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Comparison of Various Testing Methods for Low-temperature Properties of Asphalts

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The Moriyoshi Breaking Point (MBP) test, Fraass Breaking Point (FBP) test and conventional tests, *i.e.*, performance-related grade tests developed by the Strategic Highway Research Program (SHRP), were performed on asphalt of various ages at low temperatures, and the Thermal Stress Restrained Specimen Test (TSRST) on asphalt mixtures. In addition, a field investigation on relationships between the MBP of asphalt residuals aged by the High Temperature Long Time Durability test (HTLTD) and pavement-cracking temperatures was conducted. A strong correlation was found between the results of the MBP, FBP and conventional tests performed on asphalt concrete. The rate of strain and brittle point of the asphalts were linear during the various tests, and the MBP temperature after HTLTD testing could be used to prevent low-temperature cracking.

Keywords
Asphalt cement, Asphalt mixture, FBP, MBP, Low-temperature cracking, SHRP

1. Introduction

Research on the characteristics of asphalt cement at low and high temperatures has concentrated on the range from linear visco-elasticity to failure. Attention is now being focused on the Strategic Highway Research Program (SHRP) specifications[1)] and the corresponding test methods used worldwide.

The present asphalt binder specifications in most countries (including Japan) are similar to those used previously in the U.S., and specify penetration and viscosity, based on the hot mix asphalt at the plant and compacting in the field during pavement construction. Such specifications certainly differ from performance-related grade specifications. One of the main themes in pavement engineering according to the SHRP is to develop asphalt binder specifications based on performance characteristics while in service, as well as in varying environmental conditions. The performance characteristics of pavements can be estimated using such test results, and the estimated results reflect the actual findings in use. Pavement damage can be classified into six types: permanent deformation, low-temperature cracking, fatigue cracking, stripping, aging and adhesion. The SHRP performance-related specifications can be used to design asphalt mixtures by considering the traffic volume and environmental conditions in the intended location[2)].

To evaluate the performance characteristics of asphalts according to the SHRP specifications[3)], the Dynamic Shear Rheometer (DSR), Bending Beam Rheometer (BBR), Direct Tension (DT), and Pressure Aging Vessel (PAV) aging tests were developed. As testing equipment is expensive for practical use, and testing procedures are complicated, few contractors have adopted these testing methods. Simpler tests are desirable for practical use. Possible substitutes include the Fraass Breaking Point (FBP) and Moriyoshi Breaking Point (MBP) tests for assessing low-temperature cracking properties, both of which are inexpensive and easily performed. The advantages of simplicity of operation and cost effectiveness are persuading many researchers in Europe and Japan to employ these methods[4), 5)].

The objective of this study is to assess the MBP and FBP tests as cheaper and faster methods for evaluating the low-temperature characteristics of asphalts. The details examined in the study are as follows:
(1) The relationship between the MBP and FBP tests and conventional BBR and DSR tests as recommended by the SHRP for asphalt cements.
(2) The relationship between the MBP and FBP tests and the Thermal Stress Restrained Specimen Test (TSRST) for asphalt mixtures, and the relationship between the MBP and/or FBP findings and the pavement cracking temperature.

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Table 1 Properties of Asphalt Cements

Straight asphalt		AAA-1	AAB-1	AAC-1	AAD-1	AAF-1	AAG-1	AAK-1	AAM-1
Crude		Lloyd	WY Sour	Red water	CA Coast	W Tx Sour	Ca Valley	Boscan	W Tx Inter
SHRP PG		58-28	58-22	58-16	58-28	64-16	58-22	64-22	64-16
Viscosity	[60°C, poise]	864	1029	419	1055	1872	1862	3256	1992
Penetration	[1/10 mm]	160	98	133	135	55	53	70	64
Softening point	[°C]	44	48	43	48	50	49	49	52
MBP (tank)	[°C]	−31	−30	−28	−29	−20	−18	−25	−27
MBP (TFOT residual)	[°C]	−24	−23	−26	−24	−13	−10	−19	−20
MBP (PAV residual)	[°C]	−19	−16	−25	−16	−8	−6	−11	−16
FBP (tank residual)	[°C]	−21	−20	−18	−22	−10	−6	−14	−17

2. Test Program

2. 1. Materials Used

Eight randomly selected straight-run asphalts were chosen from the Material Research Library (MRL), which includes fifty types of asphalt binders that are used all over the world. The eight asphalt cements were core asphalts in the tank state, and are typical of the MRL with regard to PG grade and penetration. The main properties of these asphalt cements are shown in **Table 1**.

2. 2. Test Methods

MBP, FBP and bending tests were performed on the asphalt cement at low temperatures. The results of BBR and DSR tests were obtained from the literature, as were those of the TSRST. Two accelerated aging tests, Thin Film Oven Test (TFOT) and PAV, were also performed on the asphalt cements. Asphalt mixtures were aged using both short-term oven aging (STOV) and long-term oven aging (LTOV). These test methods are briefly introduced below.

2. 2. 1. Test Methods for Asphalt Cements

FBP test: This test was performed according to DIN U 6. However, a custom-made steel plate with a thickness of 0.1 mm and high resistance to permanent deformation was used in the test. This study used a water-cooled system, with methanol as acting as the coolant. The temperature at which the asphalt binder sample fractures in the test is called the FBP[6]. The error of the FBP of all asphalts is ±1°C.

MBP test: Two stainless steel vessels (diameter of 14 cm, depth of 1 cm) were filled with 50 g of asphalt cement and cooled to room temperature. The asphalt was then cured for 30 min at constant temperature (45°C), and submerged in a low-temperature methanol bath for 1 min. The temperatures at which the asphalt cements cracked were measured. The higher failure temperature of two specimens is called the MBP[7]. The error of the MBP of all asphalts is ±1°C.

HTLTD test: The High Temperature Long Time Durability (HTLTD) test is one method of evaluating MBPs using accelerating aging. The HTLTD test was performed using the TFOT with the same test vessels and asphalt sample weight as in the MBP test. The aging time of the HTLTD test was varied, up to a maximum of 72 h. The MBP of HTLTD-aged asphalt cement for 5 h corresponds to the MBP of the same asphalt exposed to real-world conditions on a roof for 1 month, and the MBP of asphalt aged for 24 h corresponds to that of asphalt exposed outside for 3 months[8].

Bending test of asphalt cement specimens: The specimens used for the test were the same as those in the FBP test. The test was performed using FBP test equipment capable of measuring stress and strain simultaneously. The specimens were placed in a low-temperature methanol bath. The test specimens were cured in the bath for sufficient time to completely release the thermal stress induced by the difference between ambient and bath temperatures. Bending strain at failure was calculated when tested under the same rate as the FBP test. The error of the bending test was ±0.1 MPa for stress and $\pm 200 \times 10^{-6}$ for strain. Bending strain at failure in this test used the same rate as the RSA (visco-elastic analyzer, Rheometric Scientific Co., Ltd.) in tension and direct tension of the SHRP.

BBR test: The BBR test is used to measure creep stiffness ($S(t)$) and the m-value under constant load and constant temperature. The BBR test temperature is related to the lowest surface temperature of a pavement. The m-value is the tangential slope of the stiffness-time curve at some specified time. The test beam sample (125 × 12.5 × 6.25 mm) is supported at both ends in a bath below a certain temperature. Deformation in the center of the beam was measured 60 s into the test when a 100 g load was applied to the center of the beam. The parameters are specified with maximum stiffness ($S(t)$), and minimum m-value at the test time of 60 s at the lowest pavement surface temperature plus 10°C[9].

DSR test: The DSR test was performed to study the characteristics of asphalt cement at high and/or average pavement surface temperatures. Parameters obtained from the test were the complex modulus (G^*) and phase angle (δ). Asphalt samples were clamped in parallel discs and placed into a warm chamber. Sinusoidal torque was applied to the parallel discs. Torque, displacement, and phase angle were recorded[10].

PAV test: This test emulates the characteristics of 5- to 10-year-old, in-service asphalt in the laboratory. A vessel was filled with 50 g asphalt samples. The samples were kept at 100°C under air pressure of 2.14 MPa for 20 h. The specimens from the TFOT test were used.

2. 2. 2. Test Methods for Asphalt Mixtures at Low Temperatures

TSRST: The TSRST apparatus was developed under the SHRP program, consisting of a load frame, screw jack, computer-aided data acquisition and control system, low-temperature cabinet, temperature controller and specimen alignment stand.

The test sample (50 × 50 × 250 mm) was restrained at both ends by an aluminum jig. The samples were cured at 2°C for 2 h before the test began. The specimen was cooled and contracted by decreasing the temperature at 10°C per hour, starting at 2°C. When the specimen had contracted by 0.0025 mm, it was again extended to its initial length. A computer controlled the process. The test continued until each sample was broken due the thermal stress exceeding its thermal fracture strength[11]. Fracture temperature, transition temperature and thermal fracture strength were recorded. Transition temperature is defined as the temperature at which the asphalt mixture properties change from visco-elastic to brittle.

Short and long-term oven aging tests were performed in a forced-draft oven. STOA was performed on a loose mixture of asphalt at 135°C for 4 h, and LTOA was performed on compacted specimens at 85°C for 4 days. After the aging process, the specimens were stored in a cold room at 5°C prior to testing.

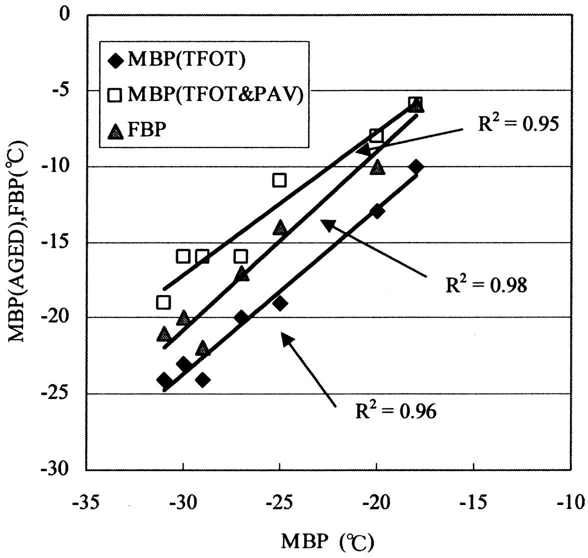

Fig. 1 Relationship between MBP (tank) and MBP (aged), FBP

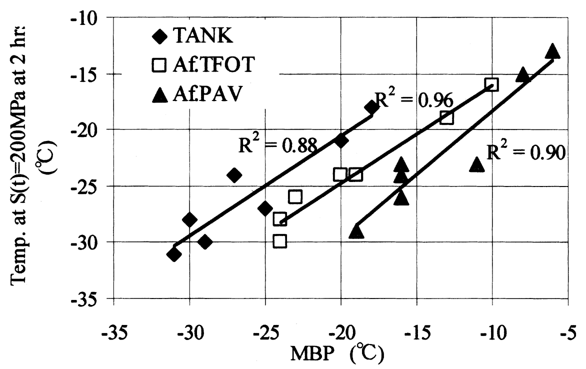

Fig. 2 Relationship between MBP and Temperatures at Limiting Stiffness from Nomograph

3. Results and Discussions

3. 1. Relationship between FBP and MBP of Asphalt Cements

Figure 1 shows the relationship between the MBP of all seven asphalt cements in the tank state and the MBP and/or FBP of asphalt cements after TFOT and/or after PAV (TFOT-PAV) aging. There was a strong correlation between the MBP in the tank state and the FBP and/or MBP after TFOT and TFOT-PAV. However, the results for the AAC-1 asphalt specimen significantly differed from the others. The correlation coefficient of the MBP and FBP for all specimens was 0.67-0.96, but 0.95-0.98 excluding AAC-1. AAC-1 may have such a significantly different breaking point from the other specimens due to much less pronounced aging. The analysis below excludes the data of the AAC-1 specimen.

3. 2. Relationship between MBP and Temperature at Limiting Stiffness of Asphalt Cements

Limiting stiffness, specified by certain tests, has been adopted for asphalt cement to avoid low-temperature fractures in engineering practice. The temperature at which the limiting stiffness is reached is called the temperature at limiting stiffness. The fracture temperature was calculated using different methods, such as the BBR (300 MPa, 60 s), Nomograph (200 MPa, 2 h), and DSR (67 MPa, 10 rad/s)[12].

Figures 2-4 show the relationship between the MBP and the temperatures at limiting stiffness of the asphalt cements in the tank state, after TFOT aging and/or after PAV (TFOT-PAV) aging. Linear regression analysis showed a good fit for the asphalt cements (excluding AAC-1), especially in the tank state. The lowest correlation coefficient was 0.83.

In addition, the relationships between the tempera-

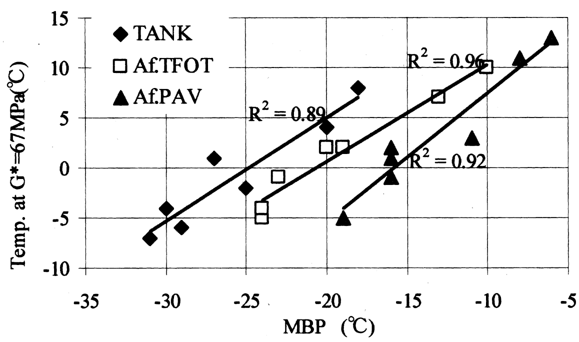

Fig. 3 Relationship between MBP and Temperatures at Limiting Stiffness from DSR

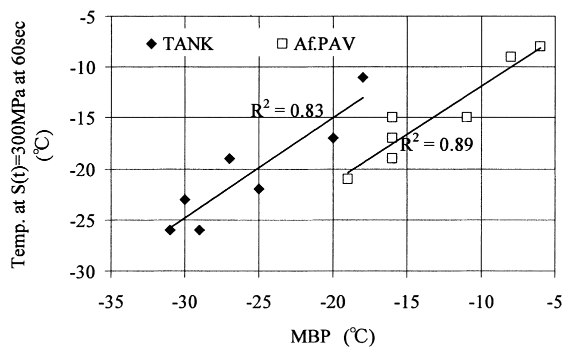

Fig. 4 Relationship between MBP and Temperatures at Limiting Stiffness from BBR

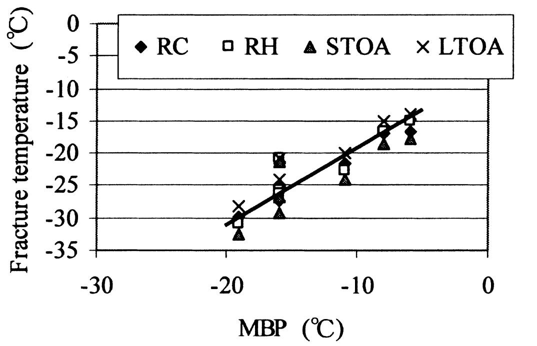

Fig. 5 Relationship between MBP and Fracture Temperatures of Asphalt Mixtures

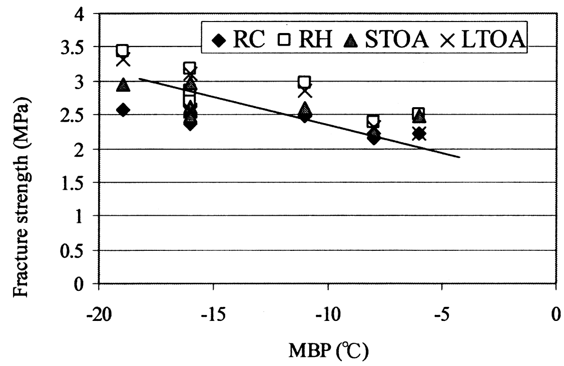

Fig. 6 Relationship between MBP and Fracture Strength of Asphalt Mixtures

tures at $m = 0.3$ in curves of stiffness-time, and FBP and/or MBP were also examined. There was little correlation with the MBP and/or FBP.

3. 3. Relationship between MBP and Thermal Fracture Properties of Asphalt Mixtures

The thermal fracture properties were obtained from the literature[13)] using the TSRST method for asphalt mixtures for the eight types of asphalt cements, along with variations of two aggregates, RC and RH (RC: limestone (with 3.7% water absorption), rough surface texture and angular surface, RH: greywacke, (with high SiO_2 content), smooth surface texture and angular shape) and two aging methods, STOA and LTOA. All together, there were four mixtures[13)]. **Figures 5** and **6** show the thermal fracture temperatures and maximum thermally induced tensile strength (fracture strength), corresponding to the thermal fracture properties of the asphalt mixtures *versus* the MBP of the asphalt cements. The relationships between the thermal fracture properties of the asphalt mixtures and the MBP of the asphalt cements were strong, regardless of the aggregate types and degree of aging of the mixtures, as shown by the high correlation coefficients between the MBP, FBP, and thermal fracture properties, and between the thermal fracture temperatures and temperature at limiting stiffness in **Table 2**.

3. 4. Relationship between MBP and Transition Temperature of Asphalt Mixtures

In addition to the thermal fracture properties discussed above, transition temperature is another interesting index. **Figure 7** shows the transition temperature of the asphalt mixtures and the MBP of the asphalt cements. The transition temperatures were obtained from the literature[9)] using the TSRST method for asphalt mixtures using the eight asphalt cements with two different aggregates and two aging methods, or four asphalt mixtures in total. The correlation coefficients shown in **Table 3** were also very high.

The correlation between the MBP and tangential slope of stiffness (dS/dT) of the mixtures is also shown in **Fig. 8**. These findings are similar to the correlation observed between the MBP and temperature obtained at $m = 0.3$ for asphalt cements. In other words, there was no significant correlation between the MBP and tangential slope of stiffness of asphalt cements or mixtures.

3. 5. Relationships between MBP and/or FBP and Low-temperature Cracking Phenomena in the Fields

A field study was conducted to investigate the relationship between MBP and/or FBP in the low-temperature cracking region during the cold season on national roads at 162 locations of a three-layer pavement (4 cm surface course, 5 cm binder course, 5 cm upper base course, for a total of 14 cm). The study showed that the lowest surface temperature in bituminous pavement in winter was directly related to the lowest ambient temperature (T_L) in winter (see **Fig. 9**). The figure shows the relationship between the lowest ambient temperature on coldest month and the average daily temperature (T_A) during the coldest month, and the relationship between MBP and FBP. The SHRP suggests that low-temperature cracking will not occur if the fracture temperature of TSRST is lower than the lowest temperature in bituminous pavement. MBP is about 10°C lower than FBP and is nearly equal to the fracture temperature of TSRST. However, the lowest ambient temperature (T_L) in winter is about 10°C lower than the average daily temperature (T_A) during the coldest month, as can be seen in **Fig. 9**. Therefore,

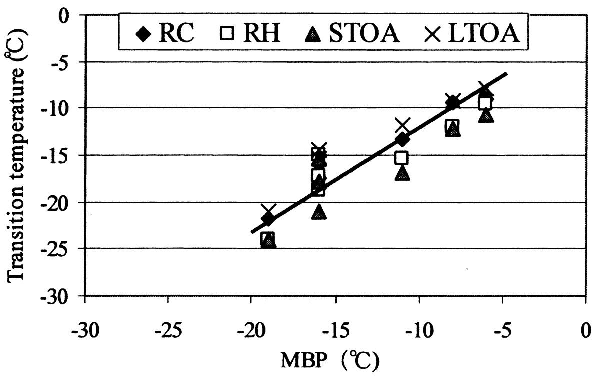

Fig. 7 Relationship between MBP and Transition Temperature of Asphalt Mixtures

Table 2 Correlation Coefficient between Various Temperatures of Asphalt Cement and Fracture Temperature of Asphalt Mixtures

		Aggregate type		Degree of aging	
	Aging states	RC[a)]	RH[b)]	STOA	LTOA
FBP	tank	0.93	0.92	0.89	0.95
MBP	tank	0.94	0.94	0.90	0.97
MBP	TFOT residual	0.94	0.94	0.91	0.96
MBP	PAV residual	0.91	0.91	0.86	0.96
$S(t)$ = 300 MPa at 60 s	tank	0.92	0.94	0.93	0.92
(BBR)	PAV residual	0.98	0.98	0.96	0.99
$S(t)$ = 200 MPa at 2 h	tank	0.96	0.97	0.96	0.95
(Nomograph)	TFOT residual	0.97	0.98	0.95	0.98
	PAV residual	0.95	0.96	0.93	0.97
G^* = 67 MPa at 10 rad/s	tank	0.96	0.97	0.96	0.95
(DSR)	TFOT residual	0.98	0.97	0.96	0.98
	PAV residual	0.96	0.97	0.93	0.98

a) Limestone (3.7% water absorption), rough surface texture and angular surface.
b) Greywacke, (high SiO_2 content), smooth surface texture and angular shape.

Table 3 Correlation Coefficient between Various Temperatures of Asphalts and Transition Temperature of Asphalt Mixtures

		Aggregate type		Degree of aging	
		RC	RH	STOA	LTOA
FBP	tank	0.93	0.89	0.90	0.89
MBP	tank	0.95	0.91	0.91	0.93
MBP	TFOT residual	0.93	0.90	0.91	0.89
MBP	PAV residual	0.96	0.90	0.89	0.96
$S(t)$ = 300 MPa at 60 s	tank	0.89	0.91	0.94	0.84
(BBR)	PAV residual	0.98	0.96	0.97	0.94
$S(t)$ = 200 MPa at 2 h	tank	0.93	0.94	0.96	0.88
(Nomograph)	TFOT residual	0.97	0.96	0.97	0.94
	PAV residual	0.97	0.95	0.96	0.94
G^* = 67 MPa at 10 rad/s	tank	0.92	0.94	0.96	0.88
(DSR)	TFOT residual	0.97	0.95	0.97	0.93
	PAV residual	0.98	0.96	0.96	0.96

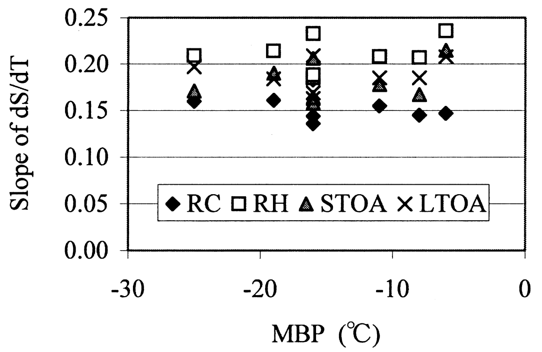

Fig. 8 Relationship between MBP and Slope of d*S*/d*T* of Asphalt Mixtures

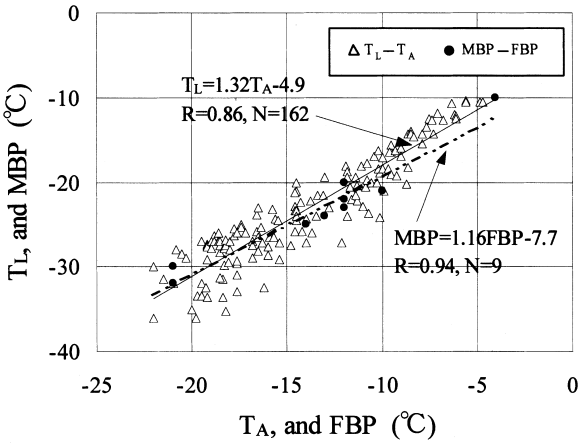

Fig. 9 Relationships between MBP, FBP, and Lowest Ambient Temperature (T_L) and Average Daily Temperature (T_A)

MBP corresponds to the lowest ambient temperature during the coldest month, and FBP corresponds to the average daily temperature during the coldest month.

To verify the above findings, these concepts were applied during the construction of the Ayabe-Miyazu Express Highway in Kyoto using a porous asphalt (surface course: 4 cm, binder content: 5.2%, length: 12 km) in 1998. The asphalt cement used in this pavement had a MBP after HTLTD (163°C, 72 h) lower than any ambient temperature expected in the field (the lowest ambient temperature within the last 10 years has been −10°C). Indications of low-temperature cracking along the Ayabe-Miyazu Express Highway have not yet been observed. This suggests that asphalt pavements made with asphalt mixtures having a MBP lower than the lowest surface temperature can prevent low-temperature cracking. In other words, in the field, the MBP temperature after HTLTD (163°C, 72 h) is a useful index to prevent low-temperature cracking in bituminous pavement in cold areas.

3. 6. Relationships between Rates of Strain and Brittle Points

Figure 10 shows the relationships between the rates

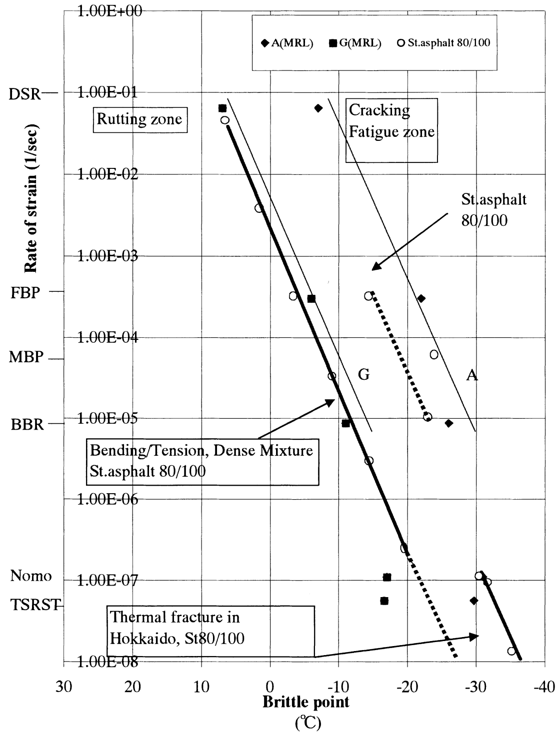

Fig. 10 Relationships between Brittle Point and Rate of Strain for Different Test Methods

of strain (this value was determined via testing) of asphalt and/or asphalt mixture and temperature (brittle points) for different test methods using the two asphalts (A (MRL) and G (MRL) asphalt: thin solid line) and a straight asphalt (straight asphalt: 80/100, thin solid line). The thick solid line shows the relationship between the brittle point of bending and/or tension test and rate of strain for a dense graded type mixture made with 5.8% straight asphalt (Pen 92 and R&B 55.8°C). However, the thermal fracture test (indicated by the thick solid line at the lower right side of **Fig. 10**, developed by Hokkaido University, was performed on a 25 × 2.5 × 2.5 cm specimen in a methanol bath with cooling rate of −30°C/h to −1°C/h. Restraint of both ends of the specimen with 5.8% straight asphalt (Pen 92 and R&B 55.8°C) in this apparatus was not as exact as in the SHRP-developed TSRST. This deficiency caused a variance of about 7°C between the real thermal fracture temperature in this test (thermal fracture estimated perfect restraint of both ends, indicated by the thick dotted line) and the original thermal fracture temperature (thick solid line), as can be seen in **Fig. 10**. Thermal fracture temperatures of TSRST for mixtures located left by 8-9°C from the thin straight line of MRL asphalts (A and G) and the slope of this line for bituminous mixture is the same as that of the asphalts.

Temperatures on the left side of the straight lines in **Fig. 10** (mixture and/or asphalt) indicate the flow zone, and data to the right indicate the brittle zone.

All temperatures of MBP were decreased by 8°C due to the loose restraint of the stainless steel vessel. The temperatures of MBP of the eight MRL asphalts coincided with the thermal fracture temperatures found in TSRST. Therefore, when the brittle temperature of one asphalt is obtained, brittle temperatures and/or fracture temperatures for the others can be found easily using **Fig. 10**.

4. Conclusions

This study supports the following conclusions:
(1) There was a strong correlation between the low-temperature properties of asphalt cements and mixtures measured by both new and conventional tests.
(2) The MBP and/or FBP of asphalt cements in various states were also strongly correlated in the tank state and during TFOT and PAV aging. The latter was observed for the first time in this study.
(3) The MBP and/or FBP of asphalt cements were correlated strongly with the temperature at limiting stiffness obtained from the Nomograph, BBR and DSR tests recommended by SHRP. An especially strong correlation was found for asphalt in the tank state. Thus, the MBP test can be used as a substitute method to estimate the low-temperature cracking properties of asphalt cements instead of the complicated SHRP tests.
(4) The MBP and/or FBP of asphalt cements were correlated with the thermal fracture temperatures and transition temperatures for asphalt mixtures, regardless of the aggregate type used for the mixtures and the degree of aging. Further, the curves showing fracture strain-temperature obtained from bending tests were proven to be similar to those obtained from asphalt mixtures using the same asphalts of Japan. Similarly, MBP/FBP can be used for evaluating the low-temperature properties of asphalt mixtures.
(5) The relationship between the rate of strain and brittle point of asphalt and/or mixture is linear based on the results obtained from various tests. If one of the brittle temperatures is obtained using a simple method, the other brittle temperatures can be found using a chart.
(6) The MBP corresponds to the lowest ambient temperature during the coldest month, and the FBP corresponds to the average daily temperature during the coldest month. Asphalt pavements built with an asphalt mixture having a MBP lower than the lowest surface temperature will not undergo low-temperature cracking, suggesting MBP temperature after the HTLTD test is a good index to determine low-temperature cracking properties in bituminous pavement in cold areas.
(7) The MBP and/or FBP of asphalt cements are useful for evaluating the low-temperature cracking properties of asphalt mixtures.

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要　　旨

アスファルトの低温性状試験法の比較

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この論文は低温で種々の劣化状態のアスファルトを用い，森吉ぜい化点（MBP）試験，フラースぜい化点（FBP）試験，SHRP（戦略的道路研究プログラム）が開発した試験との関係，およびこれらとアスファルト混合物の熱応力試験（TSRST）等との関係について述べている。加えて，高温長期耐久性試験（HTLTD）で劣化したアスファルトの森吉ぜい化点（MBP）と舗装のき裂との関係の現場調査も行っている。MBP，FBPおよびアスファルト混合物で実施した通常の試験の間に強い相関関係が得られた。ひずみ速度とアスファルトのぜい化点との関係も直線関係にあり，HTLTD後のMBP温度はアスファルト舗装の低温き裂現象を防ぐ一つの指標であることを明らかにした。

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