16             | 1.00                 | 0               | 50           | 3649.32      | 0.5579                     | 800.810               |
| 17             | 0.50                 | 0               | 50           | 2943.00      | 0.4499                     | 513.180               |
| 18             | 0.25                 | 0               | 50           | 1250.00      | 0.3210                     | 432.000               |

(*) the average of four samples was taken for each mixture

4.1 Screening and variables analyses

Screening analysis is a powerful tool used to investigate the influence of a set of variables on predicted fracture properties to choose the most essential contributing variables. The design of experiment (DOE) software was used in this paper which its outcomes are presented using a Pareto chart as shown in Figures 3. This figure shows the most essential parameters affecting fracture properties by order. Regarding fracture energy, which is shown in Figure 3 (a), the number of blows has the most significant impact on the fracture energy values followed by loading rate, and temperature. On the other hand, the order of variables according to their impact on the fracture toughness and the maximum loads is different, where they are temperature, then blow, finally the loading rate.
4.2 Effect of loading rate, temperature, and blows on fracture properties

4.2.1 Effect of loading rate

The loading rate has strong effects on the fracture performance of AC mixtures under intermediate temperature conditions because of the viscoelastic deformation characteristics of asphaltic materials, as demonstrated by many studies [4,5]. In this study, SCB specimens were tested at three different loading rates (0.25, 0.5 and 1 inc./min). The experimental results shown in Figure 4(a) indicated that Asphalt mixture at slower loading rates showed more compliant responses, while the mixtures exhibited stiffer responses with greater peak force at faster loading rates. This observation agrees with findings from previous studies [4,5]. In general, increasing the loading rate leads to an increase the maximum load (P). In addition, the fracture parameters are affected by increasing the load rate. Figures 4(b) and 4(c) show the contribution of the loading rate in the fracture toughness (Kj) and fracture energy (Gf), respectively. The results stated that increasing the loading rate leads to an increase in both fracture toughness and fracture energy. The finding is similar to the findings of the Nsengiyumva’s [14] study.
4.2.2 Effect of temperature
It is widely documented that the AC is highly temperature-dependent due to its viscoelastic nature [15,5]. Based on this, the next step was to characterize the temperature effect on the repeatability of the test results, particularly for characterizing the fracture parameters. Three different temperatures: 0, 10, and 20°C, were attempted to investigate their effects on fracture parameters and the maximum load. The results indicated that increasing temperature leads to a decrease in the maximum load and the fracture toughness as shown in Figures 4(a) and 4(b), respectively. In turn, the fracture energy was increased due to increasing the temperature as illustrated in Figure 4(c). It may be attributed to an increase in the tort of the crack path [15].

4.2.3 Effect of blows
Changing the number of blows reflects the change in fracture toughness of AC mixtures resulted from the change in the compaction energy and air void percentage. Therefore, the number of blows was reduced to 50 and the air void percentage was raised to 7% when preparing additional SCB specimens to investigate this change. These specimens were tested at 0, 10, and 20°C. The results were compared with the results of energy effort of 75 blow and air voids of 4%. It has been shown that fracture toughness, fracture energy, and maximum load response reduce when air voids increase. Figure 5(a-f) states the effect of air voids on the fracture toughness and maximum load.

Figure 4. Effect of loading rate and temperature on the fracture properties

Figure 5. Effect of blows number on the fracture properties.
5. Prediction of fracture properties behavior and ANOVA analysis

Presently, one of helpful statistical procedures that are broadly applied in optimizing the performance of any framework or system is response surface methodology (RSM) [16]. RSM is a mainstream optimization instrument that has just been effectively used to optimize numerous physical and chemical procedures. Simultaneous optimization for all elements can be accomplished in a methodical way, for example, maximizing attractive parameters and minimizing the undesirable ones, in the meantime keeping up the acceptable characteristics within specifications range. For this reason, design of expert (DOE) software program was applied for the statistical analysis and mathematical modelling.

ANOVA is usually used as a primary estimation tool to evaluate the degree of influence of the studied parameters on the test. ANOVA then uses the F-test to accept or reject the null hypothesis at a stated level of significance.

The fitted mathematical model, which is occasionally, not fulfills in describing the experimental area of the independent variable. Analysis of variance ANOVA is valuable way of assessing the fitted model [16]. ANOVA was conducted in order to achieve the interaction between the different parameters and the impact of each individual parameter. For a respectable model fit, the coefficient of determination ought to be a minimum of 0.80. A high $R^2$ value near to 1.00 demonstrates a desired and reasonable agreement between the observed and calculated results.

As shown in Table 8, p-values which are less than 0.0001 indicate that the model is significant for 95% confidence intervals. The $R^2$ values specify that there is a good correlation between actual and predicted values.

The final regression models, in terms of the independent variables and responses, are expressed by the equations (3), (4), and (5) for maximum load, fracture toughness and fracture energy, respectively.

Max load = -7226.69042 +3109.46548 * Loading +266.13971 * Temperature +166.31920 * E -77.20864 * Loading * Temperature -9.90922 * Loading * E -6.07475 * Temperature * E

Fracture Toughness = -0.97484 +0.28969 * Loading +0.036000 * Temperature +0.025280 * E -5.62071E-003 * Loading * Temperature -5.21524E-004 * Loading * E -9.50467E-004 * Temperature * E

Fracture Energy = -1256.14333 +758.36476 * Loading +26.23383 * Temperature +29.11240 * E

Table 8. Analysis of ANOVA for responses (fracture parameters and max. load).

|                           | F       | p-value   | R2      | Adj.R2   | Remarks   |
|---------------------------|---------|-----------|---------|----------|-----------|
| **Maximum Load**          |         |           |         |          |           |
| Source                    | Value   | Prob > F  |         |          |           |
| Model                     | 125.12  | < 0.0001  | 0.9855  | 0.977    | significant |
| A-Loading                 | 54.63   | < 0.0001  |         |          |           |
| B-Temperature             | 326.34  | < 0.0001  |         |          |           |
| C-E                       | 288.59  | < 0.0001  |         |          |           |
| AB                        | 7.35    | 0.0202    |         |          |           |
| AC                        | 0.28    | 0.6047    |         |          |           |
| BC                        | 73.17   | < 0.0001  |         |          |           |
| **Fracture Toughness**    |         |           |         |          |           |
| Model                     | 528.04  | < 0.0001  | 0.996   | 0.994    | significant |
| A-Loading                 | 126.32  | < 0.0001  |         |          |           |
| B-Temperature             | 1527.79 | < 0.0001  |         |          |           |
C-E        1179.65 < 0.0001
AB         6.59    0.0262
AC         0.13    0.7222
BC         302.97 < 0.0001

| Fracture Energy | Model | 92.86 | < 0.0001 | 0.952 | 0.941 | significant |
|-----------------|-------|-------|----------|-------|-------|-------------|
| A-Loading       | 66.50 | < 0.0001 |
| B-Temperature   | 54.57 | < 0.0001 |
| C-E             | 157.50| < 0.0001 |

Figure 6 shows the diagnostics of the above statistical models which demonstrate its high significance since the data point set is close to being in a linear.
6. Conclusions

In the present study, efforts were made to evaluate three variables (loading rate, temperature, and compaction effort) on the fracture parameters using the SCB test. The following conclusions were drawn:

- The fracture energy (Gf) tends to increase due to an increase in energy effort, loading rate, and temperature.
- Regarding fracture toughness (Kj), it increased with increasing energy effort and loading rate. On the other hand, the fracture toughness shows a different trend in terms of the changing in temperature where it decreases when the temperature rises from 0 to 20 °C.
- Furthermore, good correlation between the adopted variables and fracture properties was found through statistical models, where the correlation coefficients R2 for all models were greater than 0.90.

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