Flexural-Creep Stiffness of Asphalt Binders Measured by Simple Developed Apparatus

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Abstract. As the climate temperature decreases, the flexible pavement will be subjected to high tensile stresses which exceeding to the movement resistance of asphalt binder leading to low temperature cracking. SHRP identified a Bending Beam Rheometer (BBR) for measuring the value of flexural-creep stiffness of asphalt binder at low temperatures which consider this value a good indicator for resistance of low-temperature cracking. This study developed a method for measuring the flexural-creep stiffness of asphalt binder by modification of an apparatus instead of Bending Beam Rheometer due to its expensive cost and unavailable in most research laboratories. A (40-50) penetration grade of asphalt binder used in this study at different test temperatures (-5, 0, 5)°C. The experimental results indicate to the modified apparatus and developed test is suitable for testing an asphalt binder at different temperature and loading time.

Keywords: Asphalt binder, Bending Beam Rheometer, Flexural-Creep stiffness, Low temperature cracking.

1. Introduction
The climatic changes that are exposed on asphalt pavement have a significant impact on the performance of asphalt concrete mixtures and asphalt binder. As temperatures decrease, the asphalt binder will change from the plastic state to solid state and becomes very stiff with low resistance to increased viscosity [1]. When the asphalt pavement are subjected to high tensile stress, which exceeds to the movement resistance of the asphalt binder, cracks will appear within the asphalt binder and soon spread over the surface of the pavement that is known as low temperature cracking, which in turn lead to functional and structural failure of the pavements [2]. In order to investigate these cracks occurring during the design life of asphalt pavement, the asphalt binder material should be subjected to a special test for finding the value of flexural-creep stiffness at low temperatures that give a good indicator of the capability of asphalt binder to resist low temperature cracking [3]. Thus, the stiffness is defined as the degree of asphalt
binder resistance to deformation under the applied loading [4]. It assists road engineers to describe the asphalt binder behavior at low temperatures, and then the additives can be added to enhance the properties of asphalt mixtures to obtain a mixture having high durability and resistant to all environmental conditions surrounding the pavement.

To determine the flexural-creep stiffness of asphalt binder at low temperatures, a Bending Beam Rheometer (BBR) identified and specified by Strategic Highway Research Program (SHRP) was used to measure the values of creep stiffness and creep rate according to ASTM D 6648-08 [3,5]. For the importance of this apparatus and the inability to provide in most highways research laboratories due to its expensive cost, the research team fabricated a similar apparatus with the determinants of well thought out for the purpose of benefiting from it in practice and research side, and the cost of fabricating is low in compared to the price of the standard apparatus. Also, the research team adopted the test mechanism as specified in ASTM D 6648-08 in terms of the value of the applied constant load, the test duration, the temperature and the reading periods of the deflection. However, the dimensions of a different model were used, and the loading method was different. The test was conducted at different temperatures by controlling the temperature using a water bath.

2. Objectives of the study
The study purpose is to develop a method for measuring the flexural-creep stiffness of asphalt binder that used in the asphalt concrete mixtures using a modified apparatus based on the representation of the binder status in the mixture as a restrained beam. As well, in possible to consider a modified apparatus in this study is analogous to the Bending Beam Rheometer for measuring asphalt binder stiffness at low-temperature conditions.

3. Modification of apparatus
The modification of flexural-creep stiffness apparatus was carried out according to ASTM D 6648-08 [5]. The apparatus consists of several elements fabricated locally with simple raw materials available in the markets using brass and iron. The most important part of the apparatus is the hollow iron mold with internal dimensions of 52 mm length, 13 mm width and 6.5 mm thickness used to contain the asphalt binder sample as a restrained beam, where this mold is installed over its base. As well as, the cover of the balls is tightly installed over the mold to adjust the center of the bearing balls as shown in figure 1. To apply a constant load, using a loading rod has two loading points to transfer the load from the rod to the sample by two iron balls have a diameter 9.5 mm. The total loading applied on the sample is (100 gm) and distributed on two points as (50 gm) for each one which is located at a distance of (1/3 the length of the mold) as shown in figure 2. The electronic dial gauge is tied on the main holder and installed on the loading rod to record the downward movement of the rod above the sample. Also, the glass bottle filled with ice was prepared to obtain the desired temperature of the test as shown in figure 3.

4. Experimental methodology
4.1 Materials and samples preparation
In this study, the used asphalt binder has 40-50 penetration grade according to ASTM D 5-13 [6]. It supplied from AL-Daurah refinery at southwestern Baghdad in Iraq. To prepare the test samples, the material was heated at 140 °C (mixing temperature) until it became liquid to be poured into the mold, then left it at room temperature for 60 minutes for cooling. The excess asphalt binder is trimmed using a hot knife. The water bath was also prepared with the addition of an amount of ice to ensure the desired temperature of the test.

5. Results of the test
The test was conducted at different temperatures (-5, 0, and 5 °C and recording the deflection readings at (8, 15, 30, 60, 120 and 240) seconds result from applying a constant load of 100 gm. The test results indicate that the values of asphalt binder deflection increase with increasing temperature and gradually increase with time at a constant load, as shown in table 1 and figure 4.
Figure 1. The hollow iron mold and the accessories.

Figure 2. Loading procedure of the sample.

Figure 3. Process of the Testing.
Table 1. The deflection values of asphalt binder at different temperature.

| Time (sec) | -5 °C | 0 °C | +5 °C |
|------------|-------|------|-------|
| 8          | 0.02  | 0.03 | 0.06  |
| 15         | 0.03  | 0.05 | 0.1   |
| 30         | 0.04  | 0.08 | 0.14  |
| 60         | 0.06  | 0.12 | 0.21  |
| 120        | 0.09  | 0.15 | 0.29  |
| 240        | 0.14  | 0.2  | 0.36  |

Figure 4. The deflection values of asphalt binder with time.

6. Analysis of the results and discussion
The analysis of the test results depend on ASTM D 6648-08 and AASHTO T 3003-2002 which include a procedure for calculation the measured creep stiffness of asphalt binder and then estimated creep stiffness and creep rate (m-value) [5,7]. All of these parameters have importance in the design method procedure of high performance pavement (Superpave). The measured creep stiffness $S_m(t)$ can be calculated using equation (1).

$$S_m(t) = \frac{2Pa^2(3L-4a)}{bh^3\delta(t)}$$

Where:

$S_m(t)$: the measured creep stiffness, MPa
P: load, N
a: distance from the point load to outer edge of the mold, mm
L: Sample length, mm
b: Sample width, mm
h: Sample thickness, mm; and
$\delta(t)$: deflection of the asphalt binder sample, mm.
The response of asphalt binder to creep loading is plotted in logarithm scale by plotting the stiffness with respect to limited loading time from 0 to 240 seconds. The plotted data can be represented by a second-order polynomial fitting to calculate the estimated creep stiffness $S_e(t)$ using equation (2).

$$\log S_e(t) = A + B[\log(t)] + C[\log(t)]^2$$  \hspace{1cm} (2)

The creep rate (m-value) represents the slope of the stiffness-time curve, which is determined using equation (3).

$$m(t) = |d\log[S(t)]/d\log(t)| = |B + 2C \log(t)|.$$ \hspace{1cm} (3)

Where:

- $S_m(t)$: the estimated creep-stiffness, MPa.
- $m(t)$: the slope of the curve.
- $t$: loading time, sec; and
- $A$, $B$, $C$: the regression coefficients that can be calculated from equations (4,5,6,7).

$$A = [S_y(S_{x2}S_{x4} - S_{x3}^2) - S_{xy}(S_{x1}S_{x4} - S_{x2}S_{x3}) + S_{xxy}(S_{x1}S_{x3} - S_{x2}^2)]/D \hspace{1cm} (4)$$

$$B = [6(S_{xy}S_{x4} - S_{xyy}S_{x3}) - S_{x1}(S_{y}S_{x4} - S_{xyy}S_{x2}) + S_{x2}(S_{y}S_{x3} - S_{xyy}S_{x2})]/D \hspace{1cm} (5)$$

$$C = [6(S_{x2}S_{x3} - S_{x3}S_{y}) - S_{x1}(S_{x1}S_{xxy}S_{x3}S_{y}) + S_{x2}(S_{x1}S_{xy} - S_{x2}S_{y})]/D \hspace{1cm} (6)$$

$$D = [6(S_{x2}S_{x4} - S_{x3}^2) - S_{x1}(S_{x1}S_{x4} - S_{x2}S_{x3}) + S_{x2}(S_{x1}S_{x3} - S_{x2}S_{y})]/D \hspace{1cm} (7)$$

Where:

- $S_{x1} = \log 8 + \log 15 + \ldots \log 240$;
- $S_{x2} = (\log 8)^2 + (\log 15)^2 + \ldots (\log 240)^2$;
- $S_{x3} = (\log 8)^3 + (\log 15)^3 + \ldots (\log 240)^3$;
- $S_{x4} = (\log 8)^4 + (\log 15)^4 + \ldots (\log 240)^4$;
- $S_y = \log S(8) + \log S(15) + \ldots \log S(240)$;
- $S_{xy} = \log S(8) \log (8)+ \log S(15) \log (15) + \ldots \log S(240) \log (240)$;
- $S_{xxy} = [\log (8)^2] \log S(8) + [\log (15)^2] \log S(15) + \ldots [\log (240)^2] \log S(240)$.

As well as, the fraction of the variation in the stiffness values is calculated based on equation (8).

$$R^2 = [6A S_y + 6B S_{xy} + 6C S_{xxy} - S_{x2}^2] / [6 S_{x2} - S_{x2}]$$ \hspace{1cm} (8)

Where:

- $S_{x2} = [\log S(8)^2] + [\log S(15)^2] + \ldots [\log S(240)^2]$.

Based on the above procedure, the measured creep stiffness, the estimated creep stiffness, and m-value have been calculated for three samples of asphalt binder at different testing temperatures as shown in table 2 and figure 5 for the sample at temperature (-5°C), table 3 and figure 6 for the sample at temperature (0°C), and table 4 and figure 7 for the sample at temperature (5°C).

The analysis of the results showed that the measured and estimated creep stiffness decrease with increasing in loading time and test temperature; the deflection values increase with load time for the different test temperatures. This is the same as mentioned and specified from SHRP in the specification of Bending Beam Rheometer [3]. In Superpave mix design, SHRP specified that the flexural-creep stiffness must be less than 300 MPa and m-value at loading time of 60 seconds more than 0.3 [8]. These parameters were considered as important factors in choosing the asphalt binder to prevent the low-temperature cracking. Therefore, the critical temperature (the temperature at which the low-temperature cracks occurs) can be determined at the lowest temperature which has these specifications at the loading.
time of 60 seconds. Thus, the results of the asphalt binder tested in a modified apparatus showed that to be resistant to thermal cracks at the selected test temperatures (-5, 0 and 5) °C.

Table 2. Calculation of the creep stiffness with time for the sample at temperature (-5°C).

| Test Temperature (-5°C) | Time (t) (sec) | Test Load (P _t) (mN) | Deflection (d) (mm) | Measured Stiffness (MPa) | Estimated Stiffness (MPa) | Difference (%) | m-value |
|-------------------------|----------------|-----------------------|---------------------|-------------------------|---------------------------|----------------|---------|
|                         | 8              | 981                   | 0.02                | 357.67                  | 347.82                    | 0.099          | 0.50    |
|                         | 15             | 981                   | 0.03                | 238.45                  | 252.67                    | 0.142          | 0.52    |
|                         | 30             | 981                   | 0.04                | 178.84                  | 174.55                    | 0.043          | 0.55    |
|                         | 60             | 981                   | 0.06                | 119.22                  | 118.40                    | 0.008          | 0.57    |
|                         | 120            | 981                   | 0.09                | 79.48                   | 78.85                     | 0.006          | 0.60    |
|                         | 240            | 981                   | 0.14                | 51.10                   | 51.57                     | 0.005          | 0.63    |

Regression Coefficients:

A: 2.95  B: -0.42  C: -0.04  R²: 0.999999999998

Figure 5. Relationship between the creep stiffness with time for the sample at temperature (-5°C).
Table 3. Calculation of the creep stiffness with time for the sample at test temperature (0°C).

| Test Temperature (0°C) | Time (t) (sec) | Test Load (Pt) (mN) | Deflection (d) (mm) | Measured Stiffness (MPa) | Estimated Stiffness (MPa) | Stiffness Difference (%) | m-value |
|------------------------|---------------|---------------------|---------------------|-------------------------|--------------------------|---------------------------|---------|
|                        | 8             | 981                 | 0.03                | 238.45                  | 236.73                   | 0.017                     | 0.85    |
|                        | 15            | 981                 | 0.05                | 143.07                  | 143.73                   | 0.007                     | 0.74    |
|                        | 30            | 981                 | 0.08                | 89.42                   | 89.88                    | 0.005                     | 0.62    |
|                        | 60            | 981                 | 0.12                | 59.61                   | 61.19                    | 0.016                     | 0.49    |
|                        | 120           | 981                 | 0.15                | 47.69                   | 45.33                    | 0.024                     | 0.37    |
|                        | 240           | 981                 | 0.2                 | 35.77                   | 36.56                    | 0.008                     | 0.25    |

Regression Coefficients:

A: 3.31  
B: -1.22  
C: 0.20  
R²: 0.999999999999767

Figure 6. Relationship between the creep stiffness with time for the sample at temperature (0°C).
Table 4. Calculation of the creep stiffness with time for the sample at temperature (5°C).

| Test Temperature (5°C) | Time (sec) | Test Load (Pt) | Deflection (d) | Measured Stiffness (MPa) | Estimated Stiffness (MPa) | Stiffness Difference (%) | m-value |
|------------------------|------------|----------------|----------------|--------------------------|--------------------------|--------------------------|---------|
|                        | 8          | 981            | 0.06           | 119.22                   | 117.10                   | 0.021                    | 0.75    |
|                        | 15         | 981            | 0.1            | 71.53                    | 75.21                    | 0.037                    | 0.66    |
|                        | 30         | 981            | 0.14           | 51.10                    | 49.00                    | 0.021                    | 0.57    |
|                        | 60         | 981            | 0.21           | 34.06                    | 33.99                    | 0.001                    | 0.48    |
|                        | 120        | 981            | 0.29           | 24.67                    | 25.11                    | 0.004                    | 0.39    |
|                        | 240        | 981            | 0.36           | 19.87                    | 19.75                    | 0.001                    | 0.30    |

Regression Coefficients:

A: 2.86  B: -1.02  C: 0.15  R²: 0.999999999998

Figure 7. Relationship between the creep stiffness with time for the sample at temperature (5°C). The same sample of asphalt binder was tested at AmirKabir University of Technology using bending beam rheometer. This test was conducted for comparison between BBR and modified ring and ball apparatus as shown in table 5.
Table 5. Comparison between BBR and modified ring and ball apparatus.

| Parameter | modified ring and ball | BBR | Difference | error |
|-----------|-------------------------|-----|------------|-------|
| A         | 2.95                    | 3.0 | 0.05       | 0.017 |
| B         | -0.42                   | -0.4678 | 0.0478 | 0.102 |
| C         | -0.04                   | -0.0434 | 0.0034 | 0.078 |

7. Conclusions
Based on the test result obtained in this study, the conclusions can be summarized as follows:

1. The measured and estimated creep stiffness of asphalt binder decrease with increasing loading time and test temperature, and the deflection values increase with increasing loading time for the different test temperatures (-5, 0, 5)°C.
2. The asphalt binder was tested in the modified apparatus have a resistant to thermal cracks at the selected test temperatures (-5, 0, 5)°C.
3. The modified apparatus and developed test method in this study are suitable to test the asphalt binder at different loading times and different temperatures.
4. The analysis of the test results indicated what was mentioned and identified from SHRP in the specification of Bending Beam Rheometer in the testing of asphalt binder to determine the flexural-creep stiffness.
5. The possibility of using this modified apparatus in several activities as simulating the reality of asphalt binder in the asphalt mixture, measure the deflection values at different test temperatures, measure the flexural-creep stiffness properties of asphalt binder at different temperatures, identify the critical temperature of asphalt binder to prevent low temperature cracking, and establishing of master curve for various types of asphalt binder at different temperatures.
6. The modified apparatus has many features as weight lightness, small size, efficiency, low cost, no power needed, and the possibility of developing it to measure the flexural-creep stiffness of asphalt mixtures.

8. References
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