CRREL

International State-of-the-Art Colloquium on Low-Temperature Asphalt Pavement Cracking

James A. Scherocman

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**U.S. Army Corps
of Engineers**
Cold Regions Research &
Engineering Laboratory

International State-of-the-Art
Colloquium on Low-Temperature
Asphalt Pavement Cracking

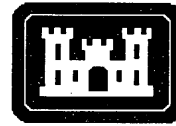James A. Scherocman   February 1991

FOREWORD

This report was prepared by James A. Scherocman, a consultant contractor, and was intended to summarize the findings of the colloquium and define research needs. We apologize for the delay.

Following are our thoughts on the significance and tone of the meeting.

We wanted to invite asphalt specialists and practitioners for frank and open discussions on low-temperature asphalt pavement cracking. Most, but not all, of the most-recognized researchers who have associated themselves with the problem through major studies or analyses of pavement behavior or asphalt rheological properties were invited. Consultants and representatives of universities, governments and industry were included. Practitioners who have studied the problem within their areas of responsibility in government agencies and state, federal and provincial governments were included. Others were select asphalt supply or industry personnel, asphalt technologists, asphalt specialists, asphalt hot mix contractors' technical personnel, and asphalt technologists from companies supplying chemical additives for asphalt. The number of attendees were limited to maximize participation and produce results in the short $2^1/_2$ days of meetings.

There was a genuine spirit of cooperation, excitement and interest displayed by all who attended. Most all who attended agreed it was a meeting of great historical significance.

The invitations did not require formal papers but welcomed them. The consultant contractor retained to prepare the report also prepared the abstracts of all available written research papers on the subject (1965–1987), which appear in this report. The report is perhaps the most comprehensive source of information on the state of the knowledge on this problem.

It is appropriate to make special mention and acknowledgement of the late Mr. James V. Evans, an asphalt technologist with Amoco Oil, who gave his support for this meeting but passed away prior to its occurrence. Jim Evans' philosophical statement in his letter to the organizers summed up succinctly the reason the meeting needed to be held: "This subject has been discussed ad infinitum with considerable agreement to disagree. But, hopefully, another airing might help 'mature' the subject if not the speakers." The original format of the meeting was outlined by Mr. Evans. We are most grateful for his insight and encouragement during the planning of this meeting.

One of the most important objectives of the meeting was to highlight that, while much has been written on this subject, the number of authors and fully tested or monitored pavements have been relatively few. The data base of detailed analysis is scant and has been used and reused by the same authors. The largest body of information and the most significant tests of roads and low-temperature environments are from Canada. While smaller studies have been carried out in the United States, they have not been as well documented as the work that has been done by Canadian researchers.

The heart of the problem of getting more research done on this subject, and the reason why more has not been done, is that asphalt mixtures in pavement structures are the most difficult engineering materials to characterize with precise standardized tests. Asphalt mixtures are made from a seemingly infinite number of sources and combinations of both course aggregate and fine aggregate mixed with a thermoplastic material (liquid when hot; solid when cold) that itself has variable thermoplastic properties. It is placed on a wide variety of supporting materials, and it is exposed to an almost infinite range of temperatures (including freeze–thaw) and a wide variety of traffic. The number of variables involved challenges the patience and genius of the best researchers who have struggled to find better tests to characterize the elusive mechanical properties of asphalt concrete pavements.

The struggle to characterize the asphalt cement or binder properties alone has absorbed the entire lifetime of some of our most dedicated researchers, as there appears to be clear agreement from all researchers that the asphalt mix stiffness, contributed to mostly by the binder, must be measured at low temperatures. We must give special mention here of the efforts of the late Herbert E. Schweyer who, in association with one of his colleagues that attended the meeting, Byron E. Ruth, has spent most of his career trying to characterize just the low-temperature, or rheological, properties of asphalt cement. The study goes on to perfect methods of more accurately characterizing both the asphalt cement and the mix stiffness at low temperatures. That is perhaps where the greatest challenge lies, because once most researchers can agree on a standard test and engineering limits on mix stiffness, we will be well on our way to a solution.

Does that mean we must give up and wait until new procedures are available? We hope not, and we encourage those who truly want to find an answer appropriate to their own agency and environment to pursue testing of all new construction as it is being built and monitoring many existing pavements to quantify changes in asphalt properties that will help them to identify when the cracking can be expected and, therefore, to characterize properties that either verify or reject various research approaches or theories that have been advanced. With the computerization of recordkeeping today, these activities are far more feasible than they were 15 years ago. As difficult and time consuming as it may be to start such a program, it is only with a wider data base that we will develop a clearer picture to direct us in addressing this problem. One positive result of the meeting is the knowledge that at least one state currently monitors the asphalt cement properties at low temperature on two test sites. While this may or may not lead to a hard and clear answer, it will greatly add to the body of knowledge that we need to identify all the variables that have been involved.

Virtually everyone agreed that the intensity of occurrence of low temperatures and the stiffness of the asphalt mixture on the surface are major factors in the occurrence and intensity of low-temperature transverse cracking.

A level of 1000 degree-days as measured by the freezing index was acknowledged by most as the point at which low-temperature cracking is serious enough to take special steps to control it. It was also agreed that it can occur at lesser freezing indexes but to a much lesser degree. Thermal shock (very large drops in temperature in a short period of time) was recognized but not focused upon specifically.

Most all agreed that the crack starts at the surface and works its way downward. While most agreed that mixture stiffness was the greatest contributor to low-temperature cracking, the manner in which mix stiffness is evaluated exposed the area of greatest disagreement among the experts. This disagreement became very intense at times.

One area of strong disagreement was whether total mixture composition most affects low-temperature cracking. One leading researcher strongly asserted that total mix composition (the nature of the aggregate, particularly fines and asphalt or mortar) and not the binder alone was the dominant factor. He considered it an error to try to predict low-temperature cracking based on properties of the binder only, and he stressed that the total mix stiffness must be studied. Most of the others making presentations at the meeting took a strong position that the properties of the binder alone were the dominant contributor to low-temperature cracking. Specifically they focused on the hardness and temperature susceptibility of the asphalt cement.

However, the manner in which temperature susceptibility is measured became the focus of even greater and more-intense debate. The three methods of measuring temperature susceptibility are as follows:

- Walthers Slope as described by actual viscosity at two temperatures was considered by one technologist as the only true method of measuring the actual rheology of binder. However, since this technologist was also the only total mixture stiffness advocate, not much discussion or debate of this method followed.
- Penetration Index, as determined by measuring penetrations at two different temperatures. Two Canadian speakers strongly supported this approach. Europeans also use this approach, and it is the approach used in the Asphalt Institute's Research Report 81.1.
- Penetration–Viscosity Number (PVN) as determined by measurement of penetration at 77°F and viscosity at 275°F. This approach was devised by the late Dr. Norman McLeod. He aggressively

promoted this concept since the early 1970s. Recent AAPT papers by another Canadian and also a U.S. researcher supported the PVN approach as a method of relating the temperature susceptibility to the degree of cracking in their recent field studies.

Where is the final, most economical, practical and complete answer? Is it in a temperature suscepti-bility grading system or a better understanding and use of temperature susceptibility? Is it in a different approach to surface and other pavement layer designs such as macadam with surface treatments, more use of thick film, open-graded cold mixes, or open-graded friction courses, sometimes called plant mix seals?

This is a very complex subject. The asphalt specialists and practitioners continue to discuss the state of the art. We encourage and look forward to future forums on this topic.

We sadly acknowledge the passing of Dr. Norman McLeod last fall.

ROBERT A. EATON
Research Civil Engineer
USA CRREL

ROBERT H. JOUBERT
District Engineer
Asphalt Institute
New England States

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Participants in the International State-of-the-Art Colloquium on Low-Temperature Asphalt Pavement Cracking:

Front row: *A. Patrick S. Selvadurai, Norman W. McLeod, Bernard F. Kallas, Richard Langlois, Edward J. Kearney, William A. Phang, Thomas Wohlscheid, Robert A. Eaton, Richard L. Davis, Robert H. Joubert, Roger C. Olson;*

Second row: *Warren D. Robertson, Prithvi S. Kandhal, Nelson Godwin, David Rand, Eric E. Harm, Philip E. McIntyre, Clifford A. Taylor;*

Third row: *Vyt P. Puzinauskas, James S. Moulthrop, Warner N. Hodgdon, Thomas W. Kennedy, Byron E. Ruth, Ernest J. Bastain, Jr., Hisao Tomita, Kenneth O. Anderson, Richard Berg;*

Fourth row: *Imants J. Deme, David A. Anderson, Woodrow J. Halstead, E. Ray Brown, Jack E. Stephens, Gale C. Page, Duncan A. McCrae;*

Fifth row: *Fred N. Finn, Joseph F. Lamond, Roderick W. Monroe, H. Richard Miller, James A Scherocman, Raymond D. Pavlovich, Vincent C. Janoo.*

International State-of-the-Art Colloquium on Low-Temperature Asphalt Pavement Cracking

JAMES A. SCHEROCMAN

INTRODUCTION

Sponsoring Organizations

The U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory, located in Hanover, New Hampshire, was the primary sponsor of the International State-of-the-Art Colloquium on Low-Temperature Asphalt Pavement Cracking, which was held on 6–8 May 1987. Cooperating organizations in sponsoring the conference included The Asphalt Institute, the U.S. Federal Aviation Administration, and the Ontario Ministry of Transportation and Communications.

The organizing commitee consisted of four people who developed the outline for the meeting, found the appropriate speakers to present different viewpoints, and invited the group who listened and commented on the various methods and procedures discussed. The four individuals responsible for the colloquium were

- Robert A. Eaton, U.S. Army Cold Regions Research and Engineering Laboratory;
- Robert H. Joubert, The Asphalt Institute;
- Philip E. McIntyre, New Hampshire Department of Transportation; and
- William A. Phang, Ontario Ministry of Transportation and Communications.

Purpose

The objective of the colloquium (an informal group discussion) was to summarize the existing knowledge of the causes of low-temperature transverse cracking in asphalt concrete pavement structures. The purpose was also to explore and identify possible contributing factors to the low-temperature cracking problem. The primary question posed to the groups was: "How do we eliminate or limit low-temperature transverse cracking in the design and construction of asphalt pavements using the best technology we have available and in what directions do we move to support the most promising technology leads or trends of future developments?"

The meeting was organized around two desired results. The first was to develop through the assembled group a summary of the current knowledge of the reasons why asphalt concrete pavement structures crack in cold weather and the factors that contribute to that cracking. In this regard, it was desired to

- Determine the factors that most researchers and practitioners agree have a significant effect on the degree of low-temperature cracking that occurs in an asphalt concrete layer;
- Determine the factors that one or several individuals feel are major contributors to the incidence of low-temperature cracking and to explore the reasons why these theories are not more widely recognized; and
- Determine the directions to be taken to initiate research needed to more fully understand the mechanisms of the causes of low-temperature cracking.

The second desired result of the colloquium was to collect the information currently available to provide input for future answers to the following questions:

- What are the most significant and widely accepted observations and determinations made by researchers that can contribute to low-temperature cracking that can be independent of or dominate over the properties of the asphalt cement binder material?
- How can those individuals who are responsible for the construction and maintenance of asphalt concrete pavement structures develop a rational specification for asphalt cement that will limit the occurrence of low-temperature cracking without, at the same time, restricting the supply of the binder material?
- What activities need to be undertaken, both on a research and on a practical level, in the near and distant future to solve the problem of low-temperature cracking?

Agenda

The colloquium took place over a period of two and a half days at the Cold Regions Research and Engineering Laboratory auditorium. The format for the seminar consisted of a series of presentations of different phases of the low-temperature cracking problem, with each speaker invited to concentrate on areas where he had

particular knowledge and data to share with the group. After each short talk the group discussed the subject just presented. A lively interchange of ideas followed each presentation.

The agenda for the colloquium was as follows:

Session 1: Wednesday morning, 6 May 1987.
Moderator: Raymond D. Pavlovich
  A. Overview of Low-Temperature Cracking: Robert H. Joubert, Philip E. McIntyre, Fred N. Finn
  B. Ste. Anne Test Road Results: Imants J. Deme
  C. Asphalt Cement Rheology at Low Temperature: Byron E. Ruth

Session 2: Wednesday afternoon, 6 May 1987.
Moderator: David A. Anderson
  D. Review of The Asphalt Institute's RR-81-1: Warren D. Robertson
  E. Viscosity Temperature Susceptibility: Vyt P. Puzinauskas

Session 3: Thursday morning, 7 May 1987.
Moderator: James A. Scherocman
  F. Penetration–Viscosity Number: Norman W. McLeod
  G. Low-Temperature Asphalt Cement and Mix Properties: Joseph L. Goodrich
  H. Low-Temperature and Normal Ductility: Woodrow J. Halstead
  I. Mix Properties: Bernard F. Kallas

Session 4: Thursday afternoon, 7 May 1987.
Moderator: Gale Page
  J. Modeling: A. Patrick S. Selvadurai
  K. Nonasphalt Cement Considerations: William A. Phang

Session 5: Friday morning, 8 May 1987.
Moderator: Thomas W. Kennedy
  L. Future Research Directions: Open Discussion

List of Participants

The meeting was attended by 48 people who were knowledgable in the areas of asphalt concrete pavement design, mix design, construction and maintenance, as listed below:

1. David A. Anderson, Pennsylvania Transportation Institute
2. Kenneth O. Anderson, University of Alberta
3. Ernest J. Bastain, Jr., Federal Highway Administration
4. Richard Berg, U.S. Army Cold Regions Research and Engineering Laboratory
5. Donald Brown, Vermont Agency of Transportation
6. E. Ray Brown, Auburn University
7. Edwin Chamberlain, U.S. Army Cold Regions Research and Engineering Laboratory
8. Richard L. Davis, Koppers Company
9. Imants J. Deme, Shell Canada Products Limited
10. Steven Dempsey, Chevron USA
11. Robert A. Eaton, U.S. Army Cold Regions Research and Engineering Laboratory
12. Fred N. Finn, ARE, Inc.
13. Nelson Godwin, U.S. Army Waterways Experiment Station
14. Joseph L. Goodrich, Chevron Research Company
15. Woodrow J. Halstead, Consultant
16. Eric E. Harm, Illinois Department of Transportation
17. Warner N. Hodgdon, Frank W. Whitcomb Construction Company
18. Vincent C. Janoo, U.S. Army Cold Regions Research and Engineering Laboratory
19. Robert H. Joubert, The Asphalt Institute
20. Bernard F. Kallas, Consultant
21. Prithvi S. Kandhal, Pennsylvania Department of Transportation
22. Edward J. Kearney, The Asphalt Institute
23. Thomas W. Kennedy, University of Texas
24. Joseph F. Lamond, U.S. Army Corps of Engineers
25. Richard Langlois, Quebec Ministry of Transportation
26. Lewis E. Link, U.S. Army Cold Regions Research and Engineering Laboratory
27. Duncan A. McCrae, Lane Construction Corporation
28. Philip E. McIntyre, New Hampshire Department of Transportation
29. Norman W. McLeod, McAsphalt Engineering Services
30. H. Richard Miller, LBD Asphalt Products Company
31. Roderick W. Monroe, Iowa Department of Transportation
32. James S. Moulthrop, Exxon Chemical Americas
33. Roger C. Olson, Minnesota Department of Transportation
34. William A. Phang, Ontario Ministry of Transportation and Communications
35. Gale C. Page, Florida Department of Transportation
36. Raymond D. Pavlovich, New Mexico Engineering Research Institute
37. Vyt P. Puzinauskas, The Asphalt Institute
38. William F. Quinn, U.S. Army Cold Regions Research and Engineering Laboratory
39. David Rand, Maine Department of Transportation
40. Warren D. Robertson, Imperial Oil Limited
41. Byron E. Ruth, University of Florida
42. James A Scherocman, Consulting Engineer
43. A. Patrick S. Selvadurai, Carleton University
44. Jack E. Stephens, University of Connecticut
45. Clifford A. Taylor, Shell Development Company
46. Hisao Tomita, Federal Aviation Administration
47. Thomas Wohlscheid, New York State Department of Transportation
48. David L. Wolfe, Dow Chemical Company

SUMMARY OF PRESENTATIONS

Overview of Low-Temperature Cracking

Robert H. Joubert, The Asphalt Institute

Bob Joubert stated that there is disagreement among technologists on whether binder properties or binder and mix properties most affect low-temperature cracking. Beyond that issue are those that try to characterize the temperature susceptibility of asphalt alone using three different methods, none of which are directly related to the others.

Joubert discussed the purpose of the seminar—to review different approaches to the low-temperature cracking problem without criticizing the various individual points of view. The colloquium participants were asked to analyze the advantages and disadvantages of each of the three present methods. He pointed out that the goal should be to develop a state-of-the-art status of low-temperature cracking, with emphasis on directions for future research.

It was pointed out that there is a great need for data on the extent and severity of the low-temperature cracking problem. In addition, it needed to be determined to what degree such cracking affected the long-term performance of the asphalt concrete pavement structure. Joubert stressed the need for broad-based support for investigating the problem, with data gathering and research being sponsored by a combination of interested groups, such as asphalt cement suppliers, paving contractors and governmental agencies.

Philip E. McIntyre,
New Hampshire Department of Transportation

Phil McIntyre discussed the extent of the low-temperature cracking problem in his state. He commented that some investigative work seemed to indicate a relationship between the number of degree-days of ambient temperature below freezing and the amount of cracking that had occurred in the asphalt concrete pavements in New Hampshire. Extensive low-temperature cracking had taken place in pavements in the northern part of the state, but little if any such cracking had occurred in pavements south of Concord, where the number of degree-days was typically less than 1000 each year.

He commented briefly on some of the factors that had changed over the last 20 years that might, in part, contribute to the increase in the low-temperature cracking problem. Among the items mentioned were

- A reduction in the degree of quality control during the construction of the asphalt concrete pavement;
- Increased traffic loads;
- A change in the type and grade of asphalt binder used;

- A change in the source of the crude oil used to manufacture the asphalt cement; and
- A change in pavement cross section due to new pavement thickness design guidelines.

McIntyre presented a list of points to be considered during the seminar. Included in that list were the following items that may be related to low-temperature transverse pavement cracking:

- Cracking seems to increase with pavement age.
- Cracking may begin at any point on the pavement surface—on either edge of the pavement or in the center of the lane.
- Defects that later become transverse cracks may be built into the pavement structure during construction by noncontinuous paving operations.
- The onset of cracking may be related to the deletion of the prime coat on the aggregate base layer, which reduced the "waterproofing" of this material.
- The use of thicker granular base layers under the asphalt concrete wearing surface appears to reduce rutting but increase the amount of cracking.
- Transverse cracking occurs on pavements that do not carry significant traffic—the passing lane of multiple-lane roadways.
- The change to a softer grade of asphalt cement (from AC-20 to AC-10) has reduced the degree of low-temperature cracking without necessarily increasing the amount of rutting.
- The number of degree-days of temperature below freezing appears to correlate to the amount of low-temperature cracking.
- The relationship between the time of day that the cracking occurs (day or night) and the change in temperature during a day (temperature gradient) when cracking occurs should be investigated.
- The level of friction or drag between the surface of the aggregate base course and the bottom of the asphalt concrete layer might affect the degree of low-temperature cracking.
- The degree of low-temperature cracking may be enhanced by thermal fatigue.
- Test methods are needed to determine the stress–strain characteristics of the asphalt concrete mix just prior to the onset of low-temperature cracking.
- Test methods used in the laboratory must be related to and correlated with the actual cracking that occurs in the pavement.
- Empirical test methods may be available to predict the onset of low-temperature cracking.

Fred N. Finn, ARE, Inc.

An overview of the low-temperature cracking problem was presented by Fred Finn. He commented that a number of research projects reported in the literature

indicated that the asphalt cement properties are the dominant controlling variable in this distress mechanism. He pointed out that suggested solutions to the problem included the use of "softer" asphalt cements and the use of binders with lower levels of temperature susceptibility. Finn discussed the fact that low-temperature cracking is often compounded by such factors as the thickness of the asphalt concrete pavement layer, the rate of change of temperature, the type of subgrade soil, the thermal coefficient of the aggregates, and the interaction with traffic loading. He stated that there is very little evidence that any of the past research has lead to a reduction in the incidence of low-temperature cracking.

Finn cited early research by Norman McLeod that showed that the occurrence of low-temperature cracking was related to the hardness of the asphalt cement, the Penetration–Viscosity Number (or pen-vis number) of the asphalt cement, the stiffness of the asphalt concrete mix, and the thickness of the asphalt concrete layer. He also discussed information derived from the Ste. Anne Test Road that indicated that the incidence of low-temperature cracking was a function of the asphalt binder type and grade. This project indicated that the binder stiffness at low temperatures and long loading times was an important characteristic to account for.

Finn commented on the criteria of the freezing index (degree-days) and the onset of low-temperature cracking. He stated that there are locations in the United States where low-temperature transverse cracking evidently occurs even though the number of degree-days is less than 500. Finn pointed out that the amount of low-temperature cracking may be related to the degree of aging of the asphalt cement binder. He also discussed the research by Haas, who found a correlation between low temperatures and the present serviceability index of the pavement structure: the cracking index was related to ride quality, with pavements having transverse cracks at greater intervals having higher serviceability index numbers.

A number of factors seem to be related to low-temperature cracking. Finn listed the most important factors as the stiffness of the asphalt cement binder at low temperatures as well as the stiffness of the asphalt concrete mix at low temperatures. He also stated that there may be a relationship between low-temperature cracking and the ductility of the asphalt cement at 39.2°F.

Finn commented on a study in Utah where the computer program COLD was used to predict the amount of low-temperature cracking in ten pavements. The correlation obtained depended on the source of the asphalt cement used in the asphalt concrete mixture. Work underway in Kansas found that low-temperature cracking occurred both in thin asphalt concrete surface courses and in thick full-depth asphalt concrete pavement structures.

Finn concluded by saying that the pavement designer really has no control over the properties of the asphalt cement except for the properties that are provided for in the specifications. He commented that modifications to those specifications could result in improved pavement performance in regard to low-temperature cracking but could also lead to a reduced supply of acceptable asphalt cement and to higher binder costs. He also stated that the Strategic Highway Research Program (SHRP) was going to investigate low-temperature cracking.

General discussion

A comment was made that failure stress is unique only for a particular set of loading and temperature conditions. In addition, part of the problem is that the temperature susceptibility of the asphalt cement is only measured on the original asphalt cement—before aging occurs. In the asphalt concrete mix, the low-temperature cracking occurs after the binder has aged to some degree in the pavement. Another comment concerned the fact that low-temperature cracking is a function of the stiffness modulus of the mix. It was pointed out that when "transverse joints" were sawed at intervals of 20 ft into a new asphalt concrete layer in Manitoba, additional transverse cracking occurred between the sawed joints.

Several people discussed the relationship between the use of a prime coat on the underlying aggregate and the amount of transverse cracking. It was pointed out, similar to the findings of Phil McIntyre, that the use of a prime coat seems to reduce the degree of transverse cracking in the overlying asphalt concrete mixture, all other factors being the same. It was stated that it was possible that the prime coat material was actually being drawn in the mix, softening the asphalt cement in the overlay and thus reducing its stiffness.

A discussion followed regarding the many small stresses that may occur at any one time in the asphalt concrete mix. In cold weather these stresses cannot dissipate readily. It was stated that short-term stresses may be more important than long-term stresses. If a short loading time is used instead of a long loading time in the laboratory test procedures, there would be a better correlation between the cracking temperature and mix stiffness. It was pointed out that the tensile strength of the mix should be evaluated at short loading times; it has been found that the tensile strength at low temperatures is independent of both temperature and loading time.

Ste. Anne Test Road Results
Imants J. Deme, Shell Canada Products Limited

The Ste. Anne Test Road was constructed in Mani-

toba, north of Winnipeg, in September 1967. Imants Deme provided data on the original materials and pavement cross sections used in various test sections. Three pavement sections were employed: 4 in. of asphalt concrete on 6 in. of granular base on a sand subgrade soil, 4 in. of asphalt concrete on 16 in. of granular base on a clay subgrade soil, and 10 in. of full-depth asphalt concrete on a clay subgrade soil. Three asphalt cements were incorporated into the asphalt concrete mixes: 150–200 penetration grade, low viscosity; 150–200 penetration grade, high viscosity; and 300–400 penetration grade, low viscosity. In addition, a slow-curing cutback asphalt, SC-5, was also used.

Three asphalt concrete mixes were manufactured: a blend of 80% limestone and 20% igneous material, with 2.5% of the aggregate passing the no. 200 sieve; a blend of 80% limestone and 20% igneous material, with 5.5% passing the no. 200 sieve; and 100% igneous aggregate. In addition, Deme stated that three asphalt contents were used in some of the mixes: Marshall optimum, 1.0% below optimum and 0.5% above optimum. A total of 29 test sections were constructed.

Deme commented that during the winter of 1967-68, the onset of transverse cracking on the test road was measured in several ways. It was found that the transverse cracking initiated at the pavement surface and propagated downward. It was also determined that most of the cracks did not penetrate into the underlying binder course asphalt concrete mix but were limited to the colder, and stiffer, surface course mix. It was concluded that the warmer asphalt pavement underlayers could sustain more expansion and contraction and were able to transmit strain without cracking better than the stiffer surface course layers.

The Ste. Anne Test Road was observed until 1975, when the eight-year-old pavement was overlaid with 5 in. of asphalt concrete made with SC-5 cutback asphalt. Conclusions reached at that time indicated the following:

- Asphalt grade had a significant effect on transverse cracking with the softer low-viscosity 300–400 pen asphalt cement exhibiting less transverse cracking than the harder 150–200 pen material made from the same crude oil.
- Asphalt type had a significant effect on low-temperature cracking, with the less-temperature-susceptible high-viscosity 150–200 pen grade binder cracking much less than the low-viscosity 150–200 pen asphalt cement.
- The SC-5 cutback asphalt, made from a high-viscosity base asphalt, exhibited no cracking in eight years.
- The thickness of the asphalt pavement structure affected the amount of low-temperature cracking

when temperature-susceptible asphalt was used; less cracking occurred in the full-depth asphalt concrete pavement layers compared to the thinner asphalt concrete courses constructed on the granular base material.
- The subgrade type affected the time of crack initiation and the cracking frequency, with more cracking occurring on the sand subgrade sections.
- Less cracking for the same binder type was found in the asphalt concrete mixes containing the 100% igneous aggregates.
- There was little influence of asphalt content or filler content (percent passing the no. 200 sieve) on the amount of transverse cracking.

Deme also reported on the condition of the SC-5 overlay. An inspection was conducted in 1987 of the resurfacing, almost 20 years after the original pavement construction. It was found that in the test sections that had cracked prior to the overlay, 13–100% of the cracks had reflected through the overlay, with some sections having developed additional cracking. Even those sections that had not cracked before the overlay (the SC-5 sections) exhibited some cracking in the SC-5 overlay.

The conclusions reached from the Ste. Anne Test Road, as discussed by Deme, included an estimate of the critical stiffness moduli at the time of transverse cracking. It was determined that the fracture was related to a stiffness modulus of the asphalt concrete mix of 2.3×10^6 psi at a time of 20,000 s, and also to a stiffness modulus of the asphalt cement binder of 1.4×10^5 psi at a time of 1,800 s. Pavements whose stiffness moduli exceeded these values cracked during the first winter.

Deme commented further that data on the original construction of the Ste. Anne Test Road was reported in Volume 13 of the *Proceedings of the Canadian Technical Asphalt Association,* published in November 1968. Further information could be found in the proceedings of both the Third and the Fourth International Conferences of the Structural Design of Asphalt Pavements, published in 1972 and 1977, respectively.

Asphalt Cement Rheology at Low Temperature
Byron E. Ruth, University of Florida

According to the information presented by Byron Ruth, the properties and characteristics of the binder material that are most related to the predicted cracking temperature of an asphalt cement are the viscosity and the temperature susceptibility of that material. In general, cracking will happen at a higher temperature when the asphalt cement has a higher viscosity and a greater degree of temperature susceptibility. Further, as the rate of cooling or temperature change increases, the predicted cracking temperature increases. A rapid increase in the rate of cooling at low temperatures, when the asphalt

cement viscosity is high, increases the chance for cracking of the asphalt concrete mixture.

Ruth commented that the thermal stresses developed in an asphalt concrete pavement are thus dependent on the rate of cooling, the coefficient of thermal contraction, the creep rate (related to asphalt cement viscosity), and the elastic properties of the material. He stated that equations have been developed using parameters that define strain, modulus and viscosity values. These three equations are then combined to develop a thermal stress equation, which is used to calculate the incremental stresses and strains for small time intervals. The resulting equation can then be employed to predict the cracking temperature for a particular asphalt cement binder.

At low temperatures, asphalt cements with high viscosities cause the asphalt concrete mix to have a much greater stiffness and a significantly higher modulus of elasticity. Asphalt cements that have relatively low viscosities at the lowest in-service pavement temperatures will yield lower tensile stresses than will asphalt cements that are temperature susceptible or that have hardened excessively in use.

Ruth stated that several approaches were investigated as possible options for failure criteria. Those methods included the use of a stress ratio, the ratio of creep strain to failure strain, and the ratio of applied creep energy to fracture energy. It was determined that failure can best be described using the concept of a fracture energy ratio. This energy ratio is calculated using both stress and creep strain and appears to be the most rational failure criterion for predicting low-temperature cracking of different asphalt concrete mixtures.

Also briefly discussed was a phenomenon he called "pavement rippling." Due to the rate of cooling of an asphalt concrete mix, the pavement, in places, can lift off of the underlying base course material. This uneven contact can greatly increase the stresses, and therefore the strains, in the asphalt concrete mix. The pavement will perform well where the asphalt concrete mix is in contact with the underlying base but will perform poorly where the material is not in contact with the base course aggregates. This rippling effect contributes to some degree to the cracking on the asphalt concrete mix and is directly related to the rate of cooling of the mixture and the degree of stress relaxation of the material.

General discussion

A comment was made about the effect of contact (or lack of contact) with the underlying base course material. It was pointed out that in the laboratory there is generally uniform contact with the materials that are beneath the asphalt concrete layer but that this may not be entirely true on the roadway. It was also stated that in the lab there is no real bonding of the asphalt concrete

layer to the substrate, while in the actual pavement structure there may be some partial bonding of the mixture to the underlying aggregates.

Another comment was related to the measurement of the viscosity of the asphalt cement. It was pointed out that the rate of shear was very important in determining the viscosity of that material. The viscosity measured depends on the rate of shear used. Another individual, however, stated that viscosity also depends on the stress level; viscosity should be measured at a standard stress rate instead of a constant shear rate. It was felt that both the sliding-plate and cone-plate viscometers were not capable of measuring the viscosity of the asphalt cement at the stress levels that are found in the asphalt concrete mix in the pavement.

Review of the Asphalt Institute's RR 81-1
Warren D. Robertson, Imperial Oil Limited

In December 1981 The Asphalt Institute published a report entitled "Design techniques to minimize low-temperature asphalt pavement transverse cracking" (Research Report No. 81-1). Warren Robertson reviewed for the group some of the important findings of that report and took the position that the Penetration Index method was the preferred way to determine the temperature susceptibility of an asphalt cement.

Robertson mentioned two major factors that affect the amount of low-temperature cracking in an asphalt concrete pavement: the winter climate and the properties of the asphalt cement binder. He also discussed several secondary factors, such as the thickness of the asphalt concrete pavement layers, the age of the pavement and the type of subgrade soil. He commented that the composition of the asphalt concrete mix itself and the properties of the aggregates used in the mix have no effect at all on the degree of low-temperature cracking in a given mixture.

The temperature susceptibility of the asphalt cement can be measured in many ways. Robertson discussed the common means of determining temperature susceptibility in the United States, Canada and Europe. In essence these methods are related to either the Penetration–Viscosity Number (PVN) or to some form of the Penetration Index (PI) procedure. Robertson pointed out that the PI is determined by using the log of penetration vs temperature. The PVN value is calculated by using the viscosity of the asphalt cement at 275°F and the penetration at 77°F. He stated that there is very little correlation between the PI and the PVN values for a given asphalt cement. He further commented that the Penetration Index relates well to the tensile modulus of the asphalt cement at a temperature of –23°F at a loading time of 1800 s, while there is poor correlation of the tensile modulus and PVN at the same temperature and

loading time. He stated that low stiffness of the asphalt cement is needed at low temperatures and that while PI provides an indication of the stiffness of the asphalt cement at low temperatures, PVN does not.

Robertson stated that the reasons why PVN does not correlate well with the amount of low-temperature cracking are due in part to the presence of wax in the asphalt cements used in the pavements. He said that all asphalt cements have some wax in them (1.5–3.0%). There is a drop in the viscosity of the asphalt cement in the temperature region where the wax melts. Thus, if the wax is present, use of the PVN method makes the temperature susceptibility of the asphalt cement appear to be worse than it actually is. Further, air-blown asphalt cements typically behave better at low temperatures than their PVN values would indicate.

Robertson briefly reviewed several methods currently available to predict the temperature at which an asphalt concrete pavement will crack. The first is based on limiting the stiffness of the asphalt cement: estimating the temperature at which the asphalt reaches a certain critical or limiting stiffness. The PI method is based on this procedure. The second means of prediction is based on the procedure of Hills, where the critical stress in the asphalt cement is determined. Pavement cracking occurs at a temperature corresponding to a certain value of thermal stress in the asphalt cement. The third method is based on work by Gaw and uses nomographs to determine the unique relationship between asphalt penetrations at 77 and 41°F and the calculated cracking temperature. Each of these methods is predicated on the stiffness of the asphalt cement. The fourth method concerns the prediction of pavement cracking temperatures from values of asphalt concrete mix stiffness. The cracking occurs when some limiting mix stiffness number is exceeded. The last method calculates the mix cracking temperature based on the thermal stress in the pavement and the mix breaking (tensile) strength. Cracking is supposed to occur at the point where the thermal stress and the breaking strength of the mix are equal.

Robertson commented that there was good correlation between the cracking temperatures predicted from Gaw's nomographs and the actual cracking temperatures measured on the Ste. Anne Test Road. He further stated, however, that the nomographs have not been shown to be as well correlated when used to predict cracking on other highways in Manitoba. In general the nomographs have indicated a lower cracking temperature than the temperature at which the pavements actually cracked.

According to Robertson the PVN method is a strictly empirical approach to the low-temperature cracking problem. Using this method, one could not find an asphalt cement that would not crack at some low tem-

perature. He also pointed out that the PVN method provided conservative predictions of the cracking temperatures for the Ste. Anne Test Road sections. Robertson thus drew the conclusion that the temperature susceptibility of an asphalt cement is much better defined by its Penetration Index than by its Penetration–Viscosity Number. He commented further that present asphalt cement specifications used in North America do not control the temperature susceptibility of the asphalt cement because those specifications are based more on PVN than on PI.

General discussion

The first comment on Robertson's presentation concerned the belief that the PVN values are well correlated with the amount of low-temperature cracking in asphalt concrete pavements; an increase in the PVN value (a more negative number) indicates an increase in the amount of low-temperature cracking. Other comments were related to the fact that there are many causes for cracking in an asphalt concrete pavement. Care must be taken to distinguish between low-temperature causes of cracking and other causes such as fatigue.

In addition, it was pointed out that the thermal coefficient of expansion of the aggregate probably had an effect on cracking, even though it had been dismissed as a primary cause of low-temperature cracking. This thought was echoed by several other individuals who believed that the properties of the asphalt concrete mix, including the coefficient of expansion and contraction of the aggregates, played a significant part in the degree of transverse cracking. The thought was expressed that all of the problems with low-temperature cracking could not be placed only on the properties of the asphalt cement binder.

Viscosity–temperature susceptibility
Vyt P. Puzinauskas, The Asphalt Institute

Vyt Puzinauskas pointed out at the beginning of his presentation that one must look at the aged properties of the asphalt cement binder, not just the original properties, if one is going to determine the amount of low-temperature cracking that would occur in an asphalt concrete mixture. He also stated that he believed that the properties and characteristics of the asphalt concrete mix must be considered, not just the properties of the binder material.

Puzinauskas defined the three best-known methods of measuring the temperature susceptibility of an asphalt cement. Those three methods are the Penetration Index (PI), the Penetration–Viscosity Number (PVN) and the Viscosity Temperature Susceptibility (VTS). He stated that when a comparison is made between PI and VTS, a poor correlation in obtained. A better correlation is

found between PVN and VTS, and a poor correlation exists between PI and PVN.

The comment was made that the shear rate used to measure viscosity is very important. For a low-viscosity asphalt cement, there is very little difference in the viscosity of the material with a change in shear rate. For a higher-viscosity asphalt cement, however, the change in viscosity is much greater with a change in shear rate.

Puzinauskas stated that the properties of the asphalt concrete mixture are important in determining the amount of low-temperature cracking that will occur in the pavement. He discussed the importance of the filler–bitumen ratio in the mix as well as the effect of the type of filler used in the mix and the effect of the filler on the viscosity of the asphalt cement. He commented that the type and volume of the aggregate, as well as the characteristics of the aggregate, do affect the cracking temperatures. Further, he said that he believed that the absorption of the aggregate must be taken into account; some of the lighter portions of the asphalt cement were absorbed into the aggregate, leaving a stiffer asphalt cement that might low-temperature crack at higher temperatures.

One must also consider that the viscosity of the asphalt cement varies with the age and degree of hardening of the material. Some asphalt cements increase in viscosity more than others under the same conditions of the pavement under traffic and at the same air void content of the mix. In addition, the change in viscosity varies in proportion to the depth of the mix in the pavement structure. There is less change in viscosity as the distance from the pavement surface increases. Data from several test projects indicate that low-temperature cracking starts at the pavement surface. This is primarily because the viscosity of the asphalt cement is greater at that point because of a greater change in the viscosity at the surface due to aging.

Puzinauskas stated that both the PI and the VTS methods of measurement give different values for different ranges of temperature. He also stated that the low-temperature viscosities of different asphalt cements vary over a wide range of values. He doubted if high-temperature test measurements could be used to predict low-temperature cracking performance of asphalt concrete mixtures. Puzinauskas also raised the point that the ductility of the asphalt cement, particularly at low temperatures, could be important in the degree of low-temperature cracking that occurs.

General discussion

A comment was made concerning the effect of filler type and amount on the stiffness of the asphalt cement. It was pointed out that the effect depended on the gradation of the filler material. If the filler increased the stiffness of the asphalt cement and the stiffness of the asphalt concrete mixture, there should be an increase in the temperature at which cracking occurs.

Penetration–Viscosity Number
Norman W. McLeod, McAsphalt Engineering Services

Norm McLeod reviewed his experiences with the problem of low-temperature cracking on in-service pavements in Ontario. He commented that when the penetration at 77°F of the asphalt binder is constant, low-temperature transverse cracking increases with an increase in temperature susceptibility; when the temperature susceptibility of the asphalt binder is constant, cracking increases as the penetration at 77°F decreases, as the asphalt cement becomes harder; and low-temperature cracking increases with pavement age, as the penetration of the binder becomes lower.

McLeod discussed the history of low-temperature cracking in Canada. He stated that there were no problems with cracking when the pavements were constructed using slow-curing cutback asphalts. The problems did occur, however, when waxy asphalts were used: the asphalt mix was tender and proper compaction could not be obtained with the rollers. He discussed the construction of three test roads in Ontario that were built in 1960. From the cracking data gathered from those three projects, it was found that there was no correlation between the number of transverse cracks and the Penetration Index of the three asphalt cements used in the mix. A correlation was obtained, however, between the degree of cracking in the different test pavements and the Penetration–Viscosity Number of the three asphalt cements.

McLeod commented that PVN is based on the properties of the asphalt cement in both the liquid and the semisolid regions. He also pointed out that the PVN value for a particular asphalt cement was a relatively constant number, whether the value was calculated for the original asphalt binder or for the thin-film oven residue. He stated that this was not true for the PI values for different asphalt cements and for different ages of the binder; the PI of the material changes with time and aging of the asphalt cement.

For the three test roads the PVN number did not change for any of the three asphalts during the life of the roadways. Further, results from other test pavements in North America, such as the six test sections constructed in the mid-1970s in Pennsylvania, showed that all of the PI numbers, regardless of how they were calculated, changed with time and with the aging of the asphalt cement binder. The same was not true for the PVN values, however. The PVN numbers for the different asphalt cements did not change with the aging of the binder materials. The same results were obtained from

a study of asphalt cement characteristics from 26 airport pavements across Canada; there was no difference in the PVN values for the asphalt cements with time.

Additional data were discussed that indicated that there was no relationship between the PI of a particular asphalt cement and its PVN value. Information from a Federal Highway Administration study of asphalt cements done in the early 1960s showed PVN and PI to be unrelated. Further, McLeod commented that one of the advantages of using PVN was that because the number did not change with time or aging of the asphalt cement, when the binder was recovered from an asphalt concrete pavement that was going to be recycled, the PVN number could be determined and then the temperature susceptibility of the original asphalt cement would be known.

McLeod commented that the use of the PVN method does not mean that asphalt cements that have a high temperature susceptibility would be eliminated from use. He suggested that asphalt cements that have more negative PVN values (i.e. they are more temperature susceptible) could be used on roadways with lower traffic volume, in areas where the climates are less severe, and in the lower layers of an asphalt concrete pavement structure. He again asserted that PVN is better related to the amount of low-temperature cracking than is Penetration Index.

General discussion

A comment was made that the amount of wax in an asphalt cement has a definite effect on the properties of the binder. It was pointed out that there is a limit on the volume of wax that is permitted in the asphalt cements used in pavement construction in Europe. It was agreed that for waxy asphalt cements there is a change in the PI value for the binder in the temperature range where the wax melts. It was also agreed that the PI number changes as the asphalt cement ages.

The comment continued, however, that for the three Ontario test roads, the asphalt cements were waxy-type materials. These materials provide ring-and-ball softening points that are different from those of asphalt cements without wax. Thus, the suggestion was made that the PVN numbers calculated using waxy asphalt cements were incorrect. It was further pointed out that only about 80% of the asphalt cements being used in North American are of the waxy type and that the PVN method would not be applicable for measuring the temperature susceptibility of these binders, which make up the vast majority of the asphalt cements used in asphalt concrete pavements.

The discussion then revolved around why the PVN value remains constant even when the asphalt cement ages. It was pointed out that even though the PVN

number is the same with time, the aging of the asphalt cement still increases the stiffness of the mix and this increase in stiffness can lead to an increased tendency for low-temperature cracking. Also discussed was the mechanism of oxidation or hardening of the binder. It was stated that the means by which oxidation occurs is not well understood. It was agreed, however, that the rheological properties of the asphalt cement do change significantly as the binder hardens.

The conversation returned to the fact that all of the test methods in use involve the measurement of the properties of asphalt cement at temperatures considerably above the temperature levels where low-temperature transverse cracking occurs. A comment was again made that test procedures need to be developed to determine the properties of the asphalt cement and the asphalt concrete mix within the temperature range where the cracking actually happens.

The discussion turned to the point that the present asphalt cement specifications do not control the temperature susceptibility of the binder material. Because the present specs require both penetration and viscosity measurements on the asphalt cement, it was felt by one individual that the existing specifications were directly related to the PVN method of predicting low-temperature cracking. It was further stated that the PVN method did not seem to do a good job of predicting or preventing low-temperature cracking. The reply provided concerned the fact that the present specifications are so broad as to allow the use of all asphalt cements being supplied. Thus it could not be construed that the existing specifications were applicable to the PVN method to control low-temperature cracking.

Once again several of the people in the group voiced the opinion that it could not be reasonably expected to predict the low-temperature performance of asphalt cement or asphalt concrete mixtures based on the measurement of binder or mix properties at higher temperatures. It was pointed out that it was probably incorrect to extrapolate backward from the higher temperatures to the low temperatures to estimate the characteristics needed. A mechanistic approach instead of an empirical approach is necessary, and the method should be capable of determining the proper measurement at the actual temperatures where low-temperature cracking occurs.

Low-temperature asphalt cement and mix properties
Joseph L. Goodrich, Chevron Research Company

Joe Goodrich commented that the present practice of selecting asphalt cements for cold climates based on using a higher-penetration-grade or lower-viscosity-grade asphalt cement than would normally be used in warmer locations is not always beneficial in reducing

the incidence of low-temperature cracking. This is because the asphalt cement of one grade (AC-10) manufactured from one crude oil might be stiffer than the asphalt cement of a more viscous grade (AC-20) made from another crude oil.

He reported on some research work conducted by Chevron that measured the low-temperature creep behavior of the asphalt concrete mixtures. Several binder materials were used, including ones that represented extremes of temperature susceptibility and other asphalt cements that were polymer-modified. These asphalts had widely different PVN values, low-temperature ductilities and other physical properties. The properties of the various asphalts were determined on the residues from the rolling thin-film oven (RTFO) test.

The creep deformation of the asphalt concrete mixes was determined at –20, 0, 20 and 40°F. From these data the limiting stiffness temperatures of the mixes were determined. A correlation was attempted between the stiffness values and some of the physical properties of the asphalt cement binders. Neither PVN at 77 and 140°F, PVN at 77 and 275°F, ductility at 39.2°F or high-temperature viscosity measurements at 140 and 275°F correlated well with the limited stiffness measurements of the asphalt concrete mixes.

Goodrich provided the following conclusions from the work completed to date:

- The dynamic analysis of the loss modulus G on the RTFO residues correlated well with low-temperature mix creep evaluation;
- Both the penetration test (200 gm, 60 s) at 39.2°F and the Fraass Brittle Point test correlated well with the limiting stiffness of the mixes; and
- Creep analysis of asphalt concrete specimens at expected low temperatures is recommended as a routine part of low-temperature mix design.

General discussion

The first comments from the group concerned the penetration test run at 39.2°F at 200 gm and 60 s instead of 100 gm and 5 s. Additional comments were in regard to the use of low-temperature viscosity measurements using the cone-plate viscometer instead of low-temperature penetration measurements. It was stated that the cone-plate viscosity is not related to the low-temperature penetration data. Problems in conducting the cone-plate viscosity at low temperatures were briefly discussed.

The discussion also concerned the properties of the asphalt cement at the glass transition temperature. It was pointed out that the creep loss modulus is a maximum at this temperature. The comment was made, however, that the glass transition temperature is not actually one temperature but really a temperature region

or range. It was also pointed out that there are different ways of determining the glass transition temperature.

It was stated that a good relationship had been found between the 39.2°F penetration test (200 gm, 60 s) and the creep modulus values at –30°F. A good correlation was also determined between penetration index and low-temperature creep modulus. Another comment was made stating that a correlation could be obtained between penetration values determined at 39.2°F, either at 200 gm and 60 s or at 100 gm and 5 s.

The next discussion was related to the running of the low-temperature creep test. It was reported that the air void content of the creep test specimens had a significant effect on the values determined. It was also suggested that if the creep testing was done using pavement cores, there could be a great deal of variation in the test results.

Low-temperature and normal ductility
Woodrow J. Halstead, Consultant

Halstead commented that the ductility test had been developed in 1903. It was originally designed to measure the stickiness of the asphalt cement. He stated that many attempts have been made to relate ductility measurements at various temperatures to the degree of low-temperature cracking of the binder material. He also stated, however, that in his opinion there is no relationship between ductility values and the cracking temperatures. He commented further that ductility seems to be correlated to the flow properties (shear susceptibility) of the asphalt cement. It is also related to the internal cohesion of the material.

Halstead commented that there is no evidence that the higher the ductility of an asphalt cement, the better the long-term performance of the binder in the asphalt concrete mixture. He stated that a certain minimum amount of ductility is needed in an asphalt cement, but it is doubtful if any "extra" ductility will reduce the amount of low-temperature cracking. Further, he commented that the ductility value measured even at 39.2°F was probably not related at all to the flow properties of the asphalt cement at very low temperatures (–30°F).

General discussion

A general discussion of the applicability of the ductility test at various test temperatures was held. There were many opinions concerning the usefulness of the test method. It was believed that some ductility value at 77°F is probably needed to eliminate some very poor performing (high wax content) asphalt cements. It was pointed out, however, that the requirement for some great amount of ductility at lower test temperatures such as 60 or 39.2°F could significantly limit the number of crude oils that could meet the requirements. Such a specification would reduce the use of waxy crudes and

crudes with high asphaltene contents.

Although the discussion of ductility and its benefits in controlling the performance of different asphalt cements was spirited, the consensus was that ductility, even run at 39.2°F, was not related to the low-temperature cracking problem in asphalt concrete mixes.

Mix properties
Bernard F. Kallas, Consultant

The measurement of stress and strain properties of asphalt concrete mixes at low temperatures was discussed by Ben Kallas. Two asphalt concrete mixes, one using gravel aggregate and the other incorporating limestone aggregate, were mixed with three grades of asphalt cement: AC 2.5, AC 5 and AC 10. Three asphalt contents were employed: optimum, 0.5 above optimum and 0.5 below optimum. The asphalt concrete mixtures were tested at five temperatures from 32°F down to –40°F. The uniaxial tensile test was employed to determine the tensile stress and tensile strain in the specimens.

A difference was found in the tensile modulus values with the different aggregates. The mix manufactured with the limestone aggregate had a higher tensile modulus and a higher fracture strength than did the gravel mix. Interestingly some 10–15% of the fracture that occurred was through the aggregate particles instead of through the asphalt cement binder. It was determined that the modulus in tension was independent of the loading time. Further, only small differences were found in the peak modulus values due to the grade of the asphalt cement.

The computer program COLD was used to predict the cracking temperature of the various mixtures. Using data from the Ste. Anne Test Road and the Colorado test project, the COLD program was found to estimate cracking temperatures that were slightly higher than the actual temperatures at which cracking occurred.

General discussion

A question was asked about the range of tensile strengths of the asphalt concrete mixes. Kallas commented that the values were in the range of 300–700 psi. It was pointed out that the tensile strength of the mixes decreased with a decrease in temperature. There was no difference in the mode of failure, however, with test temperature.

Comments were presented on the type of failure observed. It was stated that the failure was adhesive in nature, not cohesive. There was a discussion about the fracture of the aggregate in some of the mixes at failure. It was stated that fracture of the aggregate was also found when cores were cut from pavements through some low-temperature transverse cracks.

Modeling
A. Patrick S. Selvadurai, Carleton University

Selvadurai presented a list of factors that he felt influenced the initiation and propagation of low-temperature cracks in an asphalt concrete mixture. Among those are
- The initial condition of the pavement (the presence of microcracks);
- Thermomechanical processes within the components of the pavement structure;
- Transient thermal effects;
- Transient loading effects; and
- Degradation phenomena.

The low-temperature mechanical behavior of the asphalt concrete mix was modeled in terms of linear thermoelasticity. A fracture mechanics approach was used to account for flaws within the pavement structure and to analyze the propagation of those cracks in the mix. In this analysis the cracks were assumed to exist in a continuum region. The nature of the crack tip behavior influenced the stability and propagation of the cracks. Three types of cracks were modeled: open cracks, closed cracks and closed cracks with frictional closure.

Correlations are yet to be determined between the parameters that characterize the fracture process and the properties of the asphalt cement binder and the asphalt concrete mix. It was theorized that the rate of change of energy at the crack tip due to thermal effects would cause the cracks to propagate. Using this model, however, the initiation of the cracking due to low temperatures was not necessarily at the pavement surface but might be at some flaw within the pavement layers. For the low-temperature cracking problem, this model of the cracking process was still in the early developmental stage.

General discussion

A comment was made concerning the relaxation of stresses in the asphalt concrete mix. It was pointed out that any relaxation period would reduce the energy available at the tip of the cracks. Further, it was stated that the assumption of continuity is a serious oversimplification that would affect the accuracy of the model's predictions. It was suggested that the size of the aggregate particles in the specimens was an important variable that would affect the boundary condition assumptions for the model.

Nonasphalt cement considerations
William A. Phang, Ontario Ministry of Transportation

Bill Phang discussed some of the factors that affect low-temperature cracking, including climate, asphalt cement properties, mix design and pavement design. He reviewed data obtained by Ralph Haas from a number

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of airport pavements across Canada. The field data consisted of crack surveys, layer thicknesses, surface roughnesses, site temperatures, freezing index values, rainfall and pavement age.

Cores were cut from the various pavements studied. Tests conducted on these samples included stiffness modulus at three temperatures (32, 0 and –30°F), failure stress, coefficient of thermal contraction, bulk specific gravity, asphalt content, penetration and viscosity of the recovered asphalt cement, and the PVN of the recovered binder material. It was found that the amount of low-temperature cracking was a function of the minimum ambient temperature, the freezing index, the temperature susceptibility of the asphalt cement, the thickness of the asphalt concrete pavement layer, the coefficient of thermal contraction and the PVN value. The temperature susceptibility of the binder was manifested in the change of mix stiffness with changes in temperature between the test temperatures.

A model was developed that predicted the crack spacing as a function of the thickness of the asphalt concrete pavement layer, minimum air temperature, PVN number and coefficient of thermal contraction. The correlation coefficient for this model was an R^2 value of 0.70. A second model for the prediction of crack spacing was developed as a function of the thickness of the asphalt concrete pavement layer, the minimum air temperature and the increase in the stiffness of the mix between the temperatures of 32 and 0°F; for this model the R^2 value was 0.56.

General discussion

A question was asked about the availability of data on the original properties of the asphalt cements used in the different airport pavements. It was stated that the recovered asphalt cement PVN values were used to estimate the characteristics of the various binders. A comment was made that neither model included the penetration value of the binder in the correlation equation. It was also pointed out that only simple correlations were used in the model—no interactions between variables were determined.

William A. Phang, Ontario Ministry of Transportation

Bill Phang continued his presentation by stating that thermal stresses in asphalt concrete mixtures are a function of
  • Surface defects—surface flaws and induced flaws (construction joints);
  • The coefficient of thermal contraction—the absolute value of the coefficient as well as the rate of temperature drop;
  • The thickness of the asphalt concrete layer;

  • The absorption of the aggregate—the reduction in film thickness and the increase in aging of the binder;
  • The degree of base restraint—the roughness at the layer interface and the effectiveness of the bond between layers;
  • The minimum air temperature—the microclimate at the site, including elevation, moisture content and shade; and
  • The weight and volume of traffic.
In addition, volume changes in the subgrade, such as frost heave, subgrade shrinkage and freezing index, add to the potential for low-temperature cracking.

Phang discussed the coefficients of contraction for asphalt cement, asphalt concrete mix and aggregate base material. He commented that the coefficient was approximately 10 times greater for the asphalt cement compared to the asphalt concrete mix and twice as great for the mix compared to the aggregate base material. He also commented on the effect of the rate of temperature drop on the prediction of the critical cracking temperature.

General discussion

A comment was made that the coefficient of thermal expansion and contraction of a mixture is a function not only of the thermal coefficient of the asphalt cement binder but also of the aggregate used in the mix. In addition, different aggregates have different coefficient values. Further, the degree of expansion and contraction depends in part on the moisture content in the aggregate and in the mix.

Prithvi S. Kandhal, Pennsylvania
Department of Transportation

"Ken" Kandhal discussed the performance of six pavement test sections that were constructed using five asphalt cements in northcentral Pennsylvania in 1976. The amount of cracking that occurred in each of the test sections was monitored over the next few years. It was found that more extensive cracking occurred in the asphalt concrete mixes that contained the stiffest asphalt cements. A limiting value for stiffness to predict the onset of low-temperature cracking was presented.

Values of Penetration Index and Penetration–Viscosity Number were determined for each of the asphalt cements, both originally and at intervals after construction. The PI values indicated that the stiffness of the various mixes was decreasing with time and aging of the binders, which is an inverse relationship to that normally expected. The PVN numbers appeared to be much better correlated with the actual performance of the test section materials.

Kenneth O. Anderson, University of Alberta

Research was done to determine the indirect tensile strength of Marshall-size asphalt concrete specimens at various temperatures between 32 and –40°F. The samples were prepared using three sources of asphalt cement with different temperature susceptibility characteristics. The values of failure stress and failure strain at different temperatures were recorded. The values determined were compared to the numbers predicted using the computer program COLD.

Open discussion of future research directions

At the completion of the colloquium the group discussed the importance of the various factors that seemed to affect the amount of low-temperature cracking in an asphalt concrete pavement layer. To reduce the incidence of cracking, it was suggested that the following things could be done:
- Use a "softer" asphalt cement;
- Use an asphalt cement of lower temperature susceptibility;
- Build thicker asphalt concrete layers;
- Use a prime coat on top of a granular base course layer; and
- Eliminate the use of granular base courses.

The three primary methods of predicting temperature susceptibility of an asphalt cement (PI, PVN and VTS) were briefly reviewed. The members of the group were then asked to "vote" on which of the methods they thought would predict the onset of low-temperature cracking in a given pavement structure. If the individual felt that the method could be used to predict low-temperature cracking, he was asked to vote "yes." If he did not think that the method could be effectively used to predict cracking, he was asked to vote "no." If the person did not have any particular knowledge as to whether or not the method could be used as a determination of low-temperature cracking, he was asked to vote "abstain."

The following table illustrates the vote that was taken by the group. It is important to note that a person could vote "yes"or "no"on more than one method.

Method	Yes	No	Abstain
PI	29	3	17
PVN	30	9	10
VTS	9	10	30

A discussion was held concerning the ability to predict the amount of low-temperature cracking in an asphalt concrete pavement based on tests conducted on the asphalt cement binder only or on the asphalt concrete mix only. Again each individual was asked to vote "yes" if he thought that low-temperature cracking could be predicted using tests on the binder material or the asphalt concrete mix only.

Material	Yes	No	Abstain
Binder	15	24	10
Mix	29	0	20

The group then put together a list of tests that they felt should be conducted on the asphalt concrete mix at low temperatures. That list included the following:
- Indirect tensile strength;
- Coefficient of expansion/contraction;
- A time–temperature dependent modulus value;
- A stress–strain relationship at at least three (low) temperatures;
- Cracking temperature; and
- Fracture mechanics parameters.

The tests listed next were suggested to be conducted on the asphalt cement binder itself, at temperatures below 32°F:
- Creep;
- Stiffness modulus;
- Force ductility;
- Penetration;
- Viscosity;
- Fraass temperature; and
- Glass transition temperature.

The primary problem with the prediction of low-temperature cracking is that there is little, if any, correlation between the laboratory test results, on either the asphalt cement binder or on the asphalt concrete mixture, and the actual performance of those materials in the pavement under traffic.

At the end of this discussion, the meeting was adjourned.

SUMMARY OF THE FACTORS THAT AFFECT THE LOW-TEMPERATURE CRACKING OF ASPHALT CONCRETE PAVEMENTS

Introduction

A wide variety of factors that seem to affect the degree of low-temperature cracking were discussed by the speakers and those in the audience at the Colloquium on Low-Temperature Asphalt Pavement Cracking. The primary factor mentioned was the properties of the asphalt cement used in the asphalt concrete mixture. The temperature susceptibility of the bitumen was the most significant characteristic of the asphalt cement that seemed to be directly related to the amount of low-temperature cracking that occurs on the roadway. The major problem, as brought out by the various participants, was how to

best measure the temperature susceptibility of the binder: at what temperatures, under what loading conditions, and using which test equipment and procedures.

The properties of the asphalt concrete mixture also contribute to the degree of low-temperature cracking. The type of aggregate used in the mix, the gradation of the aggregate, the air void content of the mix, and the stiffness of the asphalt concrete mix all play some role in the amount of cracking. The conditions at the paving site, such as the thickness of the asphalt concrete layer, the type of the subgrade soil, the type and thickness of the subbase and base course layers, and the amount of traffic using the highway are all factors that have some unquantified influence on the degree of cracking in a given section of pavement. Environmental variables must also be considered. Items such as air temperature, pavement temperature, rate of change of temperature, freezing index and amount of rainfall may all affect the amount of low-temperature cracking but to some unknown extent.

The major difficulty with the methods proposed for predicting the onset of low-temperature cracking is that they are all correlated with a very limited set of field observations. Theory is not universally related to practice. In addition the procedures attempt to determine the critical low temperature at which the cracking will occur and typically ignore the rate of cooling of the pavement layers and the effect that the cooling rate has on the development of stresses and strains in the mixture. The lack of realistic relationships between the predicted and the actual amount of cracking and the cracking temperatures has delayed the adoption of any of the prediction methods on a widespread basis.

Properties of the asphalt cement

There is considerable agreement that the single most important factor that affects the degree of low-temperature cracking in an asphalt concrete pavement is the temperature susceptibility or stiffness of the asphalt cement. There is a considerable amount of disagreement, however, about how to measure that temperature susceptibility—what characteristics of the bitumen should be used to determine the stiffness of that material.

Some of the properties of the asphalt cement that have been measured include the penetration of the original asphalt cement at a variety of temperatures (39.2, 41, 60 and 77°F) and the viscosity of the original binder at 60, 140 and 275°F, among other temperatures. The same properties of the asphalt cement have been determined using binder that was recovered from the asphalt concrete mix after production in the laboratory, after production in the asphalt plant, or from cores cut from the in-service roadway. The question as to whether the degree of cracking is better related to the properties

of the original asphalt cement or to the aged asphalt cement is not yet answered.

The Penetration Index has been used to determine the temperature susceptibility of an asphalt cement. This number, however, can be determined in a variety of ways. In some cases the penetration of the binder and the softening point temperature are used. In other cases the Penetration Index is calculated from the penetration at two or more temperatures. The Penetration–Viscosity Number has also been proposed as a means of judging the temperature susceptibility. This method determines the temperature susceptibility of the asphalt cement as a function of the penetration of the asphalt cement at one temperature and the viscosity of the same material at another temperature. It is known that the value of temperature susceptibility measured by one method does not agree with the value determined by another method. Indeed the ranking of a number of binder materials by any one of the PI procedures may be considerably different than a ranking of those same bitumens by another of the PI methods or by the PVN method. All of these methods calculate the properties of the binder at temperatures just above or well above freezing. None of these procedures measure the properties of the bitumen at temperatures that are comparable to the pavement cracking temperatures.

The stiffness of the asphalt cement must be determined in order to predict the cracking temperature. All of the methods being used are, in some way, related to the work of van der Poel and the development of his nomograph for determining binder stiffness. Some of the input variables for the nomograph have been modified, but the primary methods used to determine the stiffness of the asphalt cement are based on variations of the original nomograph.

Other properties of the asphalt cement have been investigated. The chemical characteristics of the binder, such as the asphaltene content and the amount of saturates and aromatic constituents, have been measured. The coefficient of expansion and the coefficient of contraction of the bitumen have been determined at different temperatures. The shear susceptibility and viscosity of the material have been measured at low temperatures using different versions of sliding-plate rheometers.

Attempts have been made to relate all of these properties and characteristics of the asphalt cement to the performance of the binder material in the asphalt concrete mixture on the roadway. In some instances the correlation between some particular bitumen property and the occurrence of low-temperature cracking was good for a given set of data from a selected test section. The correlation generally did not hold, however, when a relationship was sought between that binder property and the amount of low-temperature cracking on other

pavement test sections. The correlations developed seem to apply only to the limited data from which they were derived.

Properties of the asphalt concrete

Several investigators have used different aggregates in the asphalt concrete mixtures and determined what difference the aggregate type has made in the response of the mix to low temperatures. Some research showed that the aggregate made no difference in the predicted performance of the mix. In other research efforts, however, there was a difference in the critical cracking temperature that was a function of the type of aggregate used in the asphalt concrete mixture. Similarly the gradation of the aggregate used in the mix sometimes (but not usually) affected the low-temperature response of the mix.

The amount of asphalt cement used in the mix sometimes affects the degree of low-temperature cracking. Some research projects have produced results that indicate that a change in the asphalt cement content of a given mix can have a significant effect on the performance of the mix. Other investigations, however, have found that changes in asphalt content, at least within the ranges tested in the studies, had no effect on the amount of predicted or actual cracking.

The stiffness of the asphalt cement used in an asphalt concrete mix changes with age. The effect of aging on the stiffness of the binder material itself has been determined by conducting tests on the asphalt cement that has been artificially aged using a procedure such as the thin-film oven test. Stiffness testing of cores extracted from in-service pavements, however, has been limited. The test data gathered have in most instances been quite variable. This scattering of the test results was thought to be due to several factors, including the air void content of the mix, which controls, to some extent, the amount of aging of the binder.

The stiffness of the asphalt concrete mixture is thought to be related to the occurrence of low-temperature cracking. This stiffness can be estimated in two ways: indirectly or directly. For the indirect method the stiffness is determine by means of a nomograph or modified nomograph. The stiffness of the asphalt cement binder, as determined by the van der Poel nomograph, is one of the primary inputs used to calculate the stiffness of the mixture. The values determined are related to the air void content of the asphalt concrete mixture, either as a set value or as modified to reflect the actual air void content of the mix.

Several direct methods have been used to estimate the stiffness of the asphalt concrete mix. The indirect tensile test and the tensile creep test are two of the most popular test procedures. These methods have been used on a variety of mixtures at different test temperatures. It generally has been found that the stiffness values determined are directly related to the test temperature and that the differences in the stiffness of the various asphalt concrete mixtures decreases as the test temperature reaches some critical value. In addition the measured stiffness values and those predicted using the nomographs have not been well correlated. It was also found that the stiffness of the mix, either prepared in the laboratory or determined from cores cut from the roadway, was directly affected by the air void content of the mix (and therefore its strength).

The rate of cooling that was used in the laboratory test procedures has been varied. In most cases that rate was selected based on practical considerations such as testing time and equipment constraints. It is believed that the rate of cooling, through its effect on the contraction of the asphalt concrete mixture, should have an effect on the ultimate stress contained in the samples and thus the amount of strain that the mixture can withstand prior to failure. In the majority of the investigations, however, only one rate of cooling has been used to develop the stiffness data. For investigations where two or more rates of cooling were employed, the results of the testing were inconclusive concerning the effect of the cooling rate on stiffness.

The data from some of the field test sections showed that several pavements did not crack, even though the ambient temperature was below the predicted critical temperature for the particular asphalt cement and asphalt concrete mix used in the pavement structure. Further, some pavement test sections cracked at temperatures much above the predicted critical temperature. Most of the prediction methods do not consider the rate of temperature change when determining the critical stiffness value. These procedures generally take into account only the lowest temperature at which the pavement will be subjected, which is call the critical temperature.

The mode of testing of the asphalt concrete specimens has been a subject of much discussion. Some researchers have felt that a constant-rate-of-stress test is the best way to test the mixtures. In this procedure the stress is kept uniform and the strain that develops in the specimen is measured up to some maximum failure strain. Other individuals, however, believe that the stress induced in the asphalt concrete sample should be measured, particularly during the cooling of the mix. Failure occurs when the stress in the specimen exceeds the strength of the mix. Further, there is disagreement over what values should be used for the coefficient of thermal expansion and contraction for the mix and how those coefficients vary with the temperature used to determine the coefficients.

Pavement structural design

It is well known that some of the transverse cracking occurs in pavements that have no asphalt concrete material in the pavement structure. Further, some of the transverse cracking that occurs in the asphalt concrete mix continues through the untreated aggregate shoulder at the edge of the roadway. From the Ste. Anne Test Road and other research projects, it has been determined that the type of subgrade soil can play a significant role in the amount of low-temperature transverse cracking that occurs in the pavement layers. In addition the type of material used in both the aggregate subbase and the aggregate base course layers can affect the amount of cracking in the asphalt concrete mix. The gradation of those granular materials (particularly the amount of aggregate passing the no. 200 sieve) and the amount of moisture in the aggregates have been found to have some minor correlation with the amount of low-temperature cracking that occurred in the asphalt concrete surface course.

Another factor that may have a significant role in the degree of low-temperature cracking is the use of a prime coat on the untreated aggregate base course layer. In some instances the use of the prime coat seemed to reduce the amount of cracking that was found. In other cases the amount of prime coat did not seem to be related to the amount of cracking.

The thickness of the asphalt concrete layers has been found to affect the incidence of low-temperature cracking. In general it has been found that the thicker the asphalt concrete layers, the less cracking. The relationship, however, is not the same for every test section throughout North America. For some test sections the effect of the thickness was greater than for other research projects.

Environmental conditions

The most obvious factor that directly affects the amount of low-temperature cracking is the temperature at the roadway. The ambient air temperature is one part of this factor. The pavement temperature, both at the surface of the asphalt concrete mix as well as at some depth in the mix, is more significant than air temperature. Several research projects have developed correlations between the air temperature and the temperature of the mix at different depths in the asphalt concrete layer.

As mentioned above, some researchers believe that the rate of change of temperature is as important as, if not more important than, just the lowest temperature to which the pavement will be subjected. There is evidence that pavements sometimes crack in the fall or spring, when the pavement structure is subjected to large ranges of temperature or when sudden storms bring a great change in temperature in a short time. In addition, even in the winter the amount of temperature drop on a cold, clear day seems to cause some transverse cracking in some asphalt concrete mixtures, even though the critical temperature is not reached.

The freezing index, or the number of degree-days below freezing that a pavement structure experiences, has been reported to be correlated with the degree of low-temperature cracking in the asphalt concrete mixture. The amount of rainfall, as well as the amount of solar radiation, has been found to have some relationship with the occurrence of transverse cracking. In one study the location of the projects—inland or near large bodies of water—was directly related to the amount of cracking.

The number of variables

There are a great number of variables that can play a role in the degree of low-temperature cracking in an asphalt concrete mixture. In the laboratory some of those variables can be carefully monitored. On the roadway, however, the number of factors that are outside the direct control of the researcher is increased significantly. The difference between the results determined in the laboratory and the actual cracking that occurs on the roadway is thus to be expected.

Most of the correlations that have been developed are valid only for the test sections and for the data used to develop those correlations. In several research studies it was reported that there was excellent correlation between the method used to predict the onset of low-temperature cracking and the actual cracking that occurred. It is interesting to note, however, that the data used to develop the prediction procedure came from the same project; thus there should be an excellent correlation between the predicted and measured values.

When the degree of low-temperature cracking that is found on a wide variety of projects is analyzed, the number of variables is very great. The correlation coefficient determined for single or multiple regression analysis is usually not very high, even when many variables are entered into the equations. For one study it is often found that a particular factor has a significant relationship to the amount of low-temperature cracking, while another research investigation will find that the same factor plays no role at all in predicting the incidence of cracking. Even for the asphalt cement used in the asphalt concrete mixture, one particular binder property, such as penetration at 77°F, will be important in the cracking prediction equation for one research effort but will be of little or no significance in another laboratory or field investigation. In addition the inter-relationships between the various factors often masks the actual effect of any one factor on the occurrence of low-temperature transverse pavement cracking.

The number of variables that exist on an actual pav-

ing project may be so great as to preclude any attempt in the laboratory to accurately predict the amount of low-temperature cracking that will actually occur on the roadway. In addition it is recognized that any laboratory tests that are employed to predict low-temperature cracking should be carried out in the same temperature ranges that the cracking will likely occur. Further, the failure stresses and failure strains applied to samples of asphalt concrete should be similar in magnitude to the stresses and strains actually present in the pavement structure. The research studies that have been reviewed as part of this colloquium report and that are paraphrased below should be read in light of these facts.

LITERATURE REVIEW

There have been many technical papers and reports published since the mid-1960s on the subject of low-temperature cracking of asphalt concrete pavements. Much of that literature originates from research work carried out in Canada and in Europe. Most of the conclusions were drawn from laboratory research. These studies used a variety of test methods to try to determine the degree of low-temperature cracking that might be exhibited by different combinations of asphalt cement, aggregates and mix compaction methods. In most cases those conclusions were found to be valid only for the particular materials used in the investigations.

There have also been a number of "field" research projects where the asphalt concrete roadways were used to determine the amount of low-temperature cracking that would actually take place under real traffic and environmental conditions. Although the pavement surface provided the "answers" to the question concerning the degree to which the low-temperature cracking would take place under actual environmental conditions, the debate continues as to the interpretation of those answers and to their significance. It has been found that the number of uncontrolled variables in most of the projects makes definite, universal conclusions difficult to obtain.

The following literature review briefly summarizes the primary papers and reports that have been published in the last 23 years on the subject of low-temperature cracking of asphalt concrete pavements. The papers are listed in chronological order by the year they were presented. The contents of each study are condensed below, and direct quotations are used where applicable to emphasize the author's primary points. If the paper was subjected to comments by others, and if those comments offer some additional significant insights into the points being made by the author, the additional comments are also summarized.

1. **Monismith, C.L., G.A. Secor and K.E. Secor** (1965) Temperature-induced stresses and deformations in asphalt concrete. *Proceedings of the Association of Asphalt Paving Technologists*, **34**: 248–285.

This laboratory project investigated the development of thermal stresses and deformations in asphalt concrete mixtures. A single mix was used to manufacture specimens in the form of rectangular beams. The tests included creep tests in tension at a number of temperatures, constant-rate-of-strain tests in tension to failure at different temperatures, thermal stress tests (measurement of thermal stresses in the mix due to the restraint of deformation due to temperature changes) and creep tests at constant stress at different temperatures. The creep tests were run at 110, 75, 40, –5 and –40°F.

From the tensile creep compliance data for the range of temperature employed, it was determined that the asphalt concrete mix could be considered to be thermo-rheologically simple and that a master curve could be drawn to determine the performance of the specimens at temperatures other than those used in the testing. The results of the creep testing at different temperatures were used to calculate creep strain data. The measured strains were compared to the predicted (calculated) strains, and "good agreement between these and the measured values is indicated, particularly at longer times." It was further concluded that "it would appear that it is possible, with reasonable confidence, to predict either stresses or deformations resulting from temperature changes using creep data obtained from specimens of asphalt concrete together with viscoelastic theory."

The fracture strength of the asphalt concrete depended on the temperature of the specimens and the rate of loading. The authors cited data from a number of other writers that showed that the fracture strength of asphalt concrete varied within a narrow range at low temperatures: 500–1400 psi. From the data obtained from the constant-rate-of-strain and creep tension tests, it was found that "the fracture characteristics for this mixture are quite similar to those reported in the literature to date." It was concluded that "where the temperature was assumed to vary from 0°F to –40°F, high thermal stresses were computed to occur at the surface of the pavement, stresses of a magnitude far exceeding the breaking point of the particular asphalt concrete utilized."

In the discussion period a question was asked concerning an opinion by the authors of why some pavements don't crack at low temperatures. It was stated that temperature is probably only one of the factors involved in the phenomenon of low-temperature cracking of asphalt concrete mixtures on the roadway. It was also stated that "cracking of the pavement can occur not only because of temperature but also because of many mix and climatic variables."

2. Anderson, K.O., B.P. Shields and J.M. Dacyszyn (1966) Cracking of asphalt pavements due to thermal effects. *Proceedings of the Association of Asphalt Paving Technologists,* **35:** 247–262.

The problems of non-load-associated cracking of asphalt concrete pavements in the western part of Canada were addressed by this report. It was stated that "field experience and theoretical considerations suggest two possible mechanisms promoting transverse cracking. These are (a) contraction of the asphalt concrete and (b) shrinkage of the subgrade, both of which are associated with temperature differentials between the surface and the underlying subgrade."

The authors prepared a figure to illustrate the factors related to transverse crack development. One primary factor listed was the environment, with significant considerations being the rate of change of temperature, the amount of precipitation and the amount of solar insolation. Factors affecting the pavement structure were divided into three layers: surface, base and subbase, and subgrade. For the asphalt concrete surface course, the tensile strength of the mix, the thermal conditioning of the material, the coefficient of thermal expansion and contraction of the mix, the modulus of elasticity, and the modulus of deformation were all given as important considerations. The mix properties that affected these values were listed as density, voids, asphalt cement quality, asphalt content, aggregate grading and aggregate mineralogy.

For the untreated aggregate base and subbase materials, the following factors were listed as significant considerations: thermal conditioning of the material, coefficient of thermal expansion and contraction, amount of volume change, shear strength and surface texture. The gradation, density, water content and mineralogy of the aggregate were all given as controlling factors. The volume change characteristics, thermal conditioning and strength of the subgrade soil were the significant characteristics listed by the authors. The controlling factors were given as the plasticity, texture, density and degree of saturation of the subgrade materials.

A field survey was made of almost 1500 miles of pavement in Canada. "Field testing included mapping of the cracking pattern, coring of the areas in randomly selected locations and sampling of base and subgrade." It was found that "the higher crack frequencies observed appear associated with certain asphalt sources, though several exceptions will be noted." The asphalt cement was recovered from the cores taken from the different projects, and the penetration at two temperatures, the viscosity at three temperatures and two shear rates, and the penetration ratio were determined. Ductility tests, done initially, were discarded when early test results proved inconclusive. It was found that "while higher

cracking frequencies appear associated generally with lower penetration ratios, again several exceptions are noted. Temperature–viscosity relationships for various shear rates failed to provide a satisfactory differentiation between cracked and uncracked sections."

3. Schmidt, R.J. (1966) The relationship of the low-temperature properties of asphalt to the cracking of pavements. *Proceedings of the Association of Asphalt Paving Technologists,* **35:** 263–269.

Schmidt developed the theory that the shift factor for an asphalt cement is the ratio of the viscosity of the recovered reference asphalt cement at the chosen reference temperature to which all data are to be adjusted and the viscosity of the asphalt cement at which the temperature fatigue data were developed. He also stated that the shift factor can be found by substituting experimentally determined values for the glass transition temperature and the high-temperature viscosity of the recovered asphalt cement. Using the Williams–Landel–Ferry equation, experimentally determined values for the glass transition temperature of the asphalt cement and the viscosity of the asphalt cement at some selected temperature can be employed to calculate the viscosity of the asphalt cement at some other temperature. Thus, the low-temperature viscosity of the asphalt cement can be calculated from a measured high-temperature viscosity value for the binder and its glass transition temperature.

It was suggested that at low temperatures a viscosity calculated from the glass transition temperature of the asphalt cement is more appropriate than attempting to directly measure the viscosity of the asphalt cement at the low temperature. It was shown that low-temperature viscosities do not consistently correlate with the degree of cracking on the roadway. It was stated that "in most cases, the low-temperature viscosities for both the crack-resistant and the crack-prone asphalts are almost within the experimental repeatability (19.2%) of the low-temperature viscosity test methods." Using the glass transition temperature determined for the same asphalt cements, however, it was found that the behavior of the pavement was related to that value, with a large difference in the glass transition temperature (24°F) determined between the crack-resistant and the crack-prone pavements. Further, it was found that the resistance to low-temperature cracking increased as the asphalt content in the mix increased.

4. Hills, J.F. and D. Brien (1966) The fracture of bitumens and asphalt mixes by temperature induced stresses. *Proceedings of the Association of Asphalt Paving Technologists,* **35:** 292–309.

These authors discussed the relationship between

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stress and strain for asphalt cement with reference to van der Poel's nomograph. It was stated that the nomograph provides a stiffness modulus for the bitumen that is defined as the ratio of stress to strain for a given set of loading time and temperature conditions. The stiffness modulus calculated from the nomograph is "the ratio of the constant stress to the corresponding strain in a constant load tensile creep test. Included in this definition are elastic behavior where strain is independent of time as well as viscous behavior where strain is proportional to loading time."

The authors advocated the use of Penetration Index (PI), as proposed by Pfeiffer and van Doormal, to determine the effect of changes in the consistency of the asphalt cement with changes in temperature. They calculated the thermal stress developed in the asphalt cement for different rates of cooling and for different temperatures. They found that the initial temperature of the asphalt cement when cooling commenced was not important in the calculations as long as it was higher that –20°C.

The temperature at which an asphalt cement would be expected to crack can be determined from the tensile strength of the binder, which in turn depends on the stiffness modulus and the time of loading. It was shown that the fracture temperature of an asphalt cement is a function of its penetration and its temperature susceptibility. To determine the fracture temperature of the asphalt concrete mix made with a given binder material, the values for stiffness modulus, coefficient of thermal contraction, and tensile strength for the mix would need to be known. The stiffness modulus of the asphalt concrete mix is, in turn, a function of the binder stiffness and the volume concentration of the aggregate, as provided by Heukelom and Klomp.

It was found that the fracture temperature of an asphalt concrete mix was higher than the predicted failure temperature of the pure asphalt cement. The difference in the two values was determined to be a function of the Penetration Index of the binder material. For a bitumen with a Penetration Index of –2.0, the cracking temperature of the mix was approximately 3°C above the cracking temperature of the cement. For an asphalt cement with a Penetration Index of +0.5, the difference in the cracking temperatures increased to about 10°C. Thus, as the temperature susceptibility of the asphalt cement as measured by its Penetration Index value decreases, the temperature at which the asphalt concrete mix will crack will be farther above the cracking temperature of the asphalt cement itself. The authors, however, stated that "when considering the properties of mixes, it should be borne in mind that the relevant bitumen properties are those of the bitumen recovered from the mix, i.e., due allowance must be made for the changes that inevitably occur when the mix is made, and that are likely to take place in service."

The authors measured the fracture temperature of beams of asphalt cement and asphalt concrete that were cooled at a rate of 10°C per hour. The calculated fracture temperature was compared to the temperature at which microcracks appeared in the mix. It was found that the best agreement occurred when measured values of mix stiffness modulus, determined by constant-load creep tests, were used to calculate the thermal stress instead of values derived from the asphalt cement stiffness and the volume concentration of the aggregate. It was shown that there was a benefit in using an asphalt cement with a higher Penetration Index value (a lower value of temperature susceptibility).

Further testing indicated that changes in the binder content of the asphalt concrete mixtures had little, if any, effect on the fracture temperature. The comment was made that this result is as expected since an increase in binder content would increase the coefficient of thermal expansion for the mix but decrease the stiffness of the mix at the same time. It was pointed out that the thermal stress depends on the product of these two values. Thus, a small change in one of the variables might be offset by a small change in the other variable, resulting in no change in the thermal stress of the mix with the change in asphalt content.

In the discussion section of the paper, Hills and Brien commented on some of the differences between the conditions in the laboratory where asphalt concrete beams with a zero temperature gradient are tested and asphalt concrete mixtures placed on a roadway. They stated that for a mix used as part of a pavement structure, the stresses developed in the mix can be about $1^{1}/_{2}$ times as great as the stresses developed in the laboratory testing setup, depending on the Poisson's ratio used in the calculations. They concluded with the comment that "in view of this, and other environmental factors, it would seem inadvisable at this stage to interpret the laboratory results directly as representing the situation existing in practical road structures."

The appendix of this paper provides the equations used to calculate the thermal stresses of the asphalt concrete mix as a function of temperature and time. Also provided in the appendix is a copy of the chart used to determine the Penetration Index of an asphalt cement, as given by the equation of Pfeiffer and van Doormaal. This chart is based on the difference between the temperature of the bitumen at the ring-and-ball softening point and the temperature at which the penetration of the asphalt cement is determined, as well as the penetration of the asphalt cement. In addition, the Heukelom nomograph for predicting the stiffness modulus of the asphalt cement material is provided.

5. **Hindermann, W.L.** (1966) Discussion—Symposium on non-traffic load associated cracking of asphalt pavements. *Proceedings of the Association of Asphalt Paving Technologists,* **35:** 348–351.

Hindermann looked at transverse cracks, spaced about 50 ft apart, on a road in northern Minnesota that had been subjected to several weeks of below-zero weather. He commented that the roadway was on a sandy subgrade and was unsurfaced (it had no asphalt concrete wearing surface). He concluded that this was an indication that the properties of the subgrade soil and/or the granular base course material were important factors in the thermally induced contraction of pavement structures.

In further discussion he commented that "the cracks in surfacing materials (water macadam, asphalt penetration and asphaltic cement) only reflect the soil cracks. This is clearly evident because the cracks can easily be transversely traced many feet beyond the surfacing edge and further because unpaved and paved roadways crack in a very similar fashion."

6. **Heukelom, W.** (1966) Observations on the rheology and fracture of bitumens and asphalt mixes. *Proceedings of the Association of Asphalt Paving Technologists,* **35:** 358–399.

Heukelom used the concept of the stiffness modulus of an asphalt cement, as developed by van der Poel, defined as the ratio between stress and strain as a function of loading time and temperature, to study the rheology of asphalt cements. Because the elongation at break of an asphalt cement depends largely on temperature, two types of tests have been used to a) "determine the temperature at which a bitumen obtains a certain degree of brittleness (e.g., the Fraass breaking point), and b) determine the elongation at break at a fixed temperature (e.g. the ductility)."

The author commented on the development of the stiffness modulus nomograph developed by van de Poel and the measurement of the temperature susceptibility of an asphalt cement by Pfeiffer and van Doormaal's Penetration Index calculations. He presented a new nomograph based on the assumption that the penetration at the ring-and-ball softening point was equal to 800. This nomograph for the stiffness modulus of the asphalt binder depends on input values for the viscosity of the asphalt cement at a given loading time, the temperature difference between the ring-and-ball temperature and the temperature at which the penetration of the asphalt cement is determined, and the Penetration Index of the asphalt cement.

Heukelom stated that he had verified the accuracy of his nomograph by testing hundreds of asphalt cements in a variety of grades from a large number of crude sources. He also conducted a number of tests on the various asphalt cements to determine the relationship between the different test properties and the stiffness modulus of the binder materials. For the ductility of the asphalt cement, it was found that the elongation at break for bitumens with Penetration Index values from −1.0 to +0.5 was only a function of the stiffness modulus. The relationship was independent of the source and the grade of the asphalt cement, the test temperature and the speed of the ductility test.

Using data from bending tests conducted on different asphalt cements, it was shown that the elongation at break was approximately inversely proportional to the stiffness modulus value for the same binder materials. It was concluded that certain variables affect the performance of an asphalt cement only through their influence on the stiffness modulus of the binder: the source of the asphalt cement, the penetration grade of the binder, the temperature during the loading period and the rate of elongation used during the time of loading.

The author presented data showing the relationship of bending strength to the stiffness modulus of the asphalt cement. Information was also provided on the fatigue strength of some asphalt concrete mixes, as well as the fatigue strain for the same mixes. In addition, data were provided on the tensile strengths of two types of mixtures as a function of the stiffness modulus of the asphalt cement. Finally, compressive strength values were compared with the stiffness modulus values for the same binder materials.

It was concluded that the stiffness modulus of the asphalt cement binder material could be used to "condense" the effect of temperature and loading time into a single value for each asphalt cement source and grade. Further, it was stated that the fracture properties of the asphalt concrete mixtures could be "separated into the stiffness of the asphalt cement and a 'mix factor' which is independent of the above mentioned variables, but dependent on the proportion of asphalt cement, grading of the minerals and compaction of the mix."

7. **Monismith, C.L., R.L. Alexander and K.E. Secor** (1966) Rheologic behavior of asphalt concrete. *Proceedings of the Association of Asphalt Paving Technologists,* **35:** 400–450.

Information is provided in the paper on a number of models that have been developed to characterize the behavior of asphalt concrete materials. The stress–strain characteristics of asphalt concrete materials were determined using creep, relaxation, constant-rate-of-strain, dynamic and flexural stiffness tests, all as a function of time and temperature. It was determined that asphalt concrete could be assumed to be a linear vis-

coelastic material as long as the deformations to which it was subjected were less that 0.1%. In addition the asphalt concrete mix was found to be a thermorheologically simple material, and the principle of time–temperature superposition was found to be valid.

It was stated that a simple static creep test can be used to determine the time-dependent behavior, or stress vs strain characteristics, of a mixture. Definitions were provided for both the creep modulus and the creep compliance of a mix as a function of time. The creep test was able to be employed to estimate the stiffness of the asphalt concrete material over a range of temperatures.

The authors reviewed the work of van der Poel to determine mix stiffness as a ratio of axial stress to axial strain at a given time and temperature. They also discussed the work of Heukelom and Klomp to determine the stiffness of the mix as a function of the stiffness of the recovered asphalt cement. This relationship also relies on the volume concentration of the aggregate used in the mix and is for an asphalt concrete mix having an air void content of 3%.

Data were presented comparing the stiffness values determined by nomograph and values calculated in both bending creep tests and flexural specimens. It was found that there was some scatter in the data but that the Heukelom and Klomp procedure could be used to estimate the stiffness characteristics of well-compacted (3% air voids) asphalt concrete mixtures.

8. **Puzinauskas, V.P.** (1967) Evaluation of properties of asphalt cements with emphasis on consistencies at low temperatures. *Proceedings of the Association of Asphalt Paving Technologists,* **36:** 489–540.

This research effort had as its goals to "develop a test method suitable to measure significant test properties of asphalt cements at relatively low temperatures," and to "establish low-temperature test limits for Study Specifications based on the developed method." A total of 52 asphalt cements, produced from 16 crude oils or blends of crude oils using steam or vacuum distillations, solvent precipitation, mild air-blowing and blending processes, from 8 manufacturers were investigated.

A variety of low-temperature consistency tests were run on the various asphalt cements. These included: (a) viscosities at 60 and 39.2°F over the widest possible range of shear rates, using a cone-plate viscometer, (b) viscosities at 77 and 45°F over a range of shear rates using the sliding-plate microviscometer, (c) penetration tests at 77, 60, 45 and 39.2°F using a 100-g load for 5 s and at 39.2°F using a 200-g load for 60 s, (d) ductilities at 77, 60, 45 and 39.2°F using 0.25, 1.0 and 5.0 cm/min rate of pull, (e) viscosity at 60°F over a range of shear rates with a falling-plunger viscometer and (f) tensile tests at 60 and 39.2°F on ductility test specimens using 1.0, 5.0 and 25.0 cm/min rates of extension.

From the viscosity data at different temperatures for the various asphalt cements, it was found that viscosity decreases with increasing temperature at a gradually decreasing rate. Using a plot of the double logarithm of viscosity in centistokes against the logarithm of the absolute temperature in degrees, the temperature susceptibility of the asphalt cements was calculated, based on the viscosities at 140 and 275°F. The differences found in the slopes of the temperature–viscosity lines for the different binder materials were not great. For viscosities measured at temperatures lower than 140°F at a given rate of shear, the slopes of the temperature–viscosity lines varied from the lines calculated above 140°F. This was stated to be "due to the fact that at temperatures lower than 140°F shear dependent viscosities are encountered and that such viscosities do not necessarily correlate with viscosities measured at higher temperatures. It may therefore be suggested that only the temperature susceptibilities which are calculated between viscosities measured at higher temperatures will be meaningful."

The shear rate was shown to have an effect on the measured viscosity of an asphalt cement at low temperatures. "At relatively low shear rates, the viscosity value appears to have constant value and such limiting viscosity often is termed 'initial viscosity.' However, after exceeding a certain shear rate value and with further increase in shear rate, viscosities tend to gradually decrease. These shear dependent viscosities are often called 'apparent viscosities.' The rate of viscosity decreases with increasing shear rate (i.e., slope of the logarithm of apparent viscosity versus shear rate) is often used to represent 'shear susceptibility' of different asphalts." From the test data, it was determined that the apparent viscosities of the different asphalt cements varied with shear rate over a wide range. The slope of the viscosity–shear rate lines (the shear susceptibility of the binders) varied both with the rate of shear and with the materials themselves. It was concluded that the shear susceptibilities of the various asphalt cements would be different if calculated for different shear rates.

The relationships between viscosity and penetration, viscosity and ductility, and ductility and penetration were investigated. Poor correlation was found at all test temperatures between viscosity and either penetration or ductility. It was concluded that viscosity data would be more acceptable for characterizing the properties of an asphalt cement because the shear rate could be controlled during the viscosity test, while the shear rate was unknown for either the penetration or ductility tests. Further, it was found that the apparent viscosity of a particular asphalt cement could be correlated with the tensile strength of that material. It was concluded that

such viscosity measurements might indicate the tensile strength of asphalt concrete mixtures at in-service pavement temperatures.

Puzinauskas did not believe that viscosity alone could be used to characterize the performance of the asphalt cement in the pavement structure. He stated that "any attempt at present to predict pavement behavior from the apparent viscosity of an asphalt cement, measured at a single shear rate, is of questionable value. Laboratory and field trials on paving mixtures are therefore needed to provide additional information for the future development of low-temperature consistency tests and specification limits." In the case of this research work, low temperatures only extended down to 39.2°F.

In a prepared discussion of Puzinauskas' paper, J.Y. Welborn and J.A. Zenewitz commented on the need to group the various asphalt cements tested by their viscosity–temperature susceptibilities, based on viscosity data at 140 and 275°F. The viscosity–temperature susceptibility was defined as the slope of the log–log viscosity and the log temperature curve between 140 and 275°F. It was found that a straight line could be plotted between log viscosity at 140°F and log viscosity at 275°F for all asphalt cements that had the same measured viscosity–temperature susceptibility. The 52 asphalts tested could be divided into three viscosity–temperature susceptibility groups.

9. Littlefield, G. (1967) Thermal expansion and contraction characteristics, Utah asphaltic concretes. *Proceedings of the Association of Asphalt Paving Technologists,* **36**: 673–702.

To measure the thermal expansion and contraction of asphalt concrete mixtures, the author used different penetration-graded asphalt cements (60-70, 85-100 and 120-150) with a single aggregate to mold beam specimens that were subjected to heating and cooling over a temperature range of 0 to 130°F. The change of length with changes in temperature was measured.

It was found that the thermal coefficient of expansion of the various asphalt concrete mixtures depended on the source and grade of asphalt cement used in the specimens and varied with the temperature range. Further, the majority of the total expansion of the beams tested occurred in the temperature range between 0 and 60°F, and the amount of shrinkage during cooling was determined to exceed the degree of expansion during heating. The cycles of heating and cooling also caused the density of the beams to increase with increases in the number of temperature cycles. The amount of movement of the beams with changes in temperature was found to be between 1 and $1^3/_4$ inches per 100 ft of equivalent pavement length.

A written discussion of this paper was provided by J.E. Stephens, who stated that asphalt cement exists in three states depending on temperature: a solid at low temperatures, a viscous liquid at high temperatures and a transition state between the high and low temperatures. He discussed the expansion and contraction characteristics of the asphalt concrete mixtures in terms of the changes in state of the asphalt cement.

It was stated that there was no evidence that the temperature stresses caused the change in the density of the beam specimens. Stephens pointed out that the asphalt cement expands faster than the aggregate and that during the period of heating, the expanding asphalt binder material would push the aggregate apart. During the cooling or contraction period, the amount of force available to compact the mix would be limited to the tensile strength of the binder material. He commented further that "after expansion reduced density, it appears doubtful that the tension stresses alone would be able to densify the material beyond that of the original compaction."

10. Anderson, K.O. and W.P. Hahn (1968) Design and evaluation of asphalt concrete with respect to thermal cracking. *Proceedings of the Association of Asphalt Paving Technologists,* **37**: 1–31.

For this research work the authors used the tensile splitting test to determine the low-temperature properties of asphalt concrete mixtures. Asphalt cement from three sources was used to manufacture Marshall-size asphalt concrete specimens. In addition, cores were cut from newly constructed pavements built using the same three asphalt cements. Stress–strain curves were developed for both the laboratory and the field specimens. It was found that for similar mixtures, the failure strain appeared to be primarily a function of the asphalt cement supply. Tensile failure stress, however, appeared to be a function of the aggregate.

The results of the testing showed that the occurrence of cracking was found to increase as the failure strain decreased. Further, it was determined that the failure strain varied with the source of the asphalt cement when the same grade of binder material and aggregate was used to mold the specimens tested in the tensile splitting test. It was also found that mixtures that had high Marshall stability values at 140°F generally had low failure strains at 0°F.

11. Jones, G.M., M.I. Darter and G. Littlefield (1968) Thermal expansion–contraction of asphaltic concrete. *Proceedings of the Association of Asphalt Paving Technologists,* **37**: 56–100.

One aggregate and one asphalt cement, at varying asphalt contents, were used to manufacture asphalt concrete beam specimens for testing in expansion and contraction under two types of restraint conditions. Free movement conditions were obtained by placing the

specimen on a frictionless base (ball bearings on a glass plate). A friction base was provided using sandpaper as the underlying layer for the beams samples. In addition the thermal expansion–contraction characteristics of asphalt cements from five sources were determined.

For the testing of the asphalt cement samples, the amount of thermal contraction was measured over a temperature range of –70 to 50°F. Two rates of temperature change were used: 1 min/°F and 5 min/°F. It was found that the thermal coefficients were greater when tested at 1 min/°F compared to 5 min/°F. In addition it was determined that the coefficients were different for temperature ranges above and below the glass transition temperature of the asphalt cements.

For the asphalt concrete specimens, different asphalt contents were used for each of the two base conditions. It was found that the two thermal coefficients of expansion exist in the temperature range of –10 to 140°F. The change in the coefficient value occurred at a transition temperature that varied with asphalt content but was in the range of 70 to 86°F for the asphalt cement used in the investigation. This is well above the glass transition temperature of the asphalt cement (–27°F), but the difference between the transition temperature and the glass transition temperature (85°F) was "explained by the presence of mineral filler."

For the solid state of the asphalt cement (below the transition temperature), the type of base restraint made no difference on the thermal coefficient of expansion and contraction. For temperatures above the transition temperature, however, the type of base condition influenced the coefficient of thermal expansion–contraction. Significantly less expansion–contraction occurred for the friction base conditions than for the free-movement base conditions. Further, it was determined that an increase in the asphalt content of the asphalt concrete mixture greatly increased the degree of thermal expansion and contraction in the specimens.

The coefficient of expansion was found to differ from the coefficient of contraction, particularly at temperatures above the transition temperature and under the free-movement base conditions. At low temperatures the thermal coefficient of expansion was only 4% greater than the thermal coefficient of contraction. At high temperatures the coefficient of expansion was 5–43% greater than the coefficient of contraction, again for the free-movement base conditions.

Permanent length changes were measured for the beam specimens subjected to cycles of temperature when the temperatures were above the transition point. For free-movement conditions the beams increased in length. For friction base conditions the specimens decreased in length from the original length with increasing temperature cycles. At low temperatures, however, the base conditions do not exert a significant effect on the degree of permanent shrinkage that occurs in the asphalt concrete specimens.

12. **Crawford, R.A. and D.W. Anderson** (1968) Pavement cracking as related to asphalt hardness. South Dakota Department of Highways.

A total of 189 paving projects in South Dakota were surveyed in early 1968 to determine the amount of low-temperature cracking that had occurred. Four asphalt cements, four penetration grades (85–100, 100–120, 120–150 and 200–300) and one road oil (SC-6) had been used during the construction of the asphalt concrete pavement layers. The amount of transverse cracking on each project was estimated by visual examination of the pavement surface.

It was found that all of the asphalt materials performed well in the Black Hills portion of the state. It was thought that this was due to the milder climate in this area as well as the type of subgrade soil (sandy or gravely compared to clays or shales in the rest of the state), the type of aggregate (quarried limestone or crushed limestone gravel) and the use of asphalt from a single source.

For the remainder of the state it was found that the amount of cracking was directly related to the hardness of the asphalt binder material. The lower-penetration asphalt cements exhibited a crack spacing of 50 ft or less within three years of construction. Nearly two-thirds of the jobs incorporating the SC-6 liquid asphalt showed little or no cracking after ten years. Intermediate-hardness binders showed correspondingly intermediate levels of cracking. No information was obtained on the source of any of the asphalt cements, and no cores were cut to determine the existing properties of the asphalt cements.

13. **Haas, R.C.G. and K.O. Anderson** (1969) A design subsystem for the response of flexible pavements at low temperatures. *Proceedings of the Association of Asphalt Paving Technologists,* **38**: 179–223.

Three possible causes for low-temperature cracking of asphalt concrete pavements are provided by the authors: (a) an exceeding of the tensile strength or tolerable strain of the bituminous surface by thermally induced stresses and stains—without considering traffic loads or added to traffic-imposed stresses and strains, (b) freezing shrinkage and cracking of the subgrade and propagation through the bituminous surface, and (c) freezing shrinkage and cracking of the base or subbase and propagation through the bituminous surface.

Laboratory testing for this project consisted of looking at the thin-film tensile behavior of the binder materials. Stress–strain curves were determined for tension testing of thin asphalt films at test temperatures between –60 and 70°F. Six asphalt cements were tested. The

stiffness modulus of the binders was determined using the van der Poel method. The time–temperature superposition principle was used to develop a master curve of stiffness modulus at a given reference temperature for the data from the thin-film tension tests.

Additional testing was completed using the tensile splitting test procedure. Four temperature levels were used: 40, 30, 20 and 0°F. From the data obtained, a stiffness modulus of the binder material was calculated using the method of Huekelom and Klomp and a correction for the air void content of the mix by the method of van Draat and Sommer. Further calculations were to be carried out to determine the strain in the binder, the toughness of the binder (the area under the stress–strain curve), and the work to fracture (product of the load and loading movement, determined by timing).

From plots of stiffness vs temperature for various asphalt concrete mixtures, it was found that the effect of asphalt cement source was very important. For the same asphalt concrete mixture, different asphalt cements provided different stiffness modulus values for the mix. It was concluded that the asphalt source could markedly affect the fracture temperature of the mix. It was also concluded that a good relationship existed between the results of the thin-film tension testing done as part of this research and the stiffness of the asphalt concrete mix, with the latter calculated using the procedure of Heukelom and Klomp.

N.W. McLeod presented a prepared discussion to this paper. He stated that his research and field investigations over the years had showed that transverse pavement cracking was caused by low winter temperatures and that the simplest solution to the problem of low-temperature cracking was to use a softer grade of asphalt cement. He cited a number of research works that indicated that pavement cracking is associated with mixtures that have a high stiffness modulus at low temperatures. He commented that the cause of low-temperature cracking had been well known for over 30 years—pavements that incorporate a hard asphalt cement binder and therefore have a high stiffness modulus are more prone to transverse cracking than are asphalt concrete mixtures that use a softer binder material.

McLeod also pointed out that some of the low-temperature cracking, however, also results from cracking that occurs in the subgrade soil and untreated base course material in the pavement structure. He commented that asphalt concrete pavements built over sandy subgrade soils will tend to develop transverse pavement cracks regardless of the hardness or softness of the asphalt cement used in the mix.

In a comment made at the end of the Haas and Anderson paper, V.P. Puzinauskas stated: "Undoubtedly, stiffness of asphaltic mixture is probably the most important factor influencing the service behavior of pavement, including pavement cracking associated with low temperatures. However, many factors influence stiffness of paving mixtures. For example, variations in temperature, aggregate type and properties, asphalt and filler contents, are some of such factors. I believe that most (possibly all) of these factors influence the stiffness of paving mixture by far more than the viscosity or penetration of asphalt cement."

14. **Culley, R.W.** (1969) Relationships between hardening of asphalt cements and transverse cracking of pavements in Saskatchewan. *Proceedings of the Association of Asphalt Paving Technologists,* **38**: 629–659.

Culley commented that in the Province of Saskatchewan there are two types of non-load-associated transverse cracks: those associated with shrinkage of the subgrade soil and those related to the expansion and contraction characteristics of the asphalt concrete mix. In this province the soil shrinkage cracks have been found to be wider and typically spaced at intervals of 200–500 ft. Transverse cracks caused by the performance of the mix are narrower and have a much shorter spacing of 20–50 ft.

A study of transverse cracking was done in 1963 to determine the relationship between the source of the asphalt cement (refinery), the penetration grade of the binder, and the amount of the base course prime coat on the frequency of transverse cracking. One of the major findings of that investigation was that "there was a significant relationship between frequency of cracks and the supplying refinery." As a result of this research work the specifications for the asphalt cement were modified to reduce the allowable variation in viscosity and penetration from the various refineries.

In 1966 another investigation was carried out to see what effect the new asphalt cement specifications had on the development of low-temperature cracking. The asphalt binder used on five projects was sampled at the asphalt storage tank, the plant line prior to entering the pugmill, the haul truck at the plant, the paver hopper, the roadway behind the paver but before compaction, and the pavement 12 months after construction.

The test results on the samples taken at different locations and times were analyzed to determine the effect of handling on the penetration, viscosity, temperature susceptibility and shear susceptibility of the different binders. A comparison was also made between the results of the thin-film oven test to the amount of hardening actually occurring in the batch plant pugmill. Finally a comparison was made between the amount of transverse cracking that occurred on the roadway with the amount of hardening that took place in the asphalt cement.

A number of variables were investigated in regard to their effect on the amount of transverse cracking. Those variables included the average daily traffic, the freezing index degree-days, the air void content of the mix, the retained percentage of the original asphalt cement penetration, the retained percentage of the original asphalt cement viscosity, the temperature susceptibility of the binder and the shear susceptibility of the binder. It was determined that none of the variables completely matched the number of transverse cracks that occurred during the first year of service. It was also found, however, that there were more transverse cracks on one project with an asphalt cement from one particular source than on the other projects with different binder materials. There was little difference in the performance of the other pavements with the other sources of asphalt cement.

After one year of data collection on the amount of transverse cracking that occurred on the various projects, it was concluded "that performance of an asphalt pavement, and specifically transverse cracking, is a complex phenomenon which is probably more affected by the degree of compaction and by environmental conditions than by changes in a single variable such as penetration or viscosity during handling or mixing. For example, the two asphalts from Refinery 1 had similar values for penetration and viscosity changes over 12 months but a vast difference in transverse cracking and correspondingly large differences in freezing index and air voids; asphalts from Refineries 3 and 5 had large differences in cracking, freezing indices and viscosity gains but similar air voids and penetration loss; and asphalts from Refineries 1 and 4 had differences in freezing indices and viscosity gains but similarities in air voids, penetration losses, and transverse cracking. It is, therefore, evident that transverse cracking is not a simple event and equally evident that more research into the interrelationships between asphalt properties and pavement performance is needed."

15. **Lefebvre, J.A.** (1970) A modified penetration index for Canadian asphalts. *Proceedings of the Association of Asphalt Paving Technologists,* **39**: 443–480.

Lefebvre presented a review of the development of the concept of Penetration Index (PI) by Pfeiffer and van Doormaal in 1936. This index, which is calculated from the penetration at 77°F and the temperature of the ring-and-ball softening point, is used to characterize the temperature susceptibility of asphalt cements. He commented that van der Poel developed his nomograph to determine the stiffness modulus of asphalt cements by using the Penetration Index value as a measure of the shear and temperature susceptibility of the binder material.

The purpose of the present study was to determine if the Penetration Index method could be used to characterize the rheological properties of Canadian asphalts. Thirty samples of asphalt cement from 12 crude sources were tested. The penetration of 25 of the binders was between 39 and 346, and the other five binders had penetrations above 400. The softening point, penetration and viscosity of each of the asphalt cements were measured.

It was pointed out that Pfeiffer and van Doormaal assumed that the logarithm of the penetration is a linear function of temperature and that the slope of the log penetration–temperature line could be applied as a measure of the temperature susceptibility of the binder material. Further, it was assumed that the penetration at the softening point of the asphalt cement was equal to 800. A nomograph to find the Penetration Index if the softening point and the penetration of the asphalt cement at 77°F had been determined was prepared using the work of Pfeiffer and van Doormaal.

For the asphalts used in this research, however, it was found that the plots of log penetration vs temperature were not always straight lines. It was concluded that "the assumption of a linear relationship between log penetration and temperature made by Pfeiffer and van Doormaal is valid for certain types of asphalts but cannot be applied to all asphalts irrespective of source, grade or method of manufacture. It is obvious that it is certainly not applicable to all Canadian asphalts." Another conclusion was that at the temperature of the softening point for the various asphalt cements, the penetration of those materials was not always 800. The penetration found at the softening point for the asphalts tested varied from 545 to 2125.

The author also commented that Pfeiffer and van Doormaal assumed that the viscosity of the asphalt cements that they tested was equal to 12,000 poise at the temperature of the softening point. It was found by Lefebvre that large differences existed between the observed viscosities at the softening point temperatures and the assumed value of 12,000 poise.

The Penetration Index of the various asphalt cements was calculated based on four methods: the observed softening point and penetration at 77°F, the penetration at 77°F and the temperature for 800 penetration, the penetration at 77°F and penetration at the softening point, and the penetration at 77°F and the temperature for 12,000 poise viscosity. It was found that the calculated Penetration Index varied widely depending on the method and values used to determine the number. Further, it was also found that the Penetration Index varied markedly in some cases for asphalt cements of different grades from the same crude source.

The author next determined the Penetration Index of

the various materials based on a relationship developed by McLeod using penetration at 77°F and viscosity at 140°F to estimate the temperature susceptibility of the binders. Relationships were also calculated for the penetration at 77°F and viscosity at 275°F and for viscosity at 140°F and viscosity at 275°F. From the data reviewed, it was determined that the modified Penetration Index (now called the pen-vis number or PVN), based on penetration at 77°F and viscosity at 140°F, was a better indication of the temperature susceptibility of the asphalt cements studied than the Penetration Index of Pfeiffer and van Doormaal.

A discussion of the paper by O. Kopvillem indicated that "van der Poel in his original paper in 1954 pointed out quite clearly that the PI determination via softening point and penetration is not valid for waxy asphalts especially for soft waxy asphalts in which the softening point is mainly governed by the melting point of the waxes."

A very long written discussion was provided by N.W. McLeod. He commented on the construction in 1960 of three paving projects in southern Ontario. These three projects, located about 40 miles apart, were each built with three different 85–100 penetration-graded asphalt cements incorporated into the asphalt concrete mixes. On each job a two-mile-long section of each of the three binder materials, each provided by a different supplier, was placed. For each of the asphalt cements, data were obtained at the time of construction on the penetration of the material at three temperatures (77, 39.2 and 32°F), penetration ratio, ring-and-ball softening point, ductility, viscosity at both 210 and 275°F (but not at 140°F), and the penetration and ductility on the residue from the thin-film oven test. In addition, for all three asphalts, both the Pfeiffer and van Doormaal Penetration Index values and the McLeod Penetration–Viscosity Numbers (PVN) were calculated.

McLeod reported that surveys were conducted on the type and amount of transverse cracking that had developed in each of the three asphalt cements in each of the three test roads at various times. Four types of transverse cracks were identified. Cores were extracted from the pavements in 1969 to determine the properties of the various binders. From the core data it was determined that there were no significant differences in the characteristics of the mixes themselves—asphalt content, aggregate gradation or air void content. Thus, the differences in the performance of the three pavement sections on each test road were related to the properties of the asphalt cements used in the mixtures.

From the crack survey, it was found that the number of cracks that extended all the way across the width of the pavement decreased with a decrease in the value of

Penetration Index for the binder materials. McLeod commented that this was contrary to the expected relationship between the degree of cracking and the Penetration Index numbers. From the field cracking data he concluded "that Pfeiffer and van Doormaal PI values do not always provide a realistic measure of asphalt temperature susceptibility."

It was suggested that the actual cracking that occurred on the three test roads could be better explained by the use of the Penetration–Viscosity Number for the original asphalt cements. After analysis of the data, McLeod related the increase in the number of transverse cracks with time to the decrease in the penetration of the binder materials, with the increase in hardening causing the tensile strength of the asphalt mix to be exceeded by the tensile stress induced in the mix when the pavement contracted during chilling to low temperatures.

16. **Burgess, R.A., O. Kopvillem and F.D. Young** (1971) Ste. Anne Test Road—Relationships between predicted fracture temperatures and low temperature field performance. *Proceedings of the Association of Asphalt Paving Technologists,* **40:** 148–193.

The Ste. Anne Test Road was constructed in Manitoba in 1967 to determine the low-temperature cracking potential of asphalt concrete pavements. Early conclusions from the performance of the various test sections constructed indicated that: a) "the most important variable with respect to initial low-temperature transverse cracking is the grade and type of asphalt binder used in the mix, b) the properties of the asphalt binder are also important with respect to frequency of transverse cracking but pavement structure factors are also important, c) initial cracking appears to be initiated mainly at the pavement surface at a time when the surface temperature was close to the minimum on a given day, and d) some test sections cracked and some showed no cracking at all."

Three asphalt cements (a 150–200 penetration-grade low-viscosity material, a 300–400 penetration-grade low-viscosity binder, and a 150–200 penetration-grade high-viscosity asphalt cement) were incorporated into the asphalt concrete mixes used on the test road. The stiffness modulus of each of the asphalt concrete mixtures was determined using the constant-load tensile creep test. Both the elastic component and the viscous component of the mix stiffness were calculated. The stiffness modulus itself was calculated from the combination of the elastic and viscous components as a function of loading time and temperature. Determination was also made of the breaking stress and the strain at break for the various mixtures, as well as the thermal contraction coefficient. From this information a cracking temperature for each mix was found. Curves were

drawn to determine the temperature at which the breaking stress of the mix was equal to the thermally induced stress. This point was called the predicted cracking temperature for the mix for a given cooling rate.

The predicted fracture temperatures were obtained using the stiffness modulus procedure for the asphalt cement based on the use of van der Poel's nomograph. An average coefficient of thermal expansion for the different binder materials was assumed. The tensile strength of the binders was determined using the relationship developed by Heukelom between binder stiffness and binder tensile strength. "A close relationship was found between the laboratory predicted fracture temperatures of the simulated Ste. Anne mixes and those obtained by nomographic procedures used in connection with the laboratory and field aged binders."

It was found that although mix variables other than asphalt type and grade may have an effect on the amount of low-temperature cracking in a mix, "the most significant variable seems to be the asphalt type and grade." It was also determined that "the critical pavement temperature for initial low-temperature cracking is the pavement surface temperature." Further, "the stiffness modulus at low temperature and long loading time of the Ste. Anne field-aged binders was proportional to the cracking frequencies of pavement composed of mixes containing these aged binders."

In a prepared discussion to this paper, Lefebvre commented that the authors had "attempted to predict the temperatures at which pavement cracking will occur from the properties of the binder or from the properties of paving mixtures prepared in the laboratory from the same aggregate and binders using the calculation procedure of Hills and Brien. In every case their predicted fracture temperature was lower than that at which cracking actually occurred in the field." Commenting further, Lefebvre stated, "It appears that the calculated thermal stresses in the laboratory mixes are lower than those resulting from thermal contraction in the field and/or the calculated tensile strength of the laboratory mix is higher than that of the Ste. Anne Test Road pavements."

Lefebvre presented a comparison of the stiffness values used by different individuals to predict low-temperature fracture of asphalt concrete mixes. He listed the values for maximum stiffness, loading time and his calculated equivalent mix binder stiffness value at a loading time of 0.5 hours. Burgess, Kopvillem and Young used a maximum stiffness value of the asphalt cement binder of 2500 kg/cm^2 at a loading time of 0.5 hours. Thus, for these authors the equivalent maximum binder stiffness at the 0.5-hour loading time is the same as that used in their research: 2500 kg/cm^2. W.A. Phang of the Ontario Ministry of Transportation had proposed

a maximum stiffness of the asphalt cement binder of 20,000 psi at a loading time of 2.8 hours. This was equated by Lefebvre to an equivalent maximum binder stiffness of 2500 kg/cm^2 at a loading time of 0.5 hours, the same as for Burgess et al.

McLeod suggested a maximum stiffness of the asphalt concrete mix, not just the asphalt binder, of 1,000,000 psi at a loading time of 6 hours. This value was equated by Lefebvre to a maximum stiffness modulus of 1,000 kg/cm^2 at the 0.5-hour loading time. McLeod also recommended using a limiting stiffness value of 500,000 psi at a loading time of 6 hours when the pavement environmental conditions include service temperatures of –40°F. This maximum stiffness limit can be converted to a limiting stiffness modulus of 400 kg/cm^2 at a loading time of 0.5 hours.

Another prepared discussion of this paper was presented by R.C.G. Haas and J. Hajek. They brought out that a number of possible errors can exist in determining the exact temperature at which a pavement will crack. They suggested that pavements really crack over a range of temperatures instead of at one precise temperature. The comment was also made that there is some error involved in calculating exact stiffness modulus values from the van der Poel and Heukelom nomographs due to the scales used. Further, tensile creep test results are subject to variation. They recommended that a range of temperature values to predict the onset of low-temperature cracking would be better than an "exact" predicted value.

Haas and Hajek listed a number of variables that they believed played a role in the amount of low-temperature cracking in an asphalt concrete pavement. They commented that the frequency of cracking at the Ste. Anne Test Road was much greater when the pavement layers were constructed on the sand subgrade material compared to the layers built on the clay subgrade soil. A model had been developed that listed the following possible contributing factors to the cracking problem, in addition to the stiffness of the asphalt cement binder: the type of subgrade soil, the thickness of the asphalt concrete layers, the expected minimum temperature of the pavement layers, the initial stiffness of the asphalt cement binder and the age of the asphalt concrete layers. They commented that a model that included all these variables had "a high multiple correlation coefficient and a standard error of estimate which is considered to be quite reasonable."

In their conclusion to the discussions to their paper, Burgess, Kopvillem and Young commented that the type of subgrade soil on the Ste. Anne Test Road did not affect the degree of cracking in the pavement structure if the asphalt cement binder was not susceptible to cracking. They stated that "only in the case of cracking-

susceptible binders does the effect of subgrade become evident."

The authors also presented some data that showed the change in the stiffness moduli of the three asphalt cements used in the test road from the original stiffness to the laboratory-aged stiffness to the field-aged stiffness. For the original 150–200 penetration-graded low-viscosity asphalt cement, the stiffness modulus of the original asphalt cement was calculated to be 15,300 kg/cm^2 with a penetration of 192. This same material, laboratory aged, had a stiffness value of 10,000 and a penetration of 93. The field-aged asphalt cement showed a stiffness value of 10,000 and a penetration of 91.

For the 300–400 penetration low-viscosity asphalt cement, the original stiffness modulus was determined to be 10,000 kg/cm^2 with a penetration of 313. The laboratory-aged material had a stiffness modulus of 3,100 and a penetration of 153, while the field-aged binder showed a penetration of 167 together with a stiffness modulus of 5,000 kg/cm^2. The numbers for the original 150–200 penetration high-viscosity asphalt cement were a stiffness modulus of 2,700 and a penetration of 159 for the original binder, a stiffness modulus of 3,600 and a penetration of 82 for the laboratory-aged sample, and a stiffness modulus of 2,800 kg/cm^2 and a penetration of 71 for the field-aged asphalt cement. From this information, and that of other individuals, the authors concluded that the critical stiffness value for an asphalt cement binder to prevent low-temperature cracking would be 1,000 kg/cm^2.

17. **Busby, E.O. and L.F. Rader** (1972) Flexural stiffness properties of asphalt concrete at low temperatures. *Proceedings of the Association of Asphalt Paving Technologists,* **41**: 163–187.

The authors undertook a laboratory study to determine the stiffness modulus of asphalt concrete mixtures using the flexural stiffness of asphalt concrete beams manufactured using a California kneading compactor. Three penetration-graded asphalt cements were tested: 40–50, 85–100 and 200–300 penetration grades. The flexural stiffness test was conducted at three test temperatures (–35, –5 and 25°F) to determine how the stiffness modulus and the modulus of rupture varied with asphalt consistency and temperature.

It was found that at higher temperatures with softer asphalt cements, the failure in flexure comes through the asphalt itself. At lower temperatures and with harder binders, however, failure is partly in the asphalt cement and partly in the aggregate. The modulus of rupture at low temperatures was determined to be a function of the tensile strength of the mixture. The hardest asphalt cement, the 40–50 penetration-graded material, had the lowest modulus of rupture. "This would indicate that in addition to greater stiffness, the harder asphalts tested in this investigation also have a lower tensile strength. Both these indices would decrease the resistance to cracking."

From the analysis of the test data, the authors developed a relationship between stiffness, temperature and asphalt penetration. A direct relation was found between temperature and stiffness. For stiffness and penetration the best fit was determined using log penetration vs log stiffness. As the penetration is reduced, the flexural stiffness increases at a faster-than-linear rate. For the three asphalt cements tested in this work, the authors predicted the temperature at which cracking would occur. They also came to the conclusion that for a flexural stiffness test, the limiting value of flexural stiffness to prevent low-temperature cracking would be 300,000 psi.

Comments on the presentation were made by R.C.G. Haas, who questioned the testing methods used in the flexural stiffness test. He stated that the large amount of fracture through the aggregate itself did not agree with most field experience; such aggregate fracture does not occur to that extent in the field. Haas also commented on the linear relationship that was determined by the authors between stiffness and temperature. He stated that many other investigators had found that this relationship was highly nonlinear.

18. **Fromm, H.J. and W.A. Phang** (1972) A study of transverse cracking of bituminous pavements. *Proceedings of the Association of Asphalt Paving Technologists,* **41**: 383–423.

A field study was conducted during the summers of 1966 and 1967 to identify the causes of transverse cracking of asphalt concrete pavements in Ontario. Crack counts were made and samples taken of all pavement layers and the subgrade soil. A laboratory analysis was made to determine the properties of the paving materials. For this work a total of 33 paving projects were investigated.

The type and amount of cracking that had occurred on the various projects were quite varied. Four categories were used to differentiate the types of cracks found: multiple transverse, full transverse, half transverse and part transverse. As a measure of the severity of the cracking, the Crack Index value was developed. This index was determined by adding the number of multiple and full transverse cracks with half of the number of half transverse cracks occurring in a 500-ft stretch of two-lane pavement.

The Cracking Index was used as the independent variable in a regression analysis of the factors that contribute to the low-temperature cracking frequency and severity. Test results indicating the consistency of

the asphalt cement binder materials were reduced to a single input value: the penetration of the recovered asphalt cement at 77°F. Further, the temperature susceptibility of the binder was represented by a ratio of the viscosity of the recovered asphalt cement at 60°F to the viscosity of the asphalt cement at 275°F.

The stepwise regression analysis included some 40 variables in the first run of the program. Additional runs resulted in the dropping of many variables that had low correlation coefficients. The final list of variables used in the analysis included: viscosity ratio, freezing index (degree-days), critical pavement temperature, air void content, stripping rating, penetration of the recovered asphalt cement at 77°F, percent asphaltenes, amount of material passing the no. 200 sieve in the granular base course material, and amount of material passing the no. 200 sieve in the asphalt concrete aggregate.

For the general model, including all of Ontario, the multiple correlation coefficient R (not R^2) was 0.636. For a model for the northern part of the province, the value for R was found to be 0.622, and for the southern portion of the province, R increased somewhat to 0.704. The authors discussed at length the effect of the different factors on the correlation coefficients and the importance of the various factors on predicting the Cracking Index for the different pavement sections.

The authors investigated the use of the van der Poel and Heukelom nomographs to predict the stiffness of the asphalt binders and the asphalt concrete mixtures used in the various paving projects. They concluded, however, that there was very little correlation between the stiffness values determined from the graphs and the Cracking Index developed from the field data. It was recommended, however, that "to decrease the cracking of bituminous pavements, mixes of lower stiffness modulus should be used. This can best be achieved by the use of an asphalt of lower stiffness modulus, either a soft asphalt (300–400 pen grade) or an asphalt of improved lower temperature sensitivity, asphalts with a PI of say zero or higher. No doubt, mixture stiffness can be reduced by proper selection of aggregates, but unfortunately the road builder is usually limited to locally available materials and has little choice in this matter. Neither can the builder do anything with the subgrade; if it is a fine sandy material, an asphalt mix of very low stiffness modulus should be used over the subgrade. The stiffness can most easily be controlled by proper selection of the asphalt cement and this appears to be the best way of reducing transverse cracking."

19. **McLeod, N.W.** (1972) A four-year survey of low-temperature transverse pavement cracking on three Ontario test roads. *Proceedings of the Association of Asphalt Paving Technologists,* **41**: 424–493.

McLeod reported on the amount of low-temperature cracking that had occurred on the three Ontario test roads in the eighth through the eleventh years of service under traffic. Transverse crack surveys were carried out, and the type and number of cracks were determined. Cores were cut from the pavement layers to determine the mix and binder properties.

The temperature susceptibility of the recovered asphalt cements was determined using the Pfeiffer and van Doormaal Penetration Index method. It was found that the number of transverse cracks decreased with a decrease in the Penetration Index, which the author stated is contrary to what would be expected. He concluded that the Penetration Index "values do not always provide a realistic measure of asphalt temperature susceptibility." Thus, McLeod stated that he had developed a different method for determining the temperature susceptibility of asphalt cements, based on the penetration of the asphalt cement at 77°F and the viscosity of the material at 275°F. He termed this ratio the "pen-vis number" and provided a detailed explanation of the means to calculate this number in the appendix of the paper.

From the data from the three test roads, McLeod concluded that the relationship between the amount of transverse cracking that occurred was very well correlated with temperature susceptibilities of those binders if that temperature susceptibility was expressed in terms of the Penetration–Viscosity Numbers instead of the Penetration Index. He commented that the number of transverse cracks increased very markedly with a decrease in the pen-vis number of the asphalt cement. He also stated that the pen-vis numbers showed either little change or a decrease after nine years of service.

McLeod presented a chart that indicated that low-temperature cracking could be eliminated by the "correct" choice of the asphalt cement to be used in the asphalt concrete mixture. He showed that the choice of a particular penetration grade of asphalt cement depended on the pen-vis number for the material. The higher the pen-vis number of the binder, the lower could be the penetration of the material without causing low-temperature cracking. The selection of the proper asphalt cement was based on the viscosity of the asphalt cement at 275°F, the penetration at 77°F and the lowest temperature expected to occur at a pavement depth of 2 in.

20. **Christison, J.T., D.W. Murray and K.O. Anderson** (1972) Stress prediction and low temperature fracture susceptibility of asphalt concrete pavements. *Proceedings of the Association of Asphalt Paving Technologists,* **41**: 494–523.

This research work was concerned with the prediction of thermal stress in asphalt concrete mixtures

placed on two test projects in Western Canada—one constructed in Alberta in 1966 using three sources of 200–300 penetration-graded asphalt cement and the second constructed in Manitoba (Ste. Anne Test Road) in 1967 incorporating four asphalt binders (three asphalt cements and a slow-cure liquid asphalt) with three pavement structures, two asphalt contents and two aggregate gradations. The binders and asphalt concrete mixtures were used from these two projects to determine the stiffness modulus of the materials and to predict the degree of low-temperature cracking that would occur.

Thermal stresses in the asphalt concrete pavements were calculated using five procedures: pseudoelastic beam, approximate pseudoelastic slab, viscoelastic beam, viscoelastic slab and approximate viscoelastic slab. A comparison was made between the predicted and the observed degree of low-temperature cracking on the two projects. Of the five methods investigated, the best correlation was found with the pseudoelastic beam procedure. For this procedure the stress is a function of the stiffness of the material (which depends on the temperature and the time of loading) and the coefficient of thermal expansion. In this work it was assumed that the coefficient of expansion was independent of temperature, as was Poisson's ratio.

The authors pointed out that the method described in the paper must be regarded as largely empirical. It was concluded, however, that the results obtained using the pseudoelastic beam analysis are accurate enough to be usable in predicting the amount of low-temperature cracking that will occur. This method suffers from the fact "that the predicted stresses are dependent on the arbitrarily specified loading time (for this study 7,200 seconds) and that stresses, once accumulated, remain in the pavement indefinitely. The viscoelastic methods eliminate these deficiencies but require more computational effort. The predicted cracking conditions are, of course, also directly dependent on the fracture criterion employed."

21. **Hignell, E.T., J.J. Hajek and R.C.G. Haas** (1972) Modification of temperature susceptibilities of asphalt paving mixtures. *Proceedings of the Association of Asphalt Paving Technologists,* **41:** 524–561.

The purpose of this research work was to determine the properties of different asphalt concrete mixtures over a range of temperatures from –20 to 140°F. Several mixes were tested, standard asphalt concrete as well as mixes with different percentages and types of asbestos fibers and mineral fillers. Two asphalt cements, one of high viscosity and one of low viscosity, were used in the mixes. Tests were conducted to determine the stiffness at failure, the strain at failure and the tensile strength.

Failure was defined as the point at which the maximum or peak tensile stress occurred. A constant-rate-of-extension test method, developed at the University of Waterloo, was conducted at –20, 0 and 70°F. Stress–strain curves and stiffness–time curves were plotted from the data obtained. Stiffness in this research work was similar to that defined by van der Poel.

As a result of the laboratory work, it was found that asbestos fibers could be used to modify the temperature susceptibility of the asphalt concrete mixtures at the higher mix temperatures. At low temperatures (–20°F), however, "the properties of all types of mixtures are primarily a function of the asphalt type used." It was also determined that the properties of the asphalt concrete mixes tested corresponded well with the data reported from the Arkona Test Road and the Ste. Anne Test Road. "These comparisons support the concept of limiting stiffness guidelines for the problem of low-temperature cracking."

22. **Subcommittee on Low-Temperature Behavior, Roads and Transportation Association of Canada** (1972) Low-temperature pavement cracking in Canada. *Proceedings of the Third International Conference on the Structural Design of Asphalt Pavements,* p. 581–589.

A committee report was developed to investigate the amount and cause of low-temperature cracking of asphalt concrete pavements. From a survey of the condition of pavement in the different provinces and the results of the performance of the asphalt concrete mixtures at various test roads (Alberta, Saskatchewan, Manitoba and Ontario), it was concluded that "the major cause of the cracking is thermal contraction of the bituminous layer, which is restrained by the underlying layers. However, cracking can also initiate in the subgrade." It was stated that "the major variable involved is the nature of the asphalt used."

Several methods of reducing the occurrence of low-temperature cracking were discussed. The first was to write the specifications for the asphalt concrete to exclude certain asphalts. The second was to set a limiting stiffness or strain value on the asphalt cement binder or on the asphalt concrete mixture. The next procedure was to estimate the probable fracture temperature for the mix and compare the value to the lowest temperature expected for the site of the pavement structure. The last method was to estimate the cracking frequency of the asphalt concrete mixture at different ages.

23. **Haas, R.C.G.** (1973) A method for designing asphalt pavements to minimize low-temperature shrinkage cracking. The Asphalt Insititute, Research Report 73-1.

This report summarized the state-of-the-art methods for predicting and preventing low-temperature cracking of asphalt concrete pavements. It discussed several approaches that could be used to reduce the occurrence of the cracks. The first was the use of specifications for the asphalt cement used in the mix—the selection of a grade of bitumen based on penetration and viscosity—that, based on past experience, produced mixtures that did not crack at low temperatures. The second method was the use of some limiting stiffness value for the asphalt cement—the use of a binder material that would not have a stiffness value that would exceed a certain limiting value. The third procedure was concerned with prediction of the critical cracking temperature for the asphalt concrete mixture—comparing the thermal stresses in the mix with the tensile strength of the mix. The last method was based on estimating the frequency of the low-temperature cracking and directly measuring the properties of the asphalt concrete mixture.

The author presented a mathematical model to estimate the frequency of the cracking. The input values for the model were the stiffness of the original asphalt cement, the winter design temperature, the age of the pavement, the thickness of the asphalt concrete layer and the type of subgrade soil. The dependent variable used in the model was the Cracking Index, as developed by the Ontario Ministry of Transportation and Communications. A nomograph was developed to use these inputs to predict the frequency of low-temperature cracking.

The report also described the equipment and procedure for determining the properties of the asphalt concrete mixture by direct testing, as developed by the University of Waterloo. An asphalt concrete specimen was subjected to a tensile load, at controlled temperature (30, 0 and −30°F), under a constant rate of extension. The amount of extension of the asphalt concrete mix specimen was measured under a given tensile load, for a given amount of time at a specified temperature. The stiffness of the mix was calculated as the ratio of stress to unit strain. The principle of time–temperature superposition was used to construct a master curve of stiffness modulus vs time. This value could then be used to predict the amount of cracking that might occur in the asphalt concrete mixture.

The first appendix to this report discussed indirect methods that can be used to estimate the stiffness modulus of the asphalt cement and asphalt concrete mix. A description of three indirect methods of determining the stiffness values was presented: the original van der Poel nomograph, the Heukelom method using the Bitumen Test Data Chart to correct the softening point for waxy and air-blown asphalt cements, and the McLeod procedure based on the Penetration–Viscosity value (PVN) of the asphalt cement. It was pointed out "that very appreciable differences can occur in estimating asphalt cement stiffness by indirect methods."

The author discussed a number of limitations of the indirect methods for estimating the stiffness modulus. He stated that "it is not readily apparent which method is most applicable to use in any particular case." Further, "in using the nomograph, considerable care must be taken for precision, due to the scale involved. A dull pencil can lead to appreciable errors." He also commented that "there is no estimate of error possible in determining stiffness by indirect methods, as compared to the use of direct methods."

A second appendix discussed the main test methods used to determine the stiffness of an asphalt concrete mixture by direct testing. Two primary systems were discussed. The first was the splitting tensile test (now called the indirect tension test). It was pointed out that "the mode of loading and pattern of failure do not directly simulate the actual mode of fracture that occurs in the field." The second system was the constant-rate-of-extension uniaxial tension test (creep test). The author felt that this test method "more closely simulates the actual stress state and fracture mode that occurs in the field." Descriptions of the equipment needed to run the creep test and the method of specimen preparation and testing were given.

24. **Fabb, T.R.J.** (1974) The influence of mix composition, binder properties and cooling rate on asphalt cracking at low temperatures. *Proceedings of the Association of Asphalt Paving Technologists,* **43:** 285–331.

Fabb discussed two approaches to the problem of thermal cracking of asphalt mixtures. Those two approaches were termed the indirect and direct methods.

He divided the indirect methods into two categories. The first was titled computed stresses vs computed strengths. For this method the stress was computed on the basis of pseudoelastic, approximate pseudoelastic, viscoelastic or approximate viscoelastic behavior. The stiffness of the binder was estimated at an arbitrary loading time through the use of van der Poel's nomograph, and the asphalt concrete–temperature stiffness relationship was found using Heukelom and Klomp's nomograph with the input values being the binder stiffness and the volume concentration of the aggregate. The relationship for mix stiffness was then used, together with a measured or assumed coefficient of thermal expansion for the asphalt to develop a stress–temperature relationship. The research efforts of Heukelom and Klomp were used to determine the tensile strength of the mix, and the fracture temperature was calculated where the stress in the mix exceeded the strength of that mix as the mixture cooled.

The second indirect method for determining the fracture temperature of an asphalt concrete was that of computed stresses vs determined strengths. The stresses for this method were as described in the method above, but the tensile strength of the asphalt concrete mixtures was found by use of the tensile splitting test (indirect tension test) at various temperatures.

The direct methods involved direct measurements of the stresses induced in the asphalt concrete mixture as the mix cooled. This work concerned one direct method based on the cooling of a beam of mix at a constant rate while maintaining the beam at a constant length. The stress induced in the sample was measured by strain gauges.

From the data obtained, no stress was found to develop above a temperature of 10°C. At this temperature, stress began to develop in the mix and continued to increase rapidly until a temperature of –20°C was reached. At this temperature the rate of stress increase was reduced, but the level of stress continued to increase down to a fracture temperature of –33.5°C. The author explained this phenomenon by commenting that at high temperatures, the asphalt cement is relatively soft and the binder is able to flow sufficiently to prevent stress from developing. As the temperature falls, however, the binder becomes progressively stiffer and can only partially relax the stress built up in it. At some temperature the binder behavior is essentially elastic, and the stress causes failure of the material if that stress is great enough.

Testing showed that the temperature at which the maximum stress was first reached was much more repeatable than the fracture temperature itself. For this work, then, the temperature at which the maximum stress occurred was taken as the point of failure of the mix. The failure temperatures for different binder materials were determined to all be between –25 and –40°C. Those failure temperatures were closely related to the rheological characteristics of the binder materials. Further, it was found that the stiffnesses of the asphalt cements were essentially the same, regardless of the loading time used to determine the stiffness values. It was also determined that the asphalt cements that had the greatest stiffnesses were related to the highest asphalt concrete cracking temperatures. Further, the benefits of using an asphalt cement with a lesser degree of temperature susceptibility were shown.

Two asphalt concrete mixes were tested. The first was a dense-graded mix and the second was a gap-graded material. Even with the extreme difference between the two mix designs, it was concluded that mix design had little, if any, influence on the tendency for the asphalt concrete mixtures to crack at low temperatures. In addition the effect of cooling rate on the failure temperature was also found to be insignificant. Further, it was determined that there was little effect of asphalt content on the measured fracture temperature, even with a significant change in the asphalt content of the mixes. It was thus suggested that the properties of the asphalt cement itself are the major factor in the degree of low-temperature cracking that occurs in the mix.

From this research it was concluded that "the thermal failure temperature for a given asphalt is heavily influenced by the properties of the bitumen used and can be related to the low-temperature stiffness of the bitumen calculated from its fundamental rheological properties. Low Newtonian viscosity, low-temperature susceptibility and high shear susceptibility of bitumen are all factors conducive to reducing asphalt failure temperature."

25. Shahin, M.Y. and B.F. McCullough (1974) Damage model for predicting temperature cracking in flexible pavements. *Transportation Research Record,* **521**: 30–46.

A model for predicting the development of low-temperature cracking was presented in this report. The model was based on the assumption that such cracking occurred when the tensile stress in the asphalt concrete mixture exceeded the tensile strength of that material. It was found that "temperature cycling simulates a constant strain rather than a constant stress-fatigue distress." It was further determined that the aging of the asphalt cement binder was an important factor and that the stiffness of the asphalt concrete mixes increased with time.

The model determined the average daily air temperature and solar radiation and calculated the temperature of the pavement layers at different depths on an hourly basis. The stiffness of the mix was then estimated for decreasing temperature levels from the maximum to the minimum temperature. The increments of stress and strain were accumulated to estimate the maximum value of each that occurred in the pavement layers. The maximum strength corresponding to the maximum stress was then determined. Two types of cracking were then predicted: low temperature and thermal fatigue. It was found that "the major cause of temperature cracking is low temperature or thermal fatigue, depending on the asphalt mixture properties and the surrounding environmental conditions."

The model was "verified" by comparing the predicted cracking to the actual cracking that occurred on both the Ontario test roads discussed by McLeod and the Ste. Anne Test Road. For the Ontario comparison it was found that the "agreement between the measured and predicted cracking seems to be encouraging." For the Ste. Anne data, the comparison between the measured and the predicted cracking "is reasonable."

26. Schmidt, R.J. (1975) Use of ASTM tests to predict low-temperature stiffness of asphalt mixes. *Transportation Research Record,* **544:** 35–45.

The asphalt cements used in this laboratory investigation were residues from the rolling thin-film oven test instead of original binder materials. Tests were also made on three residues recovered from creep test specimens. The limiting stiffness values of all the asphalt cements were estimated using the Heukelom Bitumen Test Data Chart. In addition a new nomograph derived from the Heukelom chart was developed. The new nomograph permitted the penetration at 39.2°F to be used as an input value. The calculated values were then entered into the van der Poel nomograph to determine the temperature at which the asphalt cement stiffness at 10,000 s was equal to 20,000 psi.

A single aggregate was used together with 10 asphalt cements made from a variety of crude oils and processing methods. Two grades of most of the binders were included in the testing program. The stiffness of the mixtures was determined using the split tension (indirect tension) creep test. A static load was applied to the side of the Marshall-sized specimen, and the deformation with time at a particular temperature was recorded. Deformations at various temperatures are measured, and the time–temperature superposition principle was used to plot a master stiffness vs time curve for each binder material. The stiffness for each material at a time of 10,000 s was then found from the stiffness–time curve. An 18°F difference was found in the estimated cracking temperature for the various asphalt cements for the limiting stiffness value of 1,500,000 psi (at 10,000 s).

Van der Poel's nomograph was also used to estimate the stiffness of the various mixtures. The Heukelom Bitumen Test Data Chart requires as one of the inputs the penetration of the asphalt cement at 39.2°F for a loading of 100 g for a time of 5 s. ASTM test procedures for penetration measurements at 39.2°F require the use of a load of 200 g and a testing time of 60 s. The author developed a correlation between the two penetration procedures. The modified Heukelom chart was then used to determine the Penetration Index of the various asphalt cements used in the test program.

A comparison was made between the cracking temperatures predicted from the tensile creep tests and the temperatures predicted using the penetration of the binders at 77 and 39.2°F. "The correlation is good, but the relationship is shifted about 10 degrees. There are no large outliers. A difference of 10 to 15 degrees between the measured and the calculated limiting stiffness temperature is an inherent limitation of estimating the stiffness of a mix from the stiffness of an asphalt. It is only expected to be accurate to within 2 or 3 degrees of

the actual stiffness of the mix. For this comparison, the same aggregate was used in all cases so that a consistent bias (or mix factor) exists in all samples."

Poor correlation was found between the limiting stiffness temperatures when the softening point or the viscosity was used instead of the two penetration numbers (at 77 and 39.2°F). In addition, when the limiting stiffness temperature was estimated from the viscosities of the binders at 140 and 275°F, no correlation was found with the temperatures calculated from the tensile creep tests. Further, ductility measurements indicated that there was no relationship between that binder property and the limiting stiffness temperature, "possibly because the ductility test cannot distinguish between the shear sensitivity and the viscosity or stiffness of asphalts." It was concluded that the indirect tension creep test could be used to determine the low-temperature stiffness of the various asphalt concrete mixtures. It was also stated that the modified asphalt test data chart (after Heukelom) could be used to predict the stiffness of the asphalt cement using the penetration of the binder material at two temperatures.

27. Finn, F.N., K. Hair and J. Hilliard (1976) Minimizing cracking of asphalt concrete pavements. *Proceedings of the Association of Asphalt Paving Technologists,* **45:** 492–529.

This paper deals with many types of cracks that occur in asphalt concrete pavements. Among the types of cracks discussed are longitudinal, transverse, polygon or alligator, block, slippage, shrinkage and reflection. Causes of cracking of all types were associated with structural design, asphalt properties, asphalt concrete mix design, construction procedures, aggregate properties, asphalt and aggregate durability, subgrade support, condition of underlying pavement, temperature, drainage and traffic.

From the information contained in prior literature, the authors provided four approaches to the design of asphalt concrete mixtures to avoid low-temperature cracking. The first involves the specifications for the binder material itself. It is suggested that penetration at 77°F and viscosity at either 140 or 275°F be employed. The second method concerns stiffness values for the asphalt cement binder and the asphalt concrete mixture. These values must be related, however, to some limiting stiffness criteria. The next method encompasses the temperature at which fracture will occur. This temperature is compared to the lowest expected temperature at the paving site. The last method is related to cracking frequency predictions, which are based on empirical correlations for particular projects and are compared with the amount of cracking that can be tolerated on other projects. It was pointed out that the factor most

within the control of the pavement designer is the grade of asphalt cement used in the mix.

28. Clark, M.F. and R.W. Culley (1976) Evaluation of air-blown asphalts to reduce thermal cracking of asphalt pavements. *Proceedings of the Association of Asphalt Paving Technologists,* **45:** 530–551.

In 1973, test sections were constructed in Saskatchewan to determine the benefit of employing an air-blown asphalt cement to reduce the temperature susceptibility and therefore the amount of low-temperature cracking of an asphalt concrete mixture. Three asphalt cements were used in the mix: a standard AC-5 with a viscosity of 471 poise and a penetration of 207, an air-blown asphalt cement having a viscosity of 3379 poise and a penetration of 88, and a second air-blown asphalt cement with a viscosity of 1362 poise and a penetration of 139.

For the three asphalt cements, penetration was measured at both 77 and 39.2°F. The viscosity of the binders was determined at 60, 100, 140 and 275°F. The ductility was found at both 39.2 and 77°F. The softening point temperature was determined. Finally the stiffness of the binders was calculated using two methods. The first was the nomograph procedure of van der Poel. The second was through the use of the sliding-plate rheometer. The former values were calculated at a reference temperature of –40°F. The rheometer stiffness values were determined at 32°F. There was a considerable difference in the two stiffness values found by the two methods.

The performance of the pavement sections was reviewed after two years. It was found that the majority of the change in the viscosity and penetration values for all of the asphalt cements occurred during the manufacture of the mix in the batch plant pugmill. Aging was occurring, however, and the penetrations and viscosities continued to change somewhat with time. Pavement cracking, as of the date of the paper, was minimal in all mixes, even though the ambient temperature reached a low of –40°F at the project site. It was determined, however, that the "temperature susceptibilities of the air-blown asphalts are improving with age whereas that for the AC-5 is deteriorating rapidly."

Both rut depth and surface wear were regarded as being essentially the same for all three test sections and were insignificant. No significant thermal cracking had occurred to date in any of the pavements, even though the standard AC-5 asphalt cement had a very high stiffness value and was expected to have cracked. Thus, after two years the benefits of using the air-blown asphalt cements had not been demonstrated.

29. Bonnaure, F., G. Gest, A. Gravois and P. Uge (1977) A new method of predicting the stiffness of

asphalt paving mixtures. *Proceedings of the Association of Asphalt Paving Technologists,* **46:** 64–104.

The stiffness of asphalt concrete mixtures was measured using a two-point bending apparatus and trapezoidal-shaped specimens. Twelve mixes were tested, including nine laboratory-prepared materials and three mixes that had been under traffic for several years. The asphalt concrete mixtures were all different from one another in both aggregate composition and binder type and content. Tests were conducted at temperatures of –15, 9 and 30°C and at three sinusoidal load frequencies. The stiffness of the mix was calculated from the magnitude of the applied load and the displacement of the end of the specimen.

The results of the testing program showed that mix stiffness is a function of temperature, time of loading, hardness and temperature susceptibility of the asphalt cement, and volume percentages of aggregates, asphalt cement and air voids in the mix. These results were used to develop two nomographs that could be used to predict the stiffness of any asphalt concrete mixture.

The stiffness of the binder, one of the input values for the nomograph, was determined using the van der Poel nomograph. Other input values included the volume occupied by the asphalt cement and the volume of the aggregate. With these values the stiffness modulus for the asphalt concrete mix was found from the nomograph.

30. Ensley, E.K. (1977) The influence of intermolecular interactions on viscosities at low temperatures: Forced-sphere and forced-cylinder viscometers. ASTM Special Technical Publication 628, p. 43–56.

The author commented that at low temperatures, asphalt cement behaves essentially as a solid. At high temperatures the binder acts as a Newtonian material, with stress proportional to strain. At intermediate temperatures the asphalt cement is viscoelastic, being neither solid nor fluid. The glass transition temperature is normally taken as the point at which the binder material changes from a solid to a viscoelastic state.

For this research work a specially built viscometer was used to find small differences in viscosities between different asphalt cements. The viscometers used the principle of measuring the velocity of an object moving through a viscous medium. Two objects were used to move through the material: a sphere and a cylinder. The forced-sphere method was employed to measure viscosity in the temperature range of 0 to 25°C. The forced-cylinder procedure was used to determine the viscosity of the asphalt cement at temperatures from 0°C down to the glass transition temperature. The data were determined at low rates of shear, with the asphalt material acting as a Newtonian or viscoelastic liquid.

Five asphalt cements were tested. The viscosities

were determined at temperatures between 25 and –6°C. It was found that the viscosities increased with decreasing shear rates for both the forced-sphere and the forced-cylinder procedures. In general, however, higher viscosity values were found for the force-cylinder method than for the forced-sphere method. Comparisons of the viscosity data were made with the results of the sliding-plate viscometer conducted on the same asphalt cements. Reasonable agreement was found. Better agreement was found with the forced-sphere than with the forced-cylinder method. It was concluded that the two methods "offer a means of determining viscosities of asphalt between 25°C and the glass transition temperature." Low shear rates, however, were necessary to obtain valid results.

31. **Gaw, W.J.** (1977) Measurement and prediction of asphalt stiffnesses and their use in developing specifications to control low-temperature pavement transverse cracking. ASTM Special Technical Publication 628, p. 57–67.

Gaw discussed methods for predicting the stiffness of asphalt cements. He commented that the most practical way to predict the stiffness values is to use the van der Poel nomograph. It was pointed out, however, that the nomograph had been "published with the restriction that it should be used only with asphalts containing less than 2 percent wax." Heukelom modified this nomographic procedure to permit the stiffness of both non-waxy and waxy asphalt cements to be determined. According to this author the accuracy of the stiffness prediction for waxy asphalts was still subject to errors, however.

At the Ste. Anne Test Road, a sliding-plate rheometer was employed to measure the stiffnesses of asphalt cements in the temperature range of 10 to –20°C. A comparison of the stiffness values determined from the van der Poel nomograph with the stiffness values predicted from the sliding-plate rheometer showed that good agreement was found for the nonwaxy high-viscosity asphalt cement, but the agreement was poor for the low-viscosity waxy binder materials. For waxy asphalts with high asphalt stiffness values, however, it was determined that "predicted asphalt stiffnesses from van der Poel's nomograph are acceptable indicators of pavement cracking trends."

A new nomograph for predicting the cracking temperature for an asphalt cement was illustrated. The procedure was developed from the data gathered at the Ste. Anne Test Road. The method is based on the penetration of the binder material at both 25 and 5°C. If both of those values are known, the predicted cracking temperature of the asphalt concrete pavement layer could be determined directly from the nomograph. It was shown that

there was good agreement between the cracking temperature calculated from the nomograph and the cracking temperatures observed at the Ste. Anne site.

Two air-blown waxy asphalt cements and one normal nonwaxy asphalt cement were used to construct a test road in Ontario. No cracking had occurred in any of the test sections after two years of service, even though the ambient air temperature had reached a low of –38°C. The nomograph was used to predict the cracking temperatures of the three asphalts. Based on either the penetrations of the original asphalt cements or the penetrations of the recovered asphalt cements, low-temperature cracking was predicted at temperatures lower than those that had occurred to date at the project site. It was also determined that the air-blowing of waxy asphalts did improve their low-temperature crack resistance.

32. **Ruth, B.E.** (1977) Prediction of low-temperature creep and thermal strain in asphalt concrete pavements. ASTM Special Technical Publication 628, p. 68–83.

Two asphalt cements were used with two aggregates to produce four asphalt concrete mixtures. Creep tests were conducted using incremental increases in applied load. It was shown that the creep rate was stress dependent. An equation was developed to predict the creep modulus values. The predicted tensile creep strains, at temperatures of 10 to 50°F, were compared to the actual strains measured during the creep test.

It was found that the "tensile creep strain rate was dependent on both the viscosity of the asphalt cement and the stress ratio. Creep rate did not appear to be influenced by asphalt content, aggregate type, or aggregate gradation."

A computer program was developed to predict thermal stress and the net contraction strains in the asphalt concrete mixtures. The results of the testing showed that some of the mixes developed considerably lower stresses than other mixtures. For equal thermal stress development, there was a 20°F difference in temperatures for two different mixes. "It is believed that this temperature difference is the same as the difference between the glass transition temperatures of the two asphalts." The pavement contraction stress–strain model was based on the creep prediction model and the viscosity–temperature relationship of the asphalt cement and its static stiffness modulus.

33. **Schweyer, H.E. and A.M. Burns** (1978) Low-temperature rheology of asphalt cements. III. Generalized stiffness–temperature relations of different asphalts. *Proceedings of the Association of Asphalt Paving Technologists,* **47:** 1–18.

This research was directed at determining the variations in stiffness of asphalt cements at low temperatures

using a constant-stress shear-mode tube flow apparatus. In addition a method was proposed to "generalize the deformation characteristics of a material as a function of time, temperature, shear susceptibility, viscosity, and shear modulus."

Stiffness was defined as stress divided by strain, but strain was separated into three components: elastic strain, delayed elastic strain and viscous strain. It was shown that stiffness as a function of time can be delineated into two asymptotic values: the shear modulus and the viscosity modulus. From the various asphalt cements tested in a constant-stress rheometer, it was found that "although some asphalts tested were essentially Newtonian in a small temperature range, no asphalt tested was Newtonian over a wide range of temperatures. Also, although no hard correlation could be made between the shear susceptibility and the temperature, the data seem to indicate a general trend of increasing non-Newtonian character with a decrease in temperature." It was also found that temperature change affects the viscosity, and thus stiffness, much more than it does shear modulus.

The authors concluded that the constant-stress rheometer could be used to determine the stiffness of asphalt cements at low temperatures. It was also determined that asphalt cements that have the same high-temperature viscosities and properties may exhibit considerably different rheological properties at low temperatures.

34. **Kandhal, P.S.** (1978) Low temperature shrinkage cracking of pavements in Pennsylvania. *Proceedings of the Association of Asphalt Paving Technologists,* **47:** 73–114.

In 1976, six pavement test sections, using asphalt cements from five sources, were constructed in the state. Except for the binders used, the asphalt concrete mixtures were similar. After one year of service, two of the test sections (which used the same asphalt cement, a propane deasphaltized material) had developed excess low-temperature cracking.

A wide number of tests were performed on the different binder materials. Penetration tests were conducted at temperatures of 39.2, 60 and 77°F. Ductility was measured at the same three temperatures. Viscosity was determined at both 140 and 275°F. The ring-and-ball softening point was also measured. The temperature susceptibility of the binders was determined on the basis of Penetration Index, calculated both on the basis of the penetration at 77°F and the ring-and-ball softening point temperature and on the ratio of the penetration values at three values, according to a method of Heukelom. The pen-vis number, using the method of McLeod, was also determined.

The stiffness modulus values for all the asphalt cements were determined by three indirect methods. The first was the Pfeiffer and van Doormaal method. The second was the Heukelom method, which uses a corrected value (a pen-pen relationship) for the calculation of the Penetration Index. Once this value was determined, however, the van der Poel nomograph was used to determine the stiffness of the binder material. The third procedure was based on McLeod's method, where the stiffness is a function of the pen-vis number of the asphalt cement.

The stiffness modulus of the asphalt concrete mixture was determined using the stiffness modulus of the asphalt cement and the volume concentration of the aggregate according to the procedure of Heukelom and Klomp. Three mix stiffness modulus values were calculated, which were related to the methods used to find the stiffness modulus values of the asphalt cement.

The test results showed that the temperature susceptibility of the asphalt cements depended on the method used to calculate the value. Generally the Penetration Index numbers based on Heukelom's pen-pen relationship were substantially lower than the Penetration Index value of using the penetration at 77°F and the softening point temperature (Pfeiffer and van Doormaal). The pen-vis numbers were found to be roughly equal to the original Penetration Index numbers. The Penetration Index values increased substantially with the age of the pavement, while the pen-vis numbers stayed constant with time.

It was also found that the stiffness modulus values of the original asphalt cements determined by the Heukelom procedure were significantly higher than the stiffness modulus values calculated by the other two methods. The difference between the van der Poel stiffness number and the McLeod stiffness number was relatively small. All of the methods, however, showed that the asphalt cements that cracked in the field had the highest values of stiffness modulus, regardless of the method used to calculate the stiffness values.

In regard to the stiffness of the asphalt concrete mixtures, which was directly based on the method used to calculate the stiffness modulus of the asphalt cement binder, all three methods used "agree on the decreasing order of the aged mix stiffness moduli determined at −10°F and 20,000 seconds loading time." It was also concluded that the limiting stiffness value proposed by McLeod of 1,000,000 psi for a loading time of 20,000 s was confirmed for these test sections.

In the discussion that followed the paper presentation, several individuals raised the point that the asphalt cements that cracked first were prepared using a propane deasphalting process. It was suggested that this type of material had different characteristics and properties

from other asphalt cements used in the test sections. It was further suggested that the propane-extracted binders were not comparable to asphalt cements made using steam or vacuum distillation.

In a prepared discussion of Kandhal's paper, W.J. Gaw commented that he had made a comparison of the limiting stiffness calculated from the data from the Ste. Anne Test Road and the asphalt cement stiffness at the expected minimum pavement temperature and a 0.5-hour loading time. The Penetration Index values used were based on the Heukelom pen-pen procedure. Gaw found that, using van der Poel's nomograph, the asphalt cement in the two sections that exhibited low-temperature cracking had exceed the calculated limiting stiffness value. The asphalt binders in the sections that had not cracked had stiffness values that were still above the limiting stiffness numbers. His conclusion was that the nomographic procedures used to predict pavement cracking temperatures are realistic.

Gaw commented further that a new nomograph had been published that allowed the predicted pavement cracking temperature to be determined directly from the penetration of the asphalt cement at a temperature of 5°C and the penetration of the asphalt cement at 25°C. It was suggested that the new nomograph could be used to characterize an asphalt cement in the same way that the penetration at 25°C and the Penetration Index had been used in van der Poel's nomograph.

In another prepared discussion W.D. Robertson stated that the temperature susceptibility of a binder material determined by the Penetration Index method and the pen-vis (McLeod) method will not be numerically equal. He stated that although there is a trend for the pen-vis number to increase as the Penetration Index number increases, this is not always the case and the correlation between the two values is only fair. He also commented that the potentially large difference between the Penetration Index and the Penetration–Viscosity Number of an asphalt cement means that the stiffness values estimated by van der Poel's nomograph using the pen-vis number instead of the Penetration Index number could be significantly in error.

35. **Gaw, W.J.** (1978) The measurement and prediction of asphalt stiffness at low and intermediate pavement service temperatures. *Proceedings of the Association of Asphalt Paving Technologists,* **47:** 457–494.

This paper concerned the use of a modified sliding-plate rheometer to determine the stiffness of asphalt cements at low temperatures. The asphalt specimen was formed between two aluminum plates and could vary in thickness from 2 to 10 mm. "The applied shear stresses are sufficiently low such that for most practical purposes, the asphalts behave as linear viscoelastic materials, and hence the measured stiffnesses are independent of the magnitude of the applied stresses."

Four asphalt cements were used in a test program to determine the stiffness of the binder materials. These materials were significantly different from one another: a low-wax-content 150–200 penetration material, a high-wax-content 150–200 penetration asphalt cement, an air-blown waxy asphalt with a penetration of 104, and a propane-extracted asphalt cement with a penetration of 33. The stiffness values were measured over a time interval of 1 s to 2 hr. Stiffness values were determined over a temperature range of 20 to –43°C. It was found that the asphalt cements behaved as highly non-Newtonian liquids at low temperatures (–40°C) as well as at moderate temperatures (10°C). In addition, both the viscosity and the stiffness values were dependent on loading time and shear rate.

Gaw calculated the stiffness of the asphalt cements tested based on both Penetration Index and pen-vis number. The Penetration Index value was determined using the method of Pfeiffer and van Doormaal except that the ring-and-ball softening point temperature was not used. The PI value was found using the Heukelom's pen-pen method because Gaw believed that the original method for determining the Penetration Index (based on the assumption that the penetration of the asphalt cement was equal to 800 at the ring-and-ball softening point temperature) is not accurate for waxy asphalts. The stiffness was also calculated using McLeod's PVN value to represent the temperature susceptibility of the binders. Both of these input values were used to find the estimated asphalt cement stiffness numbers from van der Poel's nomograph.

A comparison was made between the stiffness values measured using the sliding-plate rheometer and the values calculated from the van der Poel nomograph. Good agreement was found when the stiffness was determined using the Penetration Index values for the different binders. Poor agreement between the measured and calculated stiffness numbers were found when the PVN value was used to enter the van der Poel nomograph. It was concluded that the sliding-plate rheometer could be used to accurately measure the stiffness of asphalt cement at low temperatures.

36. **Noureldin, M.S. and P.G. Manke** (1978) A study of transverse cracking in flexible highway pavements in Oklahoma. *Transportation Research Record,* **695:** 28–33.

The purpose of this research effort was to determine the nature and extent of transverse cracking on nine pavements in Oklahoma. Maps were made of the degree of cracking on each of the sections, and cores were taken. From the cores it was found that the majority of

the cracks on the surface of the pavement did not extend through the asphalt concrete layers.

The tensile properties of the asphalt concrete mixtures were determined using the indirect tensile test conducted at 32, 23 and 14°F. "Some preliminary tensile splitting tests of field specimens were done at a lower temperature, –4°F. However, at this temperature a very brittle behavior was observed, and splitting occurred with little or no deformation of the specimens." The stiffness of the asphalt concrete mixes was calculated as the ratio of the tensile strength and the tensile strain at failure.

It was found that the tensile strength, as well as the tensile strain at failure, of the samples was significantly greater in the cores that had been cut from the pavement wheelpaths than in the cores taken from between the wheelpaths. This was attributed to the increase in the density of the wheelpath samples. It was also determined that, in general, pavements that had a greater degree of cracking had lower tensile strengths and also higher tensile strains at failure. There was a strong correlation between the tensile strains at failure and the degree of cracking. A relationship was also found between the amount of cracking and the ultimate failure stiffness, but the correlation coefficient was not high. It was concluded that the stiffness modulus values of the recovered asphalt cements were well correlated with the degree of cracking at the test sites and that "the stiffer or harder the asphalt cement in a pavement was, the greater was the degree of transverse cracking."

37. **McLeod, N.W.** (1978) Test data from three Ontario test roads after 15 years of service. *Proceedings of the Canadian Technical Asphalt Association,* **23:** 534–610.

The author provided a description of the construction of three test road projects that were constructed in Ontario in 1960 with three different asphalt cements used in each of the three jobs. All of the binder materials were 85–100 penetration-graded materials that had different temperature susceptibilities. The asphalt cements recovered from the pavement sections after 15 years were tested for recovered penetration and viscosity. The pen-vis numbers (PVN, from a calculation based on the penetration of the asphalt cement at 77°F and the viscosity of the material at 275°F) of the recovered bitumens were calculated. It was found that the asphalt cement that had the highest PVN number (–1.35) at the time of construction had an average recovered penetration value of 30. A penetration value of 31 was measured for the other two asphalt cements, which had PVN values of –0.41 and –0.23.

It was found that the number of transverse cracks in each section had increased with time. The greatest number of cracks were measured in the section that had

the highest temperature susceptibility (lowest PVN), while the fewest transverse cracks were counted in the pavements containing the asphalt cement with the highest PVN value. The stiffness modulus of the various recovered asphalt cements was determined using the van der Poel nomograph. The PVN values were used in place of the normal Penetration Index numbers for input into the nomograph. The stiffness of the asphalt concrete mixtures was estimated using Heukelom's procedure and the correction for the air void content of the mixes suggested by van Draat and Sommer. Close agreement was found between the predicted pavement stiffness modulus values and the number of transverse cracks that had occurred in the nine test sections.

McLeod concluded that the low-temperature modulus of stiffness of the asphalt cement was the most important factor causing transverse cracking. He commented, however, "that other variables of a paving mixture than the asphalt cement it contains also influence low-temperature transverse pavement cracking." He determined that there was a closer relationship between the number of transverse cracks in the pavement and the stiffness modulus of the mix than there was between the number of cracks and the stiffness modulus of the recovered asphalt cement material itself.

A series of charts were provided in the paper to permit the pen-vis number to be determined directly from a nomograph. Suggestions were provided on the use of asphalt cements of different degrees of temperature susceptibility as measured by the PVN method.

In a discussion of the paper W.D. Robertson pointed out that "in general, the PI and the PVN are not numerically equal. This is true for both vacuum reduced asphalts, on which the PVN correlation is based, and air blown products." Data were presented on 88 asphalt cements made from 19 crude oils. The Penetration Index was calculated for each of these bitumens, based on penetration measurements at 25, 10 and 4°C. Pen-vis numbers were calculated for the same materials. "The correlation between PI and PVN is poor ($R^2 = 0.53$), which indicates that there are other factors, not related to temperature susceptibility in the low-temperature region, which affect the high temperature viscosity".

It was also pointed out that "all of the factors which cause the temperature susceptibility in the high-temperature region to differ from that in the low-temperature region are not known. However, one is the presence of wax. Melting of crystalline components as the temperature is increased causes a drop in viscosity, and hence an artificially low PVN value."

McLeod replied by stating that the close relationship for PI and PVN is valid only for paving grades of asphalt (not air-blown materials) produced by steam or vacuum reduction. He also commented that "asphalt cements

manufactured by steam or vacuum reduction from waxy crude oils have had high temperature susceptibilities and therefore low PVN numbers." It was his belief that pavements prepared with these waxy asphalts have developed more low-temperature transverse pavement cracks than other asphalt pavements in the same area made with asphalt cements having lower temperature susceptibility (higher PVN values).

38. **Ruth, B.E., H.E. Schweyer, A.S. Davis and J.D. Maxfield** (1979) Asphalt viscosity: An indicator of low temperature fracture in asphalt mixtures. *Proceedings of the Association of Asphalt Paving Technologists,* **48:** 221–237.

This research work used 10 asphalt cements to manufacture asphalt concrete samples for dynamic indirect tensile testing. The properties of the various binders were determined using the Schweyer constant-stress rheometer. Test temperatures for the indirect tensile specimens were 77, 41 and 23°F. The stress level applied to each specimen was determined by the testing temperature.

From the results of the dynamic indirect tensile test, it was determined that "fracture of asphalt mixtures subjected to dynamic loading is related to cumulative creep strain and fracture strain which are primarily dependent on viscosity, complex flow, and strain (shear) rate of the asphalt. Aggregate type and gradation, density of the compacted mix, or asphalt content do not appear to significantly influence the fracture strain of the asphalt mixtures. However, these variables will significantly affect the stiffness modulus of mixtures which in turn influences the stress–strain response."

39. **Eaton, R.A. and R.H. Joubert** (1979) Full-depth pavement considerations in seasonal frost areas. *Proceedings of the Association of Asphalt Paving Technologists,* **48:** 541–556.

Three test pavements were constructed of full-depth asphalt concrete (with the asphalt concrete layers placed directly on the prepared subgrade soil) and the seasonal performance of the pavement structures monitored. The first test road contained four sections, two with asphalt concrete on a granular base and two with the asphalt concrete directly on the subgrade soil. The second test road also consisted of four test sections, but in this case the asphalt concrete mix was placed on top of a thin, porous asphalt concrete mix on top of a filter fabric on top of the subgrade soil. The third test road consisted of a single, standard full-depth pavement structure.

Thermocouples recorded the temperature at various depths in the pavement layers and the subgrade soil. Benkelman beam deflection tests were conducted to measure the relative strength of the pavement sections.

The depth of the frost penetration and the amount of frost heave were determined.

It was found that the full-depth asphalt concrete pavement did suffer damage from frost heaving. The amount of damage was related to the uniformity of the preparation of the subgrade soil under the asphalt concrete mixture. The more uniform the subgrade soil and level of compaction, the more uniform was the degree of heaving within the pavement section. The full-depth sections that were constructed on subgrade soils, which varied in the amount of subgrade preparation, suffered from differential frost heaving.

40. **Dempsey, B.J., J. Ingersoll, T.C. Johnson and M.Y. Shahin** (1980) Asphalt concrete for cold regions. U.S.A. Cold Regions Research and Engineering Laboratory, CRREL Report 80-5.

A laboratory investigation was conducted to determine the properties of asphalt concrete mixtures made with three grades of asphalt cement (AC-2.5, AC-5 and AC-20) and two aggregates. For each mix a number of tests were conducted, including the Marshall test, the indirect tension test (called the Brazil test in the report) and the resilient modulus test.

Three test results (indirect tensile strength, tensile strain at failure and total vertical deformation at failure) were determined in the indirect tension test. It was found that "test temperature and asphalt grade have considerable effect on all the observed stress–strain properties (strength, strain and deformation). The rate of loading has a very significant effect on strength but not on strain or deformation, and aggregate source did not have an effect on any of these properties."

The resilient modulus was determined at two loading times for a range of temperatures. It was stated that "the resilient modulus for asphalt concrete varies widely with mix temperature, loading time, asphalt viscosity grade, aggregate type and compactive effort. The most significant factor by far is the temperature of the mix."

The stiffness of the various asphalt concrete mixtures was calculated by a computer program developed by Shahin. Inputs needed include air temperature, solar radiation, wind velocity, asphalt concrete mix thermal properties, penetration and softening point of the asphalt cement, and volume concentration of the aggregate. It was determined that the stiffness of the mixture increased with age and with the increase in the stiffness (grade) of the asphalt binder. The aggregate type was found to have little effect on mix stiffness. As expected, less low-temperature cracking was predicted when the softer grades of asphalt cement were used in the analysis.

41. **Pink, H.S., R.E. Merz and D.S. Bosniack** (1980) Asphalt rheology: Experimental determination of dy-

namic moduli at low temperatures. *Proceedings of the Association of Asphalt Paving Technologists*, **49**: 64–94.

This research work was directed toward the development of the Rheometrics Mechanical Spectrometer to determine the dynamic shear modulus in forced torsion at low temperatures. In the measurement of dynamic viscosity, the asphalt cement was subjected to a sinusoidal strain at a given frequency. The response to the applied strain was the development of a sinusoidal stress that was out of phase with the applied strain. The complex modulus value was defined as the ratio of the stress to the strain. For the testing, samples of asphalt cement 35 mm in length, 10 mm in width and 5 mm thick were used.

Five asphalt cements from different crude sources, including air-blown materials, were used in the study. The Pfeiffer and van Doormaal Penetration Index values for the asphalt cements ranged from –1.51 to +2.58. The stiffness of the binders was estimated from van der Poel's nomograph. The dynamic modulus of the materials was determined using a method proposed by G.R. Dobson using three parameters: a temperature susceptibility parameter derived from the temperature dependence of the Newtonian viscosity, a shear susceptibility parameter and a Newtonian viscosity at the reference temperature. Master curves were drawn for the modulus values for each binder to determine the response of the asphalt cements over a range of time and temperatures.

The dynamic viscosity measurements were used to determine the temperature of the asphalt cement at its limiting stiffness. Comparisons were completed between the dynamic modulus measurements made with the experimental equipment and the values calculated from both the dynamic modulus equation and the stiffness value determined from the van der Poel graph. The temperature at which the limiting stiffness value occurred was found for each of the three methods. It was determined that there was generally good agreement in the temperatures calculated from the van der Poel nomograph and the dynamic modulus equations and also with the temperatures determined using the mechanical spectrometer for the straight-run asphalt cements.

For the air-blown asphalt cements with high Penetration Index values, however, the spectrometer results indicated higher limiting stiffness temperatures than did the nomographic method. It was concluded that "direct measurement of low-temperature properties appears to be the only means at present to obtain accurate data for higher PI asphalts."

42. **Gaw, W.J.** (1981) Design techniques to minimize low-temperature asphalt pavement transverse cracking.

The Asphalt Institute, Research Report No. 81-1.

This paper is a state-of-the-art review of literature on the problem of low-temperature cracking of asphalt concrete pavement structures. It was determined that a number of factors play a role in low-temperature cracking. Those factors included "(a) climatic effects, (b) subgrade type, (c) asphalt properties, (d) mix properties and mix design, (e) pavement design and structural effects, (f) age of pavement, and (g) traffic effects."

An interim pavement design procedure to address the problem of low-temperature cracking was presented in the report. The design method included the following steps: determination of the pavement design temperature, prediction of the cracking temperature of the pavement, selection of the grade of asphalt cement to minimize low-temperature cracking, and selection of the grade of asphalt cement to optimize overall pavement performance. It was pointed out that this suggested design procedure did not take into account the effects of pavement aging, traffic or variations in pavement design. It was stated, however, that the design method "does take account of one of the more significant variables, i.e., asphalt hardness at low temperatures in a realistic manner." The study also concluded that "the application of the proposed design procedure to compare pavement cracking should also permit a more systematic evaluation of other pavement design variables such as pavement thickness, pavement aging, subgrade type, traffic effects, and mix design."

A review was made of methods for measuring the stiffness of the asphalt cement. It was pointed out that methods were needed to directly measure the stiffness of the binder material at temperatures in the range of –40°F. Laboratory equipment that applies a dynamic stress or strain to samples of asphalt cement and that is capable of measuring the stiffness of the binder material at temperatures near the limiting stiffness had been developed, but "the high frequencies employed by these instruments result in this limiting stiffness occurring at temperatures well above the pavement cracking temperatures, making it difficult to correlate these temperatures with pavement cracking." It was reported that a sliding-plate rheometer had been developed that could determine the stiffness of the asphalt cement at pavement cracking temperatures and at the limiting stiffness values for the binder material.

The study stated "for routine pavement design purposes, the most practical approach is to predict the low-temperature asphalt stiffness using van der Poel's nomograph." The nomograph was developed on the basis of using two parameters as the input criteria: the Penetration Index (PI) and the ring-and-ball softening point of the asphalt cement. The method used to calculate the PI value was that of Pfeiffer and van Doormaal, with the

penetration of the asphalt cement at the softening point assumed to be 800. For many binders and particularly for waxy asphalt cements, the penetration at the softening point is not equal to the assumed value and thus the Penetration Index number did not represent the true temperature susceptibility of the bitumen.

To overcome the problem of the use of waxy asphalt cements, this report presented an equation for calculating the Penetration Index based on the measurement of penetration at two temperatures instead of using the softening point temperature. The penetrations needed to be measured, however, under a load of 100 g at a loading time of 5 s. For penetration values determined at 39.2°F under a load of 200 g at a loading time of 60 s, the report recommended that a correlation procedure developed by Schmidt be employed to convert the penetration from the 200 g–60 s value to the necessary 100 g–5 s number at the test temperature of 39.2°F.

The Penetration–Viscosity Number (PVN) method of McLeod was reviewed. The comment was made that "McLeod's PVN system is based on an empirical correlation between penetration at 77°F, viscosity at 275°F, and Pfeiffer and van Doormaal's PI for a few carefully selected asphalts."

It was also stated that McLeod's method is reasonable for some asphalts, but for asphalts with wax contents in excess of 2% and for air-blown asphalts, "McLeod's PVN is in error." The report continued stating "at moderately low temperatures in the range of 50 to 14°F, both the PI procedure (using penetrations at two temperatures) and the PVN procedure gave reasonable results for non-waxy asphalts. At temperatures close to pavement cracking temperatures, the PI procedure gave the most accurate stiffness predictions. For waxy and air blown asphalts, the PI procedure gave the more accurate predictions over a wide range of temperature. The preferred procedure is to use PI based on penetrations at two temperatures (using 100 grams for 5 seconds), and the temperature equivalent to 800 penetration as entrance parameters to van der Poel's nomograph."

The authors of this review reported on several methods for directly measuring the stiffness of the asphalt concrete mixture. The comment was made that limiting stiffness values measured from dynamic procedures were usually conducted at test temperatures much above the actual pavement cracking temperatures. Mix stiffness was defined as the applied tensile stress of the mix divided by the measured strain and was typically determined using a tensile creep test procedure under constant-stress conditions. Mix stiffness values determined under constant-rate-of-strain procedures were stated to not be applicable since "such measurements do not result in mix stiffness information."

Mix stiffness could be predicted using the nomographic method of Heukelom, which is based on the stiffness of the asphalt cement and on a mixture with an air void content of 3%. Correlations were developed by van Draat and Sommer to allow Heukelom's nomograph to be used over a wider range of mix air void contents. Another nomograph prepared by Bonnaure could also be employed to estimate mix stiffness values over a range of air void and asphalt cement contents.

The temperature at which an asphalt concrete pavement layer will crack could be predicted from both the stiffness of the asphalt cement and the stiffness of the asphalt concrete mix. From asphalt stiffness estimates, predicted cracking temperatures could be determined "based on: a) limiting asphalt stiffness, b) critical asphalt stress, and c) nomographic cracking temperature. These procedures are dependent on the premise that asphalt properties are the major influence on pavement transverse cracking and neglect the roles played by pavement design and mix variables such as asphalt content, air void content, and aggregate."

The first method for predicting the cracking temperature was to estimate the temperature at which the asphalt cement reaches a certain limiting stiffness value. These critical stiffness values have been determined by a number of investigators and were based on a variety of loading times. It has been found, however, that loading time was not critical provided that it was reasonably long. The authors concluded that the most reasonable limiting stiffness value to use was 1×10^9 N/m^2 (approximately 143,000 psi) at a loading time of 0.5 hours.

The second procedure employed a method by Hills and was based on an estimate of the stresses in the asphalt cement. The thermal stress was calculated from an equation as the material cools and the stiffness of the asphalt cement was determined at various temperature intervals between 32 and –58°F. Hills assumed that "pavement cracking occurred at a temperature corresponding to a calculated thermal stress of 5×10^5 Newtons per square meter."

Another method for predicting the cracking temperature from the stiffness of the asphalt cement binder was also based on Hills' work. It was based on the assumption that "there is a unique relationship between asphalt penetration at 77°F and 41°F and the calculated cracking temperature." A nomograph developed by Gaw et al. was used to predict the cracking temperature directly, using only the two penetration values for the asphalt cement. No other characteristics of the binder except the penetration numbers at two temperatures were used for input.

The predicted pavement cracking temperature could also be determined using limiting mix stiffness criteria. A number of investigators have proposed such critical

stiffness values. A nomograph prepared by Bonnaure and others was recommended for use. This nomographic procedure takes into account both the asphalt content and the air void content of the asphalt concrete mixture. It was pointed out, however, that "in practice not only mix stiffness varies with asphalt content and air voids, but also mix breaking strength. This makes it extremely doubtful that any single limiting mix stiffness value can truly represent the critical mix property at the onset of pavement cracking."

The last of the presented methods was based on a modification of the last procedure, as proposed by Hills. In this method, which takes into account the changes in the mix breaking strength with changes in asphalt content and air void content, the thermal stress that develops as the pavement cools was calculated and the mix breaking strengths were determined at the same temperature intervals. Both of these values were then plotted as a function of temperature. The point where the two curves cross was taken to be the predicted mix cracking temperature.

The major problem with all of the cracking prediction methods was the lack of adequate correlation with actual cracking temperatures in real pavement layers. Further, "none of these procedures is capable of duplicating fully the restraint on the mix that occurs in the actual pavement as it cools; consequently, they fail to predict the actual pavement cracking temperature."

"Before such methods could be used to predict pavement cracking temperatures, an accurate correlation would need to be developed between predicted and observed cracking temperatures. Such a correlation has not yet been developed."

43. **Ruth, B.E., L.A.K. Bloy and A.A. Avital** (1982) Prediction of pavement cracking at low temperatures. *Proceedings of the Association of Asphalt Paving Technologists*, **51**: 53–103.

A computer program was developed to predict the critical conditions in an asphalt concrete pavement that will cause low-temperature cracking. Low-temperature asphalt rheology measurements were used to determine the viscosity of the asphalt cements recovered from asphalt concrete test specimens. The viscosity values were used to develop relationships for predicting the properties of the mix, including both static modulus and dynamic modulus. The thermal analysis of the pavement structure included input values of cooling rate, coefficient of thermal contraction, and asphalt cement viscosity–temperature susceptibility data. The program calculated the thermal stresses, incremental creep strains and stress–strain energy developed at various times during the cooling of the asphalt concrete mixtures.

Absolute viscosity measurements were performed using the Schweyer constant-stress rheometer. Four temperatures were used, including 25, 5, –5 and –10°C. The indirect tensile test was employed to determine the properties of the asphalt concrete mixes. Constant-stress tests were used to obtain the tensile creep strain rate and the elastic tensile strain. Dynamic loading was used to conduct fatigue tests to determine the dynamic modulus, the failure strain and the mix viscosity data. For the various asphalt cements and asphalt concrete mixtures investigated, a relationship was developed between the viscosity of the binder and the viscosity of the mix. Three basic equations were presented to define strain, modulus and viscosity values.

The critical temperatures were calculated based on two values of limiting stiffness: the value from the Ste. Anne Test Road and the value proposed by McLeod. These criteria, however, were found by the authors to have the following deficiencies: a) "No applied stress is defined. Thus the effect of shear susceptibility is not considered. To define a more meaningful limiting stiffness, the applied stress and the loading time would be needed, b) the effect of different cooling rates is ignored, and c) no consideration is given to the effect of different coefficients of thermal contraction."

From this research work, it was determined that "the greatest effect on the predicted cracking temperatures in the thermal analysis are the viscosity and temperature susceptibility of the asphalt. Higher cracking temperatures result from higher viscosities and greater temperature susceptibility." It was found that the predicted cracking temperature increased as the cooling rate increased, but at a decreasing rate. In addition, as the thermal coefficient of contraction increased, the temperature at which the pavement was predicted to crack increased. Further, it was found that the failure strain criteria employed to predict the cracking temperatures depended directly on the loading time used in the thermal analysis.

44. **Kallas, B.F.** (1982) Low-temperature mechanical properties of asphalt concrete. The Asphalt Institute, Research Report 82-3.

A laboratory testing program was accomplished to determine the stress–strain behavior and the fracture strength of asphalt concrete mixtures. The constant-rate-of-extension uniaxial tension test was used at temperatures from 32 to –40°F. Two aggregates (limestone and gravel) and three asphalt cements (AC-2.5, AC-5 and AC-10, all from the same source) were used to make the specimens.

It was found that the strain at fracture decreased quickly as the temperature of the test decreased to a temperature of –4°F and then decreased slightly below that temperature. At temperatures above –22°F, the grade

of the binder material affected the fracture strain, with the strain increasing with the softness of the grade of asphalt cement. Below –22°F the effect of asphalt cement grade on the fracture strain was essentially the same for all three of the bitumens. In terms of the fracture modulus, it was determined that "maximum values of the modulus occur for each asphalt grade for both aggregate mixes. The temperature at which the peak modulus occurs shifts to a higher temperature as the grade of asphalt increases."

The type of aggregate used in the mix did have an effect on the fracture strength of the two mixtures. It was found that "maximum values of fracture stress occur for each asphalt grade at varying temperatures for both aggregates. The temperatures at which the peak fracture stress occur shifts to a higher temperature as the grade of asphalt increases. Observations of the fractured surfaces of specimens indicated that fracture through the aggregate accounted for 10 to 15 percent of the area of fractured surfaces. The percentage was about the same for both aggregate mixes and all test temperatures between 32°F and –40°F." Further, there was no consistent effect of a change in the asphalt content in the mix within a range of 0.5% above and below the optimum value.

A computer program, COLD, was employed to predict the temperature at which the two mixtures would crack. Input to the program included daily air and pavement temperature data, initial temperature gradients, stiffness modulus and tensile strength values of the asphalt concrete mixture, and thermal properties of the asphalt concrete layers. It was determined that the effect of aggregate type was small compared to the effect of asphalt cement viscosity. The higher the initial viscosity grade of the binder, the higher the predicted cracking temperature of the pavement layer manufactured with that asphalt cement.

A comparison was made between the predicted cracking temperatures calculated using the COLD program and the cracking temperatures determined using the method outlined in the Asphalt Institute Research Report No. 81-1, using a simple nomograph that shows the cracking temperature as a function of the penetration of the original asphalt cement at both 77 and 41°F. It was found that the trends were similar between the two methods but that somewhat higher cracking temperatures were predicted by the COLD program compared to the nomographic method.

45. **Bell, C.A.** (1983) Use of the Shell Bitumen Test Data Chart in evaluation of asphalt data. *Proceedings of the Association of Asphalt Paving Technologists,* **52:** 1–31.

This paper is an investigation of the use of the Shell Bitumen Test Data Chart, which is used to plot viscosity and penetration values for an asphalt cement on the same diagram, to predict the penetration at 77°F and the ring-and-ball softening point of a binder material. In addition a procedure is provided to determine the classification of an asphalt cement: straight run, air-blown and waxy. The input data needed for this classification method are the viscosity of the asphalt cement at both 140 and 275°F and the penetration at 77°F. Typical plots are provided to illustrate the slope of the viscosity–penetration information for the various classes of bitumen.

The results of testing on 177 asphalt cements were used to prepare a modified asphalt classification chart that permits both penetration and viscosity to be plotted at low temperatures. Input data for the chart could include penetration at any of three temperatures: 77, 39.2 and 18°F. Viscosity data at 140 and 275°F were also used, as was the softening point temperature. From the chart a comparison of the predicted and measured penetrations at 77°F could be used to indicate the class of the asphalt cement. It was found that the prediction of the penetration value at 77°F and the softening point temperature depended on the class of the asphalt cement being tested. It was pointed out that penetration tests should be performed at at least two temperatures, instead of only 77°F, to better characterize an asphalt cement. It was suggested that the temperature susceptibility of the binder material be determined from the slope of a portion of the line on the Bitumen Test Data Chart.

46. **Keyser, J.H. and B.E. Ruth** (1984) Analysis of asphalt concrete test road sections in the Province of Quebec, Canada. *Transportation Research Record,* **968:** 54–65.

Data were collected from 23 test sections that were six to nine years old in 1980 to determine the factors that affected the low-temperature cracking of the pavement structures. Cores were taken to determine the indirect tensile strength of the mixes, and the asphalt cement was recovered to measure penetration, viscosity and softening point. The data base contained some 44 variables that were investigated to determine their effect on pavement performance.

From the information gained from the testing of the recovered asphalt cements, it was found that "parameters generated by using both penetration and softening point, such as Penetration Index (PI), are of questionable value" when used to predict the performance of the pavement layers. It was also determined that viscosity at 275°F and penetration at 77°F of the recovered asphalt cements were functions of the original grade of the binder material and the air void content of the asphalt

concrete mixture. The results of the indirect tensile tests were found to be quite variable, primarily due to the differences in the air void contents of the mixtures being tested.

Asphalt viscosity, traffic, freezing index, layer thickness and indirect tensile strength of the mixtures were evaluated to determine their effect on low-temperature cracking. It was found that "cracking increases with viscosity and traffic, decreases with an increase in freezing index, and decreases with increasing thickness and tensile strength."

A method proposed by Haas was used to predict the degree of low-temperature cracking that would occur. The stiffness of the paving mix, the winter design temperature and the type of subgrade soil were all entered into a program to calculate the cracking index of the various pavements. It was found that there was no correlation between the computed cracking index value and the amount of cracking that occurred on the actual roadways. The best relationship to predict the amount of low-temperature cracking was between two categories of traffic level and the penetration of the recovered asphalt cement at 77°F.

47. **Thenoux, G., G. Lees and C.A. Bell** (1985) Laboratory investigation of the Fraass brittle test. *Proceedings of the Association of Asphalt Paving Technologists,* **54**: 529–550.

The Fraass Breaking Point is defined as "the temperature at which bitumen first becomes brittle as indicated by the appearance of cracks when a thin film of the bitumen on a metal plaque is cooled and flexed in accordance with specified conditions." The Fraass test can be used to determine the behavior of asphalt cements directly at temperatures as low as −30°C. The objective of this study was to evaluate the ability of the Fraass test to determine the brittle characteristics of asphalt cements.

Six asphalt cements were tested. It was found that the Fraass temperature was a point of equal stiffness for all of the binder materials. The stiffness values calculated were higher than determined by other research work and approached the limiting stiffness value for asphalt cement as estimated by the van der Poel nomograph. It was pointed out that the Fraass temperature can be plotted on the Shell Bitumen Test Data Chart to provide a low-temperature point of reference for the properties of the various binder materials.

48. **Marks, V.J. and C.L. Huisman** (1985) Reducing the adverse effects of transverse cracking. *Transportation Research Record,* **1034**: 80–86.

Field test sections were constructed in Iowa in 1980 to attempt to reduce the amount of transverse cracking of asphalt concrete pavements. The sections included the use of two asphalt cements, the sawing and sealing of transverse joints in the new pavement to control cracking, and a change in the asphalt content of the asphalt concrete mixtures.

Two binders were incorporated into the mixes. The temperature susceptibility of the materials was determined by calculating the pen-vis number of each material. One of the asphalt cements had a PVN value of −0.6, while the other material had a PVN number of −1.2. The same aggregate was used to produce both an asphalt concrete binder course mix and a surface course mix. In several of the mixtures the asphalt content was increased 1% over the optimum found in the mix design procedure. Transverse joints were cut into the surface of some of the mixtures at spacings of 40, 60, 80 and 100 ft and were sealed with a rubber asphalt material.

Crack surveys conducted yearly at the site showed that there was a considerable difference in the amount of transverse cracking that occurred in the sections built with the two binder materials. Transverse cracks appeared in the section that had the asphalt cement with the low PVN value at approximately a 35-ft spacing in less than two years. After $3^1/_2$ years the transverse crack spacing for the section containing the asphalt cement with the higher PVN value was 170 ft, while the crack spacing of the other section remained the same (35 ft). It was determined that the recovered viscosity of the two asphalt cements was essentially the same after four years in the pavement.

It was found that "both the penetration and the PVN of the extracted asphalt cement relate well to the frequency of transverse cracking." The penetration of the more temperature-susceptible material had decreased from 75 to 40. The penetration of the less temperature-susceptible binder had decreased from 100 to 55. The pen-vis number for both of the asphalt cements remained relatively constant from the time of original construction until the tests four years later. It was also found that an increase in the asphalt content of the mixtures reduced the amount of transverse cracking that occurred on the project.

49. **Ruth, B.E., M. Tia and K. Badu-Tweneboah** (1986) Factors affecting the cracking of asphalt concrete pavements. *Proceedings of the Canadian Technical Asphalt Association,* **31**: 96–109.

The authors suggested that the majority of the pavements crack because of thermal and load-induced stresses. These stresses are caused by "the combined effects of (a) degree of hardening of the asphalt binder, (b) high deflection response to loading and (c) insufficient fracture strain tolerance at the low exposure temperatures." It was stated, however, that the problem

"may be complicated by the effect of 'thermal rippling' when the pavement is rapidly cooled resulting in a large temperature differential between the surface and the bottom of the pavement." It is suggested that this rapid cooling "can be very detrimental particularly when traffic is too light to seat the pavement during the cooling process before being subjected to one or more heavy vehicles." It is further suggested that "the softer the binder at low temperatures the less 'rippling' and the lower the potential for pavement cracking."

The low-temperature characteristics of various asphalt cements were determined using a Schweyer constant-stress rheometer. The measured viscosity values were used to determine the stress–strain behavior of various asphalt concrete mixtures taken from in-service pavements.

It was concluded that "low asphalt viscosity and adequate mix fracture energy are required at low temperatures to prevent or minimize pavement cracking from thermal contraction, 'thermal rippling' and load effects."

50. Anderson, K.O., S.C. Leung, S.C. Poon and K. Hadipour (1986) Development of a method to evaluate the low temperature tensile properties of asphalt concrete. *Proceedings of the Canadian Technical Asphalt Association,* **31:** 156–189.

Three asphalt cements at two penetration grades (85–100 and 200–300) were used to manufacture indirect-tension-test specimens. The temperature susceptibility characteristics of the binders were determined by four criteria: the pen-vis number using the penetration at 77°F and the viscosity at 140°F, the pen-vis number using the penetration at 77°F and the viscosity at 275°F, the Penetration Index assuming the softening point temperature is equal to a penetration of 800, and the Penetration Index using the slope of the log penetration vs temperature. Significant differences were found in the temperature susceptibility values determined by the different methods.

One aggregate was used with the six binders to manufacture specimens for the indirect tension test. The samples were tested at temperatures of 0, –10, –20 and –30°C. The failure stress and failure strain were determined for each of the mixtures. It was noted that the test temperature had a significant effect on the level of failure stress, with the failure stress increasing as the temperature decreased. Failure strain was found to decrease as the test temperature decreased but at a decreasing rate at the lower temperatures. For each binder material there was a critical temperature below which failure strain remained relatively unchanged.

Each source of asphalt exhibited its own stress–strain curve. In addition the failure strain of the softer asphalt cement was generally higher than the failure strain of the harder material. At –30°C, however, the failure strain of both materials was essentially the same. The results of the indirect tension test indicate that the asphalt concrete mixtures that can withstand greater failure strains are more resistant to low-temperature cracking.

51. Hugo, F., V.P. Servas and D.R.F. Snyman (1987) HVS-aided validation of pavement behavior at low temperatures. *Proceedings of the Association of Asphalt Paving Technologists,* **56:** 168–197.

This study used the Heavy Vehicle Simulator to investigate the effect of low temperatures on the premature cracking of asphalt concrete pavements. Cooling units were used to reduce the temperature of the pavement surface to –10°C at a cooling rate of 2°C per hour. After the pavement surface reached the desired temperature, up to 2000 repetitions of a single wheel load was applied to the asphalt concrete mixtures before the surface temperature increased to 0°C. Both dense-graded and gap-graded mixes were tested. Some of the mixtures were artificially aged using ultraviolet irradiation before being subjected to the wheel loading.

For the sections tested at the low temperatures, it was found that the aged and unaged asphalt concrete mixes "showed severe cracking in contrast to the adjacent areas tested at ambient temperature." At low temperatures there was a difference in the behavior of the gap-graded mixes, with the aged gap-graded materials exhibiting more cracking than the unaged mixes. No differences due to aging of the mix were found with the dense-graded asphalt concrete mixtures.

52. Haas, R., F. Meyer, G. Assaf and H. Lee (1987) A comprehensive study of cold climate airport pavement cracking. *Proceedings of the Association of Asphalt Paving Technologists,* **56:** 198–245.

The authors developed computer models to predict the occurrence of low-temperature cracking in Canada. Core samples were collected from 26 airport pavements. Tests conducted on the recovered asphalt cement included penetration at 77°F, viscosity at 140 and 275°F, specific gravity and residual asphalt content. Direct tensile test measurements at 0, –17 and –34°C were used to determine the stiffness properties of the binder materials. Stiffness modulus values were calculated from the ratio of failure (peak) stress to the strain at that failure stress. The Penetration–Viscosity Number (PVN) of the recovered asphalt cements was also calculated.

The amount of transverse and longitudinal cracking on the various airport pavements was measured. The amount of cracking was correlated to some 32 variables. On the basis of a simple correlation of single variables,

it was found that "transverse cracking is very dependent upon climatic factors such as the minimum attained temperature in the area, the Freezing Index (which is itself highly correlated with minimum temperature), the temperature susceptibility of the mix in terms of stiffness drop between 0°C and –17°C, the recovered bitumen temperature susceptibility in terms of McLoed's Pen Vis Number (PVN), the asphalt layer thickness and the coefficient of thermal contraction of the asphalt concrete."

"Other parameters such as spring reduction factors, base thickness, subbase thickness, runway widths, overlay ages and construction year, asphalt content, consistencies of the bitumen at 25°C, 60°C, and 135°C taken individually, stiffnesses and stresses at 0°C, –17°C, and –34°C taken individually, bulk specific gravity, quality of drainage and presence of fines in the soil have no significant effect on transverse and longitudinal crack spacings. Finally, the failure stress at –34°C has a significant correlation with transverse cracking, although this does not have a readily apparent physical explanation."

Multiple regression models were developed, and an attempt was made to eliminate variables that were correlated with one another. It was found that the best single independent variable to explain the amount of transverse cracking was the minimum temperature recorded at the test site. For a two-independent-variable model, the minimum temperature and the pen-vis number (PVN) provided the best model. The best three-independent-variable model included the variables minimum temperature, the pen-vis number and the coefficient of thermal contraction of the asphalt concrete mixture. The same three variables plus the thickness of the asphalt concrete layer provided the highest correlation coefficient ($R^2 = 0.70$) for a four-independent-variable model. Thus, approximately 70% of the cause of the transverse cracking on the airport pavements could be explained by these four factors.

53. Kandhal, P.S. and W.C. Koehler (1987) Effect of rheological properties of asphalts on pavement cracking. ASTM Special Technical Publication 941, p. 99–117.

The stiffness moduli of the asphalt cements used to construct six pavement test sections in 1976 were calculated by two methods. The first was based on the procedure suggested by Heukelom from the Bitumen Test Data Chart. The Penetration Index value was determined from penetration measurements made at three temperatures. The second method was that of McLeod, with the temperature susceptibility of the binder determined from the pen-vis number. Both the PI and the PVN values were determined for the original materials and from recovered asphalt cements after 20 months and 7 years of service. It was determined that the PI values (based on penetration values only, not softening point) were generally lower than the PVN values on the original asphalts and higher than the PVN values after field aging. Further, it was found that the PVN numbers remained essentially unchanged during the aging process, while the PI numbers changed significantly. The PI values did not maintain a consistent ranking of the test sections with time and aging.

The stiffness modulus of the asphalt cements was determined by both the Heukelom method (PI based on penetration measurements only) and the McLeod method (based on PVN). The van der Poel nomograph was used to calculate the estimated stiffness values. It was found that the stiffness modulus values determined using the pen-vis numbers correlated better with the amount of transverse cracking than did the modulus values based on Penetration Index.

The stiffness of the asphalt concrete mixtures was determined from the stiffness modulus of the asphalt cement (based on either PI or PVN) and the volume concentration of the aggregate. Stiffness modulus values were determined for the original asphalt concrete mixtures as well as for aged mixes. Creep modulus values were determined from pavement cores at four temperatures (39.2, 20, 0 and –20°F). Stress–strain curves were constructed and the time–temperature superposition procedure used to fashion master creep curves. The stiffness modulus of the six asphalt concrete mixes was determined at a temperature of –10°F and a loading time of 20,000 s.

The creep stiffness modulus values of the mixes were "generally consistent with the transverse cracking indexes. The incidence of cracking increases with the increase in the stiffness modulus."

The stiffness modulus values determined using the PVN values were also found to be consistent with the amount of cracking, but the modulus values based on Penetration Index were not related to the degree of cracking on the six test sections. It was also found that McLeod's value for limiting stiffness of 1,000,000 psi for a loading time of 20,000 s "seems to be confirmed on this project." The transverse cracking that occurred on the test sections took place when the stiffness modulus values of the mix approached this limit. It was concluded that measuring the temperature susceptibility of aged asphalt cements by PVN instead of by PI provided a better relationship to actual pavement performance.

54. Dauzats, M. and A. Rampal (1987) Mechanism of surface cracking in wearing courses. *Proceedings of the Sixth International Conference: Structural Design of Asphalt Pavements,* p. 232–247.

A modification of a model originally developed by M.Y. Shahin was used to predict the low-temperature cracking in asphalt concrete mixtures. One computer program calculated the hourly temperature variations that occurred at different depths in the mixtures based on air temperature, solar radiation, wind velocity and the thermal properties of the asphalt concrete mixtures. A second program calculated for the daily minimum pavement temperature the stiffness modulus of both the asphalt cement and the asphalt concrete mixtures, as well as the strength and the maximum stress and strain in each mix at each depth in the pavement structure. The stiffness modulus of the asphalt cement was determined using van der Poel's nomograph. The stiffness modulus of the asphalt concrete mixture was found through the use of Heukelom and Klomp's nomograph.

It was found that more cracking was predicted when harder asphalt cement binders (40–50 penetration grade compared to 60–70 penetration grade) were used in the mix. It was also determined that the degree of cracking that took place on the roadway could not be correlated to the thermal properties of the binder and the mix alone. The amount of surface cracking was also related to the action of rolling loads on the pavement structure. Another model was developed to superimpose the effect of traffic on the effect of the thermal stresses and strains on the degree of low-temperature cracking that developed.

55. **Deme, I.J. and F.D. Young** (1987) Ste. Anne Test Road revisited twenty years later. *Proceedings of the Canadian Technical Asphalt Association,* **32**: 254–283.

The Ste. Anne Test Road was constructed in 1967 and incorporated 29 test sections. Two subgrade soils were used on the site, a clay and a sand. Three asphalt concrete mixes were used, together with four asphalt binders (three asphalt cements and one slow-cure liquid asphalt). Three asphalt contents were also employed in the mixes. The temperatures at the paving site were monitored. Maps were prepared to show the location of the transverse cracking on the various sections.

After eight years of service (just before the pavement sections were overlaid), the test sections were surveyed and a number of conclusions were drawn. The use of the softer asphalt cements resulted in less transverse cracking. The asphalt cement with the greater temperature susceptibility, as determined by the Penetration Index values, was found to have cracked more than the higher PI asphalt did. The slow-cure SC-5 liquid asphalt exhibited no cracking during the first eight years. The thicker the asphalt concrete layer (40 vs 250 mm), the less the cracking. Significantly more transverse cracking was found on the pavement sections constructed on the sand subgrade compared to the clay subgrade. The type and quality of aggregate had some effect on the frequency of cracking, but the change in asphalt content, within a range of 1%, did not have any significant effect. The mineral filler content of the mix also did not affect the degree of cracking.

The stiffness modulus of the various binders was measured directly using the Shell sliding-plate rheometer. The stiffness modulus was also estimated using van der Poel's nomograph. Both of these methods confirmed that the pavement had cracked during the first winter when the stiffness of the field-aged asphalt cements exceeded a modulus value of 1×10^9 N/m^2 at a 0.5-hour loading time. Pavements with the high-viscosity 150–200 penetration asphalt cement did not crack during the first winter because the stiffness of the binder remained above the critical value. The stiffness value of the SC-5 material was low enough to prevent cracking for the eight years before overlaying for pavements built both on the sand and the clay subgrade soils.

No data were available for the stiffness values of the original asphalt concrete mixtures. A relationship was developed between temperature and mix stiffness from the low-temperature tensile creep tests of samples of the mix taken after the pavement was placed in service. It was determined that "based on the critical pavement temperature regime at the initiation of transverse cracking, the critical mix stiffness was estimated to be 1.8×10^{10} Newtons per square meter." It was also found that "contrary to the recovered binder data, which indicated that binder stiffness changed little over time at low-temperature extremes, the stiffness of mix specimens cut from test pavements showed an increase from 1970 to 1972 at all temperature levels....This has been attributed to molecular structural formation in the asphalt which is known to increase binder consistency over a period of time, commonly referred to as 'age hardening' or 'structural hardening' (as distinct from 'chemical aging' which refers to the asphalt oxidation process)."

Cracking temperatures for the asphalt concrete mixtures were predicted from the estimates of mix stiffness that were obtained from constant-load creep tests and from the tensile breaking stresses that were obtained at a constant rate of strain. The accumulated thermal stress was calculated for the thermal contraction coefficient and the mix stiffness at a number of temperatures. The cracking temperature was determined from a plot of breaking stress and thermal stress, both as a function of temperature, and the point at which the two curves intersected. The predicted cracking temperatures were found to be lower than the observed field cracking temperatures.

"The mix stiffness moduli at low temperatures and long loading times were all determined using the constant stress/load tests. Except for the condition at break, constant rate of strain tests lead to empirically irrecon-

cilable differences in loading time and cannot be used in stiffness modulus determination."

"The mix breaking stresses were measured under constant rate of strain conditions in the temperature range of 25 to –40°C. For this type of testing only the conditions at break yield a rational test value, i.e., breaking stress, stiffness modulus and loading time pertain to the observed time to specimen failure." The test results "indicated that the mix breaking stress was a function of the mix stiffness." It was also found that the thermal coefficients of linear contraction of the asphalt concrete mixtures were independent of the source and type of the asphalt cements, and the differences found between the mixtures were "attributable to differences in the aggregate/mix characteristics. Consequently, when comparing the tendencies of mixes to crack at low temperatures, when the only variable is the asphalt binder, it should suffice to compare mix stiffness at temperatures close to the anticipated cracking temperature."

It was concluded, from the investigation of the performance of the original asphalt concrete mixtures up to the point of overlay, that "transverse cracking may be prevented, delayed or reduced for a considerable number of years by selecting for use an asphalt which has a sufficiently low stiffness modulus at the prevailing low-temperature extremes. When binder stiffness is near the critical limit, then pavement thickness, mix aggregate characteristics, subgrade variables and traffic can be anticipated to influence the nature and frequency of transverse cracking." A nomograph was presented to predict the critical cracking temperature based on testing to the asphalt cement binder material. The nomograph was based on the initial cracking of the Ste. Anne Test Road pavement layers and "it is left to the user to select a suitable safety factor." The nomograph allowed the critical cracking temperature to be found using only the penetration of the asphalt cement at 5 and 25°C.

The Ste. Anne Test Road was overlaid in 1975, eight years after first construction, using a 5-inch layer of mix containing an SC-5 binder material. The overlay was inspected in 1987, 20 years after initial construction of the original, underlying pavement structure. It was found that anywhere from 13 to 100% of the cracks in the original pavement structure had reflected through the new overlay. It was also determined that all of the test pavements exhibited some degree of transverse cracking at the time of this last investigation.

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James A. Scherocman

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The International State-of-the-Art Colloquium on Low-Temperature Asphalt Pavement Cracking was held in Hanover, N.H., on 6–8 May 1987. The objective was to review and summarize the existing knowledge of the causes of low-temperature transverse cracking of asphalt concrete pavement. Discussion also suggested directions for future research needed to more fully understand the mechanisms of the causes of low-temperature cracking. Overlays were not discussed.

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