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Development of an Experimental Method for Asphalt Concrete Overlay Reflective Cracking Evaluation

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Abstract: From a concept normally used in metallic material science, the parameter "Impact Toughness" was used in this study to evaluate the ability of various asphalt mixtures to resist reflective cracking in composite pavements. In this paper, Impact Toughness was defined as the area underneath the load-displacement curve of three point bending specimen subjected to impact loading. From fracture mechanics and energy principal, it was proved that the Impact Toughness of an asphalt mixture can be correlated to its ability of resisting reflective cracking; the higher the Impact Toughness value, the stronger the material. Further, the optimum testing temperature was determined to be 15°C, established from stress-temperature curves of six asphalt mixtures. The laboratory testing results indicated that the aggregate gradation and the asphalt binder type were major factors that influenced the mixtures' Impact Toughness. Dense graded asphalt mixtures had higher Impact Toughness value than gap graded and modified asphalt mixtures had higher value than unmodified ones. The maximum size of the aggregate used in the mixtures affected their Impact Toughness as well.

To validate the test results, a pavement model consisting of an asphalt concrete overlay on top of a Portland cement concrete pavement joint was constructed and subjected to repeated loading of an Asphalt Pavement Analyzer (APA). The number of loading required for the crack to appear on the asphalt overlay surface was termed as the fatigue life. The results showed that there was an excellent linear relationship between the fatigue life of the pavement model and the Impact Toughness. Therefore, it is evident that the Impact Toughness of asphalt mixtures can represent the ability of the mixtures to resist reflective cracking and can provide guidance for asphalt mixture selection and design.

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Key words: *Experimental method; Impact Toughness; Reflective cracking.*

Introduction

Composite pavement structure, consisting of an asphalt concrete overlay on top of jointed or cracked concrete pavement slabs, is one of common pavement structure in China and many other countries. One of the primary distresses of this type of pavement is reflective cracking [1-3], which can have major effects on its performance. Over the years, many methods have been employed to remediate this type of distress [4-6], such as the use of geofabric or geogrid as a separation layer, etc. These methods did improve the performance of the pavement by delaying the occurrence of the reflective cracking. However, to prevent the reflective cracking, the quality and performance of the asphalt mixture can have major influence. Therefore, how to evaluate the ability of the asphalt mixture for resistance of reflective cracking is a very important topic.

In this study, a parameter "Impact Toughness" was defined and used to evaluate the ability of various asphalt mixtures for their resistance to reflective cracking. "Impact Toughness" is a concept normally used in metallic material science [7-9]. From both the theoretic analyses based on fracture mechanics [10-13] and energy principal and the laboratory testing, it was found that an excellent correlation existed between the Impact Toughness of asphalt mixtures and their ability to resist reflective cracking. The effects of various asphalt mixtures properties, such as asphalt binder type, aggregate gradation, etc., on the Impact Toughness were also evaluated.

Background

When applying a loading to materials, it causes stresses and corresponding strains in the materials. For a microelement in a viscoelastic material, the stress-strain curves under loading and unloading will be different and form a looped curve, as shown in Fig. 1. The area of the enclosed loop represents the total energy stored and the looped curve is termed as Hysteresis loop. In the process of repeated loading, part or all of the energy represented by the area of the Hysteresis loop will be converted to heat energy and stored inside the material. The accumulated heat energy will increase the temperature of the material and cause plastic deformation, and eventually induces fatigue damage. It is intuitively clear that, for a material, during each cycle of loading and unloading, the less energy it stored, the more durable the material against fatigue damage. The fatigue life under repeated loadings can be represented in Eq. (1).

$$N_f = a(1/W_0)^b \tag{1}$$

where,

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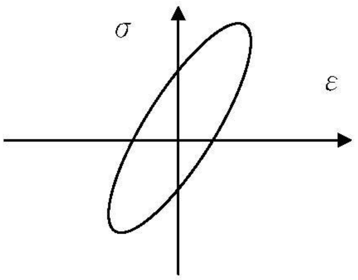

Fig. 1. Hysteresis Loop.

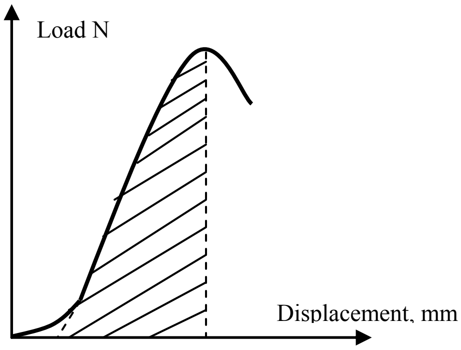

Fig. 2. Load-displacement Curve.

N_f = fatigue life, cycles
a, b = material parameters
W_0 = initial stored energy under the fist loading cycle

Eq. (1) indicates that, the smaller the stored energy under the first loading cycle, the longer the material's fatigue life. One of the methods in studying fatigue property of materials involves measuring the Hysteresis loop by laboratory testing and establishing its relationship with the material's fatigue life. The total energy stored in a materials before it fails can also be used to indicate the materials fatigue property; the larger the total stored energy, the longer its fatigue life.

When traveling on rigid or composite pavement, the wheel-joint/crack contact duration is very short, similar to the characteristic of impacting loading. Therefore, if the load-displacement curve of the asphalt concrete mixture under impact loading until failure can be determined, the areas under the load-displacement curve represents the energy required to cause the failure. Fig. 2 shows the load-displacement curve of the material under impact loading and the shaded area is defined as Impact Toughness (I). Following Eq. (1), the N_f becomes 1 under this situation and the equation can be written as:

$$I = G(W_0) \tag{2}$$

where I represents the Impact Toughness.

Eq. (9) shows that the Impact Toughness is a function of W_0. When the asphalt mixture fractures under impact loading, based on the law of energy conservation, most stored energy is used to produce new (fractured) surface. Higher value of Impact Toughness indicates greater ability the asphalt mixture can resist reflective cracking.

The J-integral is a fracture criterion that defines the behavior of an elastic material or an elastic-plastic material within small deformation region. It is a field parameter that can be defined in two ways; the loop integration and the deformation power. The loop integration is obtained by the linear integration of the stress, strain and deformation in the area surrounding the tip of the crack in the material. The deformation power definition is based on the correlation between the deformation power caused by the displacement at the point of loading and its corresponding crack length change rate.

Past researches have shown that J-integral is a parameter that can indicate the start of a crack. When the J-integral surrounding tip of the crack reaches the critical value, J_C (plane stress) or J_{IC} (plane strain), the crack starts propagating. J_C or J_{IC} is termed as J-integral fracture toughness, representing the resistance to cracking of the material. In accordance with the Deformation Power definition, J-integral can be expressed as the following equation:

$$J = -\frac{dU}{da} + \oint_C t_i \frac{du_i}{da} ds \tag{3}$$

where
C = boundary lines of the specimen
U = strain energy or deformation work per unit thickness
s = area of the specimen
a = length of the crack
t_i , u_i = stress vector and displacement vector, respectively

If the closed specimen boundary is divided into three portions, it might be expressed as following:

$$C = C_0 + C_u + C_t \tag{4}$$

where
C_0 = free boundary ($t_i = 0$)
C_u = fixed displacement boundary ($\frac{du_i}{da} = 0$)
C_t = fixed stress boundary

The integration of the close boundary line becomes:

$$J = -\frac{dU}{da} + \int_{C_i} t_i \frac{du_i}{da} ds \tag{5}$$

where
C_i = given load boundary

When comparing two specimens with a given same loading, the equation becomes:

$$J = -\frac{\partial}{\partial a}\left[U - \int_{C_i} t_i u_i ds\right] = -\left[\frac{\partial \Pi}{\partial a}\right]_{t_i} \tag{6}$$

where
Π = potential per unit thickness

In the Fracture Toughness testing under concentrated load, P, with displacement at the loading, then

$$\int_{C_i} t_i \frac{du_i}{da} ds = \frac{P d\Delta}{da} \tag{7}$$

where
Δ= displacement

Eq. (5) can be simplified as:

$$J=-\frac{dU}{da}+\frac{P d\Delta}{da} \tag{8}$$

Then,

$$J=-\left(\frac{\partial \Pi}{\partial a}\right)_P \tag{9}$$

$$J=-\left(\frac{\partial U}{\partial a}\right)_\Delta \tag{10}$$

In accordance with the Principal of Conservation of Energy, the deformation work or the strain energy in the specimen equals to the work generated by the load induced displacement. Therefore,

$$\Pi = U - P\Delta \tag{11}$$

$$U=\int_0^\Delta P d\Delta \tag{12}$$

Finally,

$$J=\int_0^\Delta \left(-\frac{\partial P}{\partial a}\right)_\Delta d\Delta \tag{13}$$

$$J=\int_0^P \left(\frac{\partial \Delta}{\partial a}\right)_P dP \tag{14}$$

From Eqs. (13) and (14), the relationship between the global load-displacement curve and the J-integral can be established. In viscoelastic materials, when external loading applies displacement work to the specimen, certain stress-strain field will be produced in the fractured specimen. J-integral is an indicator of the strength of the field. Progressing steadily, when the energy reaches the critical point, the J-integral becomes:

$$J = J_{IC} = 2\gamma \tag{15}$$

where
γ= energy required to create the new (fractured) surface

When a specimen starts cracking under a loading, the greater the area under the load-displacement at the crack initiation point, the larger the J_{IC} will be, indicating that the energy required for creating new surface (fractured surface) would be greater and the material would be more resistant to cracking. Assuming no other energy loss, Impact Toughness will be equal to J-Integral. Therefore, Impact Toughness can be used to indicate the ability of the asphalt mixture resisting reflective cracking.

Laboratory Testing Program

A laboratory testing program was carried out in this study to evaluate the feasibility of using the Impact Toughness as an indicator representing the ability of the asphalt mixture in resisting reflecting cracking. Asphalt mixture specimens, consisting of different asphalt binders and aggregates, were fabricated and were subjected an impact loading until failure. The load-displacement curve for each specimen was plotted (see Fig. 2) and the Impact Toughness was computed. To validate the concept of Impact Toughness, the Automated Asphalt Pavement Analyzer (AAPT) tests were also conducted.

Table 1. Properties of Asphalt Binders.

Properties	Unit	A-70	SBS Modified
Penetration(25℃，100g，5s)	0.1mm	71	57
Penetration Index	—	-1.16	0.04
$T_{R\&B}$	°C	51.2	90.5
Ductility (5°C，5cm/min)	cm	—	33
Ductility (15°C，5cm/min)	cm	>100	—
Elastic Recovery(25°C)	%	—	95
$\eta_{60℃}$	Pa·S	254	—
$H_{135℃}$	Pa·S	—	2.76

Materials

In this study, a conventional asphalt binder, A-70, and a Styrene-butadiene-styrene (SBS) modified asphalt binder were used. In China specifications, A-70 indicates the quality of asphalt is grade A with a penetration grade of 70 at 25°C. The properties of SBS modified and conventional A-70 asphalt binders are shown in Table 1.

Four asphalt mixtures, designated as AC-20, FAC-20, AM-20, and AC-25, with different aggregate gradations were used in the study. AC mixes were dense graded asphalt mixtures with a design void content of 4.5%. This is the most commonly used mixture type in China. FAC mixes were a type of skeleton dense structure mixes, with a design void content of 4.5%. AM mixes were asphalt macadam mixtures, with a design void content between 6.0% and 12.0%. The numbers following the letter designations represented the maximum size of the aggregates. The gradations of aggregate are shown in Table 2.

Impact Loading Test

Asphalt concrete specimens were compacted to the size of 30cm×30cm×5cm. The specimens were then cut into beams of size of 25cm×3.5cm×3.5cm. After cured in the water bath for four hours at constant temperature of 15°C, the beam specimens were subjected to impact loading, with a loading speed of 500 mm/min. Fig. 3 shows the testing device and the prepared specimens. A typical load-displacement curve is presented in Fig. 4. From the load-displacement curve, the value of the Impact Toughness was calculated using the Origin 8.0 software.

An asphalt mixture is a typical viscoelastic material. Its mechanical properties will be dependent on the temperature; therefore, temperature effects needed to be considered in the testing. Other factors, such as aggregate gradations and compositions, maximum size of the aggregate, and type of asphalt binder were also taken into consideration. Table 3 shows the experimental

Table 2. Gradations of Aggregate in Asphalt Mixture.

Asphalt Mixture	Sieves Size (mm)												Binder/Aggregate Ratio
	26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	
	Percent Passing (%)												
AC-20	100	97.5	82.5	71.0	62.0	48.0	37.0	27.0	22.0	15.0	10.0	6.0	5.0%
FAC-20	100	96.4	74.8	58.3	45.4	25.2	21.2	16.9	13.3	9.6	7.7	6.2	5.6%
AM-20	100	95.0	72.5	62.5	52.5	27.5	13.5	9.0	6.5	5.0	4.0	2.5	3.8%
AC-25	97.5	82.5	71.0	63.0	53.0	42.0	33.5	25.0	19.0	13.0	9.0	5.0	5.0%

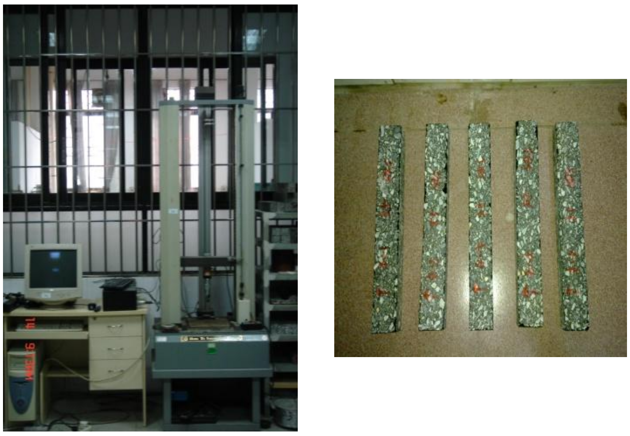

Fig. 3. Test Machine and Specimens.

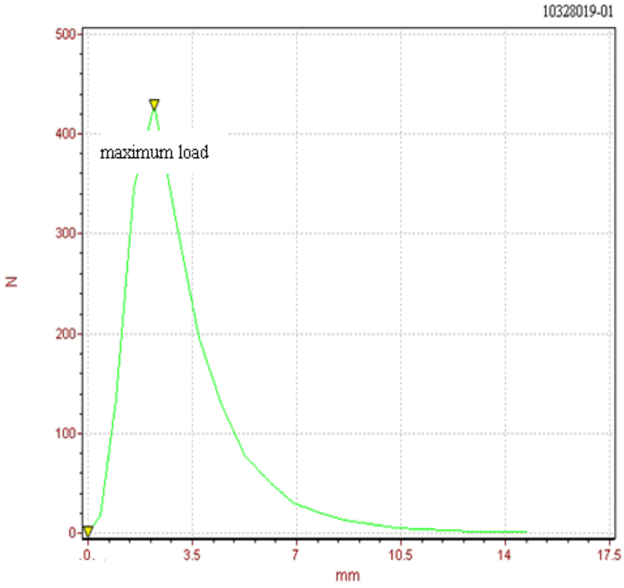

Fig. 4. Load-displacement Curve.

Table 3. Experimental Design of the Impact Loading Test.

Mixture types	SBS Modified					A-70 Asphalt				
	Testing Temperature (°C)									
	0	5	10	15	20	0	5	10	15	20
AC20	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆
AC25	—	—	—	—	—	☆	☆	☆	☆	☆
FAC20	☆	☆	☆	☆	☆	—	—	—	—	—
AM20	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆

Table 4. Impact Toughness of SBS-AM20.

Temperature (°C)	Impact Toughness （N.m）					Average （N.m）
0	0.48	0.31	0.28	0.26	—	0.33
5	0.21	0.47	0.41	—	0.37	0.37
10	0.33	0.50	0.49	0.41	0.46	0.44
15	0.81	0.77	0.62	—	0.67	0.72
20	1.14	1.36	0.87	0.96	0.79	1.02

design of the impact loading test.

Test Results and Analysis of Impact Toughness of the Mixtures

Because of the relatively large variability of the measured Impact Toughness values, for each asphalt mixture, six specimens were fabricated and subjected to the impact loading test. For a single measurement, a, if:

| a – average value of the six measurements | ≤ 1.15 * standard deviation;

the measured data was considered valid. The average values were then re-computed after removing the invalid data. The Impact Toughness values for SBS-AM20 mix are presented in Table 4. The dash lines in the table indicate those invalid data that were removed.

The impact toughness tests were performed according to the experimental design presented in Table 3 and the test results are shown in Fig. 5. From Fig. 5, the values of impact toughness of the various asphalt mixtures generally form three groups. The SBS-FAC20 and SBS-AC20 specimens had the highest values, followed by A-70-AC20 and A-70-AC25. The SBS-AM20 and A-70-AM20 had the least values of impact toughness. Data also show that type of mixture, type of binder and the aggregate gradation had major effects on the values of impact toughness. For asphalt mixture type, dense graded mix had higher value than semi-open graded mix. Compared to the unmodified asphalt binder, the SBS modified asphalt binder generally has higher viscosity and forms stronger bond with the aggregate. Therefore, it would require more energy to damage mixtures with SBS modified asphalt binder. As shown in Fig. 5, for asphalt mixtures with the same aggregate, mixtures using SBS modified binder had higher impact toughness than those with unmodified binder.

For dense graded asphalt mixtures, both with SBS modified binder, the SBS-FAC20 had higher impact toughness than SBS-AC20 had. One major factor influencing their impact toughness was the binder content, so SBS-FAC20 had higher binder content. Within the reasonable range, increasing binder content can increase the asphalt mixture’s cohesion. Therefore, under the same

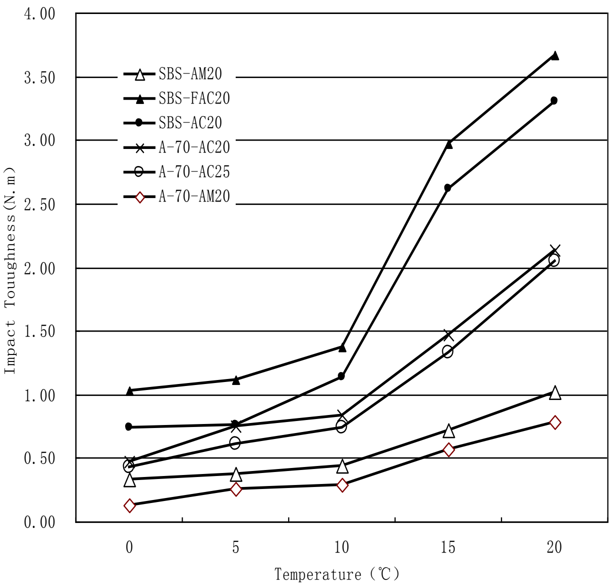

Fig. 5. Results of the Impact Toughness Test.

Table 5. Relationships between Impact Toughness and Temperature.

Types of Mixture	Regression Equation	Correlation (R^2)
SBS-AM20	$I = 0.292e^{0.0585T}$	0.94
SBS-FAC20	$I = 0.8746e^{0.0703T}$	0.90
SBS-AC20	$I = 0.6047e^{0.0846T}$	0.92
A-70-AC20	$I = 0.4704e^{0.0739T}$	0.97
A-70-AC25	$I = 0.4034e^{0.0781T}$	0.97
A-70-AM20	$I = 0.1407e^{0.0874T}$	0.96

testing condition, deformation will increase under the same stress. The increase in deformation will increase the area under the load-deformation curve under impact loading, resulting in higher impact toughness.

Fig. 5 also indicates that the Impact Toughness of the asphalt mixtures is temperature dependent. As the testing temperature increases, the value increases. Correlation between the Impact Toughness and the testing temperature were developed using regression technique and regression equations presented in Table 5. All equations show good correlation with coefficient of correlation (R^2) greater 0.90.

Optimum Test Temperature

As indicated in previous section of the paper, the Impact Toughness is not a unique value of an asphalt mixture because of the mixture's rheological property; it will be affected by the temperature at which the test is performed. With the increase of the temperature or the decrease of loading frequency, the failure mode of an asphalt mixture will transition from brittle fracture to yield damage. The temperature at the boundary is termed as the Brittleness Temperature (T_b) of the failure mode [14]. As shown in Fig. 6, in the low-temperature region (below T_b), the strain is lower and the stiffness is higher. In the temperature region above the Brittleness Temperature, as the temperature increases, the stress decreases rapidly; the strain increases rapidly; and the stiffness decreases rapidly. At the brittleness temperature, the stress is the highest. Also, an inflection point occurs at the boundary for the failure strain-temperature curve and the failure-stiffness curve. In this study, the Impact Toughness at T_b was used to assess the ability to resist reflective cracking of an asphalt mixture.

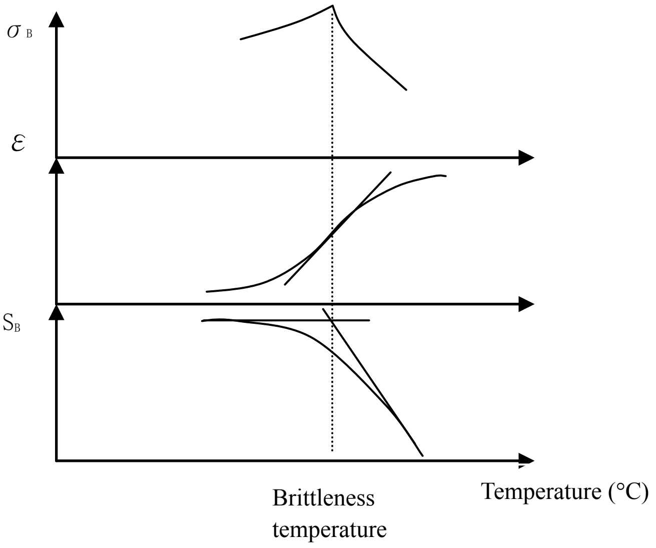

Fig. 6. Brittleness Temperature.

Asphalt specimens were subjected to Impact Toughness tests at different temperatures. Since the strains under consideration in this study are relatively low, they were considered in the elastic zone. The strength and the strain at failure were computed using the following equations:

$$\sigma_b = \frac{3P_B L}{2bh^2} \tag{16}$$

$$\varepsilon_b = \frac{6hd}{L^2} \tag{17}$$

$$S_b = \frac{\sigma_b}{\varepsilon_b} \tag{18}$$

where, σ_b = maximum stress in the specimen (MPa)
ε_b = maximum strain in the specimen (με)
S_b = stiffness at the location of maximum stress (MPa)
b = width of the specimen (mm)
h = height of the specimen (mm)
L = length of the specimen (mm)
P_B = maximum loading at failure (N)
D = deflection at midpoint at failure (mm)

Test results of the six different asphalt mixture specimens are shown in Figs. 7 to 12. All six mixtures show similar trends for the three parameters, σ_b, ε_b, and S_b vs. temperature, as those presented in Fig. 4 for typical asphalt mixtures. From these figures, it was observed that the Brittleness Temperature was 10°C for asphalt mixtures SBS-FAC20, SBS-AM20 and SBS-AC20 and 15°C for asphalt mixtures A-70-AC20, A-70-AC25 and A-70-AM20. The Brittleness Temperature seems to be affected by the type of binder

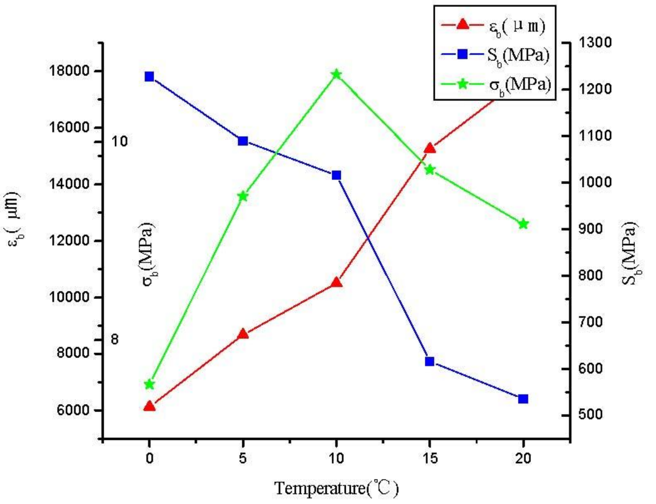

Fig. 7. Brittleness Temperature for SBS-FAC20.

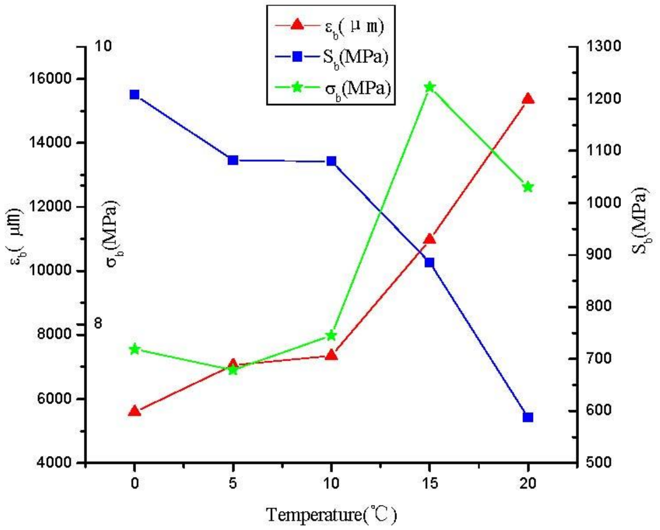

Fig. 10. Brittleness Temperature for A-70-AC20.

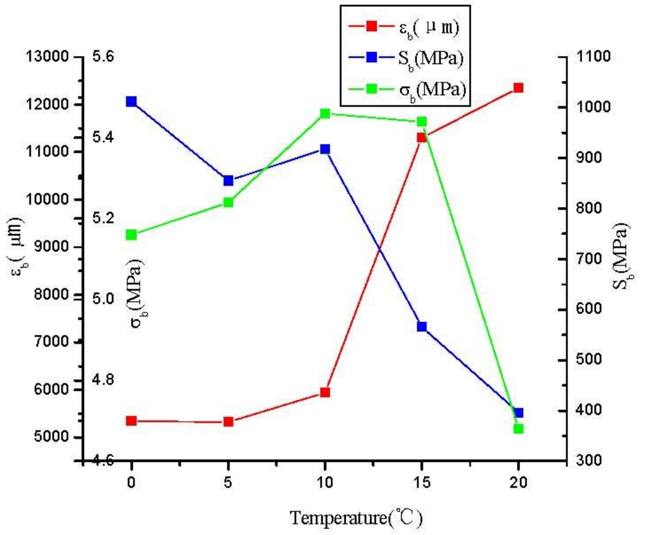

Fig. 8. Brittleness Temperature for SBS-AM20.

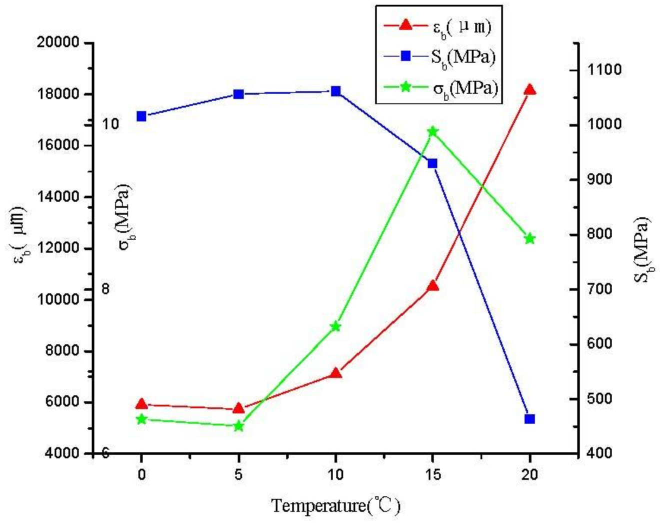

Fig. 11. Brittleness Temperature for A-70-AC25.

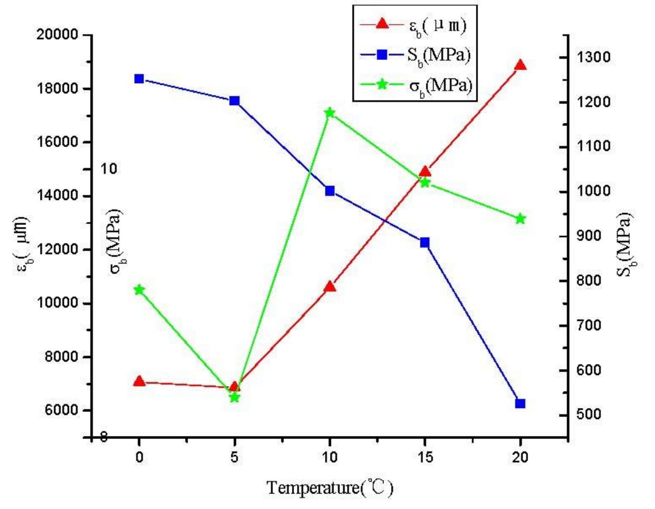

Fig. 9. Brittleness Temperature for SBS-AC20.

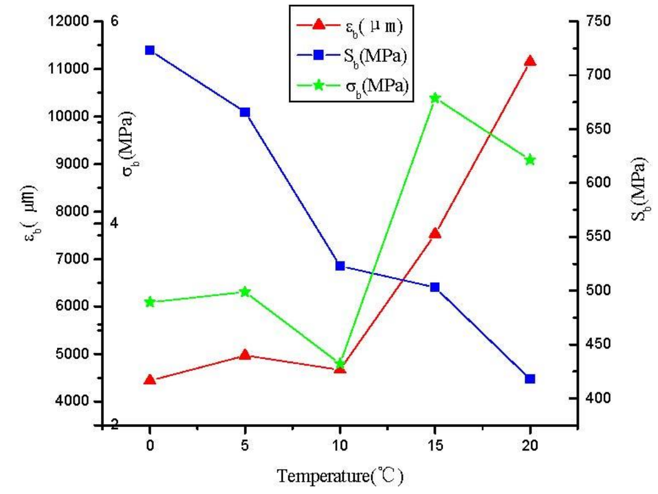

Fig. 12. Brittleness Temperature for A-70-AM20.

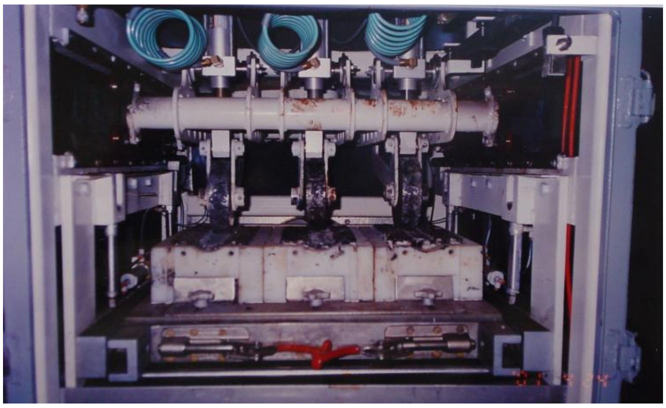

Fig. 13. Automated Asphalt Pavement Analyzer.

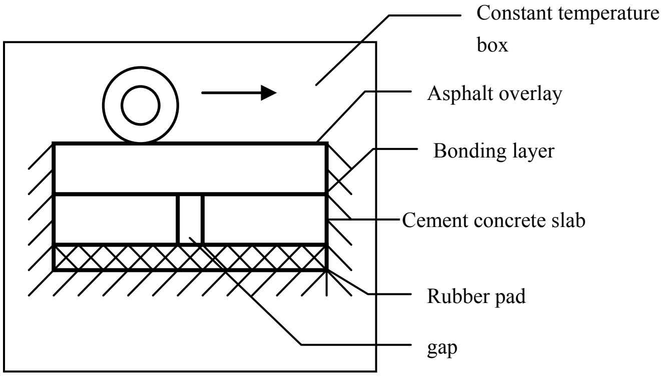

Fig. 14. Composite Pavement Model.

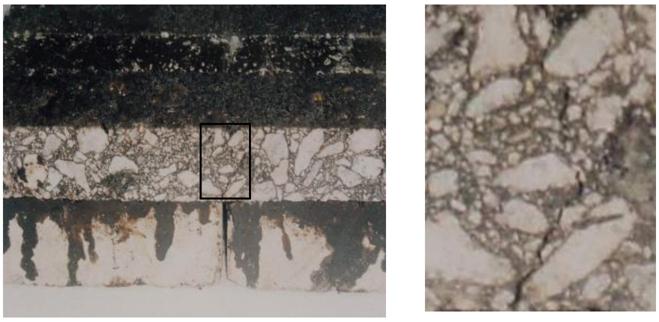

Fig. 15. Reflective Cracking.

used. SBS modified can increase the toughness of the asphalt mixture. Therefore, under the same testing condition, mixtures using SBS modified asphalt binder will have lower Brittleness Temperature. In other words, under the same loading, compared to the mixtures using unmodified binder, the failure temperature will be lower for mixtures with SBS modified binder.

As established from the test results, the Brittleness Temperature was 15°C for asphalt mixtures with unmodified binder. The ability of the mixture to resist cracking under impact loading can be best represented by the Impact Toughness determined at 15°C. For unmodified asphalt mixtures, at this temperature, the strain energy induced by the impact loading is mainly consumed by the creation of new (cracked) surface in the material. For mixtures with SBS modified binder, the Brittleness Temperature was 10°C. Therefore, at 15°C, when cracking occurs, part of the energy was consumed by the creation of new (cracked) surface and part of the energy would be used by the plastic deformation process. Also, from Fig. 5, the Impact Toughness values increase significantly as the testing temperature increases from 10°C to 15°C. The ability to resist cracking caused by impact loading can be more easily distinguished among different asphalt mixtures. In China specifications, 15°C is the standard testing temperature for fatigue testing and the reflective cracking can be considered as a type of fatigue cracking. Therefore, it is reasonable to use Impact Toughness at 15°C as the parameter for evaluation of the mixture's ability to resist reflective cracking.

Verification Test Using Automated Asphalt Pavement Analyzer (AAPA)

To verify the concept of the Impact Toughness and its effectiveness in evaluating the potential for reflective cracking, a pavement structure model was prepared and was subjected to the AAPA test since it can more realistically simulate the traffic repeated loading. Figs. 13, 14 and 15 show the AAPT test setup, a schematic presentation of the composite pavement model and the composite pavement section with reflective cracking, respectively. The model is composed of a rubber pad as the foundation, a 4.5cm thick cement concrete slab with a 3mm wide joint and a 3.5cm asphalt concrete layer. Dimensions of the model are 30cm×12.5cm×3.5cm. The model was cooled at the room temperature for over 4 hours and was then placed in the AAPA test channel at a constant temperature of 15°C for six (6) hours before testing.

As presented in Table 6, test results indicate that major factors affecting the mixture's ability in resisting reflective cracking include type and amount asphalt binder used, and aggregate gradation. Mixtures with SBS modified binder have longer life than mixtures with unmodified binder have. Dense graded mixtures have longer fatigue life than mixtures with more open graded structure. These test results confirm the analysis of the Impact Toughness test results. To further validate the relationship between the fatigue life and the Impact Toughness at 15°C of the asphalt mixtures, regression analysis was conducted and the results are shown in Fig. 16.

The relationship between the fatigue life and the Impact Toughness has the general form:

$$N_f = a \cdot I^b \tag{19}$$

where

N_f = fatigue life (cycle)

I = Impact Toughness (N.m)

a, b = equation parameters

As shown in Fig. 14, the equation in this study has the following parameters:

$$N_f = 27412 I^{2.435} \tag{20}$$

It can be seen from Fig. 16, the fatigue life of the mixtures is highly correlated with their Impact Toughness, indicated by the high correlation of coefficiation (R^2) of 0.98. Therefore, the Impact Toughness can be used an indicator of the ability to resist reflective cracking of asphalt mixtures. The third point loading flexural beam testing under impact loading is an adequate test method for determing the Impact Toughness. The test setup is simple and

Table 6. Fatigue Life of Asphalt Mixtures.

Types of Mixture	Average Fatigue Life（Cycles）
A-70-AC20	66,687
A-70-AC25	57,875
A-70-AM20	5,148
SBS-AC20	298,842
SBS-FAC20	355,519
SBS-AM20	17,378

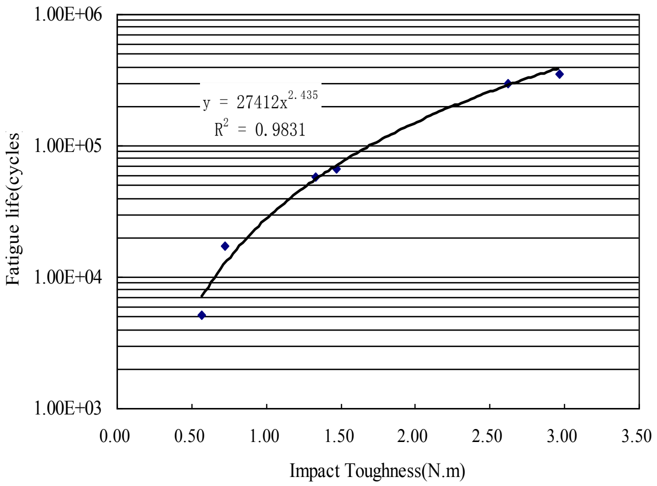

Fig. 16. Relationship of Impact Toughness and Fatigue Life.

testing time is short.

Conclusions

1. The parameter “Impact Toughness” was defined in this study. From fracture mechanics and energy principal, it was proved that the Impact Toughness of an asphalt mixture can be correlated to its ability of resisting reflective cracking.
2. From test results of the six types of different asphalt mixtures at various temperatures, it is reasonable to perform the Impact Toughness test at 15°C.
3. The laboratory testing results indicated that the aggregate gradation and the asphalt binder type were major factors that influenced the mixtures’ Impact Toughness. Dense graded asphalt mixtures had higher Impact Toughness value than gap graded and modified asphalt mixtures had higher value than unmodified ones. The maximum size of the aggregate used in the mixtures affected their Impact Toughness as well. The Impact Toughness of FAC-20 modified asphalt mixture is the largest one of six mixtures.
4. The results showed that there was an excellent relationship between the fatigue life of the pavement model and the Impact Toughness. Therefore, it is evident that the Impact Toughness of asphalt mixtures can represent the ability of the mixtures to resist reflective cracking and can provide guidance for asphalt mixture selection and design.
5. Results of this study can provide guidance in the selection and design of composite pavement, concrete bridge deck and the surface layer of a steel bridge deck.

References

1. Tsai, F.L., Lytton, R.L., and Lee, S. (2010). Prediction of reflection cracking in hot-mix asphalt overlays, *Transportation Research Record*, No. 2155, pp. 43-54.
2. Baek, J., Al-Qadi, and Imad L., (2008). Finite element modeling of reflective cracking under moving vehicular loading: Investigation of the mechanism of reflective cracking in hot-mix asphalt overlays reinforced with interlayer systems, *2008 Airfield and Highway Pavements Conference: Efficient Pavements Supporting Transportation's Future*, WA, USA, Vol. 329, pp. 74-85.
3. Knight, N.E., and Hoffman, G.L. (1985). Heavy duty membrane for the reduction of reflective cracking in bituminous concrete overlays, *ASTM Pavement Maintenance and Rehabilitation Conference*, Bal Harbour, FL, USA, pp. 51-64.
4. Zhou, F., Scullion, T., Nady, R.M., Mahboub, K., Scullion, T., McGinnis, R., Marasteanu, M., Roque, R., and Dunning, R. (2005). Overlay tester: A simple performance test for thermal reflective cracking, *2005 Meeting of the Association of Asphalt Paving Technologists - Proceedings of the Technical Sessions*, Long Beach, CA, USA, pp. 443-483.
5. Chen, D.H., Nam, B.H., and Yao, Z. (2010). Utilizing advanced characterization tools to prevent reflective cracking, *Journal of Performance of Constructed Facilities*, 24(4), pp. 390-398.
6. Perez, S.A., Balay, J.M., Tamagny, P., and Petit, C. (2007). Accelerated pavement testing and modeling of reflective cracking in pavements, *Engineering Failure Analysis*, 14(8), pp. 1526-1537.
7. Buirette, C., and Huez, J. (2010). Impact toughness enhancement of an electron beam welded Ti-6Al-4V titanium alloy through post-welding heat treatment, *TMS 2010 - 139th Annual Meeting and Exhibition*, Seattle, WA, USA, Vol. 3, pp. 593-600.
8. Dilthey, U., Lüder, F., Bleck, W., Langenberg, P., and Nagel, M. (2000). Testing of the notch-impact toughness of laser-beam-welded joints, *Welding and Cutting*, 52(10), pp. 218-221.
9. Tamminen, S., Juutilainen, I., Röning, J. (2010). Quantile Regression Model for Impact Toughness Estimatio, *10th Industrial Conference on Advances in Data Mining*, Berlin, Germany, Vol. 6171, pp. 263-276.
10. Mull, A., Othman, A., and Mohammad, L. (2005). Fatigue Crack Propagation Analysis of Chemically Modified Crumb Rubber Asphalt Mixtures, *Journal of Elastomers and Plastics*, 37(1), pp. 73–87.
11. Mull, M.A., Stuart, K. and Yehia, A. (2002). Fracture Resistance Characterization of Chemically Modified Crumb Rubber Asphalt Pavement, *Journal of Materials Science*, 37(1), pp. 557–566.
12. Pinho, S.T., Robinson, P., and Iannucci, L.(2006). Fracture Toughness of the Tensile and Compressive Fibre Failure Modes in Laminated Composites, *Composites Science and Technology*, 66(13), pp. 2069–2079.
13. Laffan, M.J., Pinho , S.T., Robinson, P., and McMillan, A.J.

(2012). Translaminar Fracture Toughness Testing of Composites, *Polymer Testing*, 31(3), pp. 481–489.

14. Zhang, X.N. (2006), The Strength and Damage of Asphalt Mixture, *Viscoelastic Mechanics Principal and Applications for Asphalt Binder and Asphalt Mixtures*, China Communication Press, Beijing, China, pp. 174-175 (in Chinese).