Failure Behavior of Bituminous Mixtures*

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Summary: *This paper describes the test results concerning the failure behavior of bituminous mixtures which is required for rational designing of pavement structures and pavement performance evaluation.*

For single load application tests, stress-strain relationships of bituminous mixtures were investigated under various loading conditions at various temperatures, and, at the same time, dynamic responses under repeated applications of load and fatigue properties of bituminous mixtures were investigated.

For conventional bituminous mixtures, it was found that strain at failure was in the order of 10^{-5} *to* 10^{-2}*, depending upon the loading and temperature conditions. In spite of the fact that strain at failure in the single load application test was in the order of* 10^{-3} *to* 10^{-2}*, it was shown that the strain level of* 10^{-4} *and* 10^{-5} *in the repeated applications of load and temperature conditions caused fatigue failure.*

Most of single load application tests were carried out by means of flexure; and the mode of failure, relationships between strength vs. temperature, strain at failure vs. temperature, and stiffness at failure vs. temperature were obtained; and convergence of the strain in ductile failure zone, $(2\sim5)\times10^{-2}$*, and in the brittle failure zone,* $(1\sim2)\times10^{-3}$*, was obtained. As a result of beam flexure tests, the movement of the transition point at which the mode of failure showed a change in the mode from brittle to ductile was observed. It was found that the movement depended upon the rate of strain, binder content, and type of mixture, but failure strains at transition points converged to* 4×10^{-3} *to* 6×10^{-3}*, independently of the type of binder, rate of strain etc.*

The effects of rate of strain, binder content, type of mixture and type of binder on rheological properties (strength, strain at failure etc.) of bituminous mixtures were investigated.

With reference to repeated applications of load, an electro-hydraulic apparatus was constructed in our laboratory to investigate the dynamic responses and fatigue properties of bituminous mixtures and tests were performed under various loading and temperature conditions. The effects of the level of applied strain and temperature on the rheological properties of the bituminous mixtures were also investigated.

1 Introduction

This paper describes the test results concerning the failure behavior of bituminous mixtures which is required for rational designing of pavement structures and pavement performance evaluation.

In general, the responses of bituminous mixtures vary depending on the changes in the following variables[1),2)].

(1) Temperature
(2) Rate of strain (loading speed)
(3) Rheological properties of binder
(4) Aggregate volume concentration of mixture, C_v, (or type of mixture)
(5) State of stress

Effects of each variable on the failure behavior of bituminous mixtures were studied in the laboratory.

At lower temperatures and rates of strain which are generally encountered in actual pavements, the relationship between stress and strain of various bituminous mixtures can be obtained by means of constant rate of strain flexure test, tension test and unconfined compression test. These are shown by the three types of stress-strain curves in **Fig. 1**[3)].

They are as follows:

Type I: Elastic (Brittle)failure
Type II: Failure at transition zone between Type I and Type III
Type III: Viscoelastic (Ductile) failure

It was found that these failures were affected by

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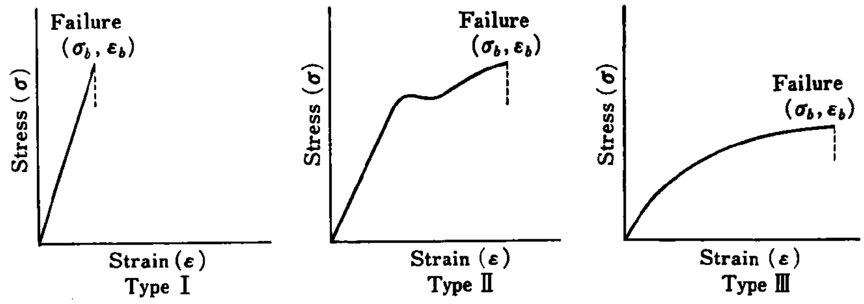

Fig. 1 Stress-Strain Relationships

Table 1 Test Conditions in Single Load Application and Type of Mixture

	Constant Rate of Strain Flexure Test	Unconfined Compression Test	Simple Tension Test	Bending Creep Test
Size of Specimen (cm)	2.5×2.5×25	2.5×2.5×5	2.5×2.5×25	2.5×2.5×25
Span Length (cm)	20		20	20
Rate of Strain (1/sec)	$3.7\times10^{-1}\sim4.1\times10^{-4}$	$(3.0\sim9.0)\times10^{-3}$	$2.2\times10^{-3}\sim5.5\times10^{-4}$	$2.8\times10^{-6}\sim5.0\times10^{-4}$*
Temperature (°C)	−20∼30	−25∼20	−5∼20	15∼40
Level of Stress (kg/cm²)	—	—	—	0.2∼7.2
Type of Mixture	Asphalt Concrete, Rolled Asphalt, Mastic Asphalt and others	Asphalt Concrete, Rolled Asphalt	Asphalt Concrete	Asphalt Concrete

* Average rate of strain.

various variables which were previously mentioned[4]. Therefore, in consideration of the different climatic and loading conditions, failure of bituminous mixtures was investigated under the following conditions[5].

1. Relatively short loading time at low temperatures (Brittle failure)——single loading
2. Relatively long loading time at high temperatures (Ductile failure)——single loading
3. Extremely long loading time at relatively high temperatures (Creep failure)——single loading and creep
4. Repeated loading at relatively lower temperatures (Fatigue failure)

The characteristics of these failures are considerably different from each other when rheologically viewed, and the level of strain at failure exists at completely different levels for each failure mode[6),7)].

In the single load test, the constant rate of strain test was adopted; and the mode of failure, relationships between strength vs. temperature, strain at failure vs. temperature, and stiffness at failure vs. temperature were observed.

An electro-hydraulic apparatus for repeated applications of load was constructed in the laboratory to investigate the dynamic responses and fatigue properties of bituminous mixtures. The apparatus was operated under various loading and temperature conditions.

2 Test Procedures and Materials

For single load application tests, the following methods were adopted.

(1) Constant rate of strain flexure test
(2) Unconfined compression test
(3) Simple tension test
(4) Bending creep test

Test conditions and mixtures studied are shown in **Table 1**.

A brief description of the apparatus and test conditions for repeated applications of load are shown in **Table 2**.

In the repeated applications of load, if the strain, ε, which varies according to the relation $\varepsilon=\varepsilon_0\sin\omega t$, is applied to a specimen (ω; angular frequency), the resulting stress, σ, will also vary sinusoidally with time, t, but it will be displaced by the phase angle, ϕ, according to the relation $\sigma=\sigma_0\sin(\omega t+\phi)$. From the peak amplitudes of stress and strain, a complex modulus, $|E^*|$, can be determined:

$$|E^*|=\frac{\sigma_0}{\varepsilon_0}$$

in which

$|E^*|$: Absolute value of complex modulus at a

Table 2 Brief Description of Apparatus and Test Conditions in Repeated Applications of Load

Brief Description of Apparatus	Maximum load: ± 200 kg Frequency: 0.1~20 Hz (sinusoidal) 0.1~2 Hz (square) Maximum Deflection: ± 5mm Test Method: Symmetrical Four Point Bending (stress control or strain control)
Test Conditions	Size of Specimen: $3\times3\times40$cm or $4\times4\times40$cm Applied Strain: 5×10^{-4}, 6×10^{-4}, 7×10^{-4}, 8×10^{-4}, 9×10^{-4}, 10×10^{-4}cm/cm Temperature: -5, 10, 15, 20°C Frequency: 10 Hz (sinusoidal wave) Type of Mixture: Asphalt Concrete (binder content 5.5%)

particular frequency of loading (kg/cm²)

σ_0: Peak amplitude of sinusoidal stress at the corresponding frequency (kg/cm²)

ε_0: Peak amplitude of sinusoidal strain at the same frequency

Fatigue life, N_f, is expressed by the accumulated number of load applications necessary to produce failure in a specimen.

3 Failure Behavior of Bituminous Mixtures

3.1 Strength, Strain, Stiffness and Temperature Relationships

The behavior of asphaltic concrete as regards flexural strength, strain at failure and stiffness at failure at various temperatures with respect to applied rate of strain is shown in **Fig. 2**.

In this figure, the author has designated the peak point of flexural strength-temperature curve as the "transition point". At the lower temperature side of the peak of the strength-temperature curve, the stress-strain curve tends to show Type I failure showing brittle failure. At the higher temperature side of the peak, viscoelastic behavior is observed, and the stress-strain curve shows Type III characteristics. The failure in this region is caused by the failure of flow characteristics; while around the peak, the stress-strain curve is somewhat similar to that of an elastic mass and may show elastic responses. This narrow zone can be expressed as a stress-strain curve of Type II. This transition point may move toward the lower or higher temperature side depending on the variables.

The strain at failure shows a gentle S-shaped curve. At the lower or higher temperature side, it appears that the values of strain at failure converge to a certain point. In these figures, the transition point corresponds almost to the point of inflexion.

Stiffness at failure decreases with increase in temperature.

The transition point shifts toward the higher temperature side when the rate of strain is increased.

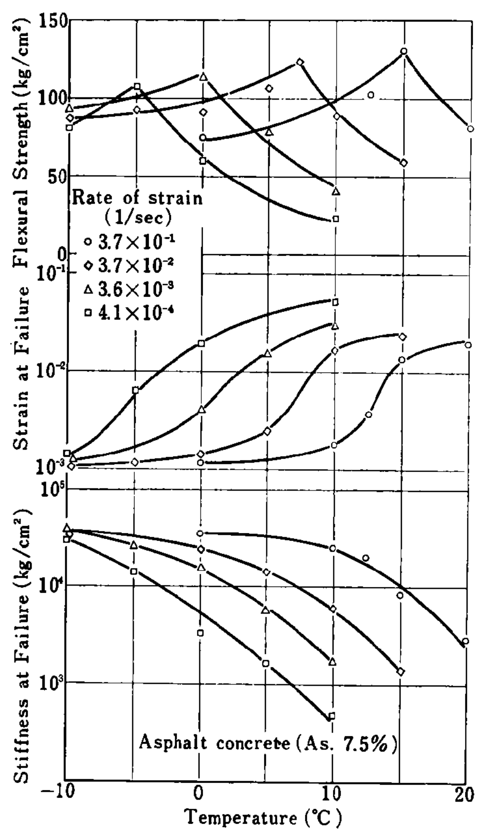

Fig. 2 Effect of Rate of Strain on Flexural Strength, Strain at Failure and Stiffness at Failure

3.2 Effect of Rate of Strain

Figure 3 shows that the strength vs. temperature curve of asphalt concrete is quite similar to the strength vs. rate of strain curve of asphalt concrete. This result implies that the temperature drop corresponds to the increase in rate of strain (**Fig. 3**). From this point of view, it appears that the failure behavior at the transition zone between Type I and Type III is highly essential in the investigation of failure characteristics of a bituminous mixture.

Figure 4 shows the effect of rate of strain on

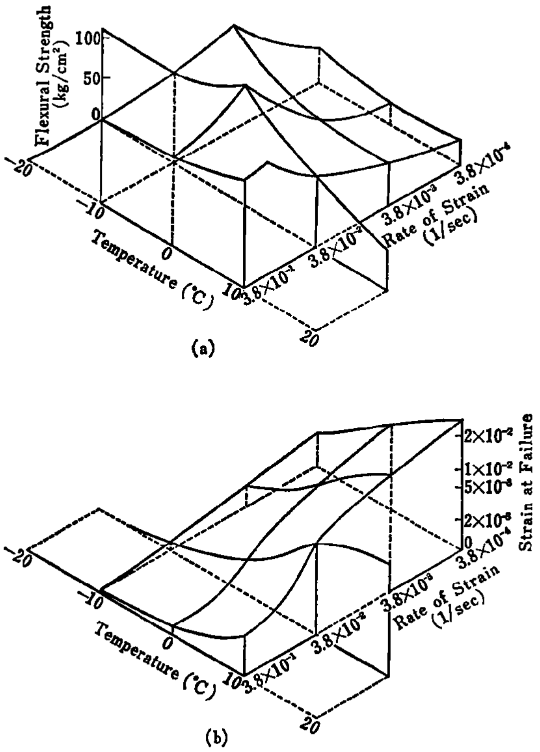

Fig. 3 Effect of Temperature and Rate of Strain on Flexural Strength and Strain at Failure (Asphalt concrete: As. 7.0%)

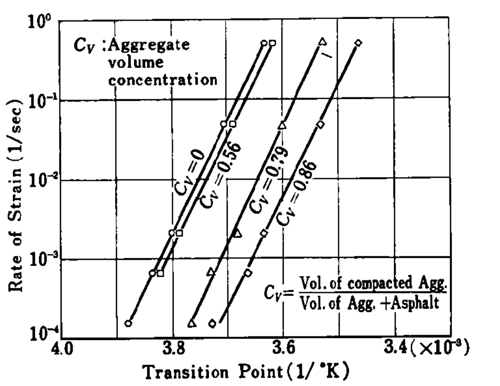

Fig. 4 Effect of Rate of Strain on Movement of Transition Point

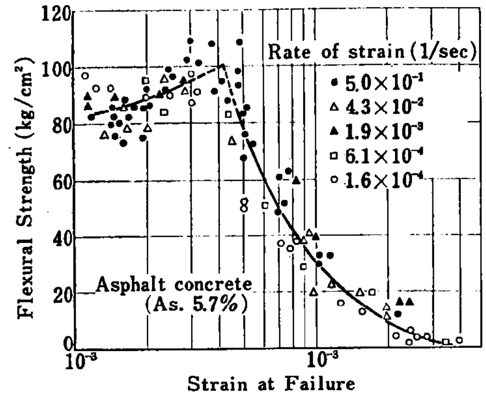

Fig. 5 Relation between Strain at Failure and Flexural Strength

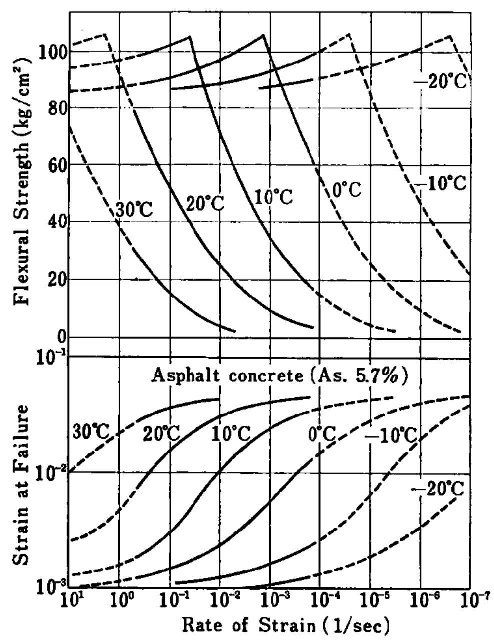

Fig. 6 Mastercurves of Flexural Strength and Strain at Failure vs. Rate of Strain

the movement of the transition point. A semi-logarithmic relationship was obtained in various types of bituminous mixtures. In ductile failure, there is an appreciable flow of material before a separation of specimen occurs, whereas in brittle failure, there is no plastic flow in the specimen.

A relation between strain at failure and flexural strength of asphalt concrete where five different rates of strain are employed is shown in **Fig. 5**. This curve shows a chevron shaped curve and its relation is independent of the rate of strain and temperature.

Based on the above concept, **Fig. 6** is obtained from the test results of the same mixtures. **Figure 6** shows that the composite master curves of strength vs. rate of strain and strain at failure vs. rate of strain were obtained as horizontal translation with respect to the rate of strain scale. This concept is quite similar to that of the time-temperature superposition principle of T.L. Smith on plastic materials subjected to tension test[8].

3.3 Effect of Type of Mixture

Type of mixture, particularly such as gradings of aggregate, binder content and void content, is also an important factor that affects the rheological properties of bituminous mixtures. **Fig-**

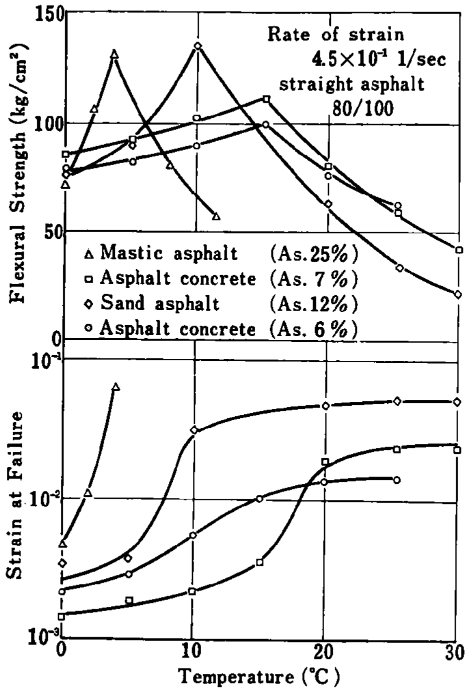

Fig. 7 Flexural Strength and Strain at Failure of Each Type of Bituminous Mixture

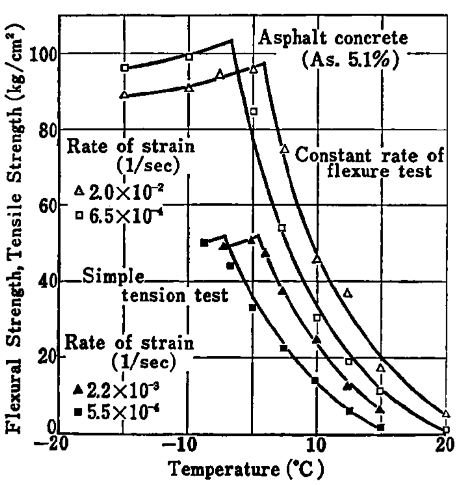

Fig. 8 Flexural Strength and Tensile Strength of Asphalt Concrete in Constant Rate of Flexure Test and Simple Tension Test

ure 7 shows the results obtained from the constant rate of strain flexure tests on four types of bituminous mixtures composed of the same binder. Generally, the strength decreases considerably in mastic type and sand asphalt type mixtures as a result of temperature drop in the elastic failure zone. This may be attributed to the lack of interlocking action of the coarse aggregate. When a bituminous mixture is composed of finer aggregate and has a richer binder content, the transition point moves toward the lower temperature side, and there is about 10°C difference between the mastic type and asphalt concrete type mixtures.

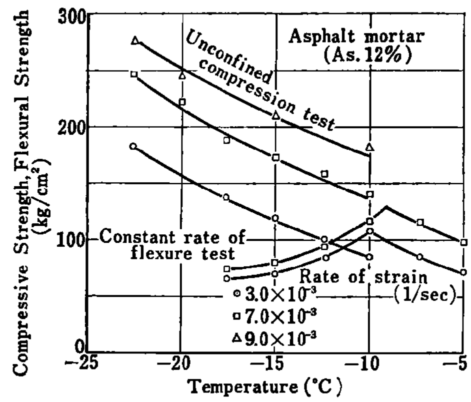

Fig. 9 Compressive Strengths and Flexural Strengths of Asphalt Mortar in Constant Rate of Flexure Test and Unconfined Compression Test

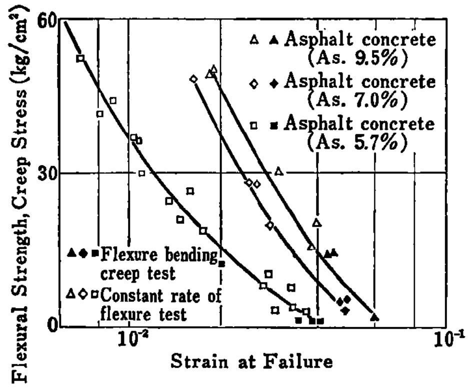

Fig. 10 Relation between Flexural Strength and Creep Stress and Strain at Failure

3.4 Failure Behavior and Loading Condition

It is important that mechanical properties of the materials be determined over a wide range of different states of stress.

Figures 8, 9 and **10** show the effects of stress conditions on strength and strain at failure. It appears that strength and strain at failure of bituminous mixtures are affected by stress conditions in the brittle failure zone rather than in the ductile failure zone.

At the transition point, strain at failure, strength and stiffness at failure of a bituminous mixture depend only upon the aggregate volume concentration of the bituminous mixture, but they are independent of the rate of strain (**Fig. 11**). At the transition point, flexural strength, strain at failure and stiffness at failure of asphalt concrete (C_v=0.86) resulted in (115±15) kg/cm²,

$(5\pm1)\times10^{-3}$, $(2\pm1)\times10^{4}$ kg/cm², respectively, independently of the test temperature.

On the other hand, the strain at failure of asphalt concrete with $C_V=0.86$ may converged to 1×10^{-3} at the lower temperature side, whereas the strain at failure of mastic asphalt below $C_V=0.7$ may be in a range of $(2\sim5)\times10^{-3}$ at low temperatures (**Fig. 12**).

4 Effects of Binder Property

Various binders with different rheological properties were applied to asphalt concrete and mastic asphalt, and their failure properties were investigated[9]. The changes in the rheological properties of binder are as follows:

Case-1 Change in penetration with constant P.I.
Case-2 Change in P.I. with constant penetration
Case-3 Change in P.I. and penetration

Case-1

Table 3 shows the test results on mastic asphalt obtained by constant rate of strain flexure test. It shows that the temperature difference between the softening point of binder and the transition point of its mixtures is nearly equal to 42～44°C. In this case, when penetration decreases and softening point rises, the brittle point moves toward the higher temperature side.

Case-2

Table 4 shows the changes of rheological properties which are represented by P.I. and the Fraass breaking point on the movement of the transition point of mastic asphalt composed of the same penetration of the binder. The temperature differences between the Fraass breaking point of binder and transition points of its mix-

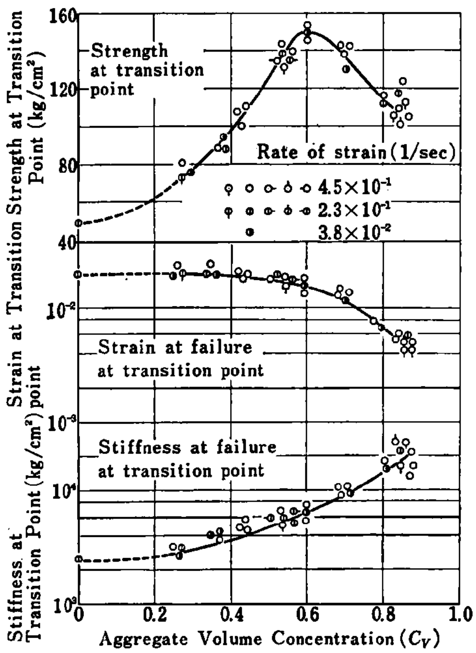

Fig. 11 Relation between Strength, Strain, and Stiffness at Transition Point and Aggregate Volume Concentration

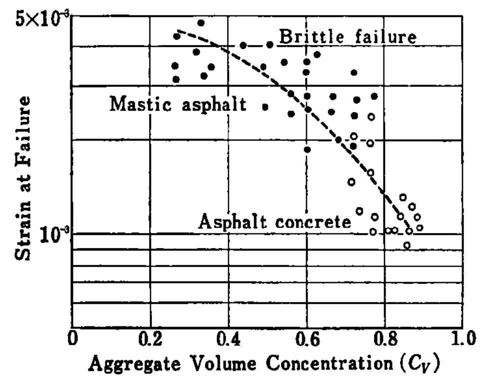

Fig. 12 Relation between Strain at Failure and Aggregate Volume Concentration

Table 3 Relation between Penetration and Transition Point of Mastic Asphalt* (P.I. Constant)

Number	No. 1	No. 2	No. 3	No. 4
Penetration (25°C, 100g, 5sec)	54	69	93	106
Softening Point (°C)	54.3	52.0	47.8	47.1
P.I. of Binder	0	0	0	0
Transition Point of Mixture (°C)	10	7.5	6.5	5.5

* Composition of Mastic Asphalt (wt%): Asphalt 25, Filler (below 0.074mm) 25, Sand (0.3～0.1mm) 50

Table 4 Effects of P.I. and Fraass Breaking Point on the Transition Point of Mastic Asphalt* (Pen. Constant)

Number	No. 1	No. 2	No. 3	No. 4	No. 5
Penetration (25°C, 100g, 5sec)	93	91	91	92	88
Softening Point (°C)	43.0	44.7	45.4	45.3	47.3
P.I. of Binder	−1.7	−1.2	−1.0	−0.9	−0.5
Fraass Breaking Point (°C)[a]	−11	−12	−14	−15	−19
Transition Point of Mixture (°C)[b]	12	9	8	8	4
Temperature Difference (°C)[b)-a)]	23	21	22	23	23

* Composition of Mastic Asphalt (wt%): Asphalt 25, Filler (below 0.074mm) 25, Sand (0.3～0.1mm) 50

Table 5 Effects of P.I. and Penetration of Asphalt on Transition Point of Mastic Asphalt*

Number	No. 1	No. 2	No. 3	No. 4	No. 5
Penetration (25°C, 100g, 5sec)	48	61	81	84	93
Softening Point (°C)	69.9	60.0	52.3	67.9	46.8
P.I. of Binder	2.6	1.6	0.7	4.0	−0.5
Fraass Breaking Point (°C)	−22	−21	−20	−34	−21
Transition Point of Mixture (°C)	16	14	12	0	17

* Composition of Mastic Asphalt (wt%): Asphalt 25, Filler (below 0.074mm) 25, Sand (0.3∼0.1mm) 50

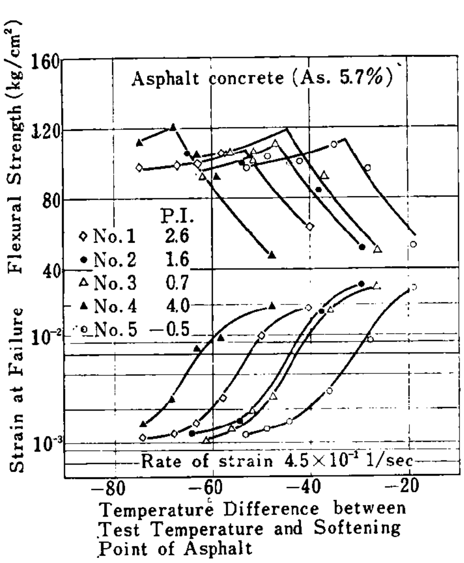

Fig. 13 Effect of Binder Property on Strain at Failure and Flexural Strength

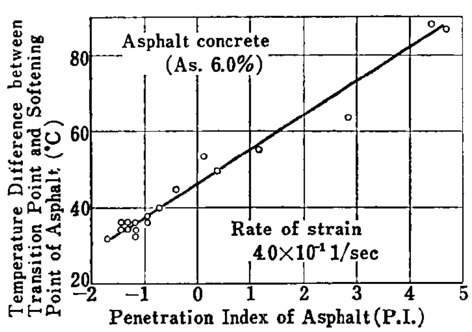

Fig. 14 Penetration Index of Asphalt vs. Temperature Difference between Transition Point of Asphalt Concrete and Softening Point of Asphalt

tures are nearly equal to 21∼23°C. It is clear that the lower the Fraass breaking point is, the lower the transition point. It may be expected that these temperature differences depend slightly on the rate of strain, and the higher the P.I. is, the lower the transition point.

Case-3

Tables 3, 4, 5 show the test results of mastic asphalt, and **Fig. 13** and **14** show the test results of asphalt concrete obtained by means of the constant rate of flexure test. It appears that the

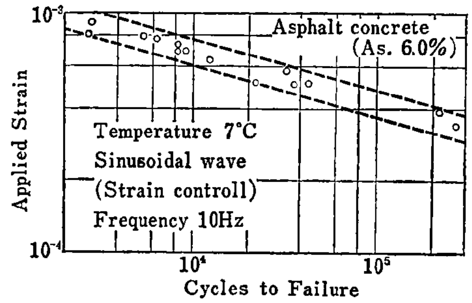

Fig. 15 Effect of Applied Strain on Cycles to Failure

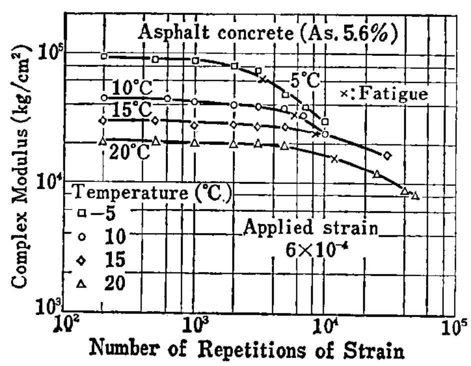

Fig. 16 Effect of Temperature on Complex Modulus and Fatigue Life

transition points of bituminous mixtures depend on P.I. and softening point of the binder. It has also been noted that the higher the P.I. of binder, the larger will be the temperature differences between the softening and brittle points of the mixtures, and that the relationship between these temperature differences and P.I. of binder seems to be linear (**Fig. 14**).

5 Repeated Applications of Load

In many instances, it is found that the majority of pavements do not fail by single loading, but fatigue failure appears at relatively low temperatures where the dominating factor affecting fatigue life is the applied strain and stress. Therefore, the endurance limit, i.e. the load which the material will support indefinitely regardless of the number of applications, can be determined by repeated applications of load.

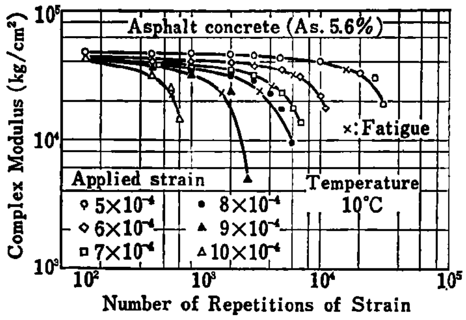

Fig. 17 Effect of Applied Strain on Complex Modulus and Fatigue Life

The apparatus for repeated applications of load adopted in this study was constructed originally by the author[10] (**Table 2**).

The effects of the level of applied strain on cycles to failure at 7°C are shown in **Fig. 15.** The plots show that the higher the level of applied strain is, the smaller cycles to failure.

Figure 16 shows the change of complex modulus of asphalt concrete under repeated loadings at various temperatures. While, **Fig. 17** shows the relationship between the drop of complex modulus and number of repetitions of strain under various levels of strain. It may be that the level of applied strain and temperature affects considerably the drop of complex modulus and fatigue life of asphalt concrete.

6 Conclusion

Following conclusions were obtained in this study.

(1) Modes of failure of bituminous mixtures under single load application tests under various loading and temperature conditions were classified into three types, namely, brittle failure, failure at transition zone and viscoelastic (ductile) failure.

(2) The strength-temperature curve shows a chevron shaped curve and the failure mode at the peak point of this curve corresponds to the failure mode in the transition zone.

(3) The strain at failure-temperature curve shows a gentle S-shaped curve and stiffness at failure decreases with increase in temperature.

(4) The transition point shifts toward the higher temperature side when the rate of strain is increased.

(5) The variables which lead to the movement of the transition point are a) rate of strain, b) rheological properties of binder, c) aggregate volume concentration (or type of mixture), d) state of stress; and the degree of movement of the transition point depends upon the degree of change of each variable.

(6) For asphalt concrete ($C_v=0.86$), the strain at failure in single load application tests is in the order of 10^{-3} to 10^{-2}, depending upon the loading conditions and temperature.

(7) It appears that the concept of time-temperature superposition principle is applicable to the failure behavior of asphalt concrete.

(8) The cycles to failure depends upon the applied strain under repeated applications of load.

(9) The increase in the number of repetitions of strain results in a considerable decrease in complex modulus of mixtures.

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