PREDICTION OF LOW-TEMPERATURE CRACKING USING SUPERPAVE BINDER SPECIFICATIONS

by

Prithvi S. Kandhal
Associate Director
National Center for Asphalt Technology

Raj Dongre
Research Engineer
Federal Highway Administration

and

Maj. Mark S. Malone
U. S. Air Force

NCAT Report No. 96-2

February 1996

"The contents of this report reflect the views of the authors who are solely responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views and policies of the National Center for Asphalt Technology of Auburn University. This report does not constitute a standard, specification, or regulation."

PREDICTION OF LOW-TEMPERATURE CRACKING USING SUPERPAVE BINDER SPECIFICATIONS

by

Prithvi S. Kandhal, Raj Dongre and Mark S. Malone*

ABSTRACT

Six different AC-20 asphalt cements were used in a Pennsylvania project in September 1976. Two of the six test pavements developed low-temperature cracking in January 1977. The remaining four test pavements started to develop cracks to different degrees after three years. This project has been well documented in the literature during its 7 years service life. Data such as theological properties of original and aged asphalt cements, hourly air and pavement temperature, and yearly crack surveys, have been reported. The samples of these six asphalt cements which were saved from 1976 to 1995 (19 years) have now been tested using Superpave binder test procedures such as bending beam rheometer (BBR). This research project was undertaken to verify whether these Superpave test procedures and specifications could have predicted the low-temperature cracking of the six AC-20 asphalt cements in the Pennsylvania project.

The maximum stiffness criteria of 300 MPa and the minimum m-value criteria of 0.30 recommended in Superpave binder specifications generally appear to be reasonable in mitigating

---

*Respectively, Associate Director, National Center for Asphalt Technology; Research Engineer, Federal Highway Administration; and Major. U. S. Air Force.

low-temperature cracking. However, the behavior ofone asphalt cement (T-3) could not be explained by these criteria. Although Asphalt T-3 had stiffness exceeding 300 MPa at the minimum design temperature it did not crack at all during its 7 years service life. There are some indications from ductility data that Asphalt T-3 may have a high failure strain. However, this needs to be confirmed by direct measurements at low pavement temperatures using the Superpave direct tension tester (DTT).

KEY WORDS: low-temperature cracking, Superpave, asphalt binder, asphalt cement, asphalt pavements, hot mix asphalt, specifications.

PREDICTION OF LOW-TEMPERATURE CRACKING USING SUPERPAVE BINDER SPECIFICATIONS

INTRODUCTION

Nonload-associated low-temperature cracking of asphalt pavements is prevalent in Canada and the northern United States. This distress causes deterioration in pavement performance through spalling, heaving, or settling at the cracks, and thus reduces the pavement's service life. When overlaid, these cracks reflect through the new overlay. It is essential to identify the theological properties of the asphalt binder, which are primarily responsible for this type of distress.

Six test pavements were constructed in Pennsylvania in September 1976 using AC-20 asphalt cements from different sources. On this closely controlled asphalt durability research project, two test pavements developed extensive low-temperature nonload-associated transverse cracking on January 28-29, 1977 (just four months after construction). The remaining four test pavements did not develop any significant transverse cracking during the first three years. After that point, these pavements gradually developed transverse cracking to different degrees. These pavements were overlaid in 1984.

During the seven years in service, periodical pavement performance evaluations were carried out, and climatological data were gathered. The theological properties of original and aged asphalt binders were evaluated from periodic core samples. The evaluation of this project during its service life has been reported in various references (1, 2, 3, 4, 5). This is the only well-documented research project concerning low-temperature cracking in the United States at this time. It was concluded that the stiffness modulus of asphalt cement binder and asphalt paving mixture were primarily responsible for low-temperature cracking. The stiffness moduli of seven-year old asphalt pavement cores were measured directly (5) by conducting diametral creep tests at four temperatures: -29, -18,-7 and 4°C (-20, 0,20 and 39°F). However, the stiffness modulus of asphalt binder was estimated at low temperatures using the van der Poel nomograph (6) modified by Heukelom (7) and McLeod (8). At that time, no suitable test equipment was available to directly measure the asphalt binder stiffness at very low temperatures of interest. Strategic Highway Research Program (SHRP) has now developed Superpave binder tests such as the bending beam rheometer (BBR) and the direct tension tester (DTT) which can directly measure the low temperature properties. These tests and related specifications were made available in March 1993 when SHRP ended Q). The senior author of this paper, who was involved in the Pennsylvania project as Bituminous Testing& Research Engineer, saved the six AC-20 asphalt cement binders used on the Pennsylvania project from 1976 to 1988 (12 years) and then transferred the samples to SHRP Materials Reference Library (MRL) in 1988. These asphalt cement samples were used by Oregon State University in SHRP A-003A project to study the aging and low-temperature behavior of asphalt paving mixtures. Now, the Federal Highway Administration (FHWA) has tested these six asphalt cements using the bending beam rheometer.

OBJECTIVE

This research project was undertaken to evaluate the low temperature properties of the asphalt cement binders used on the Pennsylvania project and to evaluate the efficacy of Superpave binder specifications in predicting low-temperature cracking which occurred on that project from January 1977 to October 1983 (the date of last inspection).

DETAILS OF TEST PAVEMENTS

The project was located in Elk County (North Central Pennsylvania) on U.S. Traffic Route 219 just north of Wilcox. The average daily traffic (ADT) on this two-lane, 6.1 -m (20-ft) wide highway was 3700. The research project consisted of 38-mm (1 .5-in) resurfacing of the existing structurally sound, flexible pavement (without any transverse cracks) in September 1976 so that the performance of each test pavement could be studied on a comparative basis. The pavement cross section after resurfacing was as follows:

250-mm (1 O-in) crushed aggregate base and 76-mm (3-in) penetration macadam (1948)
75-mm (3-in) binder and 25-mm (l-in) coarse sand mix (1962)
Surface treatment (1974)
40-mm (1.5-in) asphalt concrete wearing course (1976)

The subgrade consists of silty soil AASHTO Classification A-4. The layout plan of the six test pavements is given in Reference 1. Each test pavement was approximately 610 m (2000 ft) long in both lanes. The mix composition and compaction levels were held reasonably consistent on all test pavements; the only significant variable was the source of AC-20 asphalt cements. The mix consisted of gravel coarse aggregate and natural sand. The mix composition and Marshall design data are given in Reference 1. This mix composition had been used in the past and had given durable pavements.

Construction

Since the six AC-20 asphalt cements had different viscosities at 135°C (275°F) and 60”C (140°F), the mix temperature for each test pavement was adjusted to obtain a mixing viscosity of

170±20 mm2s (centistokes). This helped to obtain almost consistent compaction level throughout the project. The mix temperatures generally ranged from 146 to 154°C (295 to 3 10“F). AC-20 asphalt cement from each source was pumped directly from the truck tanker to the pugmill to avoid contamination.

Twenty-four cores from each test pavement were taken after construction and analyzed for mix composition and density. The mix composition conformed to the job formula. The average air void content in the completed asphalt pavement was 4.4 percent.

Properties of AC-20 Asphalt Cements

AC-20 asphalt cements were supplied by five refineries. Asphalt cements T-1 and T-5 came from the same refinery. The details of the crude sources, methods of refining, and chemical compositions of the six asphalt cements are given in Reference 2.

Samples of asphalt cements were obtained from the tankers at the hot mix asphalt (HMA) plant and tested. The properties of the original asphalt cements are given in Table 1. The penetration of asphalt cements at 25°C (77°F) ranged from 42 to 80. The viscosity at 60”C (140°F) of T-1 asphalt cement is slightly excessive for an AC-20 viscosity-graded asphalt cement. The data for all six asphalt cements were plotted on the Bitumen Test Data Chart (BTDC) developed by Heukelom (7) and are given in Reference 1.

PERFORMANCE OF TEST PAVEMENTS

No visual difference could be seen among the six test pavements when constructed in September 1976. However, two test pavements (T-1 and T-5) developed transverse shrinkage cracking due to excessive low temperature recorded in January 1977 (just 4 months after construction)

Weather Data

The air temperature at the nearest U.S. weather station (Ridgway), 22 km (14 miles) south of the project, was recorded as low as -29°C (-20°F) during the 1976-1977 winter.

At Lantz Corners, 11 km (7 miles) north of the project, Pennsylvania Department of Transportation (PennDOT) had a thermocouple installation site which was capable of recording hourly air temperature and asphalt pavement temperature 50 mm (2 in.) below the surface. According to the recorded data (Figure 1), rapid cooling occurred on 28 and 29 January, 1977, and caused cracking in T-1 and T-5 test pavements. The air temperature dropped 14° C (25° F) in 2 hours (11 AM -1 PM on January 28). Rapid cooling of pavement 50 mm (2 in.) below the surface occurred 12 hours later, a drop of 5° C (9° F) in 1 hour (11 PM - midnight). The lowest air temperature was recorded to be -29°C (-20°F), whereas the pavement temperature 50 mm (2 in.) below the surface reached -23°C (-1 O“F). It is not known when cracking occurred but it is likely sometime prior to the miniomum values recorded.

Low ambient temperatures prevailed again at the experimental site during the subsequent six winters before the project was overlaid in 1984. Table 2 shows minimum air temperatures recorded at Ridgway. Although it is estimated that the average minimum pavement temperature 51 mm (2 in.) below the surface was in the vicinity of -23°C (-1 O°F) during the eight years, it appears that pavement temperature as low as -29°C (-20°F) might have occurred, especially during 1980-1981 and 1983-1984 winters.

Visual Evaluation

These pavements were evaluated periodically by a team of eight to ten evaluators after construction. The detailed visual evaluation descriptions (including crack surveys) for the years 1977, 1979, and 1982 are given in Reference 3. The last inspection was made in October 1983 and is reported in Reference 5.

Table 3 gives the transverse cracking index for each test pavement for years 1977, 1978, 1979, 1981, and 1983. This index is defined in detail in Reference 3. Basically, it is equal to the number of full-width cracks plus one half of the half-width cracks plus one fourth of the part-width cracks per 152.5 m (500 ft) section of a two-lane roadway. A full crack goes across both lanes, a half-width crack goes across one lane only, and a part-width crack goes halfway in one lane.

As mentioned earlier, the test pavements T-1 and T-5 developed extensive cracking during the first winter (1976-1977). During the subsequent seven years, these two pavements developed more cracks, and the existing cracks appeared to widen after each successive winter. Figures 2 through 5 show the severity of cracking in May 1979. Figure 2 shows transverse cracks in both lanes of T-1 test pavement. The photograph in Figure 3 was taken in a transition zone where T-1 and T-2 Asphalts overlapped in adjacent lanes. T-1 (foreground lane) shows extensive transverse and longitudinal cracks whereas T-2 (background lane) does not show any cracking. Figure 4 shows transverse cracks in both lanes of T-5 Asphalt. Figure 5 shows transverse cracks in T-5 Asphalt (foreground lane) and no cracks in T-6 Asphalt (background lane) in a transition zone. Test pavements T-2, T-3, T-4, and T-6 did not develop any significant transverse cracking during the first three years. Since then, test pavements T-2, T-4, and T-6 gradually developed cracking to different degrees as shown in Table 3. Pavement T-3 was rated the best, with no transverse cracking. The ranking order from worst to best of the test pavements based on the cracking index after 7 years (Table 3) is: T-1, T-5, T-4, T-2, T-6 and T-3.

PAVEMENT CORE TEST DATA

Theological Properties of Recovered Asphalt Cements

The properties of original asphalt cements are given in Table 1. The properties of recovered asphalt cements (Abson method) just after construction are given in Table 4. Reference 2 contains aged asphalt properties after 20 months in service. Table 5 gives these properties after seven years service.

Reference 5 contains temperature susceptibility data such as Pen-Vis Number (PVN) and penetration index (PI) on all original and aged asphalt cements. This reference also contains stiffness moduli of asphalt cements at -23°C (- 10“F) and 20,000 seconds loading time estimated from two indirect methods developed by Heukelom (<u>7</u>) and McLeod (<u>8</u>).

Stiffness Modulus of Asphalt Paving Mixtures

<u>Indirect Determinations</u>: Stiffness moduli of the six asphalt paving mixtures containing different asphalt binders were estimated at -23°C (-1 0°F) and -29°C (-20°F) at 20,000 seconds loading time using the indirect methods of Heukelom (<u>7</u>) and McLeod (<u>8</u>). The data are given in References 3 and 5. The stiffness moduli values obtained by the McLeod method at -23°C (-1O”F) at 20,000 seconds loading time are given in Table 6.

<u>Diametral Creep Measurements:</u> Pavement cores 100 mm (4 in.) in diameter were obtained from the test sections and tested in 1 983 (after seven years' aging). Diametral creep moduli for

each asphalt were obtained using the Mark IV Resilient Modulus Device (10) at -29, -18, -7, and 4°C (-20, O, 20, and 39°F) temperatures. After the resilient modulus was obtained at one-tenth second loading time, horizontal deformations were measured at 1, 10, 100, and 1000 s under a steady sustained load. A recorder strip chart was used. Thus, the stiffness moduli of the asphalt paving mixtures were obtained over a convenient range of temperatures [-29 to 4°C (-20 to 39°F)] and over a convenient range of loading times (O. 1 to 1000 s). These data were reduced to a master curve for each asphalt type by superposition methods (10.11). Reference 5 shows the master curves at -7°C (20°F) and the shift factors *(a,)* used to construct the master curves. Ordy one core specimen was tested at each temperature. Therefore, a total of 24 creep measurements were made.

Once the master curves and shift factor curves are obtained, the stiffness moduli of the viscoelastic asphalt paving mixture can be obtained over a temperature and time of loading range much greater than those included in the original tests. The stiffness moduli of the six asphalt paving mixtures (after seven years' aging) obtained at -23°C (-1 O°F) and 20,000 second loading time are given in Table 6.

Comparison: The following observations are made on the stiffness moduli data in Table 6 obtained by indirect determinations and diametral creep measurements:

1. Stiffness moduli obtained by the diametral creep measurements are generally consistent with the transverse cracking indexes. The incidence of cracking increases with the increase in the stiffness modulus. It should be noted that Asphalt Cement T-1 has lower measured stiffness modulus compared to T-5 most likely due to higher air void content. The same consideration probably applies to Asphalt

Cement T-3 which has slightly higher stiffness modulus and lower air void content compared to T-6.

2. Stiffness moduli obtained by McLeod's indirect determination method also seem to be consistent with the cracking indexes. They are generally within a factor of 2 of the diametral creep stiffness moduli, which is expected from these" indirect nomographic methods.

McLeod (12) had concluded that low-temperature transverse cracking is likely to become serious if the pavement develops a modulus of stiffness of 6.9×10^6 kPa (1×10^6 psi) at the lowest pavement temperature to which it is exposed, for a loading time of 20,000s, corresponding to slow chilling on a cold night. This seems to have been confirmed on this project. Asphalt Cements T-1 and T-5 developed extensive transverse cracking during the first winter because the stiffness moduli were equal or above 6.9×10^6 kPa (1×10^6 psi). Asphalt Cements T-4 and T-2 developed significant cracking later when their stiffness moduli approached this limit.

SUPERPAVE BINDER TEST RESULTS AND "DISCUSSION

All six AC-20 asphalt cements were tested by Superpave binder test procedures such as (1) viscosity at 135°C (275°F) by Brookfield viscometer, (2) $G^*/\sin\delta$ of original and rolling thin film oven test (RTFOT) residue at high temperatures by dynamic shear rheometer (DSR), (3) $G^*\sin\delta$ of pressure aging vessel (PAV) residue at intermediate temperatures by DSR, and (4) creep stiffness, S, and logarithmic creep rate, m-value, at low temperatures using bending beam rheometer (BBR). A discussion of Superpave asphalt binder specifications and related test procedures is given in Reference 9. G^* is the complex modulus and δ is the phase angle of the asphalt binder when tested under dynamic loading using AASHTO TP5 procedures. Although these values were measured at various temperatures to identify the performance grade (PG) of the asphalt binders, Table 7 gives the G*/sinδ values at only 64°C (147°F) and the G*/sinδ values at 22°C (72°F) for comparative purposes. This table also gives the PG grades of the six AC-20 asphalt cements based on high and low temperature properties (9).

The following information was obtained from the weather database used in Superpave software concerning the nearest weather station in Ridgway, Pennsylvania.

Air Temperature

Low temperature (average)	-27°C
Low temperature (standard deviation)	4°c
High temperature (average)	31°c
High temperature (standard deviation)	2°c

50% Reliability Level

Maximum air temperature	31°c
Maximum pavement temperature	51°C
Minimum air temperature	-27°C
Minimum pavement temperature	-27°C
Binder Grade:	PG 52-28

98% Reliability Level

Maximum air temperature	35°c
Maximum pavement temperature	55°c
Minimum air temperature	-35°C
Minimum pavement temperature	-35°C
Binder Grade:	PG 58-40

It can be seen in Table 7 that only T-6 asphalt cement met the recommended binder grade of PG 52-28 at 50°/0 reliability level. None of the asphalt cements met the recommended binder grade of PG 58-40 at 98% reliability.

Tables 8 and 9 give the bending beam rheometer (BBR) test data (such as creep stiffness “S” and logarithmic creep rate “m”) on RTFOT residues and PAV residues, respectively, of the six asphalt cements. The Superpave binder specification has a maximum limit of 300 MPa on the creep stiffness “S” at 60 seconds and a minimum limit of 0.30 on the logarithm creep rate “m” at 60 seconds. The laboratory test temperature used is 10“C warmer than the minimum design (air) temperature at the project site, which when combined with 60 seconds loading time represents minimum field design (air) temperature and a loading rate of 2 hours. The rationale behind maximum stiffness “S” value is to minimize the level of stresses developed in the pavement when cooled. The minimum value for creep rate “m” is intended to keep the rate of relaxation above a certain value, allowing the pavement to relax stresses relatively quickly (13). Although the maximum stiffness of 300 MPa is based on Canadian experimental roads, the minimum m-value of 0.30 was selected by judgement and it has not been validated by any well-documented research projects.

Normally, S and m-values are obtained at the minimum design temperatures on the PAV residue which represents aged binder after 5-10 years service life. However, in this case it is important to determine the S and m-values on RTFOT residues which represent aging of the asphalt cement during mix production and laydown. This is needed because the low-temperature cracking of T- 1 and T-5 test pavements occurred just four months after construction and usually minimal aging occurs during relatively cold months of October through January. Since two test pavements had cracked and the remaining four test pavements did not crack on January 28-29, 1977, it would be interesting to examine the stiffness and the m-values at the minimum air temperature of -29°C (-20°F) which occurred on that night of January 1977. The minimum air temperature is being considered at this time because the present Superpave criteria considers the minimum surface pavement temperature equal to the minimum air temperature. This is likely to change in the future based on field data. It is believed that pavement temperature is generally higher (warmer) than air temperature. Stiffness and m-values given in Table 8 for three temperatures are shown graphically in Figures 6 and 7, respectively, along with the Superpave criteria.

At the minimum temperature of -29°C (-20°F), T-1 and T-5 asphalt cements, which developed extensive low-temperature cracking that first winter have stiffness well above 300 MPa. T-4 asphalt cement, which did not develop any transverse cracking, has a marginal stiffness of about 315 MPa (Figure 6). This test pavement did however, develop longitudinal cracking along the joint between the two lanes on January 28-29, 1977, whereas test pavements T-2, T-3, and T-6 did not develop either longitudinal joint cracking or transverse cracking (1). Test pavement T-4 was considered borderline in stiffness at that time also (1). It is difficult to explain the behavior of T-3 asphalt cement which has a stiffness of about 350 MPa (Figure 6) and m-value of about 0.30 (Figure 7), but did not crack at all. However, it should be noted that T-3 asphalt cement had the highest ductility at 15.6°C (60°F) just after construction (Table 4) and also after 7 years service (Table 5). It appears that a Superpave test such as the direct tension tester (DTT) may be useful in explaining the behavior of asphalt binders like T-3 which have high stiffness but may also have potentially high failure strain at low pavement temperatures. It would be interesting to evaluate the direct tension test data on all six asphalt cements at an appropriate rate of strain. However, it is not possible at this time because the DTT equipment is being re-designed. Asphalt cements T-6 and T-2 which did not crack have stiffness well below 300 MPa (Figure 6). It appears from Figure 6 that the Superpave criteria of 300 MPa maximum stiffness is reasonable.

Figure 7 shows the plots of m-value at three temperatures. At the minimum air temperature of -29°C (-20°F), T-1 and T-5 asphalt cements, which developed cracking after four months, have m-values well below the minimum Superpave criteria of 0.30. T-4 asphalt cement which developed longitudinal joint cracking after four months has a m-value of about 0.275 also below the minimum criteria. T-2 asphalt cement which did not develop any cracking after four months has a borderline m-value of about 0.295. T-3 and T-6 asphalt cements, which also did not crack after four months, have m-values equal to or exceeding 0.30. Again, it appears that the minimum m-value of 0.30 is reasonable. Figure 8 shows actual measurements of both stiffness and m-values of RTFOT residues at -28°C from Table 8 along with the Superpave criteria zone for no cracking. Both stiffness (300 MPa maximum) and m-value (0.30 minimum) criteria proposed in Superpave PG binder specification appear reasonable.

Table 9 gives the BBR test data obtained on PAV residues which represent about 5-10 years service life. The stiffness and m-value data are shown graphically in Figures 9 and 10, respectively, along with the Superpave criteria. As is evident from the cracking indexes (Table 9), all test pavements (except T-3) had cracked to different degrees after 7 years in service. During 7 years' service life, the minimum yearly air temperature had ranged from -23°C to -33°C (-1 O“F to -27°F) as shown in Table 2. The *rate* of cooling based on hourly air and pavement temperatures is very important. However, this was available only during the first winter (1976-77) as shown in Figure 1. This range of minimum air temperatures (-23°C to -33°C) is shown in Figures 9 and 10. Again, minimum pavement temperatures are considered to be equal to minimum air temperatures according to the present Superpave criteria. At the lowest minimum yearly temperature of -33°C (-27°F), which occurred in 1980-81 winter, all asphalt cements exceeded the maximum stiffness of 300 MPa (Figure 9) and all (except T-3) had cracked, as shown in Table 3. Similarly, at the lowest temperature of -33°C (-27°F), all asphalt cements were below the minimum m-value of 0.30 and all (except T-3) had cracked. Again, as was discussed in case of RTFOT residues, Asphalt Cement T-3 is an exception. This maybe because it could have the highest failure strain based on empirical ductility test data obtained in the past (Table 5). This needs to be confirmed by the DTT device. Figure 11 shows that PAV residues of all asphalt cements fall outside the Superpave criteria zone for no cracking. It appears from the stiffness and m-value data at -34°C (-29°F) in Table 9 that m-values conform to the pavement performance ranking order better than stiffness.

It should also be noted that the low-temperature stiffness of RTFOT residues and PAV residues are not significantly different. However, m-values do decrease from RTFOT to PAV aging. Since m-values do significantly affect the low-temperature cracking, it implies that asphalt pavements become more susceptible to cracking as they experience years of aging. This phenomenon was borne out in this experimental project.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Six different AC-20 asphalt cements were used in a Pennsylvania project in September 1976. Two of the test pavements developed low-temperature cracking in January 1977. The remaining four test pavements started to develop cracking after three years. This project has been well documented in the literature during its seven years service life. The data has included theological properties of original and aged asphalt cements, hourly air and pavement temperature data, yearly crack surveys, and stiffness moduli of hot mix asphalt (HMA) pavement cores at low temperatures obtained by diametral creep tests. The samples of these six asphalt cements which were saved from 1976 to 1995 (about 19 years) have now been tested using Superpave binder test procedures such as the bending beam rheometer (BBR). This has given the unique opportunity to verify whether the low-temperature Superpave binder test procedures and criteria could have predicted low-temperature cracking of the six AC-20 asphalt binders in the Pennsylvania project during their seven years' service life. The following conclusions have been drawn and recommendations made:

1. The maximum stiffness criteria of 300 MPa and the minimum m-value criteria of 0.30 recommended in Superpave binder specifications generally appear to be reasonable in mitigating low-temperature cracking. The behavior of all asphalt cements except T-3 could be explained by these criteria.
2. Some asphalt cements like T-3 may exceed the maximum stiffhess of 300 MPa but may not crack. However, asphalt cement T-3 is likely to have a high failure strain based on ductility data (it had the highest ductility at 15.6°C among all six aged asphalt cements). This needs to be confirmed by the use of direct tension tester (DTT) when its redesigned version is available in the near future. The DTT can determine the failure strain at low pavement design temperatures such as -29°C (-20°F) rather than relatively higher temperatures used in the ductility test.
3. Generally, there is no significant difference between the low-temperature stiffness of RTFOT and PAV residues. However, the m-values do decrease significantly when RTFOT residues are aged further in pressure aging vessel (PAV).

4. More research projects which involve five or six asphalt cements from different sources (refineries), like the Pennsylvania project, need to be constructed and monitored to further validate the criteria for low-temperature cracking, contained in Superpave binder specifications.

ACKNOWLEDGEMENT

The opinions, findings, and conclusions expressed here are those of the authors and not necessarily those of the National Center for Asphalt Technology, the Federal Highway Administration, or the U. S. Air Force.

REFERENCES

1. Kandhal, P. S., "Low Temperate Shrinkage Cracking of Pavements in Pennsylvania" in *Proceedings,* Association of Asphalt Paving Technologists, Vol. 47, 1978.

2. Kandhal, P. S., "Evaluation of Low-Temperature Pavement Cracking on Elk County Research Project," Transportation Research Board, TRR No. 777, 1980.

3. Kandhal, P. S., Mellott, D. B., and Basso, H. R., "Durability Study of Viscosity Graded AC-20 Asphalts in Pennsylvania," Federal Highway Administration Report No. FHWA/PA-84-O09, April 1984.

4. Kandhal, P. S. and Koehler, W. C., "Significant Studies on Asphalt Durability: Pennsylvania Experience," Transportation Research Board, TRR No. 999, 1984.

5. Kandhal, P. S. and Koehler, W. C., "Effect of Theological Properties of Asphalts on Pavement Cracking," ASTM STP 941, 1987.

6. van der Peel, C., "A General System Describing the Viscoelastic Properties of Bitumens and Its Relationship to Routine Test Data," *Journal of Applied Chemistry,* Vol.. 4, May 1964.

7. Heukelom, W., “An Improved Method of Characterizing Asphaltic Bitumens with the Aid of Their Mechanical Properties” in *Proceedings,* Association of Asphalt Paving Technologists, Vol. 42, 1973.

8. McLeod, N. W., “Asphalt Cements: Pen-Vis Number and Its Application to Moduli of Stiffness,” *Journal of Testing and Evaluation,* Vol. 4, July 1976.

9. Background of SHRP Asphalt Binder Test Methods. Demonstration Project 101, Federal Highway Administration, Office of Technology Applications, October 1993.

10. Schmidt, R. J., “A Practical Method for Measuring the Resilient Modulus of Asphalt-Treated Mixes,” Highway Research Board, HRR No. 404, 1972.

11. Haas, R. C. G., “A Method for Designing Asphalt Pavements to Minimize Low-Temperature Shrinkage Cracking,” The Asphalt Institute, Research Report No. 73-1, January 1973.

12. McLeod, N. W., “The Case for Grading Asphalt Cements by Penetration at 77°F” in *Proceedings,* Canadian Technical Asphalt Association, Vol. 20, 1975.

13. Bahia, H. V., Anderson, D. A. and Christenson, D. W., “The Bending Beam Rheometer: A Simple Device for Measuring Low Temperature Rheology of Asphalt Binders,” *Journal of the Association of Asphalt Paving Technologists,* Vol. 61, 1992.

LIST OF TABLES

TABLE 1- Properties of original AC-20 asphalt cements.

Test	Asphalt Type					
	T-1	T-2	T-3	T-4	T-5	T-6
Penetration @ 4°C (39°F), 100 g, 5 s	2.0	7.4	6.2	6.7	3.4	7.5
Penetration @15.6°C (60°F), 100 g, 5 s	11.2	25.0	24.5	23.0	16.0	29.0
Penetration @ 25°C (77°F), 100 g, 5 s	42	64	72	65	54	80
Viscosity @60”C(140”F), Pas	271.0	228.4	176.4	170.5	175.9	198.2
Viscosity @135°C (275°F), mm2s	420	402	393	355	356	406
Ductility @15.6°C (60°F), 5 cm/min, cm	150+	29	150+	117	150+	150+
Softening point (R& B), C	50.6	50.0	48.9	50.0	51.1	49.4
TFO Residue						
Penetration @ 25°C (77°F), 100 g, 5 s	26	38	45	38	37	44
Viscosity @ 60°C (140°F), Pas	550.1	683.5	398.2	469.4	324.8	572.1
Viscosity @ 135°C (275 °F),mm^{2}s	563	569	556	527	464	575
Ductility @ 4°C (39.2°F), 1 cm/min. cm	3.5	3.5	4.6	5.2	8.6	12.4
Ductility @ 15.6°C (60°F), 5 cm/min, cm	11.6	7.0	95.2	12.8	90.6’	33.0

‘Value suspect.

TABLE 2- Minimum air temperatures at U.S. Weather Station, Ridgway, PA.

Winter	Minimum Air Temperature “C (°F)
1976-1977	-28.9(-20)
1977-1978	-27.8 (-18)
1978-1979	-31.7 (-25)
1979-1980	-24.4 (-12)
1980-1981	-32.8 (-27)
1981-1982	-30.0 (-22)
1982-1983	-23.3 (-10)

TABLE 3. Cracking Index from transverse cracking survey data

Date	Test Pavements					
	T-1	T-2	T-3	T-4	T-5	T-6
October 1977	51	0	0	0	38	0
May 1978	69	0	0	0	50	0
May 1979	76	0	0	0	54	0
August 1981	92	9	0	12	64	7
October 1983	92’	26	0	30	64[a]	11

[a] Crack survey could not be done in these sections in 1983 because of heavy patching over the deteriorated cracks.

TABLE 4- Properties of recovered AC-20 asphalt cements (just after construction).

Test	Asphalt Type					
	T-1	T-2	T-3	T-4	T-5	T-6
Penetration @ 4°C (39°F), 100 g, 5 s	1.5	4.5	4.5	4.0	2.0	5.8
Penetration @15.6°C (60°F), 100 g, 5 s	7	17	16	13	9	20
Penetration @ 25°C (77°F), 100 g, 5 s	24	40	43	34	29	49
Viscosity @ 60°C (140°F), Pas	552.6	572.9	378.9	382.9	401.9	461.1
Viscosity @ 135°C (275°F), mm^2/s	565	569	526	487	488	576
Softening point (R& B), C	56.7	53.3	53.9	53.3	54.4	53.9
Ductility @ 4°C (39.2°F), 1 cm/min, cm	0.2	4.6	13.9	5.9	0.6	14.9
Ductility @ 15 .6°C (60°F), 5 cm/min, cm	8.3	7.2	48.5	10.0	15.5	34.0
Ductility @ 25°C (77°F), 5 cm/min, cm	150+	80	150+	150+	150+	150+

TABLE 5- Properties of recovered AC-20 asphalt cements (after seven years).

Test	Asphalt Type					
	T-1	T-2	T-3	T-4	T-5	T-6
Penetration @ 4°C (39°F), 100 g, 5 s	3.0	5.3	4.0	3.7	2.0	4.3
Penetration @ 15.6°C (60°F), 100 g, 5 s	9	13	14	10	8	15
Penetration @ 25°C (77°F), 100 g, 5 s	13	25	33	23	18	34
Viscosity @ 60°C (140°F), Pas	1799	2081	1174	1665	1302	1206
Viscosity @ 135°C (275°F), mm^2/s	856	848	720	770	691	802
Softening point (R& B), “C	62.8	60.0	59.4	60.6	61.7	58.3
Ductility @ 15.6°C (60°F), 5 cm/min, cm	1.2	4.5	14.0	5.0	4.0	11.2

TABLE 6- Stiffness modulus (psi)[a] of apshalt paving mixtures at -23°C (- 10“F) and 20,000s loading time.

	Asphalt Type					
	T-1	T-5	T-4	T-2	T-6	T-3
Transverse cracking index (1983)	92	64	30	26	11	0
Air voids content (cores), % (7 years)	3.4	1.6	1.5	1.8	1.4	0.6
Diametral creep modulus (7 years)	1.9X 10^6	255 x 10^6	2.0 x 10^6	1.65 x 10^6	1.25 x 10^6	1.35 x 10^6
McLeod Method						
After 7 years	2X10^6	1.65 x 10^6	1 x 10^6	8.4 x 10^5	5.1 x 10^5	5.1 x 10^5
Just after construction	1.15X10^6	1 x 10^6	8x10^5	4.8 x 10^5	3.4X10^5	4.4 x 10^5
Original asphalt	6.4 x 10^5	4.2 x 10^5	2.75 x 10^5	2.55 x 10^5	1.55X10^5	1.95 x 10^5

al psi = 6.895 kPa.

TABLE 7- Superpave binder test results.

TEST	Asphalt Type					
	T-1	T-2	T-3	T-4	T-5	T-6
<u>Original Binder</u>: Brookfield Viscosity at 135°C, Pas G*/sin/i at 64°C, kPa	 0.312 1.61	 N/A 1.25	 0.300 1.16	 0.275 1.30	 0.260 0.97	 0.312 1.48
<u>RTFOT Residue</u>: G*/sinδ at 64°C, kPa	3.15	5.51	2.66	3.16	2.09	3.73
<u>PAV Residue</u>: G*/sinδ at 22°C, kPa	10,774	3,897[a]	5,186	4,734	7,625	3,450
Lowest temperature meeting Superpave criteria (stiffness and m-value)	-1 8°C	-1 7°C[b]	-26°C	-23°C	-22°C	-28°C
PG Grade	64-16	64-16	64-22	64-22	58-22	64-28

[a] Measured at 19°C rather than 22°C.

[b] Extrapolated.

TABLE 8. Bending beam rheometer test data on RTFOT residue

Performance Ranking Order	Cracking Index		Minimum Design Temperature					
			-34°C		-28°C		-22°C	
	4 months	7 years	Stiffness[a] (MPa)	m-Value	Stiffness[a] (MPa)	m-Value	Stiffness[a] (MPa)	m-Value
T-1 (Worst)	51	92	1191[b]	0.133[b]	800[b]	o.202[b]	346	0.300
T-5	38	64	881	0.172	473	0.258	251	0.350
T-4	o	30	520[b]	0.230[b]	280[b]	0.284[b]	138	0.347
T-2	o	26	370	0.248	202	0.302	95	0.325
T-6	o	11	458	0.268	236	0.334	92	0.398
T-3 (Best)	o	0	580[b]	0.238[b]	309[b]	0.313[b]	133	0.381

[a] Two-hour loading time

[b] Average of two tests, remaining data are based on one test.

TABLE 9. Bending beam rheometer test data on PAV residues

Performance Ranking Order	Cracking Index (7 years)	Minimum Design Temperature					
		-34°C		-28°C		-22°C	
		Stiffness* (MPa)	m-Value	Stiffness[a] (MPa)	m-Value	Stiffness[a] (MPa)	m-Value
T-1 (Worst)	92	993	0.161	741	0.205	469	0.255
T-5	64	802	0.187	515	0.247	278	0.300
T-4	30	500	0.211	287	0.263	153	0.305
T-2	26	436	0.220	241	0.250	129	0.270
T-6	11	473	0.260	250	0.300	111	0.365
T-3 (Best)	o	591[b]	0.224[b]	326[b]	0.281[b]	160b	0.346[b]

‘Two-hour loading time

[b] Average of two tests, remaining data are based on one test.

LIST OF FIGURES

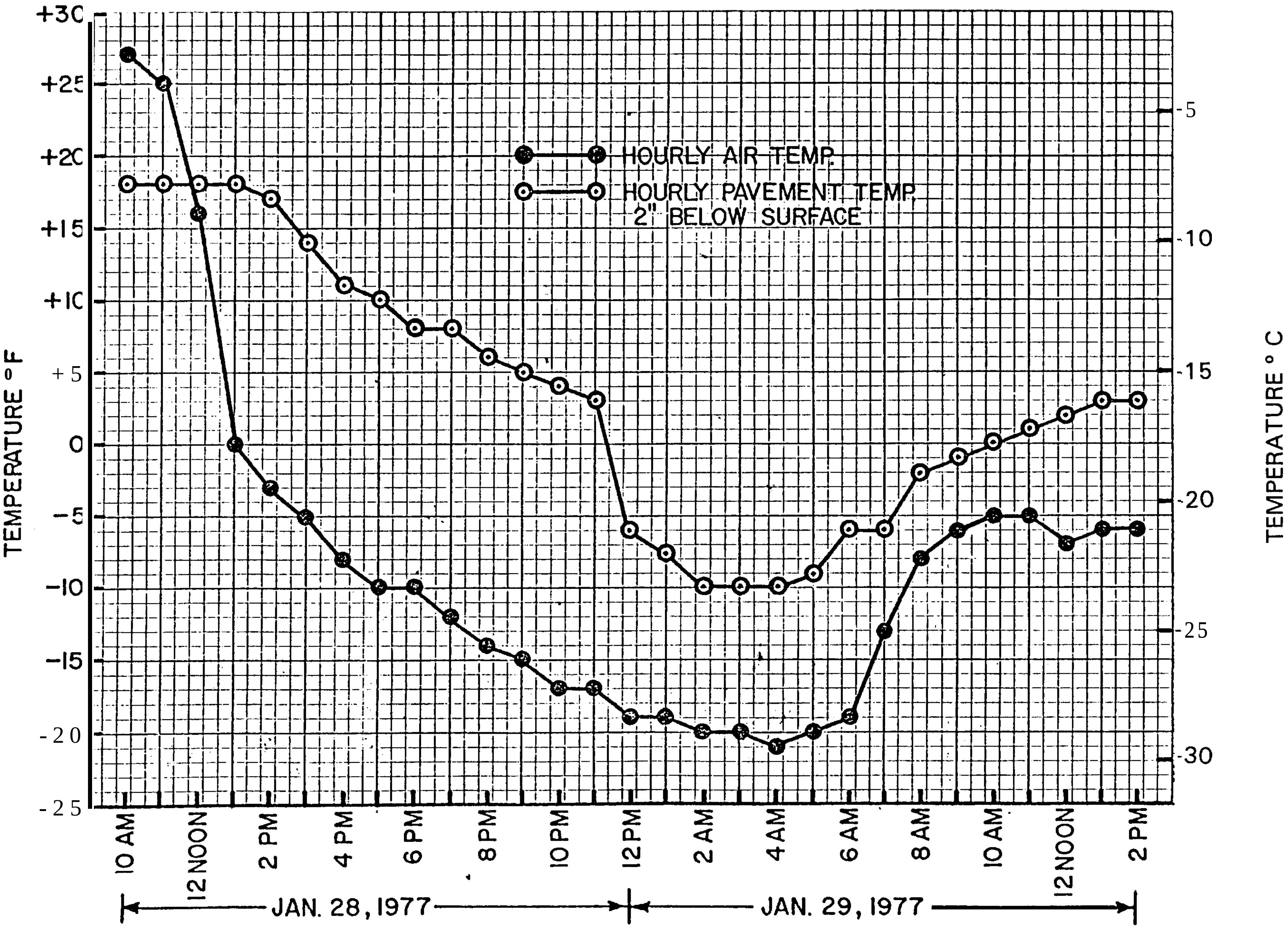

FIGURE 1. Hourly air and pavement temperature data (January 28-29, 1977)

FIGURE 2. Asphalt T-1 in both lanes showing transverse cracking

FIGURE 3. Asphalt T-1 (foreground lane) and Asphalt T-2 (background lane)

FIGURE 4. Asphalt T-5 in both lanes showing well-defined full- and half-width transverse cracks.

FIGURE 5. Asphalt T-5 (foreground lane) and Asphalt T-6 (background lane)

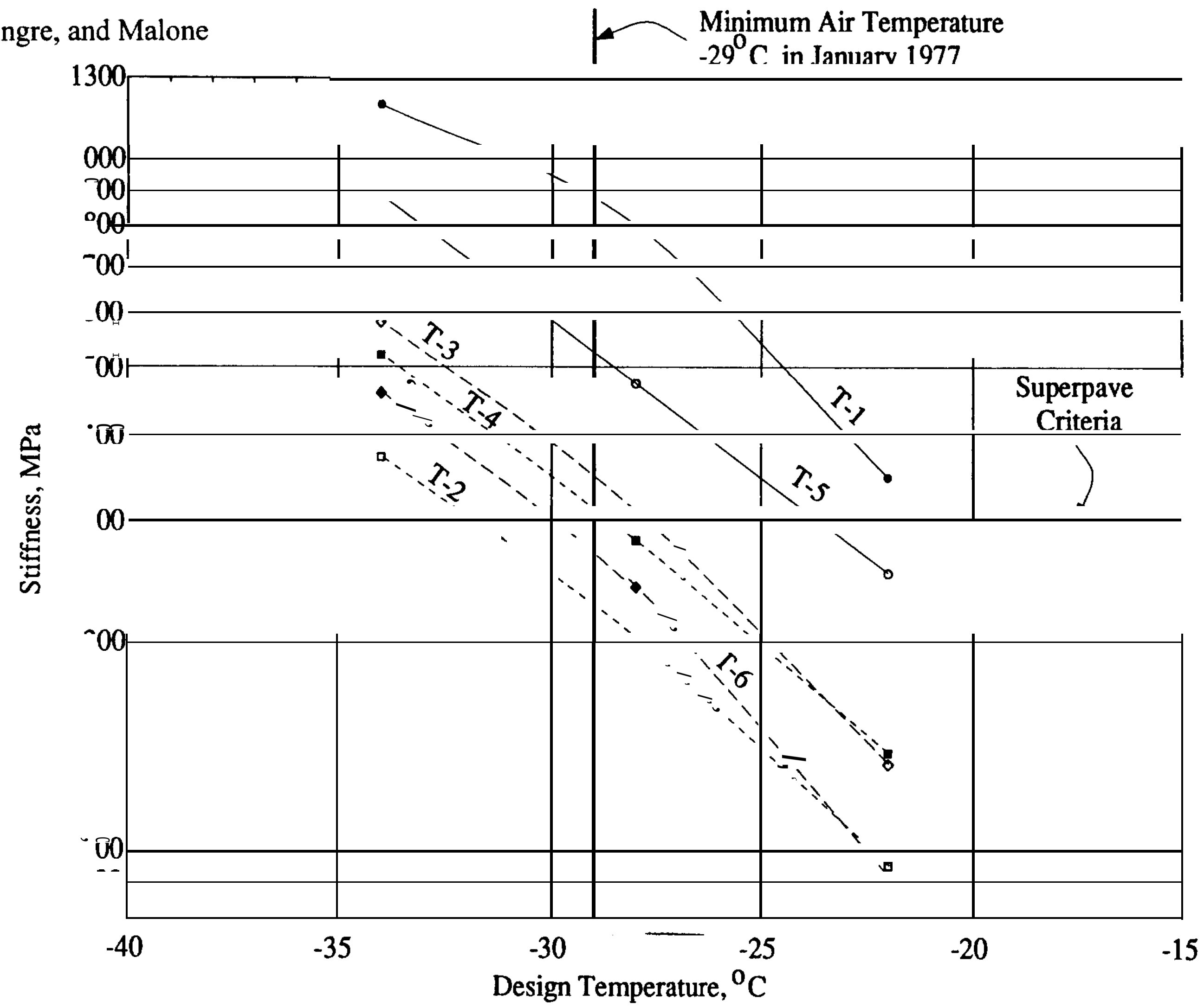

FIGURE 6. Stiffness of RTFOT residues

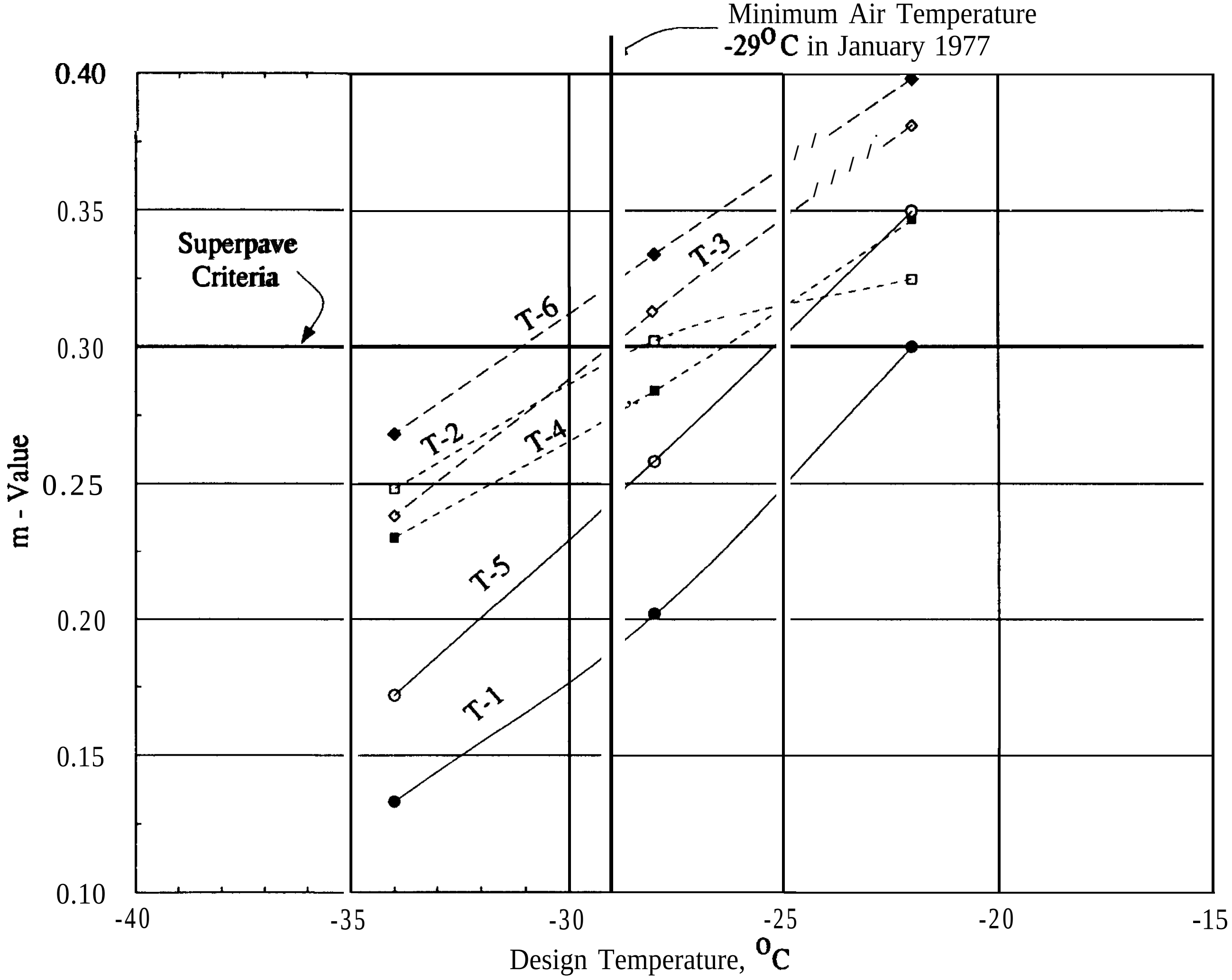

FIGURE 7. **m-value** of RTFOT residues

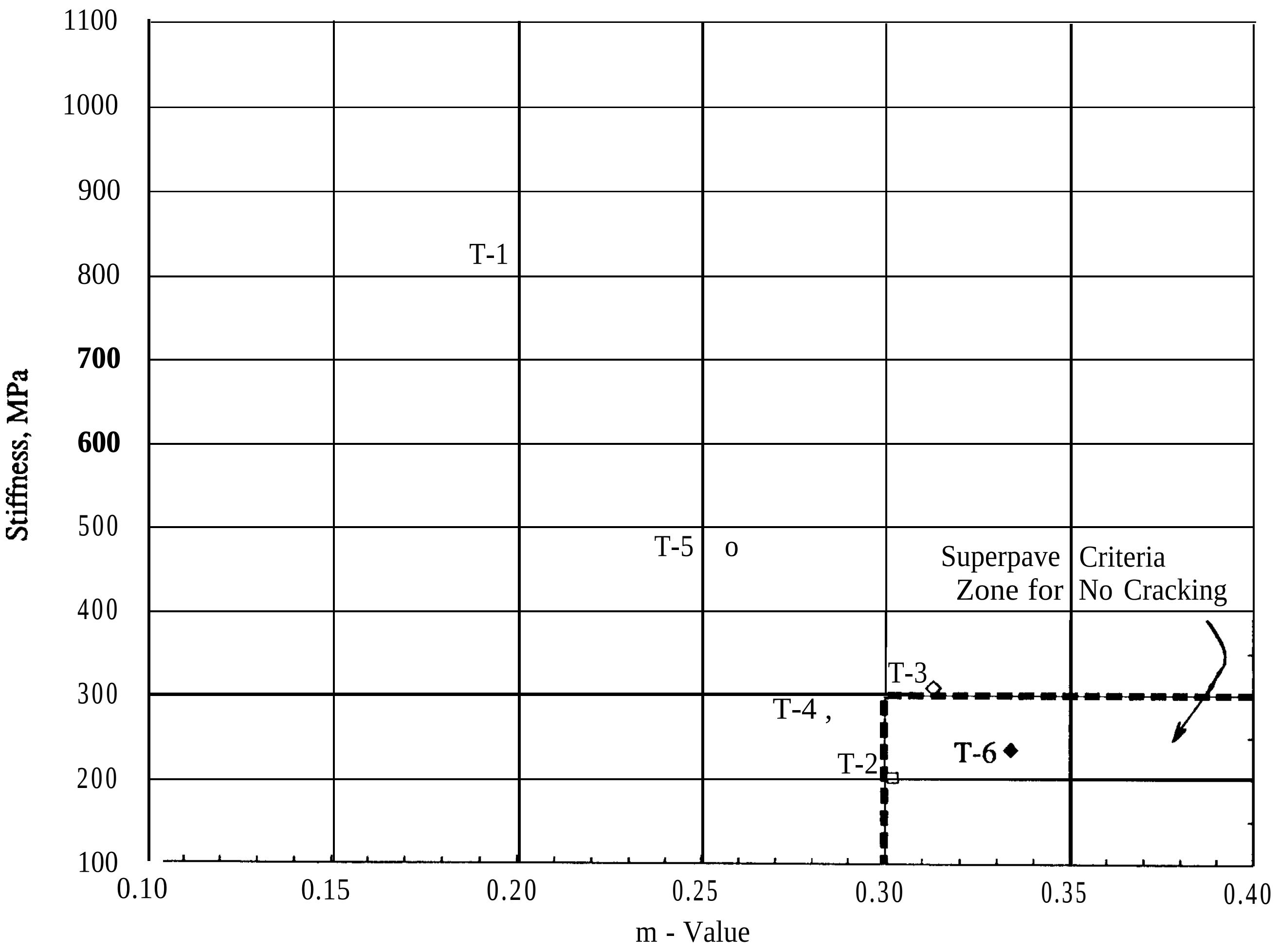

FIGURE 8. Stiffness and m-value at -28°C of RTFOT residues

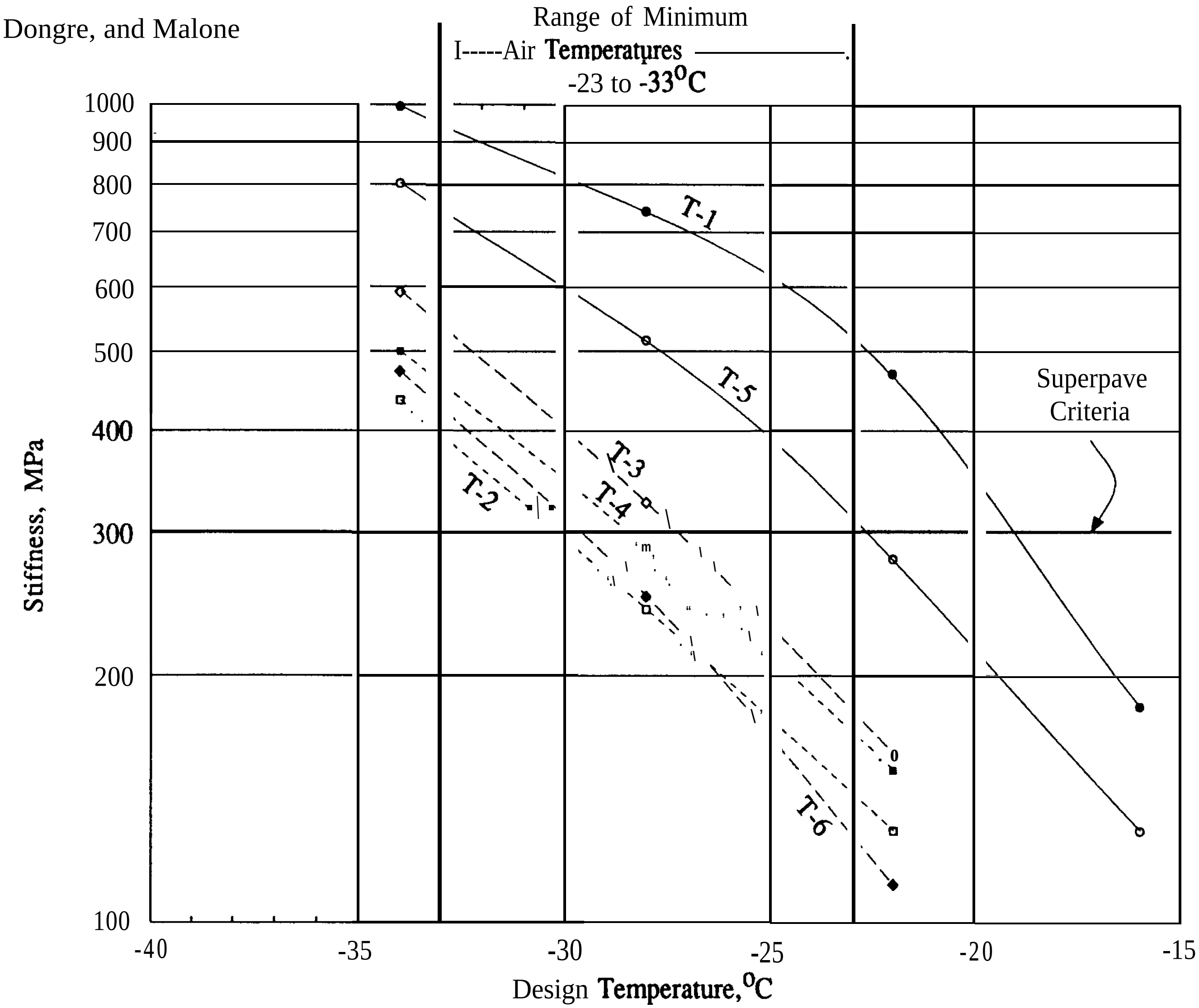

FIGURE 9. Stiffness of PAV residues

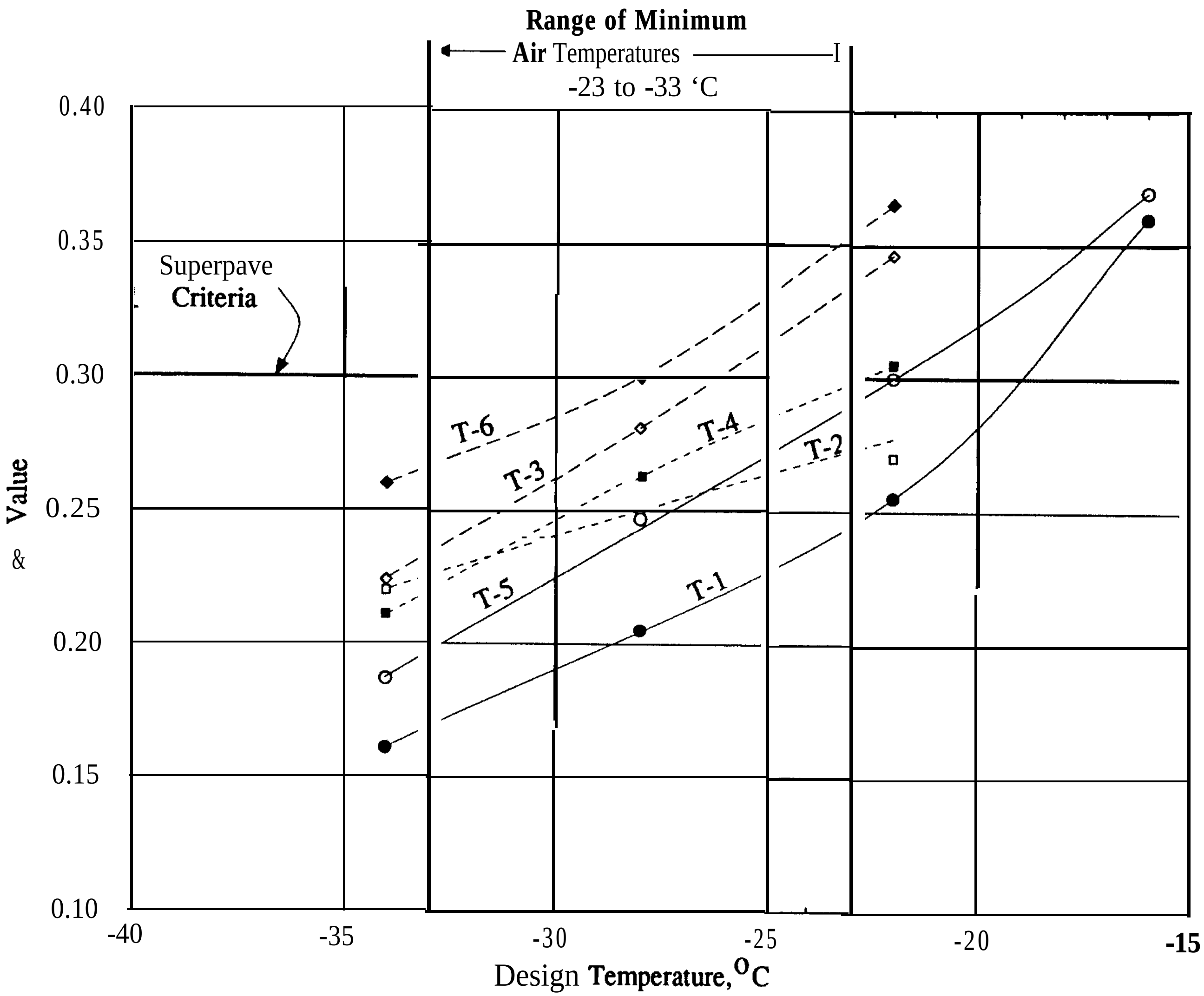

FIGURE 10. m-value of PAV residues

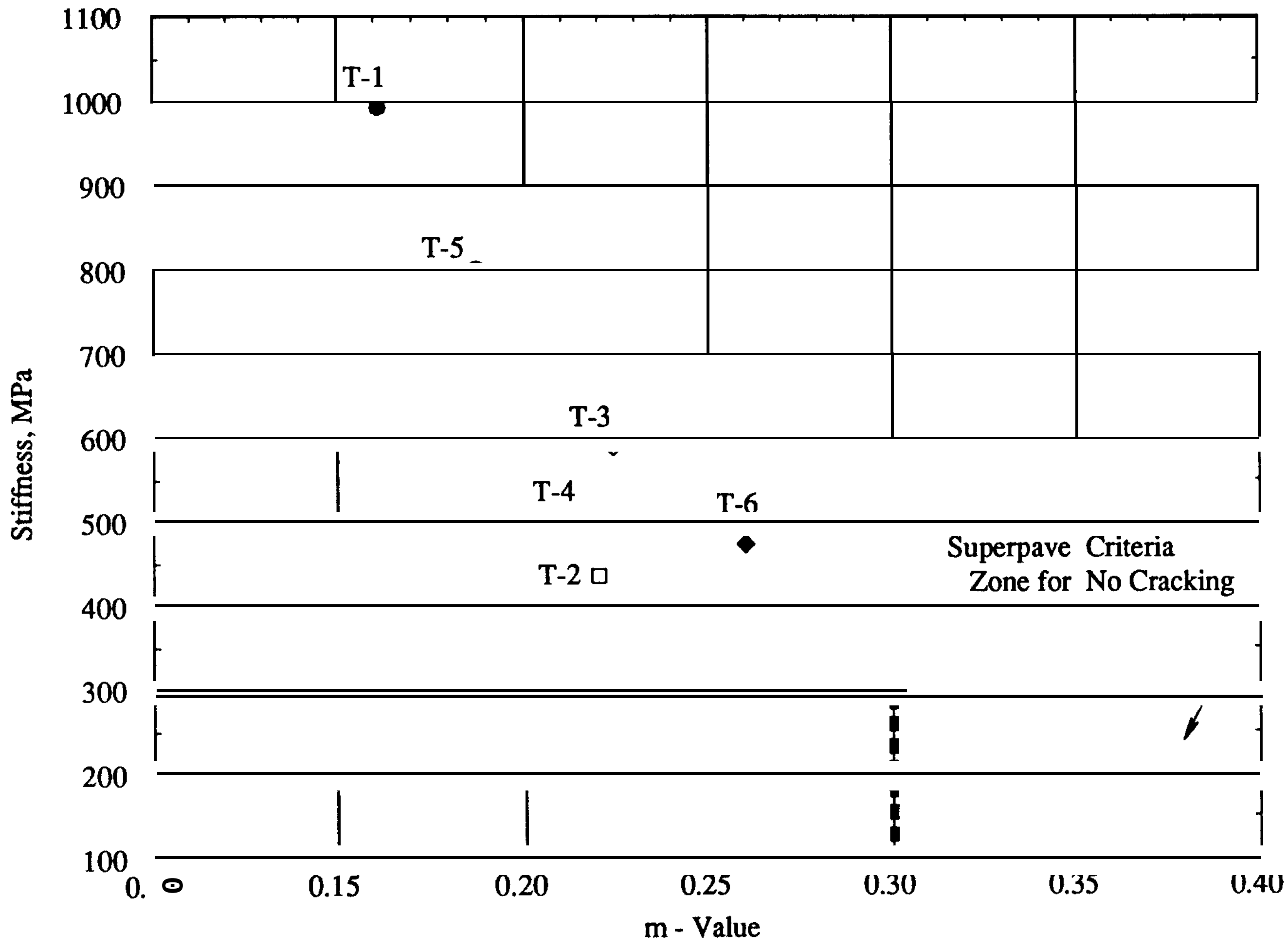

FIGURE 11. Stiffness and m-value at -34°C of PAV residues