Effectiveness of High-ductility Modified Asphalt for Earthquake Resistant Reinforcement of Asphalt Sealing Dam

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ABSTRACT: Being higher in ductility than cement concrete and excellent in responsivity to the deformation of the dam body, asphalt concrete is applied for sealing of earth dams and rock filled dams. In Japan, since the introduction of asphalt facing technology from Germany in the latter half of the 1960s, this technology has been field proven at more than 10 high-dams (dam height: 15 m or more) and at many other places including medium- and small-scale storage reservoirs. The earth dam with asphalt surface shielding, i.e., one of the high-dams, located in Shizuoka Prefecture was struck by a medium-scale earthquake about 25 years after the start of its operation and suffered damage mostly by cracking regarded as the cause of this earthquake. For repair work of the asphalt facing, an asphalt concrete having deformation responsivity able to cope with large-scale earthquakes was called for. Therefore, we developed a high-ductility modified asphalt and applied it in the repair work for this dam.As compared with straight asphalt, the developed modified asphalt is 1/4 to 1/10 in stiffness (S value) by BBR tests, twice in m-value and excellent in deformation responsivity and stress relaxing capability. Moreover, according to the results of unconfined compression tests and flexural tests, the asphalt concrete with developed asphalt shows a fracture strain about 4-7 times as great as that of the conventional asphalt concrete, which shows that the developed asphalt has a high ductility.

KEY WORDS: Asphalt facing, Asphalt sealing Dam, Earthquake, Modified asphalt, repair work

1 INTRODUCTION

In Japan, a quake-prone country, there are not a few earth dams and reservoirs with asphalt facing because asphalt mixtures are excellent in deformation responsivity. After the lapse of about 40 years since the introduction of the asphalt facing technology into the country, cracks and other damages resulting from the degradation of asphalt facings and linings have appeared here and there in those dams and reservoirs constructed at first after the introduction of the technology. In the event that such dams and reservoirs are stricken by a giant earthquake, it is highly possible that damages to the surface of asphalt facing (hereinafter referred to as the asphalt impervious layer) will develop due to rapid and large deformation of the dam and reservoir bodies and degrade the sealing capability, making it impossible to ensure the safety of the dams and reservoirs.

In March 1996, an earthquake of magnitude 5.8 occurred, originating from the vicinity of Lake Kawaguchi in Yamanashi Prefecture, and struck one (HF dam) of the internally paved type uniform fill dams, located in Shizuoka Prefecture southwest of Tokyo at a distance of about 15 km from the earthquake source. According to the results of the survey after this earthquake, noticeable damages detrimental to the soundness of the dam were not discovered in the dam body, but cracks were detected in the asphalt facing. Therefore, it was decided to carry out a full-scale repair work. For the repair design of this dam, it was requested to consider details about the occurrence of damages and make the asphalt facing so high in ductility as to be able to respond to the deformation of the dam body by earthquake shocks, should the dam be stricken again by a great earthquake after completion of the repair work

With this as background, we developed a high-ductility modified asphalt improved in deformation responsivity and stress relaxing capability and applied it to the asphalt impervious layer.

This paper presents the laboratory investigation results on the effectiveness of the developed high-ductility modified asphalt (hereinafter referred to as the SFAs) in reinforcing the quake resistance of the asphalt facing.

2 DEVELOPMENT OF HIGH-DUCTILITY MODIFIED ASPHALT (SFAs)

As is well known, asphalt is a material with temperature dependency. Though high in ductility at high temperatures, this material decreases in ductility and embrittles at low temperatures. Therefore, the conventional asphalt impervious layer is so high in ductility at high temperatures in summer etc. as to be able to respond to rapid and large deformation of the dam body by earthquakes. While at low temperatures in winter etc., it decreases in ductility and may exhibit a brittle behavior leading to fracture, depending on the temperature region and deformation speed particularly in the case of rapid and large deformation of the dam body like its behavior at earthquake.

The developed SFAs uses as the main modifier a styrene-butadiene-styrene block (SBS), one of the thermoplastic elastomers widely used for field-proven modified asphalts for road paving and is improved particularly by decreasing the temperature susceptibility so as to have a high ductility in a wide temperature region from high to low temperatures.

The SBS used as the main modifier is a material which imparts a high modifying effect by forming a continuous network of rubber with a relatively small addition amount - because it swells by adsorbing the marten content of asphalt. The SFAs is a material improved in both ductility at low temperatures and deformation resistance (slope stability) at high temperatures by increasing the addition amount of SBS and using a special additive together with it.

The basic properties of the SFAs are shown in Table 1.

Table 1: Basic properties of SFAs

Item	Unit	SFAs	StAs60/80
Penetration	1/10mm	177	69
Softening point	°C	84.0	48.0
Viscosity at 60°C	Pa･s	11,300	208
Flexural strain (−10°C)	($\times 10^{-3}$)	384	49

The SFAs is great in penetration and high in softening point as compared with straight asphalt 60/80 (hereinafter referred to as the StAs 60/80) generally used for impervious asphalt mixtures, so its temperature susceptibility is very low. Moreover, the viscosity at 60°C of this material is very high, which is also one of its characteristics. The viscosity at 60℃ is one of the engineering parameters representing the consistency of asphalt. Being high in this viscosity, this material is high in deformation resistance to plastic flow and therefore can be expected to improve the slope stability of the asphalt impervious layer in summer when the temperature in the vicinity of the pavement surface rises up to about 60℃. In addition, its flexural strain at –10℃ is about 8 times as great as that of the StAs 60/80, which shows that its flexibility at low temperatures is very high.

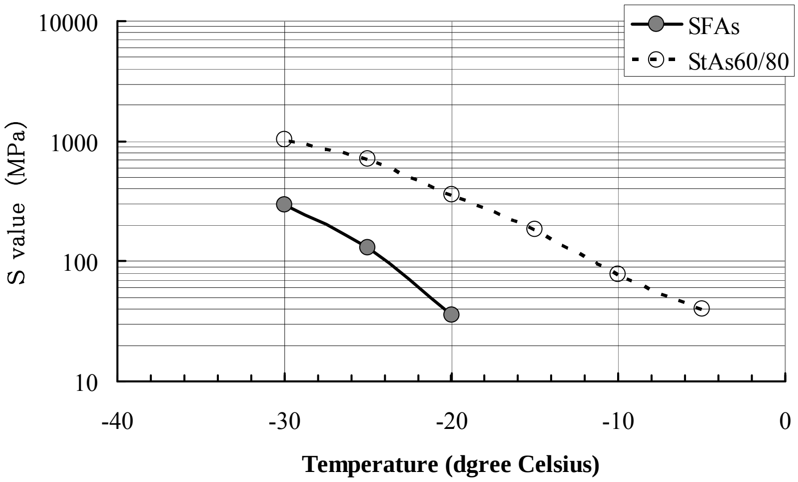

Figure 1: BBR Test Results (S-value)

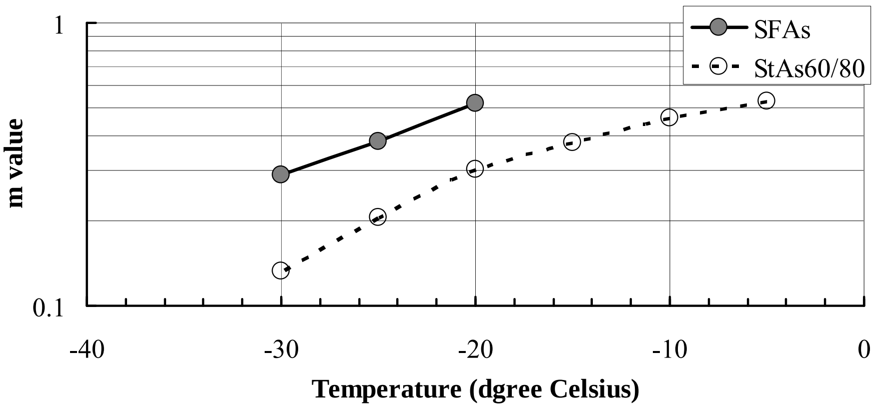

Figure 2: BBR Test Results (m-value)

Figure 1 and 2 show the stiffness (S-value) and m-value determined by bending beam rheometer test (hereinafter referred to as the BBR test). The SFAs is similar to the StAs 60/80 in both S-value and m-value in the temperatures region lower by 10℃ or more than that of the StAs 60/80, which shows that this material is improved in low-temperature brittleness and stress relaxing capability.

3 EFFECTIVENESS OF SFAs FOR REINFORCING QUAKE RESISTANCE OF ASPHALT FACING

The effectiveness of the SFAs for reinforcing the quake resistance of the asphalt facing was evaluated through a laboratory experiment of the impervious asphalt mixture with the SFAs (hereinafter referred to as the SFAs mixture). The laboratory tests and evaluation items used for investigation are as shown below.

The mix proportion of the impervious asphalt mixture subjected to the laboratory tests is shown in Table below:

Table 2: Mix proportion of impervious asphalt mixture

Asphalt content (%)	Vegetable fiber (%)	Mixing ratio of aggregates (% by weight)				
		Crushed stone 13-5mm	Crushed stone 5-2.5mm	Coarse sand	Fine sand	Stone dust
8.5	0.15	24.0	16.5	37.5	8.0	14.0

Note: The vegetable fiber used is arbocel ZZ8/1. The addition amount is expressed as a percentage to 100% of mixture.

(1) Flexural test: deformation responsivity, low-temperature brittleness
(2) Low-temperature cracking test: stress relaxing capability
(3) Repeated load test: deformation responsivity, stress relaxing capability
(4) Slope flow test: slope stability (resistance to plastic flow)

3.1 Flexural Test

3.1.1 Test method

In the flexural test, the flexural strength and fracture strength of the asphalt mixture were measured, the deformation responsivity was evaluated by the fracture stress-fracture strain curve and the low-temperature brittleness was evaluated from the brittle point (peak temperature for flexural strength) obtained from the flexural strength-temperature curve.

The test conditions are shown in Table3.

Table 3: Flexural test conditions

Item	Specification
Specimen size (mm)	50×50×300
Loading condition	3-point loading
Span (mm)	200
Test temperature (℃)	-30～15(every 5℃)
Loading speed (mm/min)	0.05, 0.5, 5.0, 50

3.1.2 Test results

Figure 3 shows the relation between fracture strain and fracture stress in the flexural test.

As seen from the table, the fracture strain of the SFAs is greater than that of the impervious asphalt mixture with StAs 60/80 (hereinafter referred to as the StAs 60/80 mixture) at any fracture stress. Therefore, this material has a high deformation responsivity.

Figure 4 shows the flexural strength in the test with the highest loading speed of 50 mm/min. By comparing the brittle points obtained from the flexural strength-temperature curve, it can be known that the brittle point of the SFAs mixture is lower by 15℃ or more than that of the StAs 60/80 mixture, so this material is excellent in low-temperature brittleness.

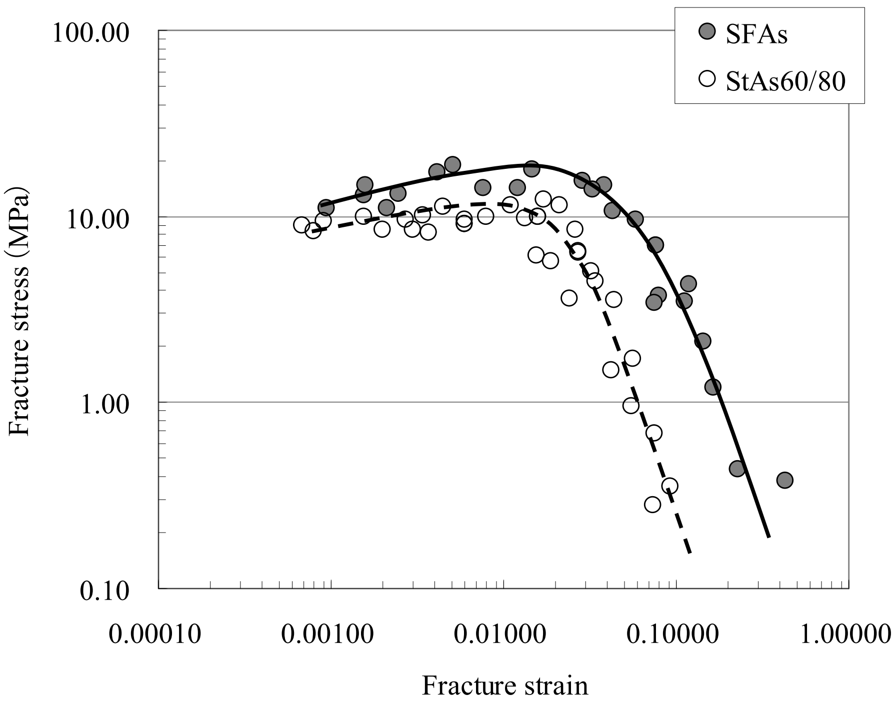

Figure 3: Fracture stress vs. fracture strain

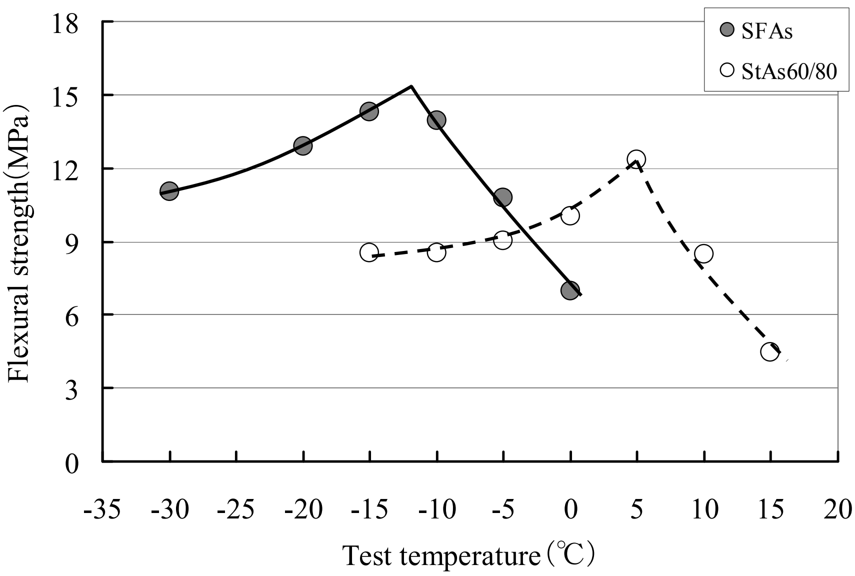

Figure 4: Flexural strength (loading speed: 50 mm/min)

3.2 Low-Temperature Cracking Test

3.2.1 Test method

Te low-temperature cracking test is a test by which to determine variations in stress generated at varying temperatures when the asphalt mixture is cooled down at a given temperature gradient. This test was done chiefly for the purpose of evaluating the stress relaxing capability.

In this test, a rod-like specimen (25 x 25 x 250 mm) bound at both ends by a steel jig made of invar is cooled at a given temperature gradient (in the present test, the starting temperature was 10℃ and the temperature gradient was –3℃/hour) and the stress generated in the specimen is calculated from the strain measured by the steel jig. A schematic view of the test is shown in Figure 5. The relation between temperature and generated stress in this experiment ca be explained by the curved-line section and straight-line section in the schematic view of Figure 6. The curved-line section is the temperature region in which the stress relaxing capability of the asphalt mixture develops and the specimen stress relaxes gradually. With further decrease in temperature, the stress relaxing capability disappears and an elastic behavior appears. Therefore, the ratio of stress generation to temperature variation changes linearly, finally resulting in fracture. Here, the temperature at which the transition from the curved-line section to the straight-line section of the temperature-generated stress curve occurs is referred to as the stress relaxation limit point, and the temperature at which fracture results is referred to as the fracture point.

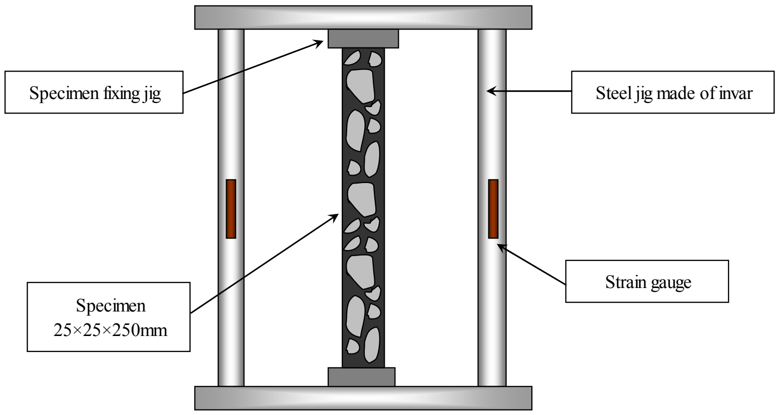

Figure 5: Schematic view of low-temperature cracking test

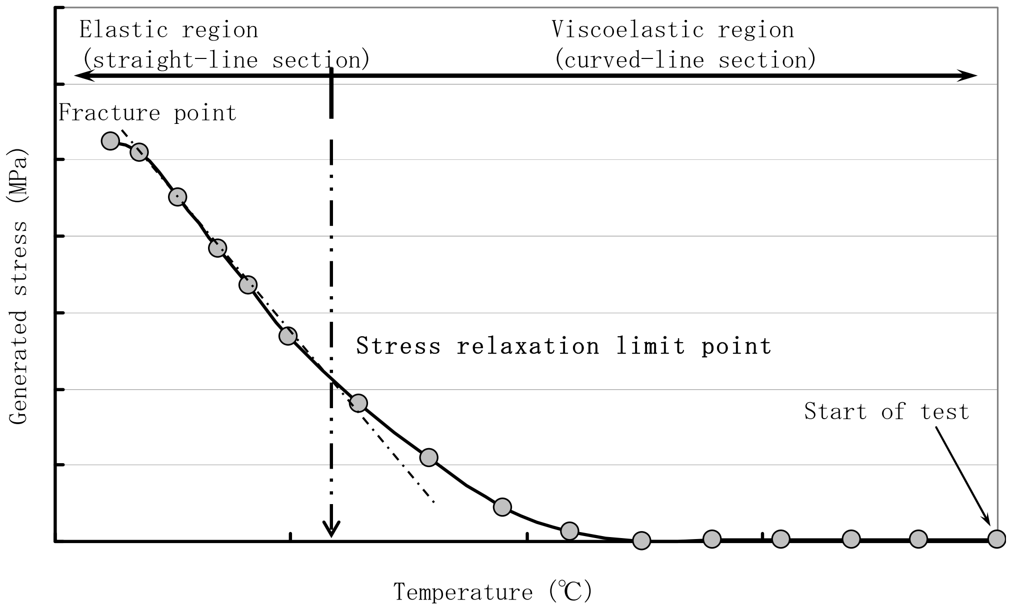

Figure 6: Schematic view

3.2.2 Test results

Figure 7 shows the results of the low-temperature cracking test performed under the above-mentioned test conditions. The stress relaxation limit point shown by an arrow in the middle of Figure 7 is about -30℃ for the SFAs and about –18℃ for the StAs 60/80. Thus, the SFAs is lower by 10℃ or more in stress relaxation limit point , so its stress relaxing capability at low temperatures is high.

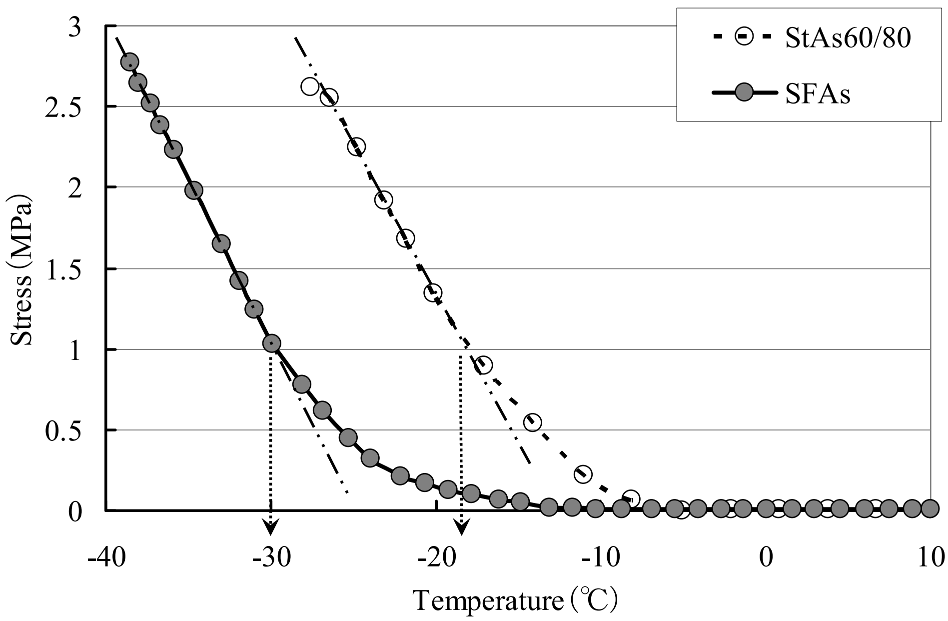

Figure 7: Results of low-temperature cracking test

3.3 Repeated Load Test

3.3.1 Test method

The repeated load test was carried out, and the responsivity to deformation repeated by earthquake shocks and the capability of relaxing the resulting stresses were evaluated from the relation between stress and strain, number of load cycles to fracture, etc.

This test is an axial tensile test. Therefore, a dumbbell-like specimen as shown in Figure 8 was fabricated by using a special mold form and an electric small tamper to prevent stress concentration at the fixed parts of the specimen. The test conditions are shown in Table 4.

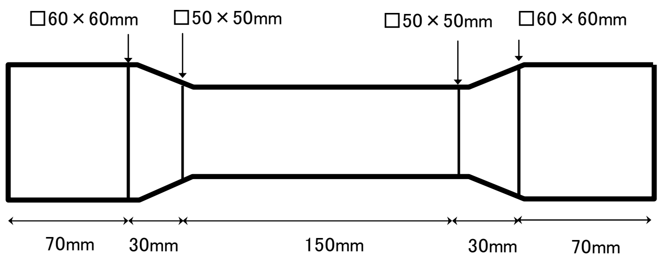

Figure 8: Shape of specimen

Table 4: Test conditions

Control method	Strain control
Waveform	Sine wave
Frequency (Hz)	1, 2, 4
Test temperature (degree Celsius)	0

3.3.2 Test results

Figure 9 shows a hysteresis loop of stress (σ)-strain (ε) at 1, 10 and 20 load repetitions and at fracture for the StAs 60/80 mixture and SFAs mixture, selecting the test results that are nearly equal in the number of load cycles.

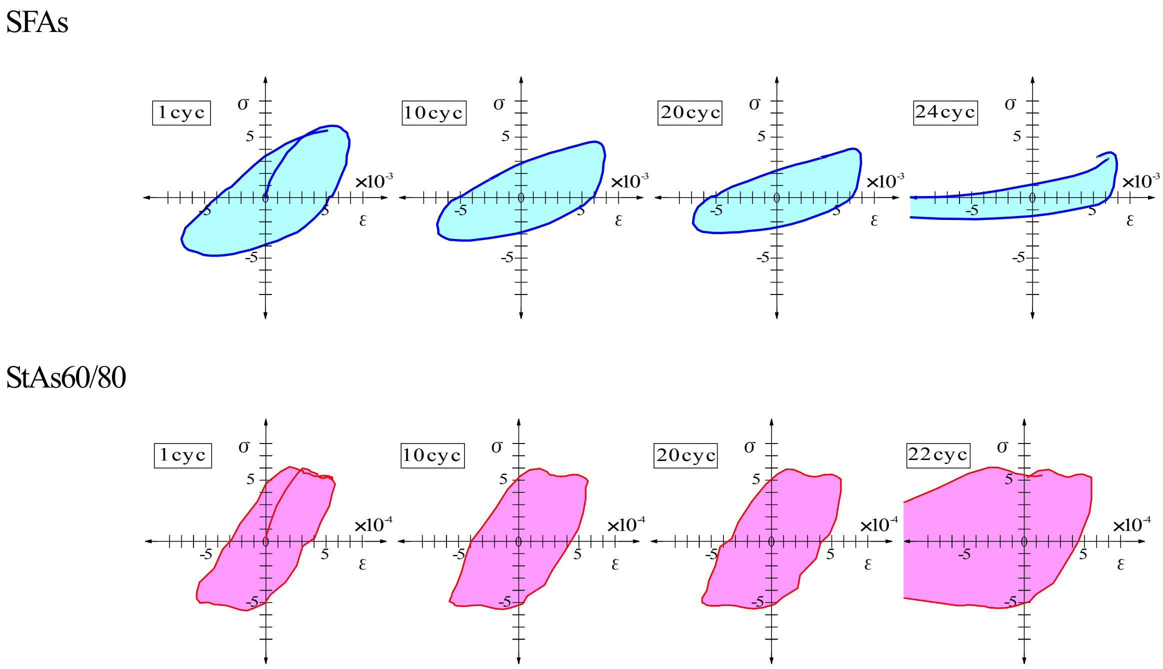

Fig. 9: Number of load cycles and Hysteresis Loop of stress-strain

The values of strain and number of load cycles applied in the experiment in which the relevant results were obtained are as sown below. It is clear that the strain of the SFAs mixture is 10 times or more as great as that of the StAs 60/80 mixture.

SFAs mixture	No. of load cycles to fracture = 24
StAs 60/80 mixture	No. of load cycles to fracture = 22

As seen from Figure 9, the peak axial stress of the SFAs mixture decreases with increasing number of load cycles and the area enclosed by the loop decreases gradually, while that of the StAs 60/80 mixture virtually does not decrease with the number of load cycles and the shape of the hysteresis loop remains unchanged until fracture results.

Next, Figures 10 shows the relation between the peal value of tensile stress (σpi) at each cycle and the number of load cycles for the SFAs mixture and StAs mixture. The data on theY-axis is normalized by dividing the value of σti by the value of σt1 at the first cycle and the data on the X-axis by dividing the number of load cycles (Ni) by the number of load cycles at fracture (Nf). As seen from Figure 10, the ratio of stress decrease at fracture by loading for the SFAs mixture is in the range of σpi / σti = 0.2-0.7. On the other hand, the StAs 60/80 mixture is small in stress decrease to fracture and exhibits brittle decay leading to fracture by slight stress decrease.

From these results, it is assumed that when the deformation of the dam body by earthquake shocks is repeated at a low number of cycles, the allowable strain of the SFAs mixture is greater than that of the StAs 60/80 mixture and the ratio of stress generation to the repeated deformation is also greater though there may be variations with conditions such as deformation speed, degree of strain and number of load cycles to fracture. On the other hand, the StAs 60/80 mixture virtually does not exhibit stress decrease to fracture, but is presumed to exhibit brittle fracture leading to fracture by slight stress decrease. That is, the SFAs mixture is considered to be high in deformation responsivity and stress relaxing capacity as compared with the StAs 60/80 mixture.

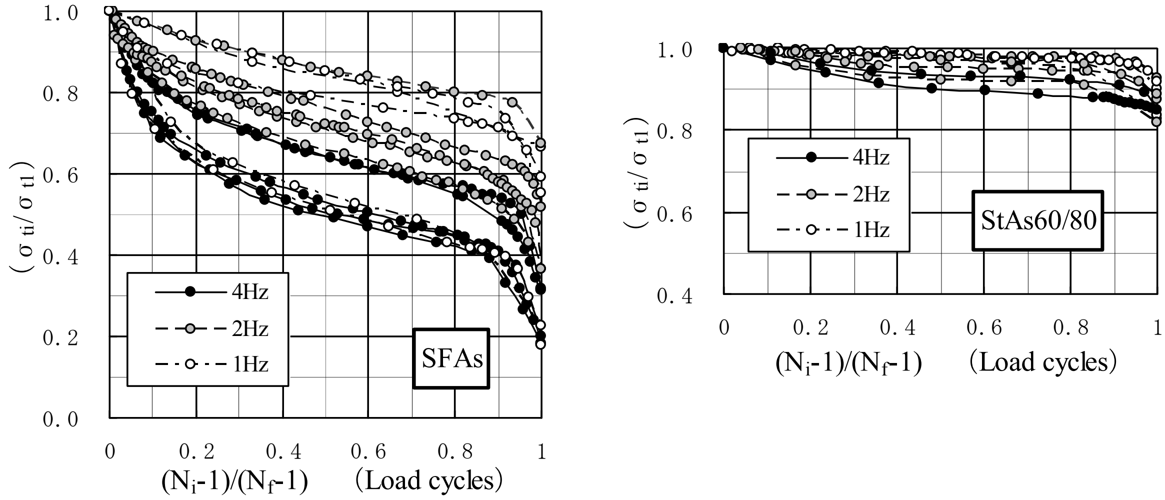

Fig. 10: Peak value of tensile stress vs. number of load cycles

3.4 Slop Flow Test

3.4.1 Test method

On the slope of the asphalt facing at high temperatures in summer etc., there may be cases where dripping called the slope flow takes place under the dead weight. The occurrence of the slope flow results in increasing voids and stripping off asphalt due to dilatancy and constitutes a factor leading to degradation of the sealing property. Therefore, the slope flow test was done to evaluate the slope stability.

This test is carried out in the following way. That is, the test temperature is set at 60℃, assuming the highest surface temperature in summer in the country. The asphalt mixture specimen (90 x 250 x 50 mm) is placed on a stand inclined with the slope gradient (1:25 (about 22o) in the present test) of the asphalt facing subject to evaluation, and the flow value of the specimen toward the underpart of the slope is measured.

3.4.2 Test results

The results of the slope flow test are given in Table 5.

The SFAs mixture exhibits a flow value of about 1/3 that of the StAs 60/80 mixture and is high in resistance to plastic flow at high temperatures under service conditions, so it is excellent in slope stability.

Table 5: Results of slope flow test (1/10mm)

Type	Flow value after 24 hours	Flow value after 48 hours
SFAs mixture	68	68
StAs 60/80 mixture	191	191

5 CONCLUSIONS

A summary of the information obtained from laboratory tests is given below:

(1) The SFAs is large in penetration and high in softening point as compared with the StAs 60/80, so it is very

low in temperature susceptibility.

(2) The SFAs is about 8 times as high as the StAs 60/80 in flexural strain and very high in flexibility in the low-temperature region.

(3) The SFAs exhibits similar values in terms of stiffness and m-value by the BBR test in the temperature region lower by 10℃ or more as compared with the StAs 60/80, so it is improved in low-temperature brittleness and stress relaxing capability.

(4) The fracture strain by the flexural test of the SFAs mixture is greater than that of the StAs 60/80 mixture at any fracture stress, so the SFAs mixture has a high ductility.

(5) The brittle point by the flexural test of the SFAs mixture is lower by 15℃ or more than that of the StAs 60/80 mixture, so the SFAs mixture is excellent in low-temperature brittleness.

(6) The SFAs mixture is lower by 10℃ or more than the StAs 60/80 mixture in the stress relaxation limit point determined by the low-temperature cracking test, so it is high in stress relaxing capability.

(7) The SFAs mixture is 10 times or more as high as the StAs 60/80 mixture in fracture strain in the repeated load test, so it is high in deformation responsivity.

(8) The StAs 60/80 mixture exhibits brittle fracture in the repeated load test, while the SFAs mixture is large in the ratio of stress decrease to repeated deformation, so it is high in stress relaxing capability.

(9) The flow value of the SFAs mixture in the slope flow test is about 1/3 that of the StAs 60/80 mixture, so the SFAs mixture is excellent in slope stability.

(10) The possibility of applying the SFAs mixture for repair work and of manufacturing and applying it in the same manner as the StAs 60/80 mixture was confirmed.

(11) It was also one of the development targets to make it possible to manufacture and apply the SFAs mixture in the same manner as the StAs 60/80 mixture. This possibility could be verified in the present repair work. Now, the service condition is still good though three or more years have passed after completion of the repair work.

As mentioned above, the impervious asphalt mixture using the SFAs developed for the purpose of improving ductility such as deformation responsivity and stress relaxing capability is high in deformation responsivity, stress relaxing capability and low-temperature brittleness. We could confirm that this material is effective for construction and repair of asphalt facings of dams etc. which are expected to encounter a large-scale earthquake.

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