# Thermal Stress Restrained Specimen Test To Evaluate Low-Temperature Cracking of Asphalt-Aggregate Mixtures

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The thermal stress restrained specimen test (TSRST) has been developed as an accelerated laboratory test to evaluate the thermal cracking resistance of asphalt concrete mixtures. This work was conducted at Oregon State University under a Strategic Highway Research Program contract. A statistical analysis of TSRST results indicated that asphalt type and degree of aging have a significant effect on fracture temperature. Air voids content and aggregate type have a significant effect on fracture strength. The fracture temperature of relaxed specimens was colder than that of nonrelaxed specimens. The decrease in fracture temperature because of stress relaxation was significant for stiffer asphalts and not significant for softer asphalts. Fracture strength was lower for relaxed specimens. Fracture temperature was highly correlated with SHRP low-temperature asphalt cement index test results, namely, the limiting stiffness temperature and the ultimate strain at failure. A ranking of asphalt concrete mixtures based on fracture temperature from the TSRST compared favorably with a ranking based on fundamental properties of the asphalt cement.

Low-temperature cracking is attributed to tensile stresses induced in asphalt concrete pavement as the temperature drops to an extremely low temperature. If the pavement is cooled to a low temperature, tensile stresses develop as a result of the pavement's tendency to contract. The friction between the pavement and the base layer resists the contraction. If the tensile stress induced in the pavement equals the strength of the asphalt concrete mixture at that temperature, a microcrack develops at the edge and surface of the pavement. Under repeated temperature cycles the crack penetrates the full depth and across the asphalt concrete layer.

Several factors reported to influence thermal cracking in asphalt concrete pavements may be broadly categorized under material, environmental, and pavement structure geometry. Specific factors under each of these categories are as follows (*1*):

- Material factors, such as asphalt cement (stiffness or consistency), aggregate type and gradation, asphalt cement content, and air voids content;
- Environmental factors, such as temperature, rate of cooling, and pavement age; and
- Pavement structure geometry, such as pavement width and thickness, friction between the asphalt concrete layer and base course, subgrade type, and construction flaws.

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The thermal stress restrained specimen test (TSRST) has been developed as an accelerated laboratory test to evaluate the thermal cracking resistance of asphalt concrete mixtures. The TSRST development work was conducted at Oregon State University under a Strategic Highway Research Program (SHRP) contract entitled "Performance-Related Testing and Measuring of Asphalt-Aggregate Interactions and Mixtures."

The purposes of the research work presented in this paper are to (a) identify a suitable laboratory test or tests that will provide an estimate of the low-temperature cracking resistance of asphalt concrete mixtures, (b) validate another SHRP contractor's hypothesis for low-temperature cracking, and (c) relate fundamental properties of asphalt cement to the thermal cracking characteristics of asphalt concrete mixtures.

## TSRST

A number of test methods have been used to evaluate low-temperature cracking in asphalt concrete mixtures. Vinson et al. (*1*) evaluated the test methods in terms of properties measured, simulation of field conditions, application of test results for use in existing mechanistic models, and suitability for aging and moisture conditioning. On the basis of the evaluation of the test methods by Vinson et al., TSRST was judged to have the greatest potential to evaluate low-temperature cracking susceptibility of an asphalt concrete mixture. The test has been used successfully by several investigators to characterize the response of asphalt concrete mixtures at low temperatures.

The basic requirement for the test apparatus associated with TSRST is that it must maintain the test specimen at constant length during cooling or temperature cycling. Initial efforts to accomplish this involved the use of "fixed frames" constructed from Invar steel (*2–6*). In general, these devices were not satisfactory because as the temperature decreased the load in the specimen caused the frame to deflect to a degree that the stresses relaxed and the specimen did not fail. Arand (*7*) made a substantial improvement in the test system by inserting a displacement "feedback" loop that insured that the stresses in the specimen would not relax because the specimen length was continuously corrected during the test. The major properties measured in the TSRST are the low-temperature thermal stress characteristics, tensile strength, and fracture temperature under one or more temperature cycles. The TSRST system developed under the SHRP program is shown in Figure 1*a*. The system consists of a load frame, screw jack, computer data acquisition and control system, low-temperature cabinet,

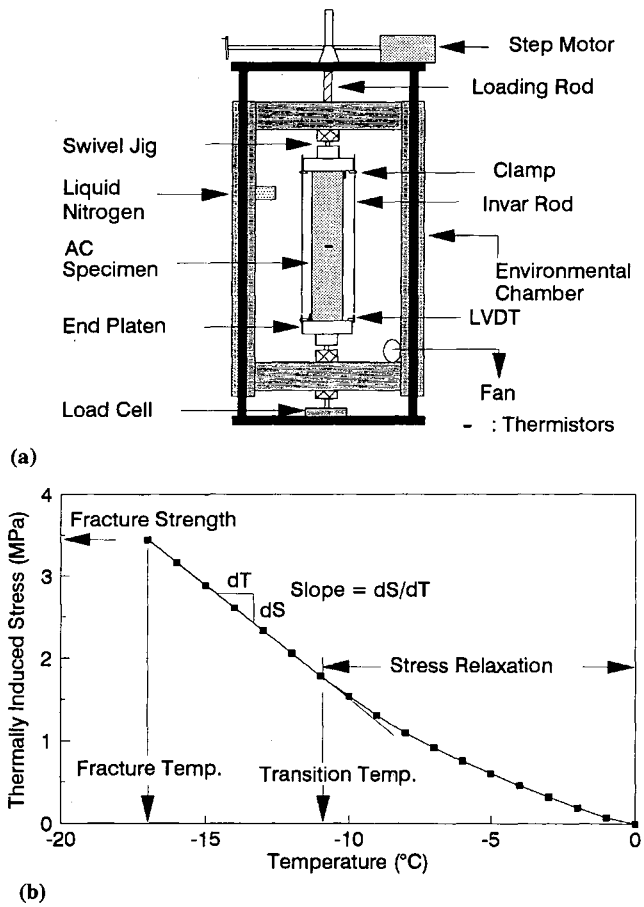


**FIGURE 1 TSRST: (*a*) schematic of apparatus, (*b*) typical results.**

temperature controller, and specimen alignment stand. A beam or cylindrical specimen epoxied to end platens is mounted in the load frame, which is enclosed by the cooling cabinet. The chamber and specimen are cooled with vaporized liquid nitrogen. As the specimen contracts, two linear variable differential transformers (LVDTs) sense the movement, and a signal is sent to the computer, which in turn causes the screw jack to stretch the specimen back to its original length. This closed-loop process continues as the specimen is cooled and ultimately fails. Throughout the test, measurements of elapsed time, temperature, deformation, and tensile load are recorded with the data acquisition system. The detailed specification and test protocol for TSRST are available elsewhere (*8*).

Typical TSRST results are shown in Figure 1*b*. The thermally induced stress gradually increases as the temperature decreases under a constant rate of cooling until the specimen fractures. At the break point, the stress reaches its maximum value, which is referred to as the fracture strength, with a corresponding fracture temperature. The slope of the stress-temperature curve, $dS/dT$, increases until it reaches a maximum value. At colder temperatures, $dS/dT$ becomes constant and the stress-temperature curve is linear. The transition temperature divides the curve into two parts—relaxation and nonrelaxation. As the temperature approaches the transition temperature, the asphalt cement becomes stiffer and the thermally induced stresses are not relaxed beyond this temperature.

## TEST PROGRAM

### Experiment Design

The experiment design was divided into two phases. The experiment design for Phase I was developed to evaluate the suitability of the TSRST to characterize low-temperature cracking of asphalt concrete mixtures. The experiment design for Phase II was developed to measure the relationship between the low-temperature cracking characteristics of asphalt concrete mixtures and fundamental properties of asphalt cement. The test variables and materials employed in each experiment design are shown in Table 1.

### Materials

The asphalts and aggregates involved in the experiment designs were selected from the SHRP Materials Reference Li-

**TABLE 1 Experiment Design**

| Design Variables | Phase I Experiment | Phase II Experiment |
|---|---|---|
| | Levels | Levels |
| Asphalt Type | 4 | 14 |
| Aggregate Type | 2 (RB and RL) | 2 (RC and RH) |
| Aggregate Gradation | 1 (Medium) | 1 (Medium) |
| Aging | None | 2 (STOA and LTOA) |
| Specimen Size | 3.8 x 3.8 x 20.4 cm<br>5.0 x 5.0 x 25.0 cm | 5.0 x 5.0 x 25.0 cm |
| Stress Relaxation | Yes | No |
| Air Voids Content | 2 (4 and 8 %) | 2 (4 and 8 %) |
| Rate of Cooling | 1 (10 °C/hr) | 1 (10 °C/hr) |

brary (MRL). The asphalt cements considered in the Phase I experiment were identified in the SHRP MRL as AAG-1, AAG-2, AAK-1, and AAK-2. On the basis of a consideration of the physical properties of the asphalt cements, the thermal cracking resistance of the mixtures should be AAK-2 (greatest resistance) > AAK-1 > AAG-2 > AAG-1 (least resistance). Mineral aggregates from two sources were identified in the SHRP MRL as RB and RL. The RB aggregate is a crushed granite from California that has a rough surface texture and angular shape (relatively nonstripping); the RL aggregate is a chert from Texas that has a smooth surface texture and round shape.

The asphalt cements considered in the Phase II experiment were selected from several crude sources with a wide range of temperature susceptibility characteristics. Mineral aggregates from two sources were identified in the SHRP MRL as RC and RH. The RC aggregate is an absorptive limestone from Kansas that has a rough surface texture and angular surface; the RH aggregate is a silicious greywacke (high $SiO_2$ content) that has a rough surface texture and angular shape. The asphalt cements considered in the experiment designs are given together with the asphalt grade in Table 2.

### Sample Preparation

A medium gradation for all aggregates was used in preparing asphalt concrete mixtures. The asphalt cement contents (by dry weight of aggregate) used with the RB aggregates were 5.1 percent for asphalts AAK-1 and AAK-2 and 4.9 percent for asphalts AAG-1 and AAG-2; the asphalt cement contents with the RL aggregate were 4.3 percent for asphalts AAK-1 and AAK-2 and 4.1 percent for asphalts AAG-1 and AAG-2. In the Phase II experiment, the asphalt cement content used with the RC aggregate was 6.25 percent for all asphalts; with the RH aggregate it was 5.2 percent for all asphalts. Beam samples (15 × 15 × 40 cm) were prepared using a Cox kneading compactor. Four test specimens (3.8 × 3.8 × 20.3 cm or 5.0 × 5.0 × 25.0 cm) were sawed from each beam sample.

Short-term and long-term aging were performed in a forced draft oven for the Phase II experiment. Short-term oven aging (STOA) was performed on loose mixture at 135°C for 4 hr, and long-term oven aging (LTOA) was performed on compacted specimens at 85°C for 4 days.

## TSRST RESULTS FOR ASPHALT-AGGREGATE MIXTURE

### Phase I Experiment

*Specimens Designated 20.3/3.8RB (3.8 × 3.8 × 20.3 cm)*

Typical thermally induced stress curves observed for two asphalts (AAG-1 and AAK-2) showing extreme fracture temperatures are compared in Figure 2*a*. AAG-1H and AAK-2H indicate higher air voids content, and AAG-1L and AAK-2L indicate lower air voids content. Thermally induced stresses develop more rapidly, and the relaxation of the stresses ceases at a warmer temperature in specimens with stiffer asphalt. Thus, the stress in specimens with stiffer asphalt will equal the strength of the specimens at a warmer temperature, thereby resulting in fracture at a warmer temperature. On the basis of a statistical analysis of the results, specimens with lower air voids fracture at higher stress levels, and the fracture temperature tends to be slightly warmer.

*Specimens Designated 25/5RB and 25/5RL (5.0 × 5.0 × 25.0 cm)*

Typical thermally induced stress curves observed for specimens with two asphalts (AAG-1 and AAK-2) with different aggregates (RB and RL) are compared in Figure 2*b*. Specimens with RL aggregate tend to fracture at a warmer temperature and lower stress level. On the basis of a statistical analysis of the results, fracture strengths are greater for specimens with higher air voids, but no significant difference in fracture temperature between specimens with higher and lower air voids was noted.

*Stress Relaxation*

Stress relaxation tests were performed to investigate the effect of stress relaxation on the low-temperature cracking characteristics of asphalt concrete mixtures. Stresses were relaxed at −22°C for specimens with asphalts AAK-1 and AAK-2 and at −14°C for asphalts AAG-1 and AAG-2 for 6 hr while cooling the specimen at 10°C/hr.

**TABLE 2 Asphalt Cements Used in Experiment Designs**

| MRL Code | AAA-1 | AAB-1 | AAC-1 | AAD-1 | AAF-1 | AAG-1 |
|---|---|---|---|---|---|---|
| Grade | 150/200 | AC-10 | AC-8 | AR-4000 | AC-20 | AR-4000 |
| MRL Code | AAG-2 | AAK-1 | AAK-2 | AAL-1 | AAM-1 | AAV-1 |
| Grade | AR-2000 | AC-30 | AC-10 | 150/200 | AC-20 | AC-5 |
| MRL Code | AAW-1 | AAX-1 | AAZ-1 | ABC-1 | | |
| Grade | AC-20 | AC-20 | AC-20 | AC-20 | | |

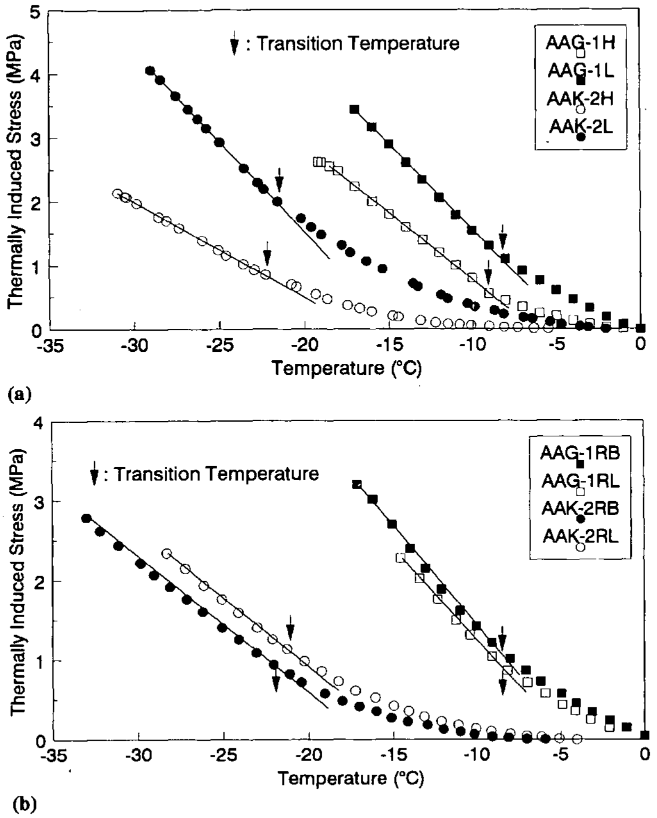


**FIGURE 2 Typical stress-temperature curves: (*a*) 20.3/3.8RB, (*b*) 25/5RB and 25/5RL.**

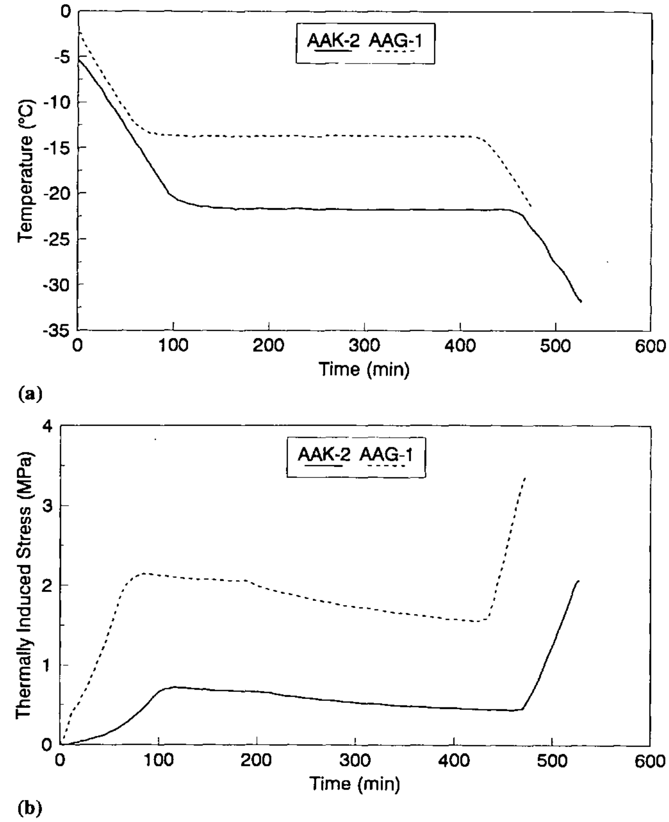


**FIGURE 3 Typical results in stress relaxation test: (*a*) cooling schedules, (*b*) stress variations with time.**

Figure 3*a* presents typical cooling procedures employed in the stress relaxation test. Typical thermally induced stress curves observed from the tests are shown in Figure 3*b*. Initially, stresses in the specimen increase as the temperature is lowered. When the temperature is held constant, the stresses are relaxed. After the relaxation period, stresses increase again upon cooling. On the basis of a statistical analysis of the results, fracture strengths following a stress relaxation cycle are greater for specimens with lower air voids, and no significant difference in fracture temperature was noted.

## Phase II Experiment

### *Fracture Temperature*

Figure 4 shows variations of fracture temperatures (warmest, coldest, and mean) for STOA and LTOA specimens depending on asphalt type for the RC aggregate. The fracture temperatures exhibited a wide range depending on asphalt type. The mean fracture temperatures of specimens with RC aggregate ranged from −32.1°C (AAA-1) to −18.6°C (AAF-1) for STOA and from −27.8°C (AAA-1) to −13.6°C (AAG-1) for LTOA. For specimens with RH aggregate, mean fracture temperatures ranged from −32.2°C (AAA-1) to −16.3°C (AAG-1) for STOA and from −29.3°C (AAA-1) to −13.6°C (AAG-1) for LTOA. The fracture temperature was coldest for specimens with asphalt AAA-1 and warmest for specimens with asphalt AAF-1 or AAG-1.

### *Fracture Strength*

Figure 5 shows variations of fracture strengths (highest, lowest, and mean) for STOA and LTOA depending on the asphalt type for the RC aggregate. The fracture strengths exhibited a wide range depending on the asphalt type. The mean fracture strengths of specimens with RC aggregate ranged from 1.9 to 2.9 MPa for STOA and from 2.1 to 2.9 MPa for LTOA. For specimens with RH aggregate, mean fracture strengths ranged from 2.6 to 3.5 MPa for STOA and from 2.0 to 3.4 MPa for LTOA.

## STATISTICAL ANALYSIS OF TSRST RESULTS

Statistical analyses were performed using Statistical Analysis System (SAS) (*9*) to evaluate the effects of test variables included in the experiment designs on the TSRST results. Because the air voids contents were not fully controlled, a source variable VOID was considered to be a covariate (i.e., continuous variable) in the analysis. The analysis of covariance was performed using a general linear model (GLM) procedure. The analysis of covariance combined some of the features of regression and analysis of variance. Typically, the covariate was introduced in the model of an analysis of variance.

The GLM procedure provides Type III hypothesis tests. The Type III mean squares indicate the influence of that factor after the effects of all the other factors in the model have

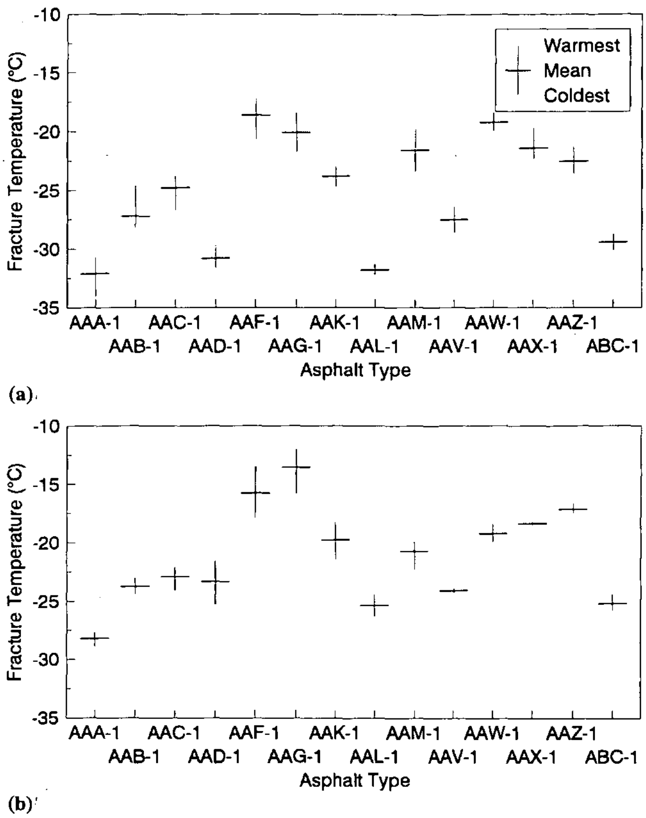


**FIGURE 4 Fracture temperature of mixtures with limestone aggregate (RC): (*a*) short-term aged mixtures, (*b*) long-term aged mixtures.**

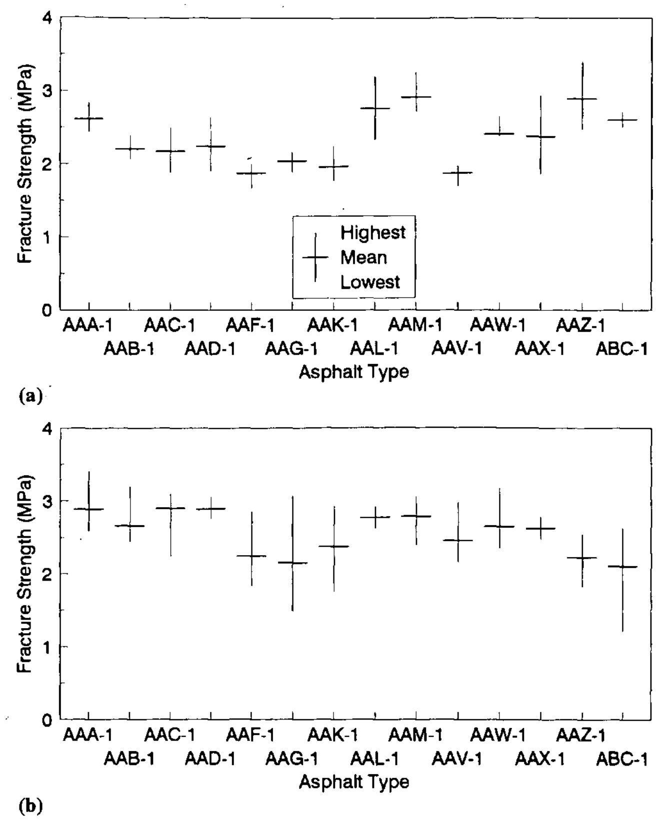


**FIGURE 5 Fracture strength of mixtures with limestone aggregate (RC): (*a*) short-term aged mixtures, (*b*) long-term aged mixtures.**

been removed. The procedure can also provide least-squares means (LSMEAN) of dependent variables. LSMEAN of a dependent variable is the mean value estimated for a given level of a given effect and adjusted for the covariate (air voids content).

The repeatability of the TSRST was evaluated in terms of the coefficient of variation for the test results from the Phase I experiment.

### Phase I Experiment

#### *Repeatability of TSRST*

The evaluations were performed for the test results of 20.3/3.8RB, 25/5RB, and 25/5RL at a monotonic cooling rate of 10°C/hr. Because the test results presented in the previous section indicated that fracture temperature was not sensitive to air voids content, the coefficient of variation for fracture temperature was evaluated for a specific asphalt cement. The coefficient of variation for fracture strength was evaluated depending on target air voids content for a specific asphalt cement.

The repeatability of fracture temperature was considered to be excellent. The coefficients of variation were less than 10 percent for fracture temperature. The repeatability of fracture strength was considered to be reasonable. The coefficients of variation for fracture strength are less than 20 percent, except for asphalt AAG-2 (25/5RB).

#### *Effect of Specimen Size*

Statistical analysis was performed on the test results of 20.3/3.8RB and 25/5RB. From both the Type III $P_r > F$ values and mean squares, both asphalt type and specimen size are identified as significant factors of fracture temperature. On the basis of the Type III mean squares, fracture temperature is most affected by asphalt type followed by specimen size. LSMEAN of fracture temperature for 20.3/3.8RB and 25/5RB depending on asphalt type are compared in Figure 6*a*. Fracture temperatures for 25/5RB are lower than those for 20.3/3.8RB. This difference may be because of the longer time required for the larger specimen to reach thermal equilibrium.

From both the Type III $P_r > F$ values and mean squares, the air voids content is identified as the most significant factor in fracture strength. Fracture strength is most influenced by air voids content. Asphalt type and specimen size are not significant. The Type III mean square for air voids content is extremely high compared with asphalt type and specimen size. LSMEAN of fracture strength for 25/5RB and 20.3/3.8RB are compared depending on asphalt type in Figure 6*b*. Fracture strengths of 20.3/3.8RB are greater than those of 25/5RB except for asphalt AAG-2. This difference may be because

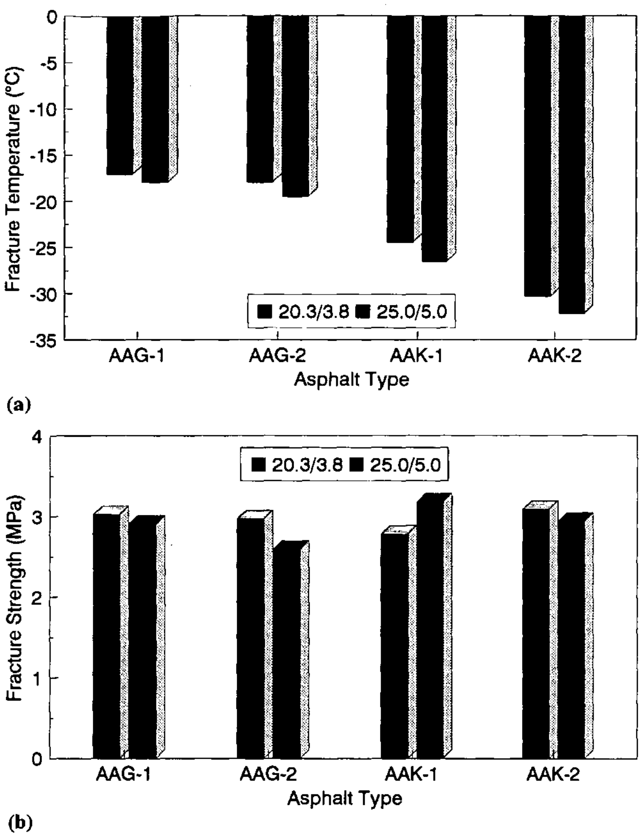


**FIGURE 6 Effect of specimen size: (*a*) fracture temperature, (*b*) fracture strength.**

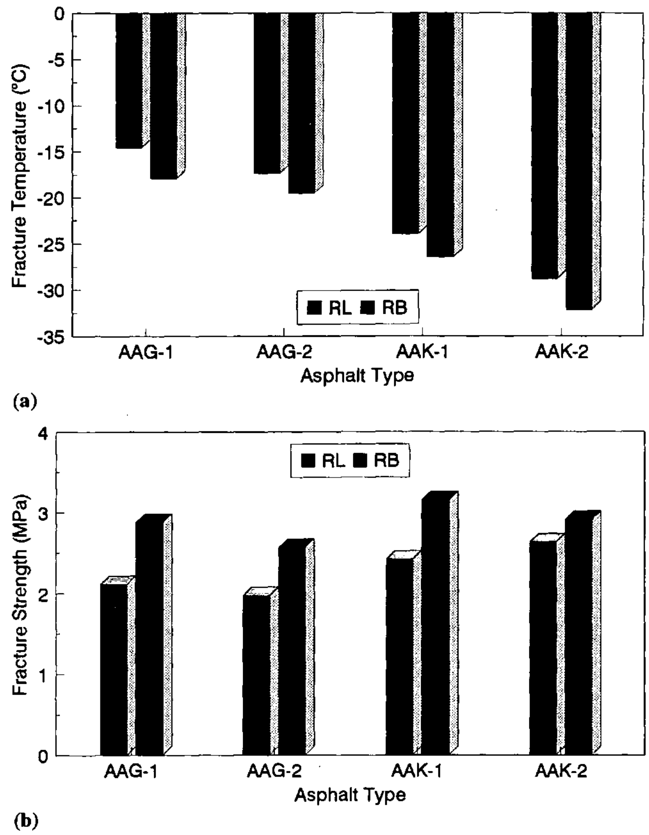


**FIGURE 7 Effect of aggregate type: (*a*) fracture temperature, (*b*) fracture strength.**

of nonuniformity of some specimens with smaller cross sections that resulted from poor compaction. Little or no breakage of aggregate was observed in the fracture surface of those specimens. Fracture at the interface between aggregate and asphalt was dominant. The overall fracture strength for 20.3/3.8RB is slightly greater than that for 25/5RB. The extent seems to be less than expected because the aspect ratio (length/width) of the smaller specimen (5.3) was slightly greater than that of the larger specimen (5.0).

### *Effect of Aggregate Type*

The test result of 25/5RB and 25/5RL were statistically analyzed to evaluate the effect of aggregate type. From the Type III $P_r > F$ values, asphalt type and aggregate type are significant factors for fracture temperature. On the basis of the Type III mean squares, fracture temperature is most affected by asphalt type followed by aggregate type. Figure 7*a* compares LSMEAN of fracture temperature for aggregates RB and RL depending on the type of asphalt. Fracture temperatures are warmer for RL aggregate than for RB aggregate. The overall fracture temperature of the RL aggregate is 2.84°C warmer than for the RB aggregate.

From the Type III $P_r > F$ values, air voids content and aggregate type are significant factors of fracture strength. On the basis of the Type III mean squares, fracture strength is most influenced by air voids content followed by aggregate type. Figure 7*b* shows LSMEAN of fracture strength depending on asphalt type and aggregate type. As shown, fracture strengths for the RL aggregate are lower than those of the aggregate. The overall fracture strength for the RB aggregate is approximately 0.6 MPa higher than that for the RL aggregate.

The RB aggregate showed better resistance to low-temperature cracking than did the RL aggregate. The better performance of the RB aggregate may be attributed to its rough surface texture and angular shape. Aggregate with a rough surface texture and angular shape can provide more bonding and interlocking between aggregate and asphalt cement, thereby leading to a higher fracture strength and a colder fracture temperature. Breakage of aggregate was frequently observed together with breakage of asphalt cement in the fracture surface of specimens with RB aggregate. In the case of specimens with RL aggregate, no breakage of aggregate was observed, and fracture at the interface between aggregate and asphalt was dominant. A rough surface texture and angular shape of aggregate can give better interlock and bonding, thereby resulting in a colder fracture temperature and a higher fracture strength.

### *Effect of Stress Relaxation*

Test results with stress relaxation were analyzed together with test results without stress relaxation. From the Type III $P_r >$

$F$ values, asphalt type, stress relaxation, and the interaction between asphalt type and stress relaxation are significant factors of fracture temperature. On the basis of the Type III mean squares, fracture temperature is most affected by asphalt type followed by stress relaxation and the interaction between asphalt type and stress relaxation. LSMEAN of fracture temperature for relaxed and nonrelaxed specimens are compared depending on the type of asphalt in Figure 8*a*. The decrease in fracture temperature caused by stress relaxation is greater for specimens with stiffer asphalts AAG-1 and AAG-2. In the case of specimens with softer asphalts AAK-1 and AAK-2, no significant difference in fracture temperature between relaxed and nonrelaxed specimens can be seen. The overall fracture temperature for a relaxed specimen is slightly colder than that for a nonrelaxed specimen.

From the Type III $P_r > F$ values, air voids content and stress relaxation are significant factors of fracture strength. On the basis of the Type III mean squares, fracture strength is most affected by air voids content followed by stress relaxation. Stress relaxation tends to decrease the fracture strength of the specimen. Figure 8*b* shows the LSMEAN of fracture strengths for relaxed and nonrelaxed specimens depending on asphalt type. Fracture strengths for relaxed specimens with AAG-1, AAK-1, and AAK-2 are 0.4 to 0.7 MPa lower than those for nonrelaxed specimens. However, in the case of specimens with AAG-2, no significant difference in fracture strength between relaxed and nonrelaxed specimens was observed. The overall fracture strength for a relaxed specimen is approximately 0.4 MPa lower than that for a nonrelaxed specimen.

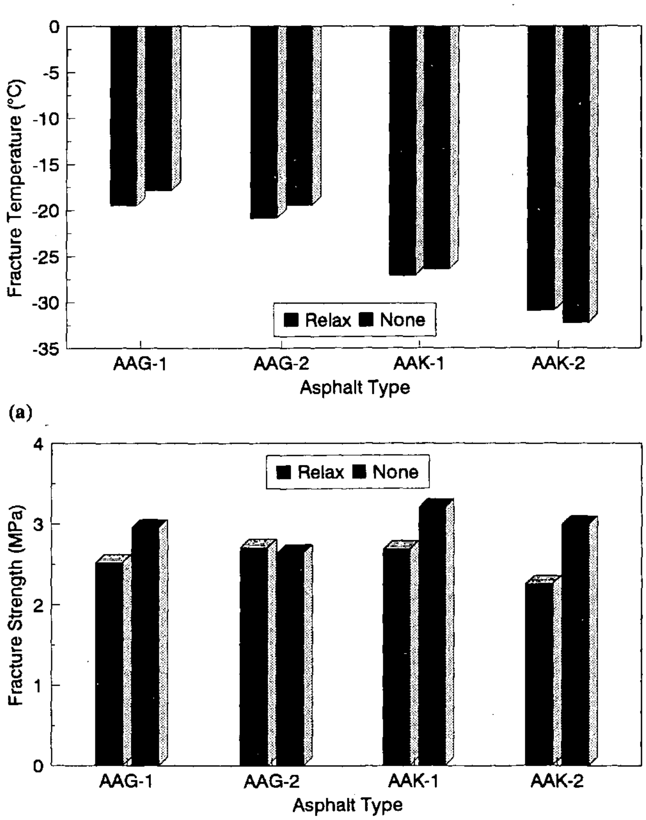


**FIGURE 8 Effect of stress relaxation: (*a*) fracture temperature, (*b*) fracture strength.**

### Phase II Experiment

The source variables considered in the analysis were asphalt type (AAA-1 through ABC-1), aggregate type (RC and RH), degree of aging (STOA and LTOA), and interactions between source variables. Air voids content (VOID) was considered to be a covariate. The dependent variables are fracture temperature (FRTEMP) and fracture strength (FRSTRE).

#### *Fracture Temperature*

From the analysis for the dependent variable FRTEMP, the Type III $P_r > F$ values for all the factors are statistically significant at 95 percent confidence level. The ranking for the factors considered in the fracture temperature model on the basis of the Type III mean squares is AGE > ASP > VOID > AGG * AGE > AGG > ASP * AGE > ASP * AGG. However, the Type III mean squares for the factors AAG, ASP * AGE, ASP * AAG, and AGG * AGE are not significant compared with the factors ASP, AGE, and VOID. The Type III mean squares for AGE and ASP are much greater than those for VOID. Thus, fracture temperature is most affected by the degree of aging and asphalt type followed by air voids content, whereas aggregate type and the interactions between asphalt type, degree of aging, and aggregate type have a minor influence on fracture temperature.

LSMEAN of fracture temperature for STOA and LTOA specimens are compared in Figure 9. Fracture temperatures are considerably warmer for LTOA specimens. The difference (LTOA − STOA) in fracture temperature for specimens with RC aggregate ranged from 2.1°C to 6.7°C with an average of 4.7°C. For specimens with RH aggregate, the difference ranged from 0.6°C to 5.1°C with an average difference of 3.4°C.

#### *Fracture Strength*

ASP * AGG is not a significant factor because the Type III $P_r > F$ value is 0.1461 > 0.05. The Type III mean square for

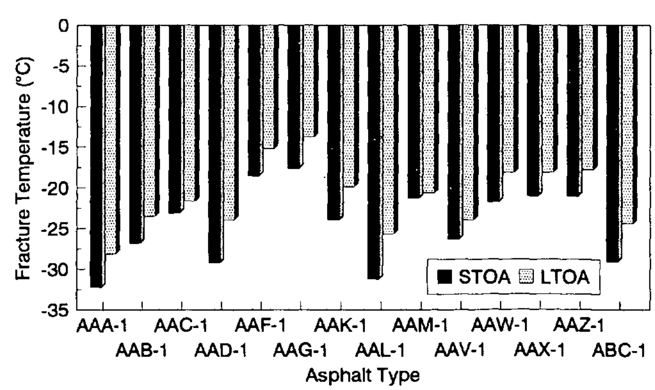


**FIGURE 9 Comparison of fracture temperature for short-term and long-term aged mixtures.**

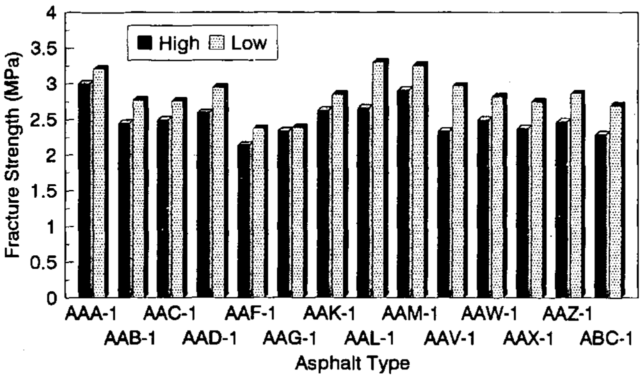


**FIGURE 10 Comparison of fracture strength for mixtures with high and low air voids.**

ASP * AGE is not significant compared with others. The ranking for the significant factors of the fracture strength on the basis of Type III mean squares is VOID > AGG > AGG * AGE > AGE > ASP. The Type III mean squares for VOID and AGG are much greater than those for the other factors. Thus, fracture strength is highly affected by air voids content and aggregate type and is also affected by asphalt type, degree of aging, and, to a much lesser extent, the interaction between aggregate type and degree of aging.

LSMEAN of fracture strength for specimens with higher and lower air voids content are compared for a specific asphalt type in Figure 10. Fracture strengths are greater for specimens with lower air voids content.

### Ranking of Asphalts for Resistance to Low-Temperature Cracking

The low-temperature cracking resistance performance ranking asphalts was determined using LSMEAN of the fracture temperature. The performance rankings of asphalts in the Phase I experiment are AAK-2 (coldest) > AAK-1 > AAG-2 > AAG-1 (warmest). The ranking of asphalts identified in the TSRST is in excellent agreement with the ranking on the basis of the physical properties of asphalt cements.

In the Phase II experiment, a score ranging from 1 to 14 was assigned to each asphalt. A lower score is associated with a colder fracture temperature. The ranking of asphalts on the basis of the TSRST results is presented together with the ranking defined under the A-002A contract in Table 3. The ranking of asphalt concrete mixtures on the basis of fracture temperature compares very favorably with the ranking on the basis of fundamental properties of the asphalt cements given by A-002A.

### Relationship Between Fracture Temperature and Fundamental Properties of Asphalts

Fracture temperature was compared with the A-002A low-temperature index test results, specifically the limiting stiffness temperature ($S_t$ = 200 MPa at 2 hr) and the ultimate strain at failure. The relationship between fracture temperature and limiting stiffness temperature is shown in Figure 11*a*. Fracture temperature exhibits a good correlation with the limiting stiffness temperature. The relationship between fracture temperature and ultimate strain at failure is shown in Figure 11*b*. A good correlation was obtained between fracture temperature and the ultimate strain at failure.

## CONCLUSIONS

On the basis of results presented in this paper, the following conclusions are appropriate.

- The repeatability of the TSRST on the basis of the coefficient of variation can be considered as excellent for fracture temperature and reasonable for fracture strength.
- TSRST results provide an excellent indication of low-temperature cracking resistance of asphalt concrete mixtures; a ranking of low-temperature cracking resistance of asphalts on the basis of TSRST fracture temperature is in good agree-

**TABLE 3 SHRP A-003A and A-002A Ranking of Asphalt Cements for Resistance to Low-Temperature Cracking**

| Asphalt Type | Fracture Temperature (°C) | A-003A Rank | A-002A Rank |
|---|---|---|---|
| AAA-1 | -30.27 | 1 | 1 |
| AAL-1 | -28.34 | 2 | 2 |
| AAD-1 | -26.70 | 3 | 3 |
| ABC-1 | -26.70 | 4 | 4 |
| AAB-1 | -25.41 | 5 | 5 |
| AAV-1 | -25.24 | 6 | 9 |
| AAC-1 | -22.48 | 7 | 7 |
| AAK-1 | -22.07 | 8 | 5 |
| AAM-1 | -21.01 | 9 | 8 |
| AAW-1 | -19.95 | 10 | 9 |
| AAX-1 | -19.59 | 11 | 12 |
| AAZ-1 | -19.48 | 12 | 12 |
| AAF-1 | -16.86 | 13 | 11 |
| AAG-1 | -15.83 | 14 | 14 |

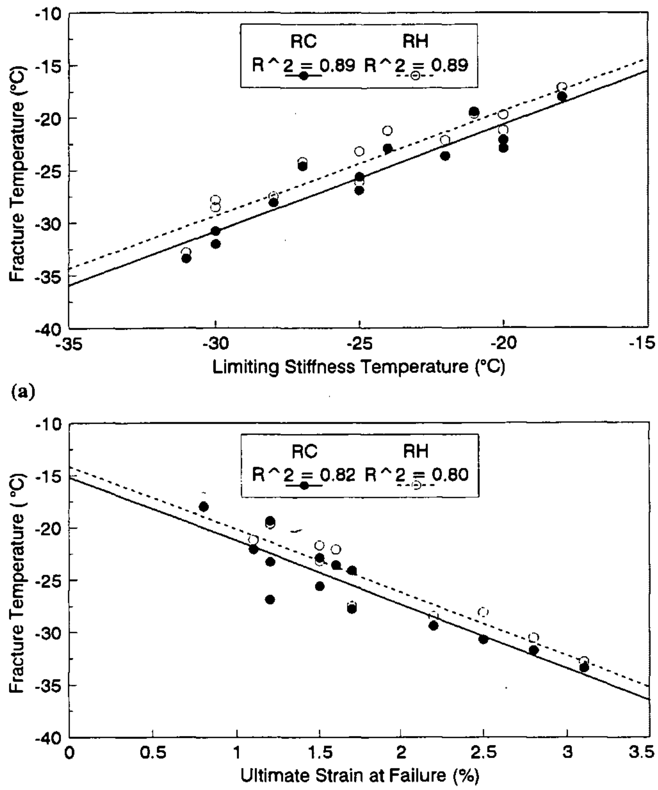


**FIGURE 11 Fracture temperature of short-term aged mixtures versus A-002A low-temperature index test results: (*a*) limiting stiffness temperature, (*b*) ultimate strain at failure.**

ment with a ranking on the basis of fundamental properties of the asphalt cements.

- Fracture temperature is most sensitive to asphalt type and degree of aging; to a lesser extent fracture temperature is also affected by aggregate type, specimen size, and stress relaxation.
- Fracture strength is most sensitive to air voids content and aggregate type; to a lesser extent fracture strength is also affected by asphalt type, degree of aging, specimen size, and stress relaxation.
- Aggregate with a rough surface texture and angular shape can provide better resistance to low-temperature cracking, leading to fracture at a higher stress level and a colder temperature.
- TSRST results were affected by specimen size; fracture temperature was colder for larger specimens; and fracture strength was greater for smaller specimens.
- Stress relaxation tends to lower fracture temperature and decrease fracture strength; fracture temperature of relaxed specimens was colder than that of nonrelaxed specimens; the decrease in fracture temperature caused by stress relaxation was significant for stiffer asphalts and was not significant for softer asphalts; and fracture strength was lower for relaxed specimens.
- Fracture temperature was highly correlated with SHRP low-temperature asphalt cement index test results, namely, the limiting stiffness temperature and the ultimate strain at failure.

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