



RESEARCH

2009-42

Asphalt Mixture and Binder Fracture Testing for 2008
MnROAD Construction

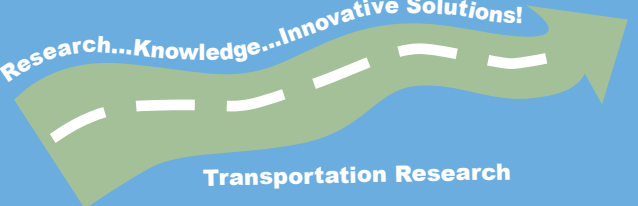


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Asphalt Mixture and Binder Fracture Testing for 2008 MnROAD Construction

Final Report

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EXECUTIVE SUMMARY

Good fracture properties are an essential requirement for asphalt pavements built in the northern part of the US and in Canada for which the predominant failure mode is cracking due to high thermal stresses that develop at low temperatures. Currently, there is no agreement with respect to what experimental methods and analyses to use to investigate the fracture resistance of asphalt materials. This report summarizes the results of an experimental effort to characterize the low-temperature behavior of asphalt mixtures and binders from the recently reconstructed cells at the MnROAD facility. In depth analysis of the data was not part of this study; this will be accomplished in several concurrent research projects.

INTRODUCTION

A summary that details the laboratory sample preparation and test methods used in this research effort is provided in this report. The objective of this effort was to obtain laboratory test data on the low-temperature fracture properties of asphalt binders and mixtures used in the 2008 MnROAD reconstruction project. In depth analysis of the data was not part of this study; this will be accomplished in several concurrent research projects.

The University of Minnesota has already delivered the raw data files and Excel files with the results and partial analyses as part of the deliverables for each task. Testing was performed on the asphalt mixtures and binders samples described in Table 1 and Table 2, respectively.

Table 1. Asphalt mixtures tested.

| ID | Cell | Mix type | Description | PG | RAP | Comments |
|-----------|-------------|-------------------------|---|-----------|-----------------------------------|--|
| A | 2 | Novachip | | 64-34 | none | |
| B | 2 | SPWEB440F | level 4 Superpave | 64-34 | none | |
| C | 5 | PASSRC | <i>permeable stress relief course</i> | 64-22 | none | <i>Couldn't be compacted Replaced by M</i> |
| D | 6 | SPWEB440 F Special | 4.75 taconite Superpave | 64-34 | none | |
| E | 16 | SPWEB440 C Special | warm asphalt wear course | 58-34 | 20% | |
| F | 16 | SPWEB430 C Special | warm asphalt nonwear | 58-34 | 20% | |
| G | 20 | SPNWB430 B | non wear | 58-28 | 30% non fractionated | |
| H | 21 | SPNWB430 B Special | non wear | 58-28 | 30% fractionated | |
| I | 22 | SPNWB430 C Special 1 | non wear | 58-34 | 30% fractionated | |
| J | 86,88 | SPWEB440 H Special 1 | porous asphalt | 70-28 | none | |
| | 87 | SPWEB340B | <i>level 3 Superpave</i> | 58-28 | 20% | <i>Not available Replaced by K</i> |
| K | 5 | SPWEB440B | shoulder mix | 58-28 | 5% manufactured waste shingles | |
| L | 24 | SPWEB440C | control for warm mix asphalt | 58-34 | 20 % | |
| M | 15,17 21 | SPWEB440B | shoulder mix | 58-28 | 5% tear off shingles | |

Table 2. Asphalt binders tested.

| ID |
|-----------------------------|
| PG 70-28 |
| PG 64-34 |
| PG 64-22 |
| PG 58-34 (WMA) |
| PG 58-34 |
| PG 58-28 |
| extracted RAP (standard) |
| extracted RAP (coarse) |
| extracted RAP (fine) |

For each mixture the theoretical maximum specific gravity G_{mm} and the bulk specific gravity G_{mb} (at N_{des}) were determined according to AASHTO T 209-05 and AASHTO T 166-05. The air voids were calculated as $1 - (G_{mb} / G_{mm})$ and expressed in percentage. The values are presented in the Table 3.

Table 3. Specific gravities for the asphalt mixtures.

| Loose mix type | G_{mb} | G_{mm} | Air Voids |
|----------------|----------|----------|-----------|
| A | 2.362 | 2.493 | 5.3% |
| B | 2.412 | 2.499 | 3.5% |
| D | 2.436 | 2.563 | 5.0% |
| E | 2.397 | 2.517 | 4.8% |
| F | 2.437 | 2.499 | 2.5% |
| G | 2.435 | 2.518 | 3.3% |
| H | 2.432 | 2.528 | 3.8% |
| I | 2.416 | 2.514 | 3.9% |
| J | 2.06 | 2.558 | 19.5% |
| K | 2.418 | 2.534 | 4.6% |
| L | 2.392 | 2.524 | 5.2% |
| M | 2.378 | 2.608 | 8.8% |

Using the compaction data, a target weight and height were calculated for each mixture to achieve the desired value of 7% air voids. Two exceptions were observed. It was difficult to obtain the G_{mb} value for the porous mix “J”; due to the high air voids content, a lot of water

drained out when the cylinder was moved from the bath to the scale. In this case the target was set to 100 gyrations for the test cylinders. Mixture “M”, after 100 gyrations, still had 8% air voids. For the test specimens the target was set to 100 gyrations.

For each mixture eight cylinders were compacted. If needed, after the first two cylinders the target was adjusted to obtain a better match. Out of them, four were tested in the laboratory, and two were sent back to the Minnesota Department of Transportation (Mn/DOT). The target values and the air voids are shown in Table 1.4.

Table 4. Air voids for the compacted loose mix cylinders.

| Mix ID | Target | | Cylinder ID | | | | | | | | UofM | Mn/DOT |
|--------|-----------|------------|-------------|------|------|-----|-----|-----|-----|-----|---------|--------|
| | Weight, g | Height, mm | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | | |
| A | 6900 | 172.97 | 7.9 | 7.1 | 7 | 7.1 | 7.2 | 7.2 | 6.8 | 7 | 2.3.4.5 | 6&8 |
| B | 7125 | 174.72 | 7.5 | 7.6 | 7.4 | 7.8 | 6.6 | 6.5 | 6.9 | 6.4 | 1,2,3,5 | 6&7 |
| D | 7325 | 174.72 | 7.3 | 7.6 | 7.6 | 7.5 | 6.5 | 7 | 6.8 | 6.7 | 1.2.4.6 | 7&8 |
| E | 7200 | 175.83 | 7.2 | 7.2 | 7 | 7.1 | 7 | 7 | 6.9 | 7 | 3.4.5.6 | 7&8 |
| F | 7100 | 175.50 | 7.3 | 7.5 | 7.1 | 7.4 | 7.2 | 7.1 | 7.7 | 7.1 | 1.3.4.5 | 6&8 |
| G | 7200 | 175.83 | 6.95 | 6.95 | 6.85 | 6.9 | 6.9 | 6.8 | 6.7 | 6.8 | 1.2.3.4 | 5&8 |
| H | 7200 | 175.20 | 6.7 | 7.1 | 7.1 | 7.1 | 6.8 | 6.8 | 6.7 | 7 | 2.3.4.5 | 6&8 |
| I | 7200 | 175.86 | 7 | 7 | 6.6 | 7.1 | 7.1 | 6.9 | 7 | 7 | 1.2.4.5 | 7&8 |
| J | 6100 | 100 gyr | 19.7 | | | | | | | 19 | 3.4.5.6 | 7&8 |
| K | 7200 | 174.50 | 7.2 | 7.3 | 7 | 7.5 | 7.4 | 7.3 | 7.5 | 7.2 | 1.2.3.6 | 7&8 |
| L | 7100 | 173.00 | 7.5 | 7.5 | 7.2 | 7.2 | 7 | 7 | 7.2 | 7.3 | 3.4.5.6 | 7&8 |
| M | 7300 | 100 gyr | 8.8 | 8.8 | 8 | 8 | 8 | 8.1 | 8 | 8.1 | 3.4.5.6 | 7&8 |

For the performance tests, the compacted cylinders were not subject to any long-term aging in the laboratory. The mixtures were only heated long enough to split into the proper weights and then heated to the compaction temperature (or something like that – describe the process).

TASK 1

This task consisted of sample preparation and Semi Circular Bend (SCB) testing on the mixtures described in Table 1. The SCB tests were conducted on each mix at three test temperatures (at a single air void and laboratory conditioning level) with three replicates per temperature. The test temperatures were selected based on the PG of the binder as follows:

- PG +10°C
- 12°C below (PG +10°C)
- 12°C above (PG +10°C).

A MTS servo-hydraulic testing system equipped with an environmental chamber was used to perform the SCB test. The SCB samples were symmetrically supported by two fixed rollers and had a span of 120mm. Teflon tape was used to reduce the friction from the two rollers. The Indirect Tension test (IDT) loading plate was used to load the SCB specimens. The load line displacement (LLD) was measured using a vertically mounted Epsilon extensometer with 38 mm gage length and ± 1 mm range; one end was mounted on a button that was permanently fixed on a specially made frame, and the other end was attached to a metal button glued to the sample. The crack mouth opening displacement (CMOD) was recorded by an Epsilon clip gage with 10 mm gage length and a +2.5 and -1 mm range. The clip gage was attached at the bottom of the specimen. Considering the brittle behavior of asphalt mixtures at low temperatures, the CMOD signal was used as the control signal to maintain the test stability in the post-peak region of the test. A constant CMOD rate of 0.0005mm/s was used and the load and load line displacement (P-u) curve was plotted. A contact load with maximum load of 0.3 kN was applied before the actual loading to ensure uniform contact between the loading plate and the specimen. The testing was stopped when the load dropped to 0.5 kN in the post peak region. All tests were performed inside an environmental chamber. Liquid nitrogen was used to obtain the required low temperature. The temperature was controlled by the environmental chamber temperature controller and verified using an independent thermometer.

The load and load line displacement data were used to calculate the fracture toughness and fracture energy. It was shown that the stress intensity factor K can be reasonably calculated using the following equation:

$$\frac{K_I}{\sigma_0 \sqrt{\pi a}} = Y_{I(s_0/r)} + \frac{\Delta s_0}{r} B \quad [1]$$

where

K_I = Mode I stress intensity factor;

σ_0 = $P/2rt$

P = applied load;

r = specimen radius;

t = specimen thickness.

Y_I = the normalized stress intensity factor

$$Y_{I(s_0/r)} = C_1 + C_2(a/r) + C_3 \exp(C_4(a/r)) \quad [2]$$

C_i = constants;

a = notch length;

$\Delta s_0 / r = s_a / r - s_0 / r$

s_a / r = actual span ratio;

s_0 / r = nearest span ratio analyzed in the derivation of this equation (0.80, 0.67, 0.61, 0.50)

$$B = 6.55676 + 16.64035\left(\frac{a}{r}\right)^{2.5} + 27.97042\left(\frac{a}{r}\right)^{6.5} + 215.0839\left(\frac{a}{r}\right)^{16}$$

The fracture energy G_f was calculated according to RILEM TC 50-FMC specification that has been extensively used in the study of concrete. The work of fracture is the area under the loading-deflection (P-u) curve and the fracture energy (G_f) can then be obtained by dividing the work of fracture with the ligament area, which is calculated as the product of the ligament length and the thickness of the specimen. This is shown in equation 3.

$$G_f = \frac{W_f}{A_{lig}} \quad [3]$$

where W_f is the work of fracture and

$$W_f = \int P du$$

A_{lig} is the area of the ligament.

The tail part of the P-u curve can be reasonably obtained by fitting the data curve in the post-peak region following two methods described elsewhere (Li 2005, Marasteanu et al, 2007). In the first method, the area of the tail was computed as

$$W_{tail} = \int_0^{peak\Delta L} \frac{a}{x^2} dx$$

In the second method, the area of the tail was computed as

$$W_{tail} = \int_0^{peak\Delta L} b \cdot x^c dx$$

Summary plots of the parameters obtained as a result of the tests in this task are shown in Figures 1 to 6 and in Tables 5 and 6.

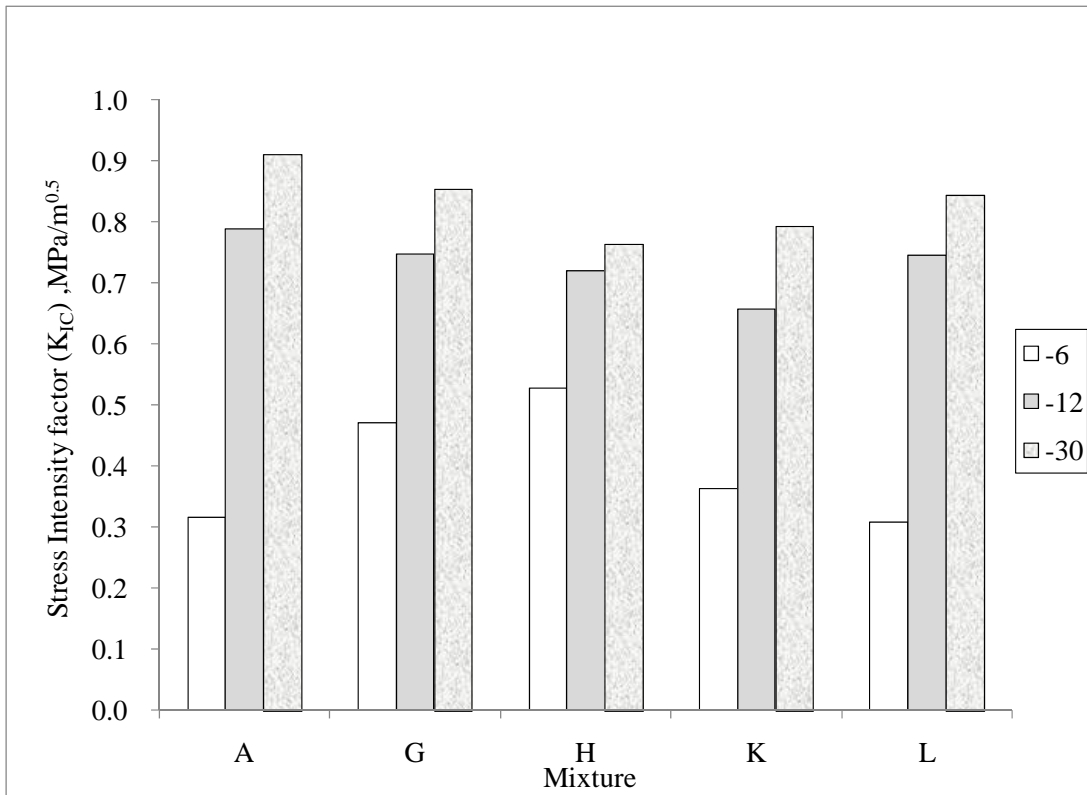


Figure 1. Mixture SCB fracture toughness values (mixtures A, G, H, K, L)

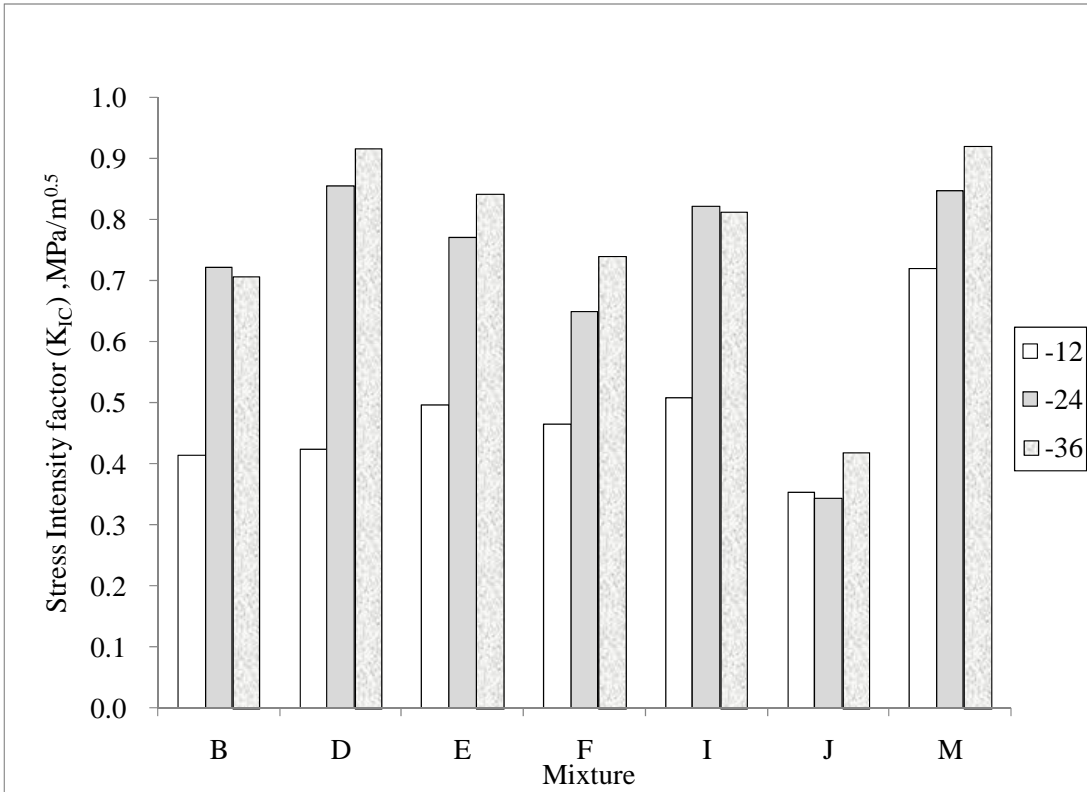


Figure 2. Mixture SCB fracture toughness values (mixtures B, D, E, F, I, J, M)

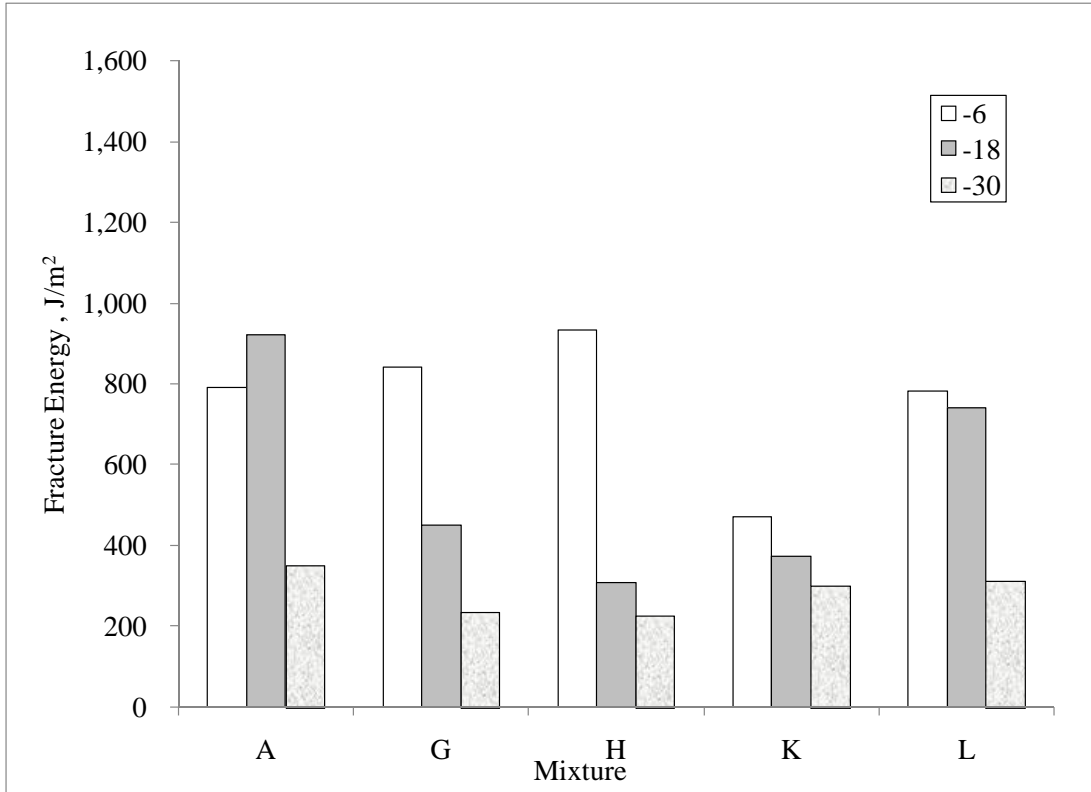


Figure 3. SCB fracture energy values obtained with method 1 (mixtures A, G, H, K, L)

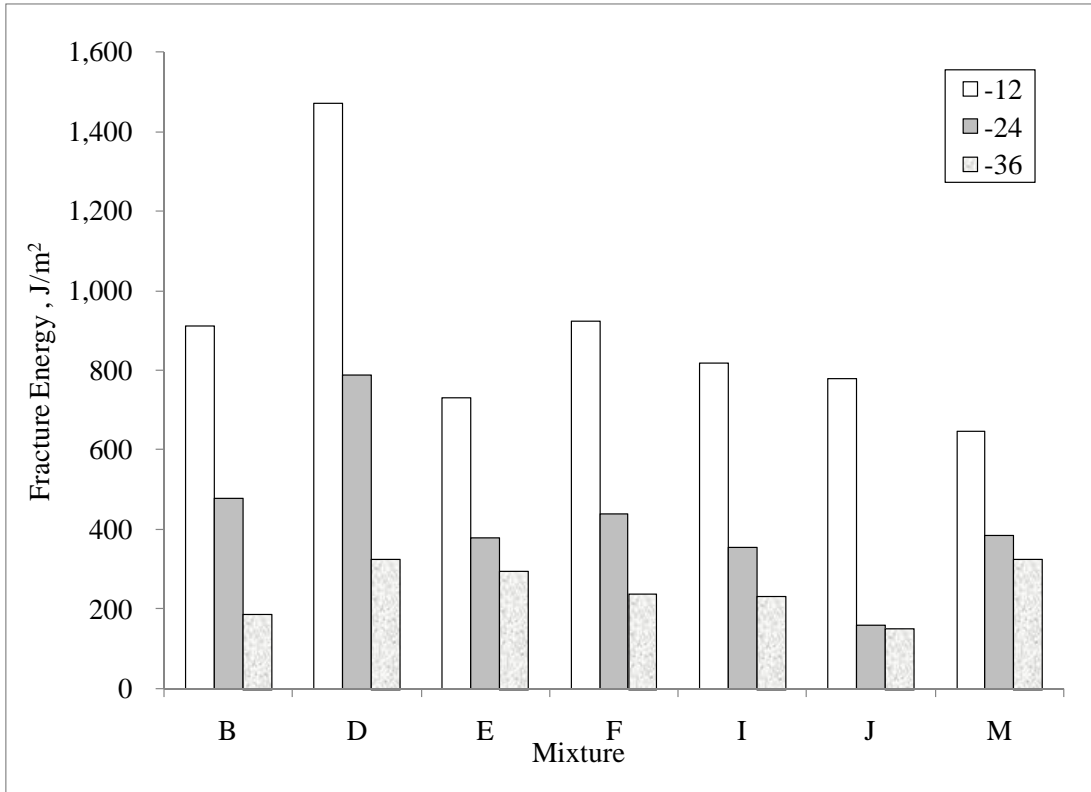


Figure 4. SCB fracture energy values obtained with method 1 (mixtures B, D, E, F, I, J, M)

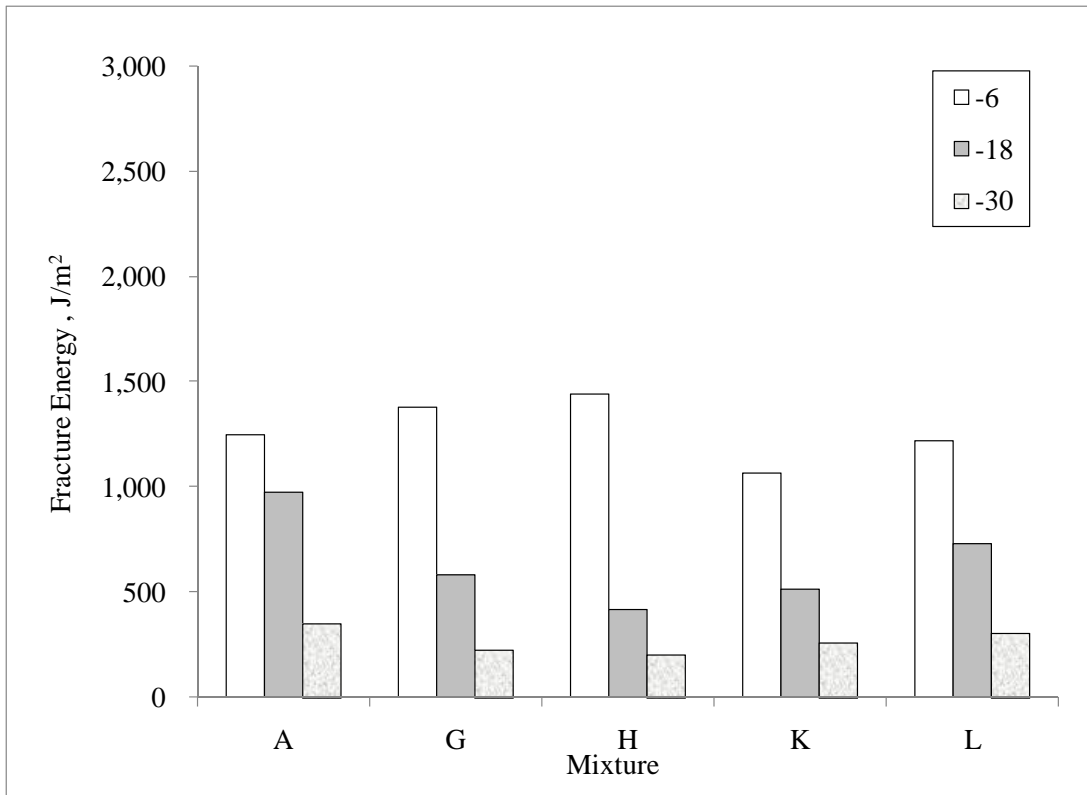


Figure 5. SCB fracture energy values obtained with method 2 (mixtures A, G, H, K, L)

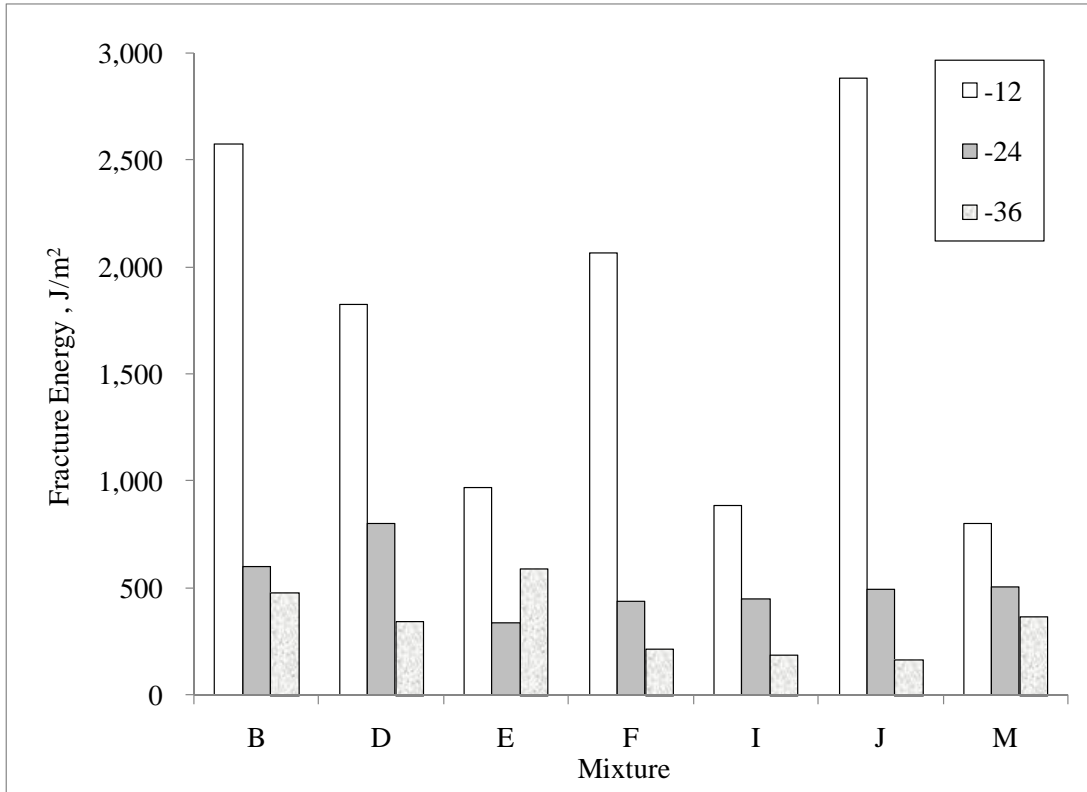


Figure 6. SCB fracture energy values obtained with method 2 (mixtures B, D, E, F, I, J, M)

Table 5. Summary of mixture SCB fracture toughness results.

| Mix ID | T °C | K _{IC} (Stress intensity factor) , kPa/m ^{0.5} | | | | |
|--------|---------|--|-------|--------|---------|-------|
| | | R1 | R2 | R3 | Average | CV(%) |
| A | -6 | 302.8 | 374.4 | 268.1 | 315.1 | 17.2% |
| | -18 | 779.8 | 785.9 | 799.5 | 788.4 | 1.3% |
| | -30 | 886.6 | 909.3 | 935.5 | 910.5 | 2.7% |
| B | -12 | 348.8 | 482.2 | 412.1 | 414.3 | 16.1% |
| | -24 | 644.2 | 779.1 | 739.0 | 720.8 | 9.6% |
| | -36 | 679.3 | 793.5 | 649.5 | 707.4 | 10.8% |
| D | -12 | 440.4 | 415.1 | 417.6 | 424.4 | 3.3% |
| | -24 | 794.7 | 833.2 | 935.8 | 854.6 | 8.5% |
| | -36 | 917.0 | 918.4 | OL | 917.7 | 0.1% |
| E | -12 | 468.5 | 529.6 | 489.7 | 495.9 | 6.3% |
| | -24 | 812.7 | 797.9 | 703.7 | 771.4 | 7.7% |
| | -36 | 791.7 | 896.0 | 841.3 | 843.0 | 6.2% |
| F | -12 | 460.1 | 470.0 | 461.2 | 463.8 | 1.2% |
| | -24 | 635.3 | 683.4 | 630.0 | 649.6 | 4.5% |
| | -36 | 725.3 | 772.7 | 724.0 | 740.7 | 3.7% |
| G | -6 | 448.3 | 533.0 | 428.5 | 469.9 | 11.8% |
| | -18 | 697.2 | 716.6 | 824.5 | 746.1 | 9.2% |
| | -30 | 833.5 | 988.2 | 742.8 | 854.8 | 14.5% |
| H | -6 | 458.9 | 619.1 | 506.1 | 528.0 | 15.6% |
| | -18 | 716.3 | 608.4 | 832.0 | 718.9 | 15.6% |
| | -30 | 727.6 | 881.4 | 683.3 | 764.1 | 13.6% |
| I | -12 | 469.0 | 452.4 | 601.3 | 507.6 | 16.1% |
| | -24 | 794.6 | 826.5 | 845.7 | 822.2 | 3.1% |
| | -36 | 803.7 | 860.3 | 778.4 | 814.1 | 5.2% |
| J | -12 | 355.0 | 350.3 | NA | 352.7 | 0.9% |
| | -24 | 379.1 | 292.5 | 356.1 | 342.6 | 13.1% |
| | -36 | 389.1 | 449.0 | 422.0 | 420.0 | 7.1% |
| K | -6 | 344.0 | 307.8 | 433.8 | 361.8 | 17.9% |
| | -18 | 642.1 | 641.0 | 688.1 | 657.1 | 4.1% |
| | -30 | 763.5 | 762.8 | 856.6 | 794.3 | 6.8% |
| L | -6 | 292.0 | 336.5 | 293.5 | 307.4 | 8.2% |
| | -18 | 772.2 | 786.0 | 677.0 | 745.0 | 8.0% |
| | -30 | 710.9 | 819.0 | 1006.1 | 845.3 | 17.7% |
| M | -12 | 670.9 | 788.4 | 702.2 | 720.5 | 8.4% |
| | -24 | 873.5 | 770.5 | 898.7 | 847.6 | 8.0% |
| | -36 | 1019.0 | 835.4 | 910.3 | 921.6 | 10.0% |

OL = Outlier

NA = Not Available

Table 6. Summary of mixture SCB fracture energy results.

| Mix ID | T °C | G _f (fracture energy) , J/m ² , Method 1 | | | | | G _f (fracture energy) , J/m ² , Method 2 | | | | | D(%) |
|--------|------|--|------|------|------|-------|--|------|------|------|--------|-------|
| | | R1 | R2 | R3 | Ave | CV(%) | R1 | R2 | R3 | Ave | CV(%) | |
| A | -6 | 749 | 1090 | 532 | 791 | 35.6% | 1013 | 1997 | 723 | 1245 | 53.6% | 36.5% |
| | -18 | 1035 | 821 | 911 | 922 | 11.7% | 944 | 956 | 1020 | 973 | 4.2% | 5.2% |
| | -30 | 343 | 401 | 310 | 351 | 13.1% | 350 | 422 | 290 | 354 | 18.6% | 0.8% |
| B | -12 | 868 | 1062 | 804 | 911 | 14.7% | 3587 | 1308 | 2825 | 2573 | 45.1% | 64.6% |
| | -24 | 303 | 579 | 551 | 478 | 31.8% | 406 | 737 | 648 | 597 | 28.7% | 20.0% |
| | -36 | 136 | 245 | 188 | 190 | 28.8% | OL | 217 | 741 | 479 | 77.5% | 60.4% |
| D | -12 | 1568 | 1404 | 1436 | 1469 | 5.9% | 1787 | 1648 | 2042 | 1826 | 10.9% | 19.5% |
| | -24 | 646 | 883 | 839 | 789 | 15.9% | 746 | 861 | 788 | 798 | 7.3% | 1.1% |
| | -36 | 347 | 305 | OL | 326 | 8.9% | 282 | 416 | OL | 349 | 27.3% | 6.6% |
| E | -12 | 774 | 731 | 690 | 731 | 5.7% | 1392 | 694 | 822 | 969 | 38.4% | 24.5% |
| | -24 | 441 | 335 | 362 | 380 | 14.5% | 398 | 312 | 290 | 334 | 17.1% | 13.8% |
| | -36 | 356 | 237 | 296 | 296 | 20.0% | 898 | 367 | 511 | 592 | 46.4% | 49.9% |
| F | -12 | 910 | 900 | 956 | 922 | 3.2% | 2942 | 1505 | 1744 | 2064 | 37.3% | 55.3% |
| | -24 | 276 | 373 | 666 | 438 | 46.4% | 446 | 431 | OL | 438 | 2.3% | 0.0% |
| | -36 | 277 | 224 | 217 | 239 | 13.7% | 246 | 200 | 211 | 219 | 11.1% | 9.3% |
| G | -6 | 950 | 811 | 766 | 843 | 11.4% | 1029 | 1071 | 2024 | 1375 | 40.9% | 38.7% |
| | -18 | 394 | 387 | 566 | 449 | 22.6% | 410 | 660 | 669 | 580 | 25.3% | 22.5% |
| | -30 | 207 | 293 | 207 | 236 | 21.1% | 173 | 296 | 210 | 226 | 27.9% | 4.3% |
| H | -6 | 1027 | 984 | 787 | 933 | 13.7% | 1734 | OL | 1150 | 1442 | 28.6% | 35.3% |
| | -18 | 340 | 213 | 375 | 310 | 27.6% | 361 | OL | 472 | 416 | 18.9% | 25.6% |
| | -30 | 212 | 208 | 257 | 226 | 12.1% | 197 | OL | 219 | 208 | 7.5% | 8.7% |
| I | -12 | 725 | 831 | 895 | 817 | 10.5% | OL | 952 | 813 | 882 | 11.1% | 7.4% |
| | -24 | 352 | 371 | 341 | 355 | 4.3% | OL | 535 | 360 | 448 | 27.5% | 20.8% |
| | -36 | 274 | 222 | 205 | 234 | 15.4% | OL | 191 | 184 | 188 | 2.6% | 24.3% |
| J | -12 | 787 | 770 | NA | 778 | 1.6% | 1830 | 3938 | NA | 2884 | 51.7% | 73.0% |
| | -24 | 146 | 105 | 226 | 159 | 38.7% | 178 | 526 | 771 | 492 | 60.6% | 67.7% |
| | -36 | 162 | 163 | 134 | 153 | 10.7% | 0 | 125 | 372 | 166 | 114.3% | 7.5% |
| K | -6 | 471 | 471 | OL | 471 | 0.0% | 1004 | OL | 1122 | 1063 | 7.9% | 55.7% |
| | -18 | 424 | 325 | 368 | 372 | 13.4% | 462 | 635 | 433 | 510 | 21.5% | 27.0% |
| | -30 | 267 | 299 | 338 | 301 | 11.8% | 249 | 269 | 260 | 259 | 3.9% | 16.2% |
| L | -6 | 764 | 794 | 791 | 783 | 2.1% | 1109 | 1112 | 1441 | 1221 | 15.6% | 35.9% |
| | -18 | 747 | 841 | 634 | 740 | 14.0% | 737 | 805 | 650 | 731 | 10.6% | 1.4% |
| | -30 | 204 | 431 | 300 | 311 | 36.6% | 189 | 459 | 281 | 310 | 44.3% | 0.5% |
| M | -12 | OL | 675 | 617 | 646 | 6.3% | OL | 710 | 886 | 798 | 15.5% | 19.0% |
| | -24 | 501 | 319 | 339 | 386 | 25.9% | 440 | 453 | 611 | 501 | 18.9% | 22.9% |
| | -36 | 332 | 419 | 224 | 325 | 30.1% | 450 | 449 | 209 | 369 | 37.6% | 12.0% |

D = Difference (%) between Average of Method 1 and Method 2

$$= \frac{Ave_{method\ 2} - Ave_{method\ 1}}{Ave_{method\ 2}} \times 100(\%)$$

TASK 2

In this task, IDT creep and strength testing and BBR creep testing of thin mixture beams were performed. The IDT tests were conducted at the same three temperatures as the SCB, with three replicates per temperature.

For IDT, two parameters, creep compliance and strength were determined using the current AASHTO specification T 322-03, “Standard Method of Test for Determining the Creep Compliance and Strength of Hot-Mix Asphalt (HMA) Using the Indirect Tensile Test Device.” The IDT specimens were first tested for the creep stiffness and later for the strength. Both procedures are specified in AASHTO T 322-03 and the resultant parameters are calculated as follows:

- Creep stiffness:

$$D(t) = \frac{\Delta X \cdot D_{avg} \cdot b_{avg}}{P_{avg} \cdot GL} \cdot C_{cpl}, \text{ where}$$

$D(t)$ – creep compliance,

ΔX – trimmed mean of the horizontal deformations,

D_{avg} – average specimen diameter,

b_{avg} – average specimen thickness,

P_{avg} – average force during the test,

GL – gage length (38mm)

C_{cpl} – creep compliance parameter at any given time, computed as

$$C_{cpl} = 0.6354 \cdot \left(\frac{X}{Y} \right)^{-1} - 0.332, \text{ where}$$

X – horizontal deformation,

Y – vertical deformation.

Creep stiffness $S(t)$ at the time t was calculated as the inverse of the creep compliance $D(t)$, i.e. $S(t) = 1/D(t)$.

- Tensile strength:

$$S = \frac{2 \cdot P_{fail}}{\pi \cdot b \cdot D}, \text{ where}$$

P_{fail} – failure (peak) load,

b, D – specimen thickness and diameter, respectively.

The AASHTO procedure leads to one value of the creep stiffness $S(t)$ for a given mixture at each temperature. An alternative method, referred to as the Zhang, Drescher and Newcomb method (ZDN) was also used based on work described elsewhere (Zofka 2008, Zhang et al. 1997).

For BBR, the thin mixture beams were cut from gyratory cylinders and then tested based on the method described in NCHRP Idea 133 (2009). The same three test temperatures used for SCB and IDT testing were used. Three replicates were tested at each temperature. Both IDT creep compliance and BRR creep compliance were converted to relaxation modulus values using Hopkins and Hamming interconversion method. The relaxation modulus was further used to calculate thermal stresses and intersect it with the IDT strength master curve. A summary of IDT strength values is given in Table 7 and Figures 7 and 8 show plots of the average values for the mixture tested. From Figures 9 to Figure 20 show the relaxation master curves and from Figures

21 to 32 show thermal stress curves using two different cooling rates plotted together with the IDT strength curve.

Table 7. Summary of mixture IDT strength results.

| Mix ID | T °C | IDT Strength , MPa | | | | |
|--------|---------|--------------------|------|------|---------|--------|
| | | R1 | R2 | R3 | Average | CV (%) |
| A | -6 | 3.16 | 3.46 | 3.15 | 3.25 | 5.4% |
| | -18 | 4.78 | 4.67 | 4.42 | 4.62 | 4.0% |
| | -30 | 5.15 | 4.78 | 4.76 | 4.89 | 4.5% |
| B | -12 | 3.31 | 3.13 | 3.12 | 3.19 | 3.4% |
| | -24 | 4.46 | 4.20 | 4.15 | 4.27 | 3.9% |
| | -36 | 3.77 | 3.67 | 3.30 | 3.58 | 6.9% |
| D | -12 | 3.76 | 3.55 | 4.24 | 3.85 | 9.2% |
| | -24 | 6.27 | 4.74 | 6.10 | 5.70 | 14.7% |
| | -36 | 6.58 | 5.76 | 5.49 | 5.94 | 9.5% |
| E | -12 | 3.76 | 3.84 | 3.66 | 3.75 | 2.5% |
| | -24 | 4.92 | 4.43 | 5.17 | 4.84 | 7.8% |
| | -36 | 3.96 | 4.18 | 4.31 | 4.15 | 4.3% |
| F | -12 | 3.52 | 3.21 | 3.15 | 3.29 | 6.0% |
| | -24 | 3.57 | 4.31 | 3.90 | 3.93 | 9.3% |
| | -36 | 3.08 | 3.66 | 3.74 | 3.49 | 10.2% |
| G | -6 | 4.04 | 3.98 | 4.12 | 4.05 | 1.8% |
| | -18 | 4.44 | 4.51 | 4.24 | 4.40 | 3.3% |
| | -30 | 3.89 | 4.32 | 3.79 | 4.00 | 7.0% |
| H | -6 | 4.17 | 3.80 | 3.75 | 3.91 | 5.8% |
| | -18 | 4.12 | 4.52 | 5.01 | 4.55 | 9.8% |
| | -30 | 3.99 | 4.28 | 5.02 | 4.43 | 12.0% |
| I | -12 | 4.24 | 3.68 | 4.20 | 4.04 | 7.8% |
| | -24 | 4.31 | 4.97 | 4.93 | 4.74 | 7.8% |
| | -36 | 4.41 | 4.50 | 5.11 | 4.67 | 8.1% |
| J | -12 | 1.42 | 1.78 | 1.67 | 1.62 | 11.4% |
| | -24 | 2.53 | 2.13 | 1.99 | 2.21 | 12.6% |
| | -36 | 2.16 | 1.83 | 1.53 | 1.84 | 17.1% |
| K | -6 | 3.07 | 3.21 | NA | 3.14 | 3.2% |
| | -18 | 4.32 | 3.39 | 4.03 | 3.91 | 12.2% |
| | -30 | 3.98 | 3.30 | 3.64 | 3.64 | 9.4% |
| L | -12 | 4.41 | 3.95 | 3.72 | 4.03 | 8.6% |
| | -24 | 4.30 | 4.73 | 4.05 | 4.36 | 7.9% |
| | -36 | 4.77 | 4.67 | 4.16 | 4.53 | 7.2% |
| M | -6 | 3.58 | 3.81 | 3.94 | 3.78 | 4.8% |
| | -18 | 4.98 | 4.42 | 4.22 | 4.54 | 8.7% |
| | -30 | 4.57 | 3.89 | 3.65 | 4.03 | 11.9% |

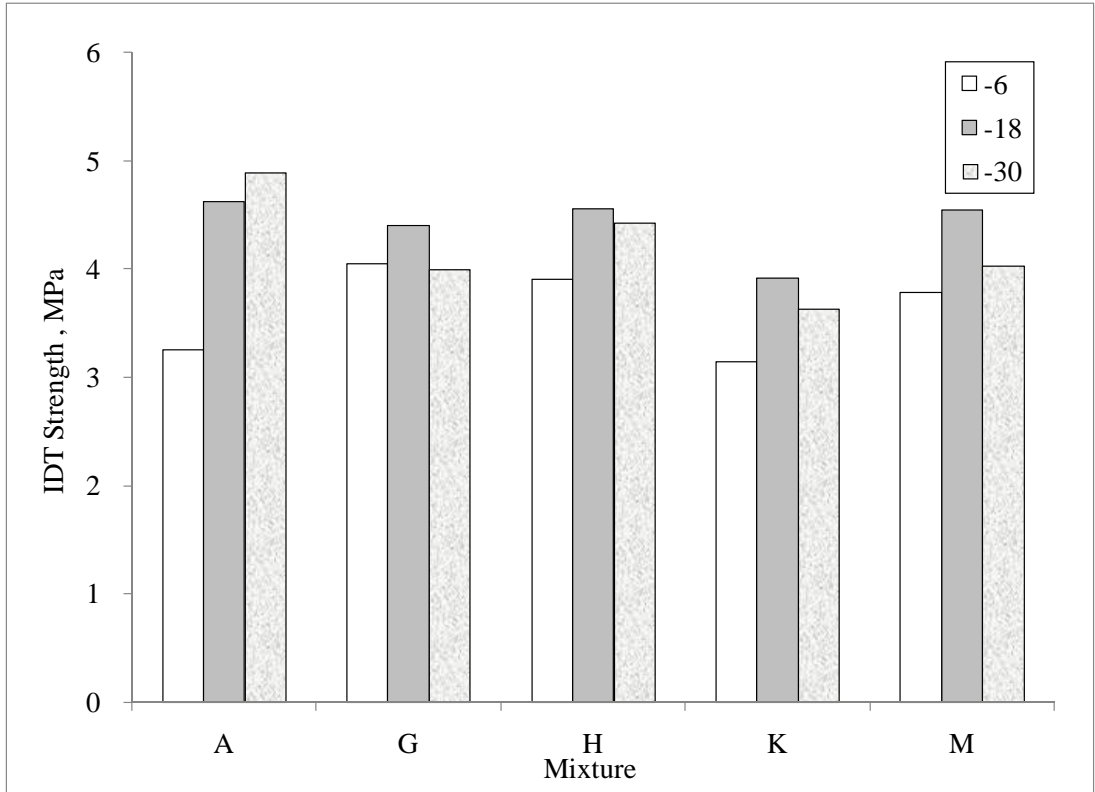


Figure 7. IDT strength values (mixtures A, G, H, K, M)

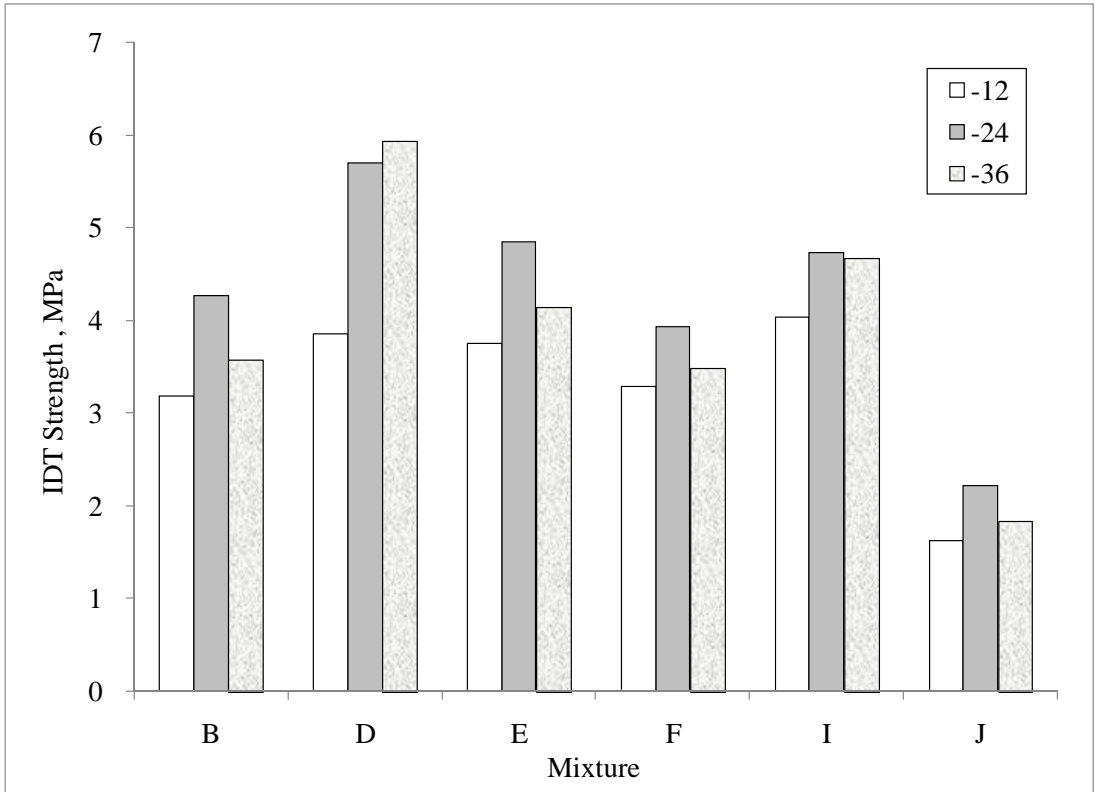


Figure 8. IDT strength values (mixtures B, D, E, F, I, J)

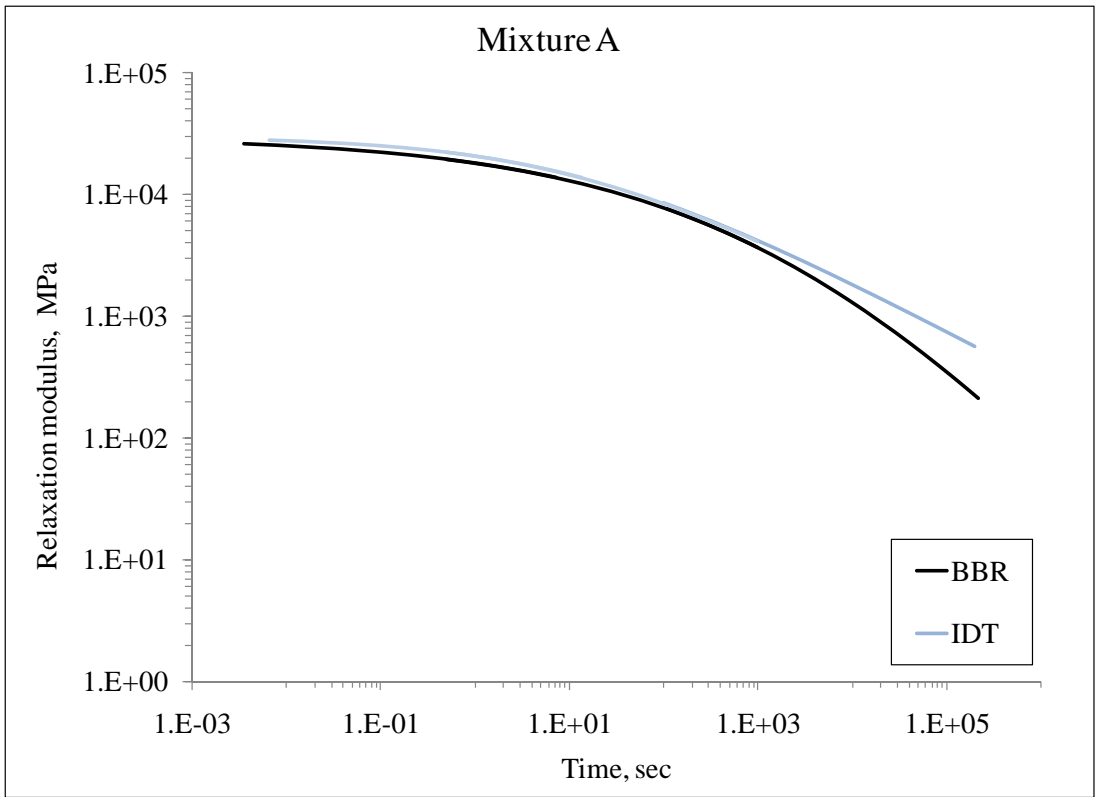


Figure 9. Relaxation modulus mastercurve at -18°C, mixture A

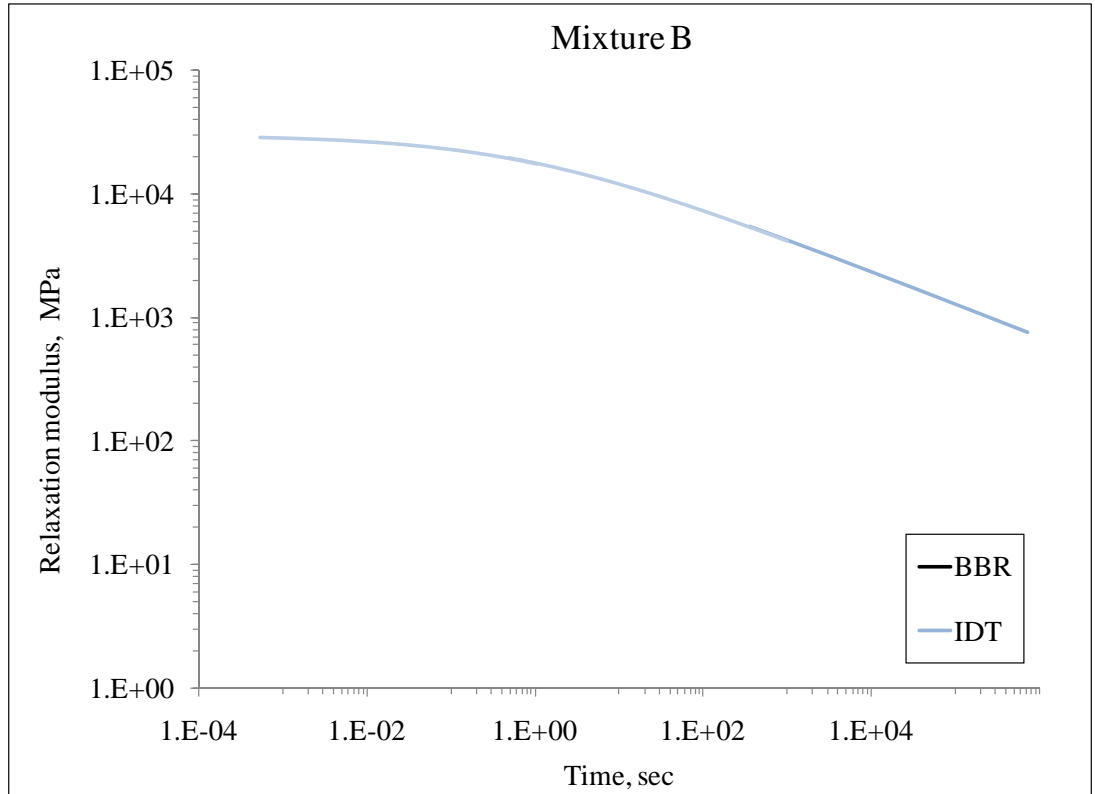


Figure 10. Relaxation modulus mastercurve at -24°C, mixture B

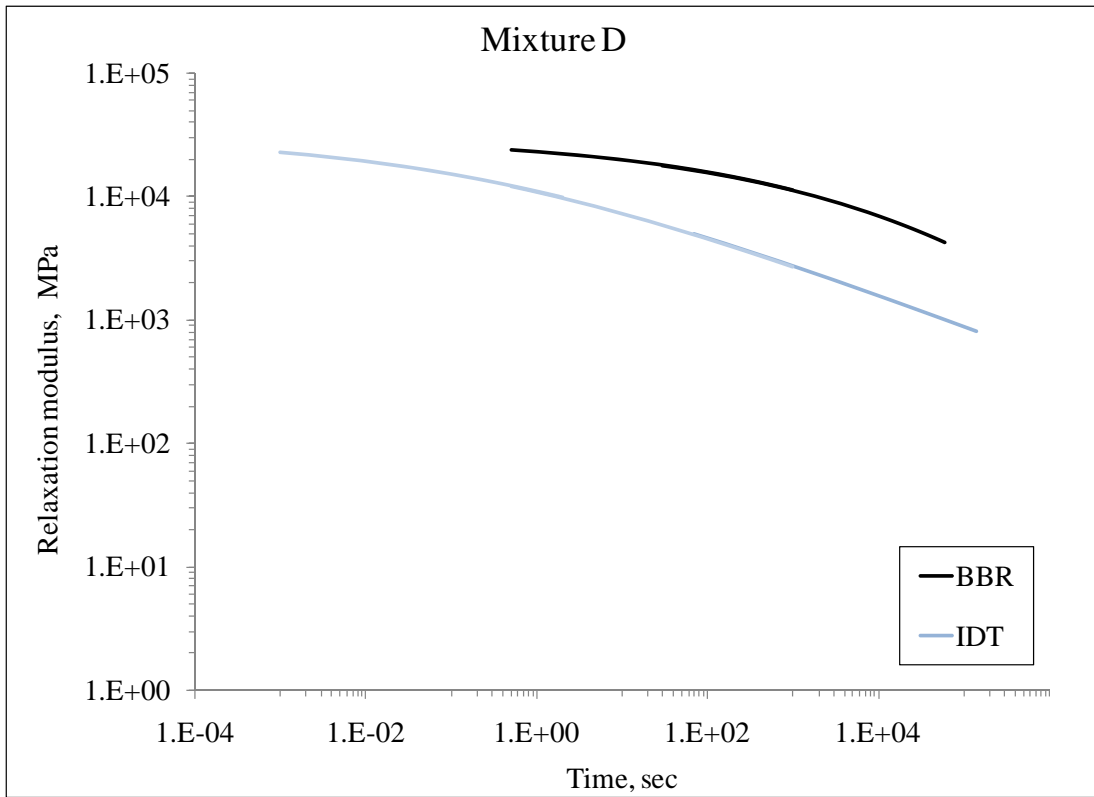


Figure 11. Relaxation modulus mastercurve at -24°C, mixture D

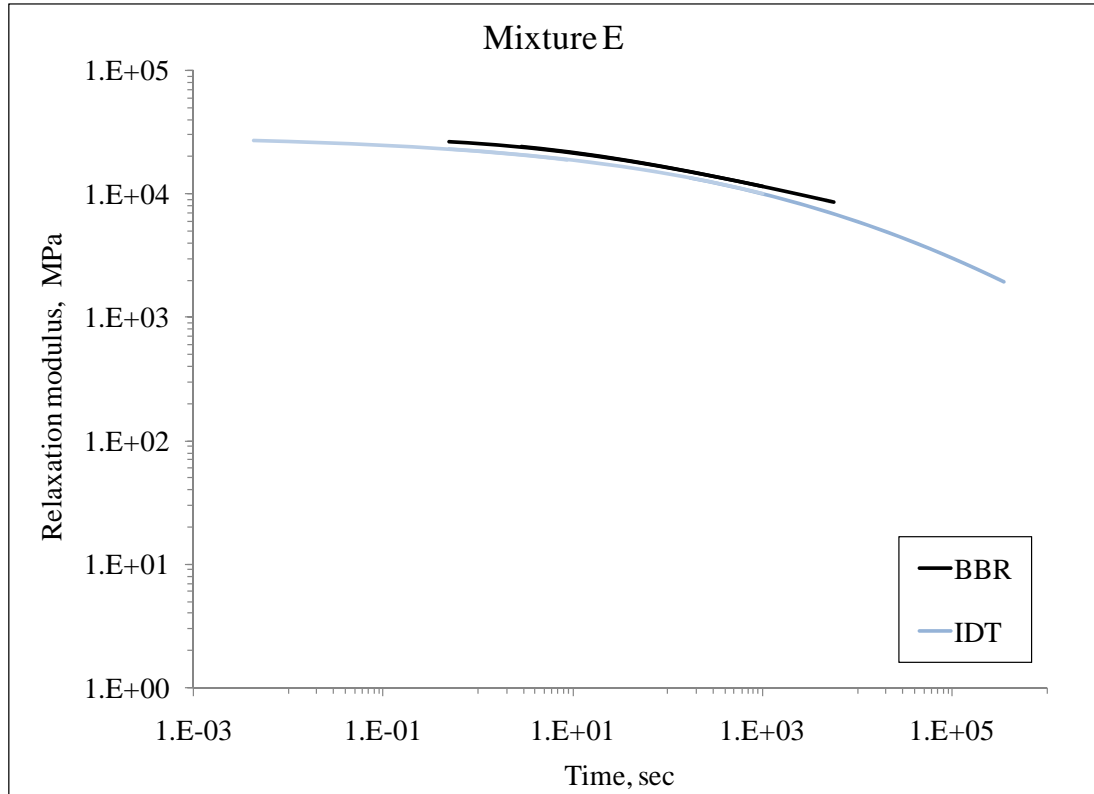


Figure 12. Relaxation modulus mastercurve at -24°C, mixture E

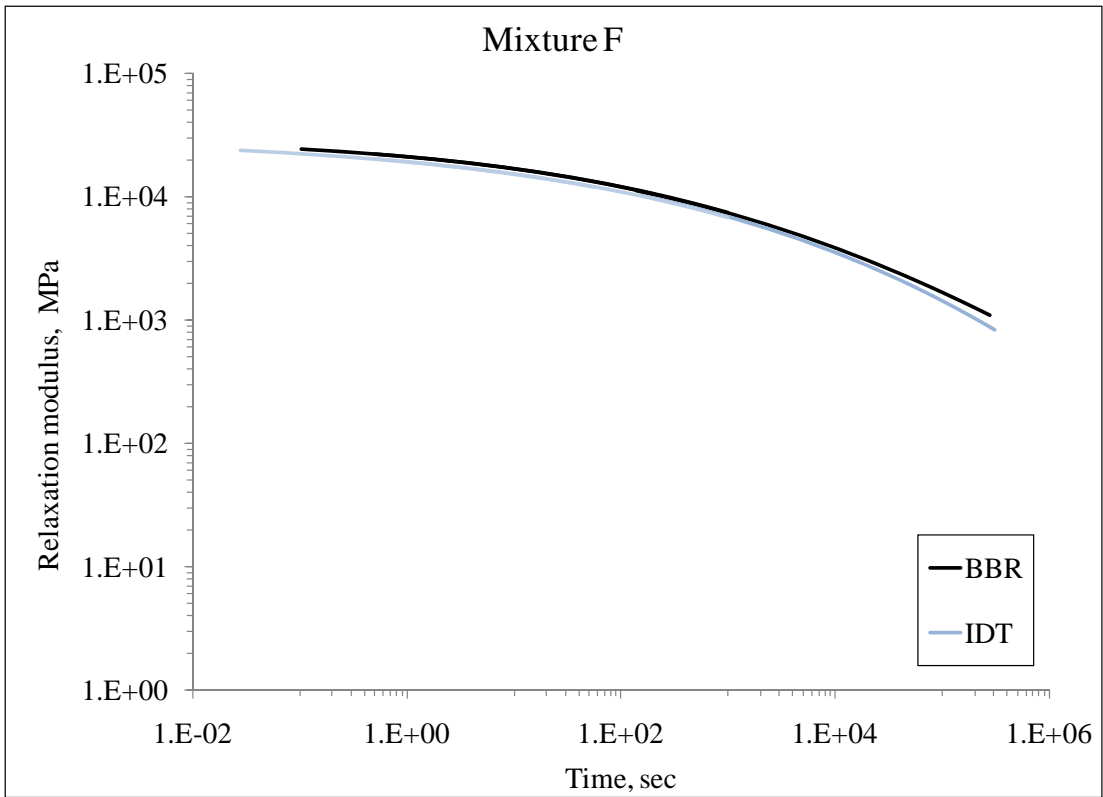


Figure 13. Relaxation modulus mastercurve at -24°C, mixture F

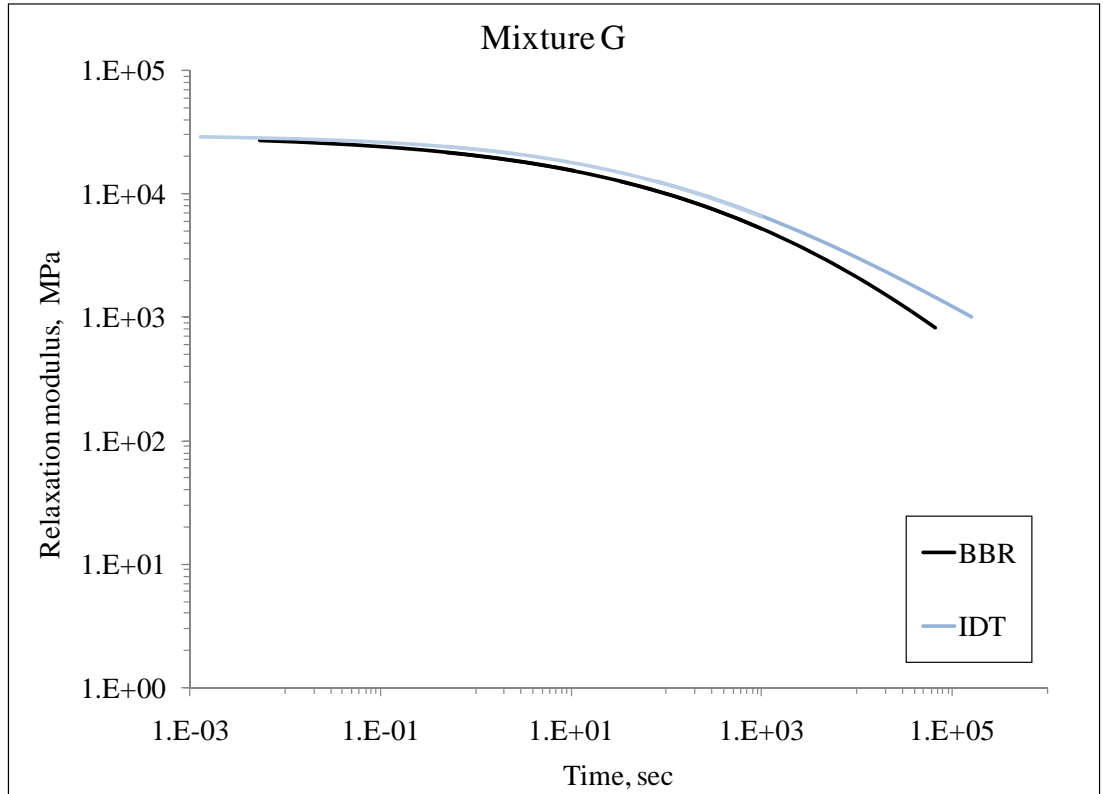


Figure 14. Relaxation modulus mastercurve at -18°C, mixture G

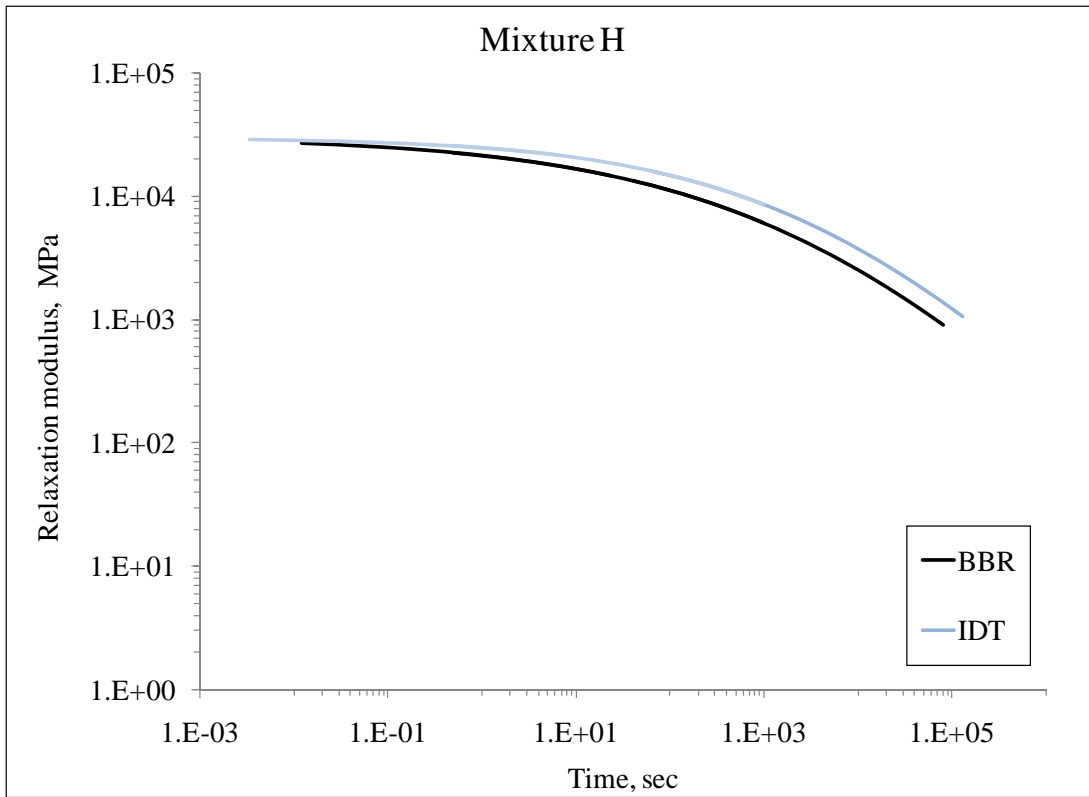


Figure 15. Relaxation modulus mastercurve at -18°C, mixture H

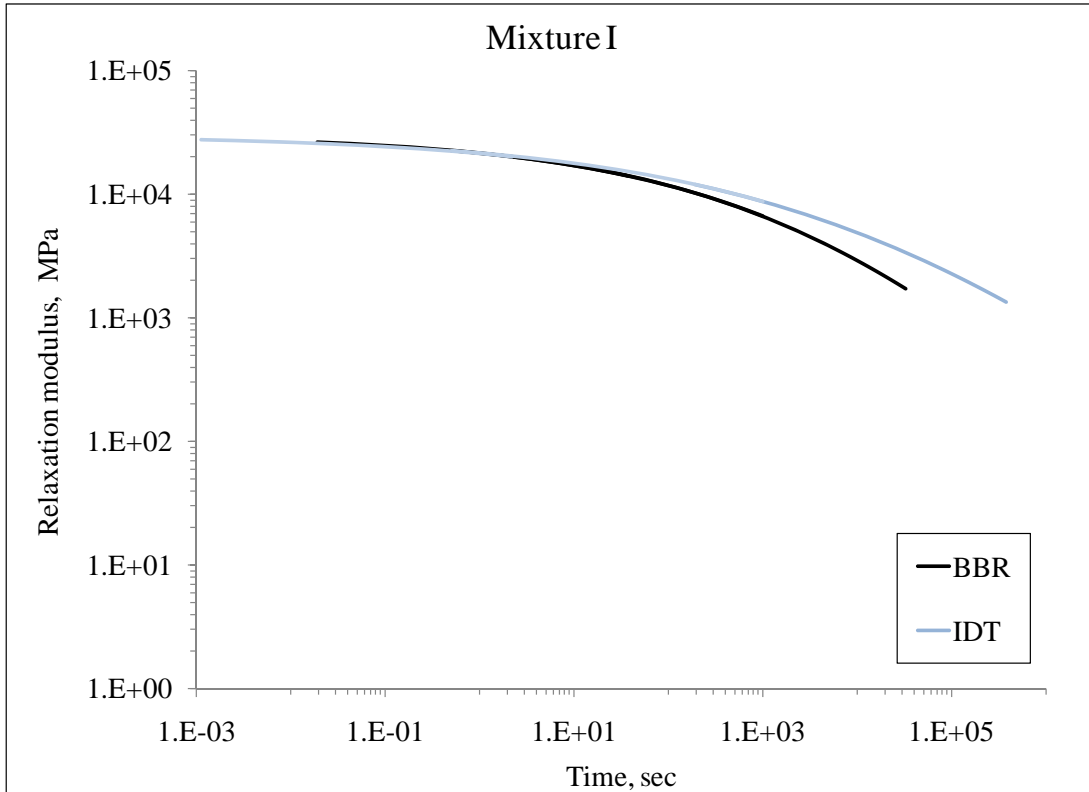


Figure 16. Relaxation modulus mastercurve at -24°C, mixture I

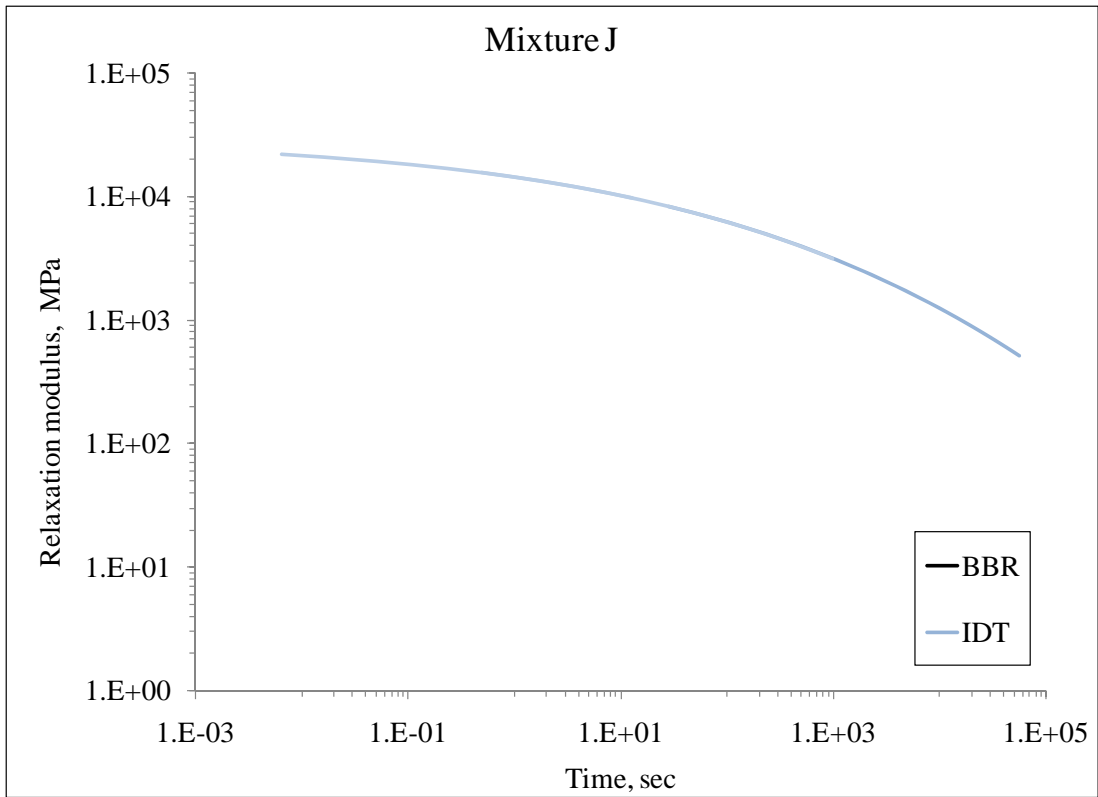


Figure 17. Relaxation modulus mastercurve at -24°C, mixture J

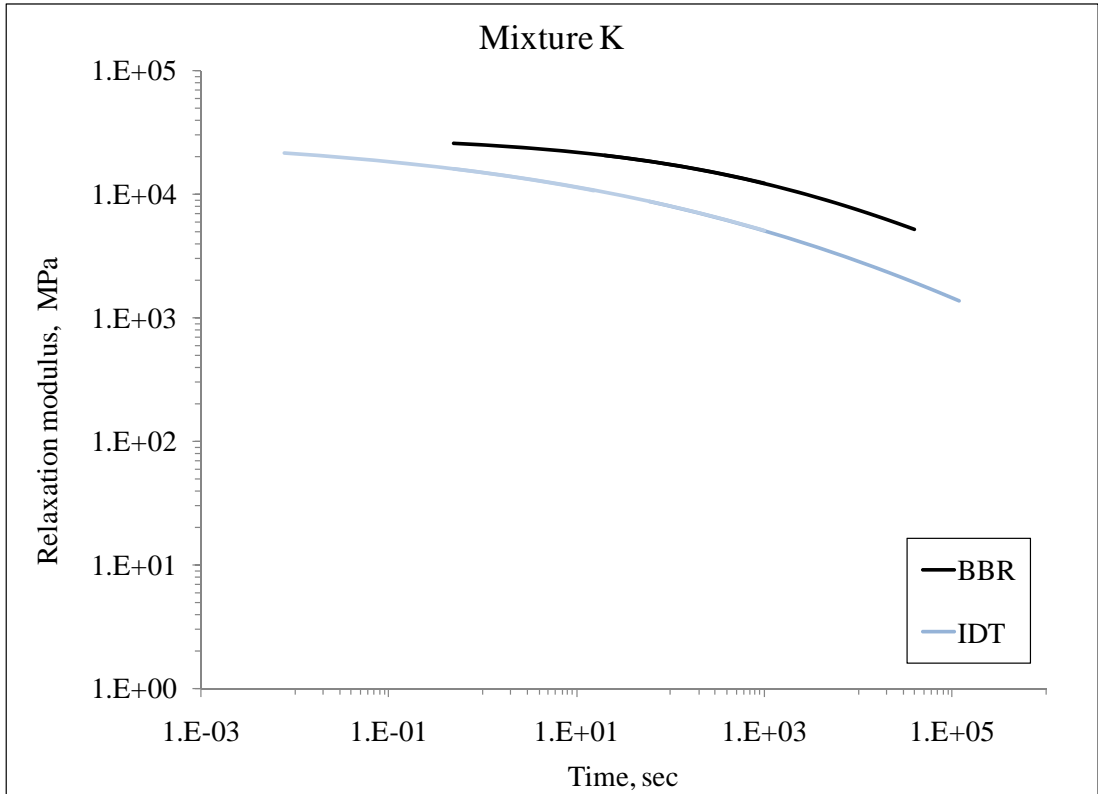


Figure 18. Relaxation modulus mastercurve at -24°C, mixture K

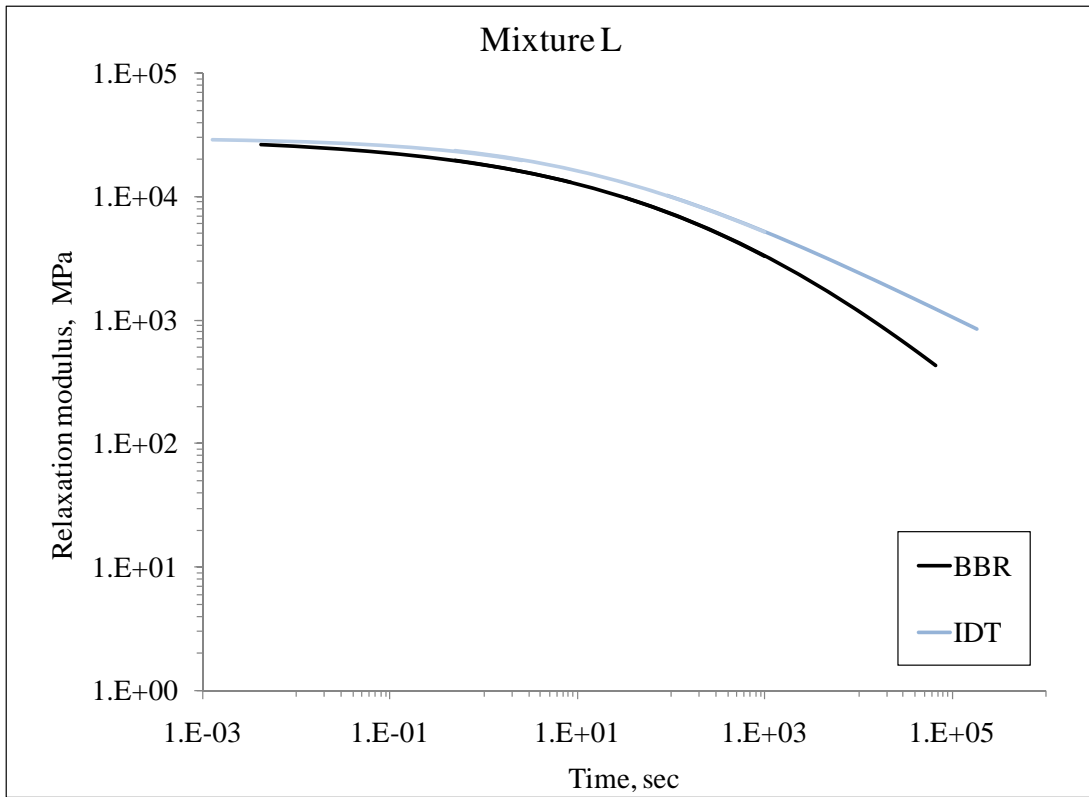


Figure 19. Relaxation modulus mastercurve at -24°C, mixture L

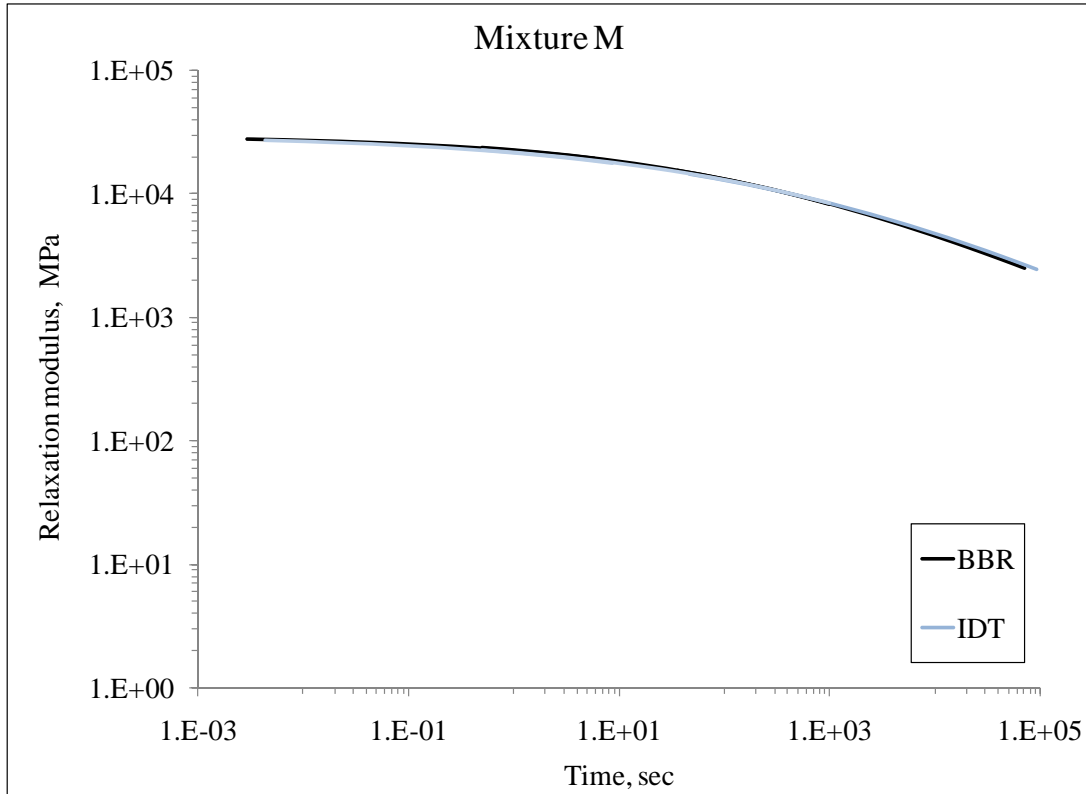


Figure 20. Relaxation modulus mastercurve at -18°C, mixture M

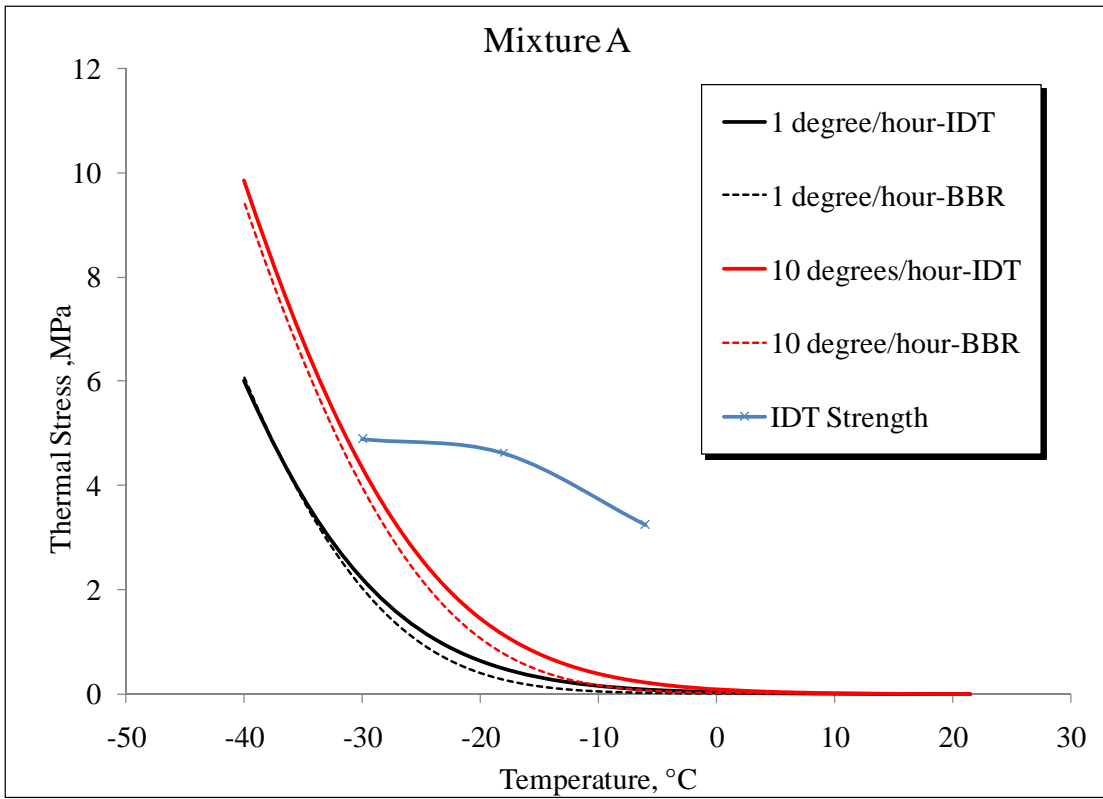


Figure 21. Thermal stress calculation for mixture A

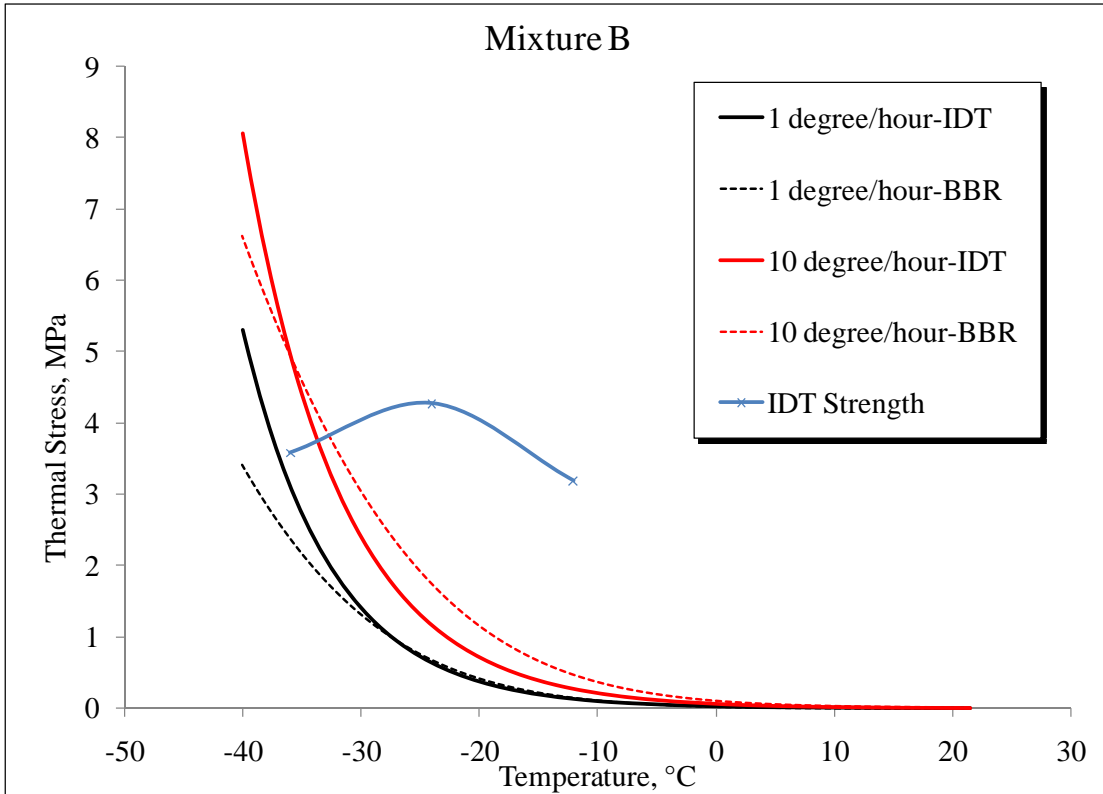


Figure 22. Thermal stress calculation for mixture B

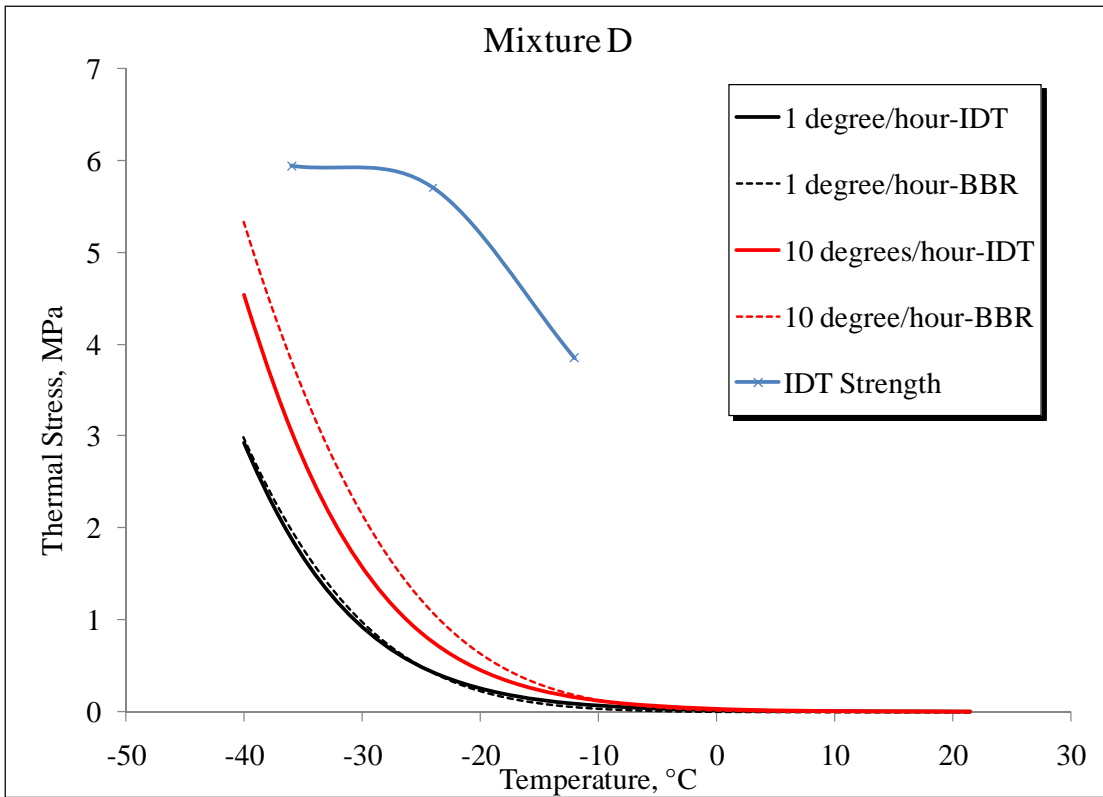


Figure 23. Thermal stress calculation for mixture D

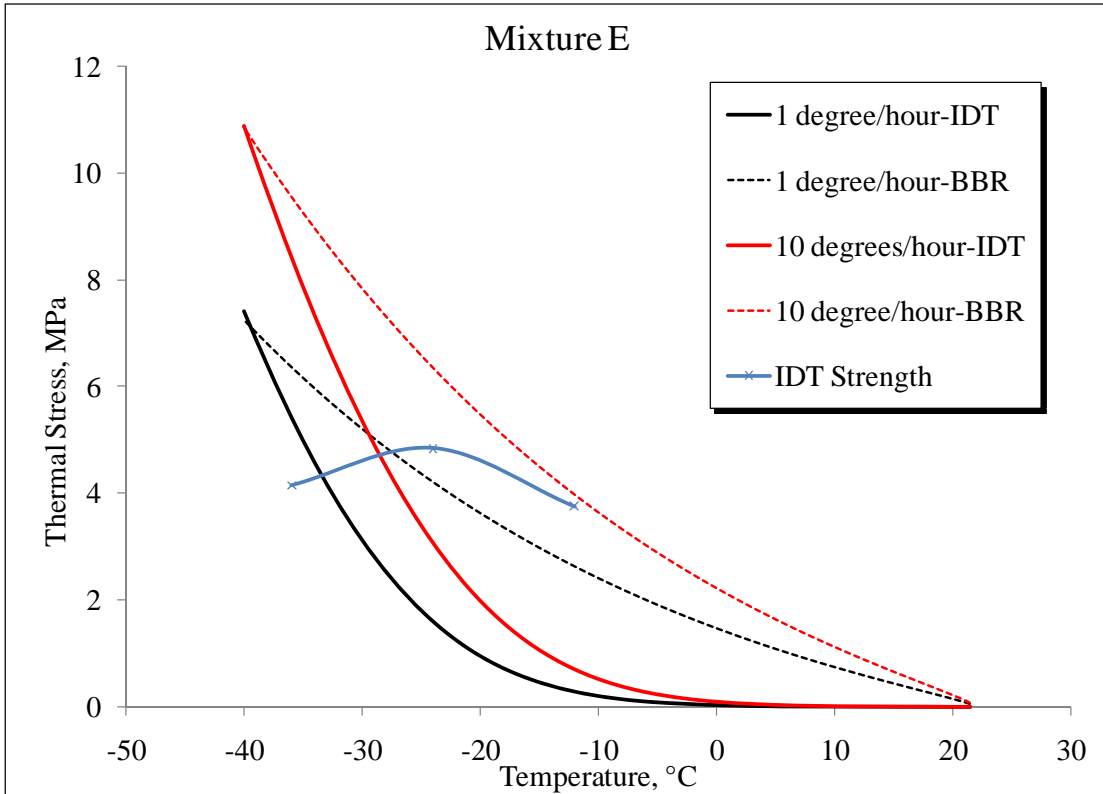


Figure 24. Thermal stress calculation for mixture E

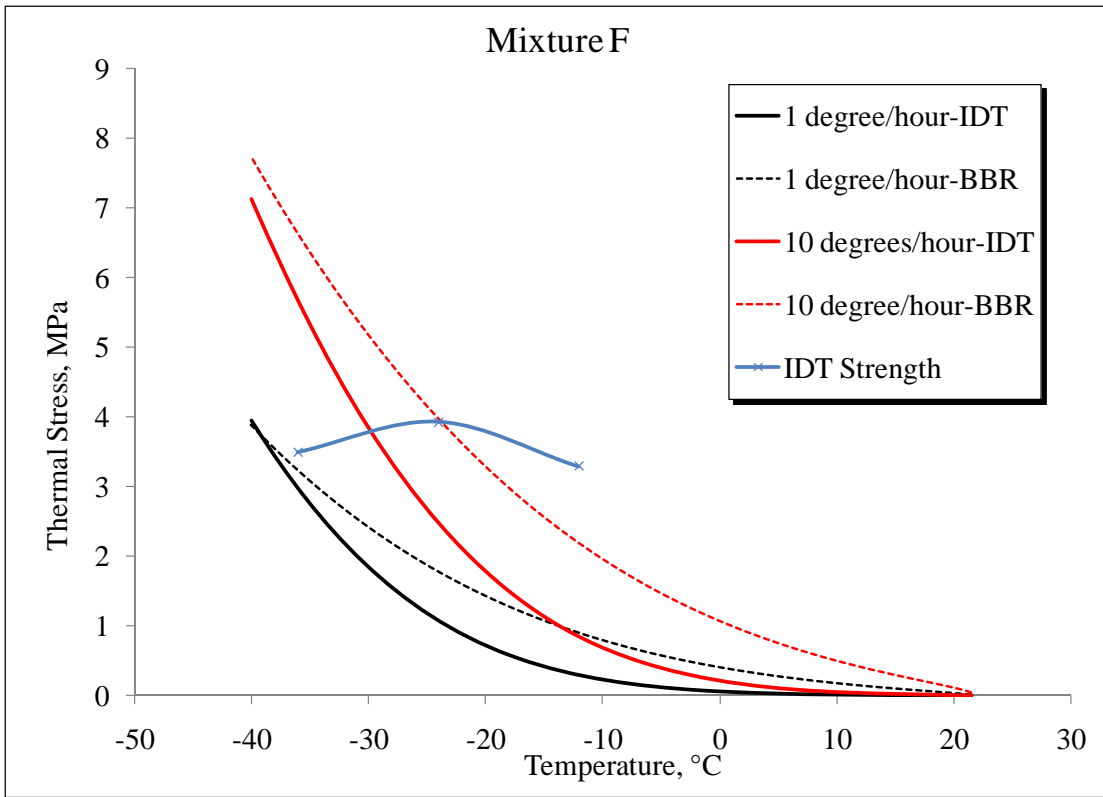


Figure 25. Thermal stress calculation for mixture F

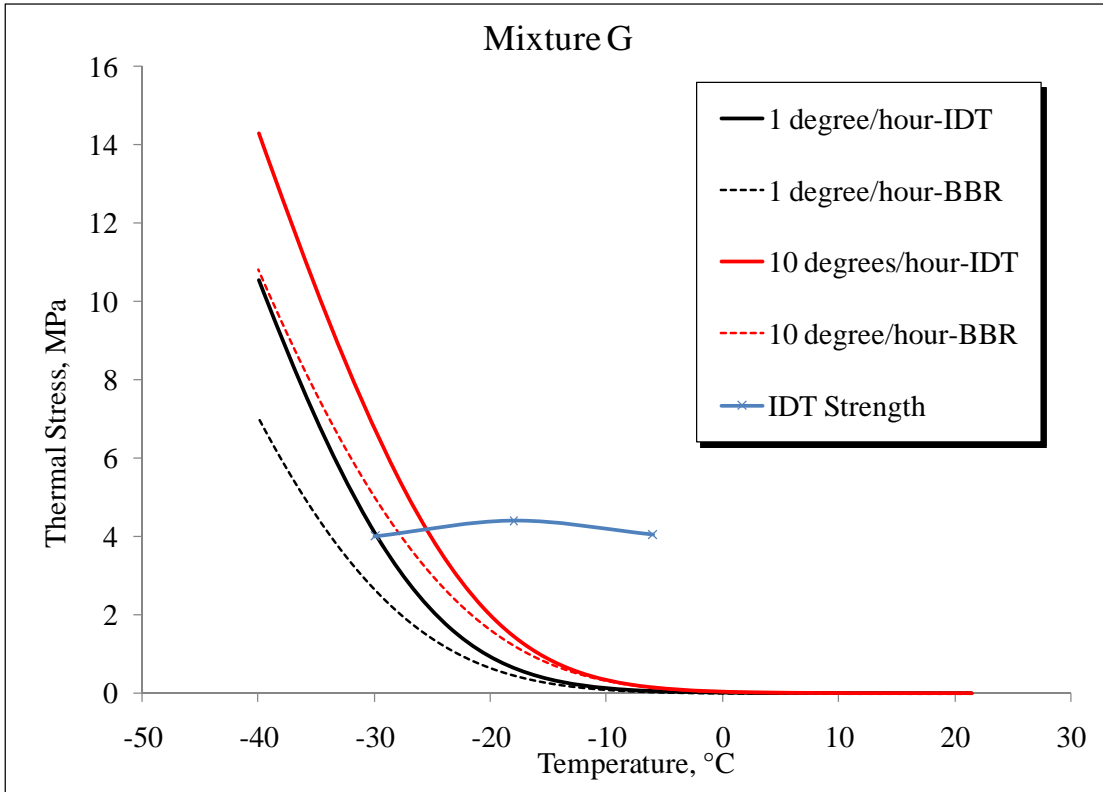


Figure 26. Thermal stress calculation for mixture G

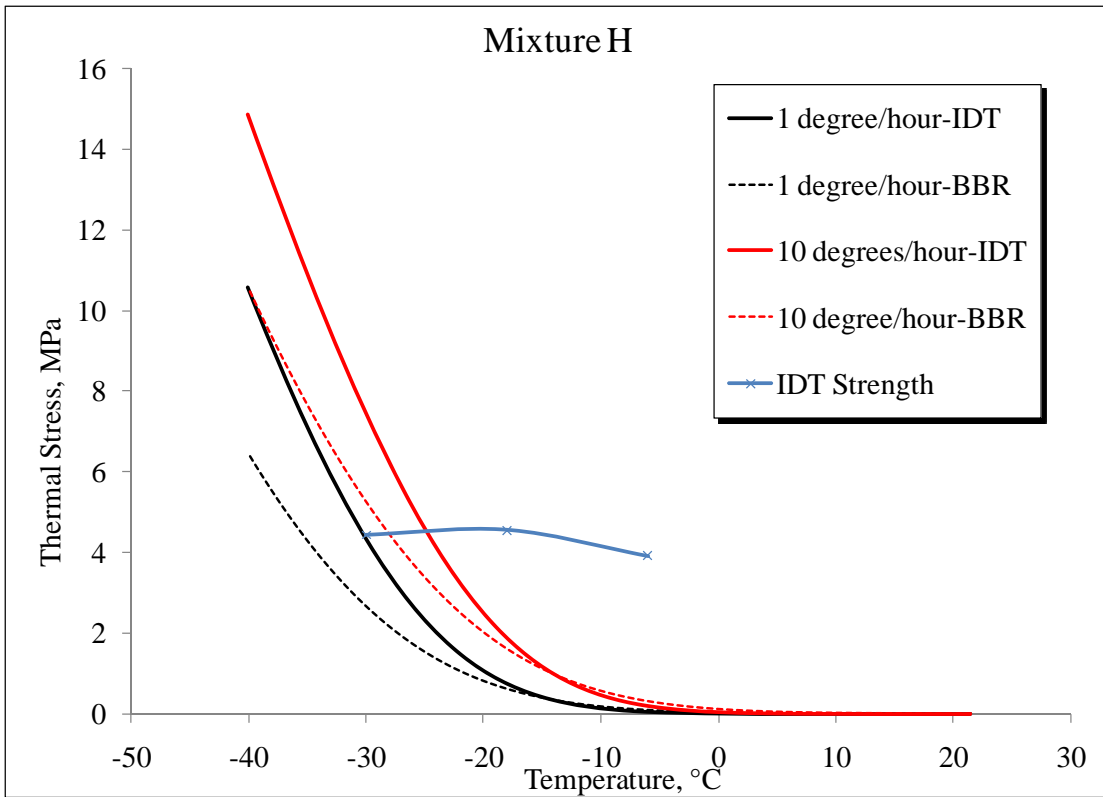


Figure 27. Thermal stress calculation for mixture H

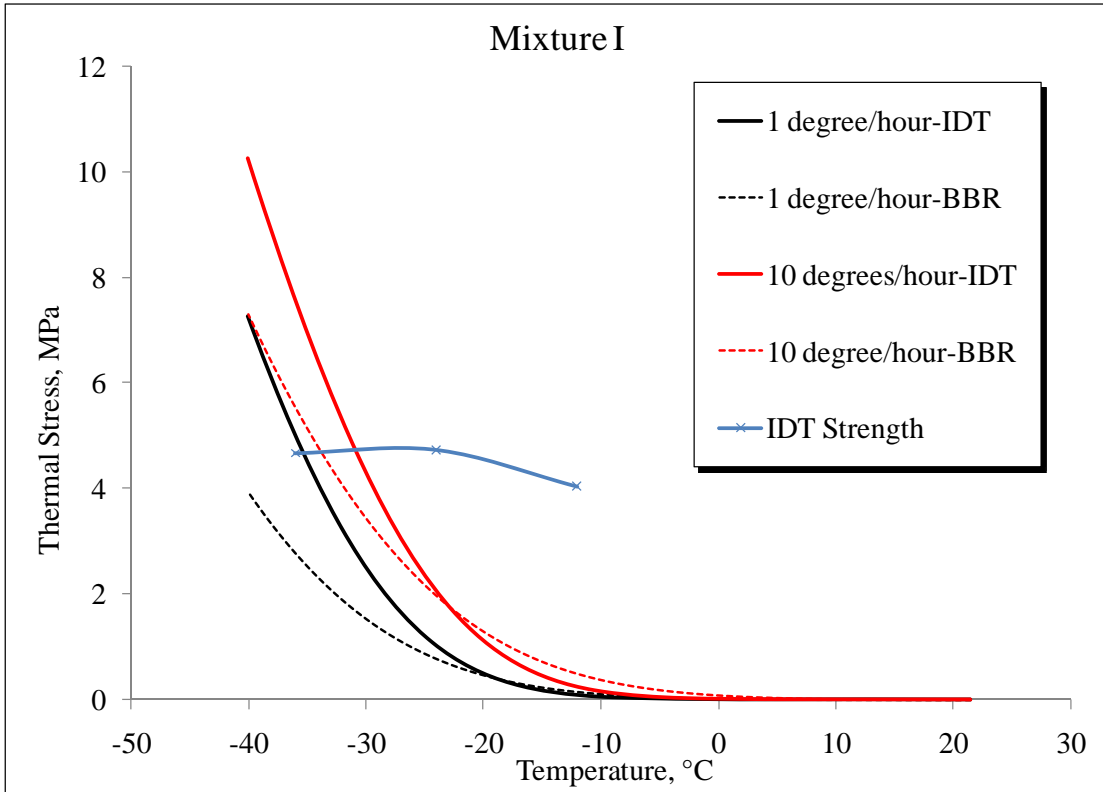


Figure 28. Thermal stress calculation for mixture I

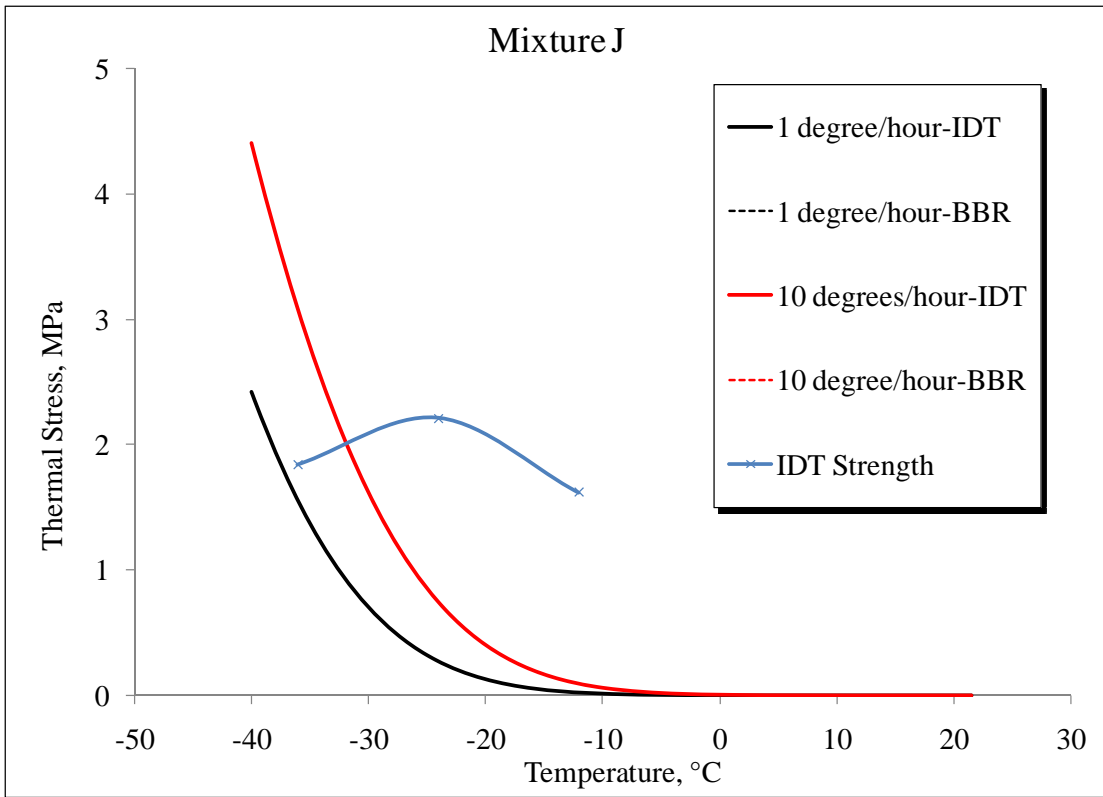


Figure 29. Thermal stress calculation for mixture J

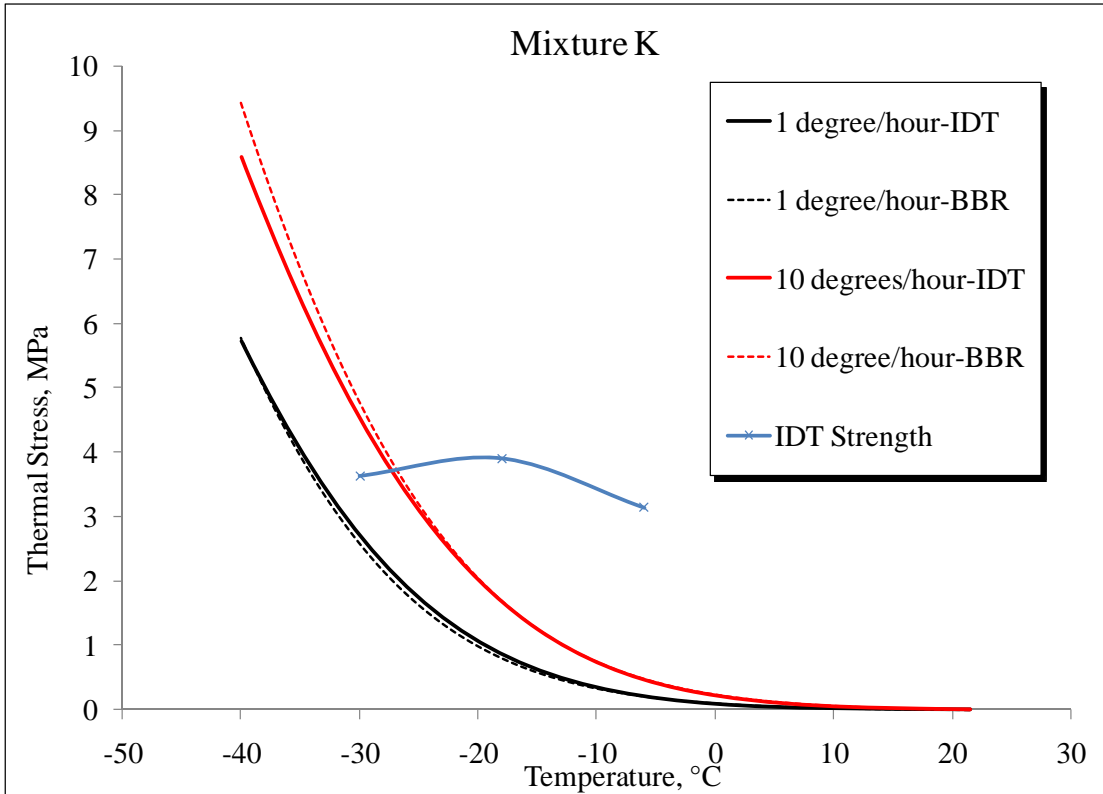


Figure 30. Thermal stress calculation for mixture K

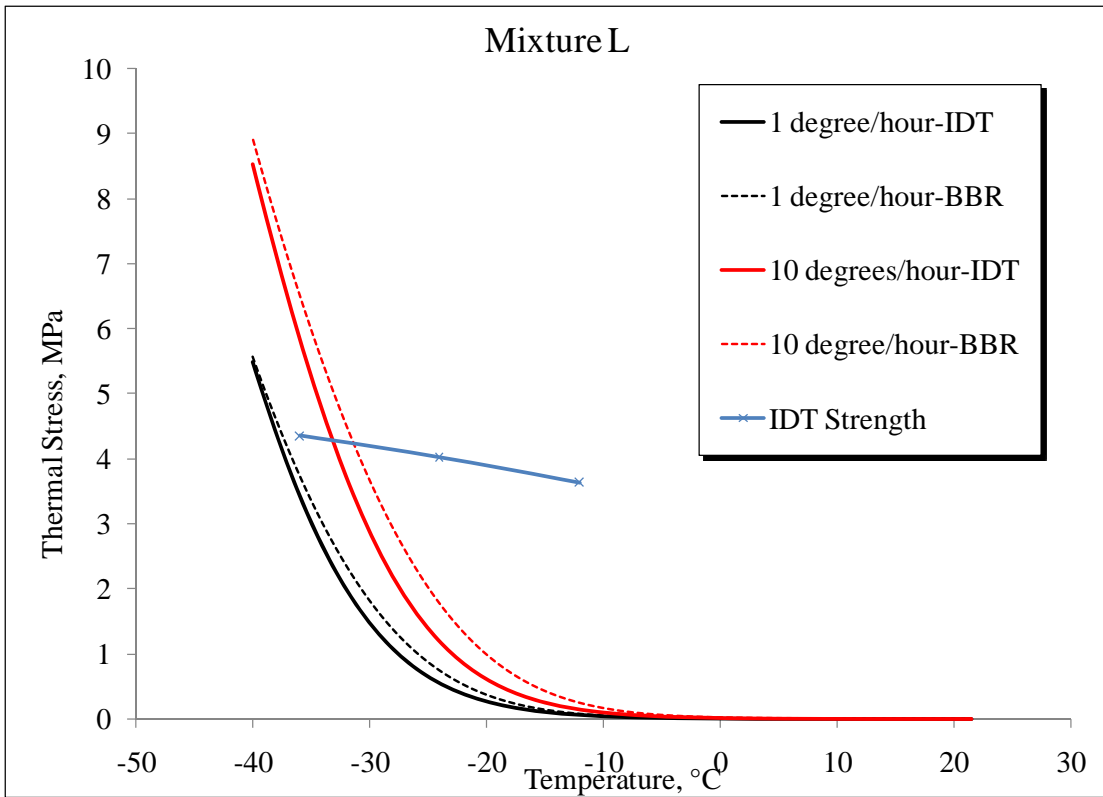


Figure 31. Thermal stress calculation for mixture L

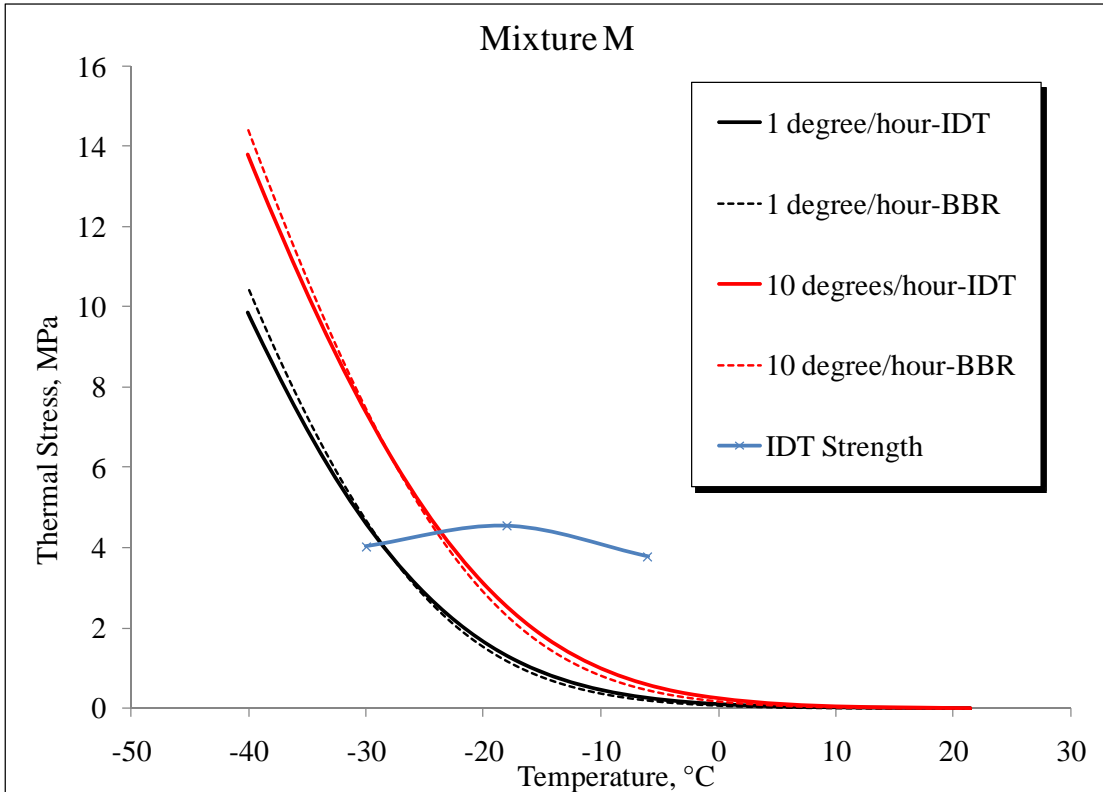


Figure 32. Thermal stress calculation for mixture M

TASK 3

In this task, direct tension (DT) and double edge notch tension (DENT) tests were performed on the PAV and extracted asphalt binders described in Table 2. The DT tests were conducted at two temperatures, PG + 10°C and PG + 4°C; three to six replicates were tested at each temperature depending on how much material was available.

To further investigate low-temperature fracture behavior of the asphalt binders, DENT tests were also performed at the same temperatures using the procedure described elsewhere (Zofka and Marasteanu 2007). A razor blade was used to make 1.5mm pre-cracks on both sides of the test specimens and a strain rate was 1%/min was used. Asphalt binder mode I critical stress intensity factor (fracture toughness) K_{IC} was calculated using the following equation:

$$K_{IC} = \frac{P}{B\sqrt{W}} \frac{\sqrt{\frac{\pi a}{2W}}}{\sqrt{1 - \frac{a}{W}}} \left[1.122 - 0.561 \left(\frac{a}{W} \right) - 0.205 \left(\frac{a}{W} \right)^2 + 0.471 \left(\frac{a}{W} \right)^3 + 0.190 \left(\frac{a}{W} \right)^4 \right]$$

where:

- P – peak load [kN],
- B – specimen thickness [mm]
- W – half width of the specimen [mm],
- a – length of the notch and pre-crack [mm].

An example of stress strain curves obtained from the Direct Tension data is shown in Figure 33. Summaries of the results obtained with the two test methods are shown in Tables 8 to 12.

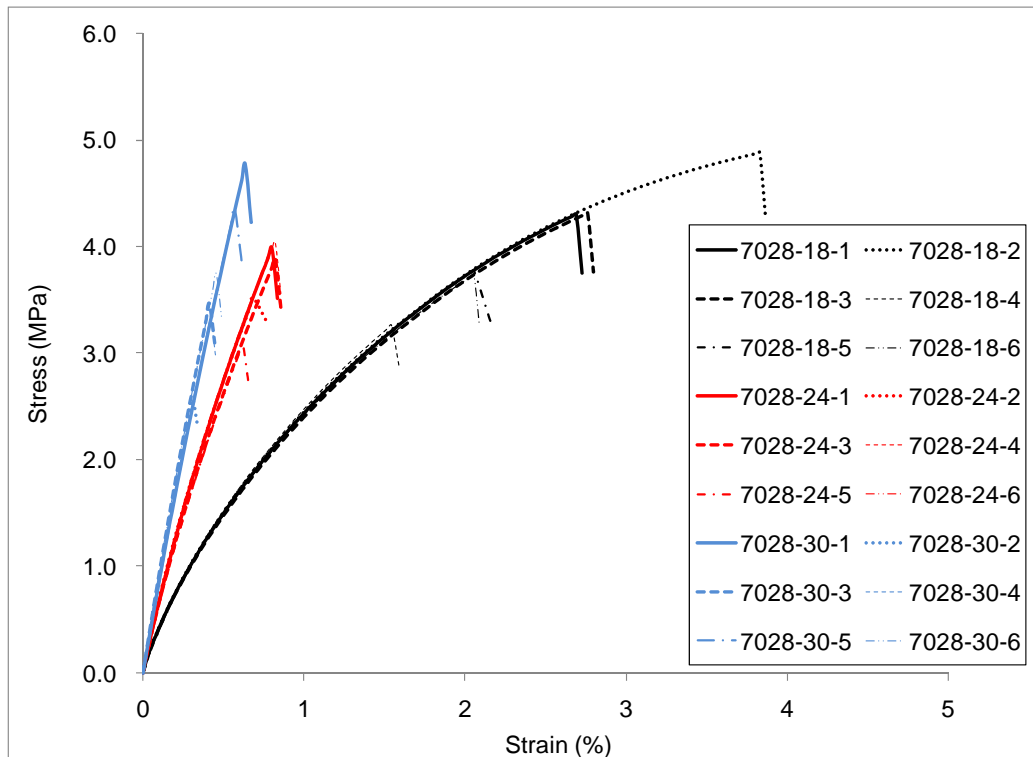


Figure 33. DTT stress-strain curves for asphalt binder PG64-22

Table 8. Summary of asphalt binders DTT strength results.

| Binder ID | T °C | DTT Strength , MPa | | | | | CV(%) |
|-------------|---------|--------------------|------|------|------|------|-------|
| | | R1 | R2 | R3 | R4 | Ave | |
| 21-Fine | -18 | 4.29 | 3.98 | 3.44 | 3.17 | 3.72 | 13.7% |
| | -24 | 5.07 | 4.23 | 3.67 | 3.48 | 4.11 | 17.4% |
| | -30 | 4.67 | 3.79 | 1.75 | 1.34 | 2.89 | 55.6% |
| 21-Coarse | -18 | 5.85 | 5.75 | 3.98 | 3.32 | 4.72 | 26.9% |
| | -24 | 4.94 | 4.46 | 4.44 | 2.48 | 4.08 | 26.8% |
| | -30 | 3.57 | 2.62 | 2.28 | 2.27 | 2.68 | 22.7% |
| 21-Standard | -18 | 5.11 | 4.95 | 4.85 | 1.91 | 4.20 | 36.5% |
| | -24 | 6.26 | 6.13 | 6.00 | 4.64 | 5.76 | 13.1% |
| | -30 | 5.63 | 3.60 | 3.05 | 1.97 | 3.56 | 43.0% |
| PG-58-28 | -18 | 3.68 | 3.65 | 3.61 | 3.57 | 3.63 | 1.2% |
| | -24 | 5.18 | 4.44 | 4.17 | 4.14 | 4.48 | 10.9% |
| | -30 | 4.52 | 4.23 | 3.97 | 3.87 | 4.15 | 7.0% |
| PG-58-34 | -24 | 5.34 | 4.44 | 4.26 | 4.12 | 4.54 | 12.1% |
| | -30 | 5.14 | 5.08 | 5.05 | 4.59 | 4.97 | 5.1% |
| PG-58-34W | -24 | 3.93 | 3.90 | 3.58 | 3.47 | 3.72 | 6.1% |
| | -30 | 4.19 | 4.17 | 3.70 | 3.51 | 3.89 | 8.9% |
| PG-64-22 | -12 | 4.85 | 4.05 | 3.16 | 2.91 | 3.74 | 23.6% |
| | -18 | 4.59 | 4.40 | 4.38 | 4.08 | 4.36 | 4.8% |
| | -24 | 4.28 | 3.49 | 2.90 | 2.82 | 3.37 | 20.0% |
| PG-64-34 | -24 | 5.12 | 4.64 | 4.16 | 4.11 | 4.51 | 10.5% |
| | -30 | 5.37 | 5.36 | 4.89 | 4.84 | 5.12 | 5.7% |
| PG-70-28 | -18 | 4.82 | 4.33 | 4.31 | 3.83 | 4.32 | 9.3% |
| | -24 | 4.32 | 4.32 | 4.30 | 4.16 | 4.28 | 1.9% |
| | -30 | 5.22 | 4.82 | 4.25 | 3.97 | 4.57 | 12.3% |

Table 9. Summary of asphalt binders DTT strain at failure results.

| Binder ID | T °C | DTT Strain at failure , % | | | | | CV(%) |
|-------------|---------|---------------------------|------|------|------|------|-------|
| | | R1 | R2 | R3 | R4 | Ave | |
| 21-Fine | -18 | 1.23 | 1.04 | 0.95 | 0.81 | 1.01 | 17.6% |
| | -24 | 0.92 | 0.69 | 0.58 | 0.55 | 0.69 | 24.6% |
| | -30 | 0.53 | 0.40 | 0.17 | 0.13 | 0.31 | 63.3% |
| 21-Coarse | -18 | 2.85 | 2.57 | 2.48 | 1.04 | 2.23 | 36.5% |
| | -24 | 0.95 | 0.86 | 0.81 | 0.40 | 0.76 | 32.2% |
| | -30 | 0.40 | 0.30 | 0.25 | 0.23 | 0.30 | 25.7% |
| 21-Standard | -18 | 2.18 | 2.00 | 1.95 | 0.49 | 1.65 | 47.5% |
| | -24 | 1.30 | 1.30 | 1.23 | 0.83 | 1.17 | 19.2% |
| | -30 | 0.69 | 0.40 | 0.32 | 0.21 | 0.41 | 50.1% |
| PG-58-28 | -18 | 1.35 | 1.30 | 1.35 | 1.25 | 1.31 | 3.6% |
| | -24 | 0.90 | 0.76 | 0.67 | 0.69 | 0.75 | 13.5% |
| | -30 | 0.48 | 0.44 | 0.42 | 0.40 | 0.44 | 8.4% |
| PG-58-34 | -24 | 2.65 | 1.95 | 1.77 | 1.75 | 2.03 | 20.8% |
| | -30 | 1.00 | 1.03 | 0.90 | 0.86 | 0.95 | 8.3% |
| PG-58-34W | -24 | 1.58 | 1.48 | 1.36 | 1.26 | 1.42 | 9.8% |
| | -30 | 0.74 | 0.75 | 0.63 | 0.55 | 0.67 | 14.0% |
| PG-64-22 | -12 | 3.94 | 2.42 | 1.53 | 1.36 | 2.31 | 51.0% |
| | -18 | 0.95 | 0.91 | 0.88 | 0.82 | 0.89 | 6.5% |
| | -24 | 0.49 | 0.40 | 0.29 | 0.29 | 0.37 | 25.9% |
| PG-64-34 | -24 | 3.99 | 3.30 | 2.24 | 1.91 | 2.86 | 33.6% |
| | -30 | 1.14 | 1.12 | 1.03 | 0.93 | 1.06 | 9.2% |
| PG-70-28 | -18 | 4.01 | 2.89 | 2.81 | 2.16 | 2.97 | 25.9% |
| | -24 | 0.89 | 0.87 | 0.87 | 0.89 | 0.88 | 1.6% |
| | -30 | 0.70 | 0.63 | 0.52 | 0.47 | 0.58 | 17.9% |

Table 10. Summary of asphalt binders DENT strength results.

| Binder ID | T °C | DENT Strength , MPa | | | | CV % |
|-------------|---------|---------------------|------|------|------|-------|
| | | R1 | R2 | R3 | Ave | |
| 21-Fine | -18 | 0.62 | 0.59 | 0.54 | 0.58 | 6.9% |
| | -24 | 0.68 | 0.67 | 0.56 | 0.64 | 10.3% |
| 21-Coarse | -18 | 0.57 | 0.46 | 0.44 | 0.49 | 14.1% |
| | -24 | 0.97 | 0.57 | 0.47 | 0.67 | 39.3% |
| 21-Standard | -18 | 0.54 | 0.47 | 0.39 | 0.47 | 16.7% |
| | -24 | 0.70 | 0.61 | 0.46 | 0.59 | 20.0% |
| PG-58-28 | -18 | 0.68 | 0.52 | 0.46 | 0.55 | 20.8% |
| | -24 | 0.78 | 0.71 | 0.70 | 0.73 | 5.9% |
| PG-58-34 | -24 | 1.09 | 1.08 | 1.04 | 1.07 | 2.3% |
| | -30 | 0.99 | 0.82 | 0.61 | 0.81 | 23.7% |
| PG-58-34W | -24 | 0.91 | 0.90 | 0.84 | 0.88 | 4.3% |
| | -30 | 1.16 | 0.84 | 0.64 | 0.88 | 29.7% |
| PG-64-22 | -12 | 0.85 | 0.80 | 0.76 | 0.80 | 5.6% |
| | -18 | 0.43 | 0.36 | NA | 0.39 | 14.0% |
| PG-64-34 | -24 | 1.83 | 1.42 | 1.14 | 1.46 | 23.8% |
| | -30 | 1.42 | 1.39 | 1.31 | 1.38 | 4.3% |
| PG-70-28 | -18 | 1.79 | 1.75 | 1.57 | 1.70 | 6.9% |
| | -24 | 1.44 | 1.27 | 1.07 | 1.26 | 14.9% |

Table 11. Summary of asphalt binders DENT strain at failure results.

| Binder ID | T °C | DENT Strain at failure , % | | | | CV % |
|-------------|---------|----------------------------|------|------|------|-------|
| | | R1 | R2 | R3 | Ave | |
| 21-Fine | -18 | 0.07 | 0.07 | 0.07 | 0.07 | 5.5% |
| | -24 | 0.06 | 0.06 | 0.05 | 0.05 | 7.8% |
| 21-Coarse | -18 | 0.08 | 0.06 | 0.08 | 0.08 | 19.1% |
| | -24 | 0.11 | 0.06 | 0.04 | 0.07 | 49.1% |
| 21-Standard | -18 | 0.07 | 0.06 | 0.05 | 0.06 | 18.5% |
| | -24 | 0.08 | 0.06 | 0.04 | 0.06 | 29.8% |
| PG-58-28 | -18 | 0.10 | 0.06 | 0.06 | 0.07 | 29.6% |
| | -24 | 0.06 | 0.06 | 0.06 | 0.06 | 6.3% |
| PG-58-34 | -24 | 0.17 | 0.20 | 0.16 | 0.17 | 12.3% |
| | -30 | 0.08 | 0.07 | 0.05 | 0.07 | 26.5% |
| PG-58-34W | -24 | 0.15 | 0.15 | 0.13 | 0.14 | 8.8% |
| | -30 | 0.11 | 0.08 | 0.06 | 0.08 | 30.6% |
| PG-64-22 | -12 | 0.18 | 0.15 | 0.15 | 0.16 | 8.4% |
| | -18 | 0.04 | 0.03 | NA | 0.03 | 12.9% |
| PG-64-34 | -24 | 0.45 | 0.27 | 0.21 | 0.31 | 41.6% |
| | -30 | 0.14 | 0.13 | 0.14 | 0.14 | 4.0% |
| PG-70-28 | -18 | 0.48 | 0.44 | 0.38 | 0.43 | 12.1% |
| | -24 | 0.17 | 0.13 | 0.11 | 0.13 | 22.4% |

Table 12. Summary of asphalt binders DENT K_{IC} results.

| Binder ID | T °C | K_{IC} (Stress intensity factor) , kPa/m ^{0.5} | | | | CV % |
|-------------|---------|---|-------|-------|-------|-------|
| | | R1 | R2 | R3 | Ave | |
| 21-Fine | -18 | 103.1 | 98.3 | 89.9 | 97.1 | 6.9% |
| | -24 | 113.7 | 111.8 | 93.7 | 106.4 | 10.4% |
| 21-Coarse | -18 | 95.0 | 76.0 | 74.0 | 81.7 | 14.2% |
| | -24 | 161.7 | 94.9 | 78.7 | 111.8 | 39.4% |
| 21-Standard | -18 | 90.3 | 79.3 | 64.4 | 78.0 | 16.7% |
| | -24 | 116.8 | 102.4 | 77.5 | 98.9 | 20.1% |
| PG-58-28 | -18 | 113.3 | 86.2 | 76.4 | 92.0 | 20.8% |
| | -24 | 130.0 | 117.9 | 117.5 | 121.8 | 5.8% |
| PG-58-34 | -24 | 182.1 | 179.6 | 174.3 | 178.7 | 2.2% |
| | -30 | 165.6 | 136.9 | 101.9 | 134.8 | 23.7% |
| PG-58-34W | -24 | 151.5 | 149.6 | 139.7 | 146.9 | 4.3% |
| | -30 | 193.2 | 141.0 | 106.5 | 146.9 | 29.7% |
| PG-64-22 | -12 | 141.3 | 133.1 | 126.2 | 133.5 | 5.7% |
| | -18 | 72.3 | 59.3 | NA | 65.8 | 14.0% |
| PG-64-34 | -24 | 306.1 | 237.0 | 190.5 | 244.5 | 23.8% |
| | -30 | 237.8 | 233.0 | 218.9 | 229.9 | 4.3% |
| PG-70-28 | -18 | 299.7 | 292.0 | 262.5 | 284.7 | 6.9% |
| | -24 | 241.0 | 212.4 | 178.6 | 210.6 | 14.8% |

REFERENCES

1. American Association of State Highway and Transportation Officials (AASHTO) Standard T314-07, "Standard method of test for determining the fracture properties of asphalt binder in Direct Tension (DT)," *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, 27th Edition, 2007.
2. American Association of State Highway and Transportation Officials (AASHTO) Standard T 322-03, "Determining the Creep Compliance and Strength of Hot-Mix Asphalt (HMA) Using the Indirect Tensile Test Device", *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, 27th Edition, 2007.
3. Marasteanu, M., Velasquez, R., Falchetto, A.C., Zofka, A., *Development of a Simple Test to Determine the Low Temperature Creep Compliance of Asphalt Mixtures*, IDEA Program Final Report, NCHRP-133, June 2009.
4. Zofka, A., "Investigation of Asphalt Concrete Creep Behavior Using 3-Point Bending Test." Ph.D. Thesis, University of Minnesota, Minneapolis, July 2007.
5. Zofka, A., Marasteanu, M., "Development of Double Edge Notched Tension (DENT) Test for Asphalt Binders", *Journal of Testing and Evaluation*, ASCE, Vol. 35, No. 3, 2007.
6. Li, X., "Investigation of the Fracture Resistance of Asphalt Mixtures at Low Temperature with a Semi Circular Bend (SCB) Test." Ph.D. Thesis, University of Minnesota, Minneapolis, 2005.
7. Zhang W., Drescher A., Newcomb D. E., Viscoelastic analysis of diametral compression of asphalt concrete, *Journal of Engineering Mechanics*, Vol. 123, No. 6, 1997, pp. 596-603.