PROPOSED METHOD OF PRODUCING ASPHALT CONCRETE BEAMS FOR LOW-TEMPERATURE TESTING

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The cracking of asphalt concrete pavements from influences of low temperatures has become an expensive maintenance item to highway departments in cold climates. It has been recognized that flexural tests of beams of bituminous paving mixtures conducted at low temperatures furnish indexes that disclose the thermal sensitivity of the binders. However, the difficulty in reproducing suitable specimens has caused high coefficients of variation in test results. Therefore, the objective of this investigation was to standardize a procedure of making beams that have the characteristics of asphalt concrete wearing courses. The California kneading compactor was modified to form beams 15 by $3\frac{1}{4}$ by $3\frac{1}{2}$ in. in size. Two types of aggregates and five different asphalt cements were used in bituminous mixtures. Viscosity control determined the mixing and the compacting temperatures. A technique of beam making consisting of combinations of tamping blows at different foot pressures and of a static load consistently produced homogeneous specimens of acceptable densities and proper aggregate orientation. From results of this investigation, it appears practicable to form and test beams in state, municipal, and commercial laboratories. The determination of the rheological properties of paving mixtures made with indigenous aggregates and diverse asphalt cements will predict the suitability of the binders at the minimum temperature of a region.

•METEOROLOGICAL records indicate that Wisconsin experienced its worst winter in 100 years during the 1971-72 season: worst in terms of amount of snowfall, number of days of subzero temperatures, and number of freeze-and-thaw cycles. Because some 93 percent of our paved roads are bituminous covered, the transverse cracking of the viscoelastic material induced by low temperatures has become a topic of increasing importance to maintenance departments. This premature non-load-associated cracking has serious implications with respect to accelerating losses in serviceability of these thermoplastic pavements and has become an annual multimillion dollar problem in the northern tier of states in the United States and bordering provinces of Canada.

Cracking of bituminous surfaces may occur from causes other than the excessive tensile stresses developed by high thermal gradients. Other internal forces can result from in-service asphalt cement aging and from moisture absorption and loss in mixes containing absorptive aggregates. External tensile forces in a surface course can be caused by reflective cracking, i.e., volume change of the subgrade or of the base course or both from moisture loss. Tensile stresses are also developed from the bending of the bituminous mat under traffic loadings from loss of support due to settlement of the subgrade and from differential swelling of the subgrade.

Usually, one or more of these causative factors contribute to pavement failure. However, this investigation is confined to the behavior, at low temperatures, of densely graded asphalt concrete.

LABORATORY INVESTIGATIONS

Objective

The primary objective is to standardize a method of making an asphalt concrete beam that, in the laboratory, has the density characteristics, homogeneity, and aggregate orientation of surface courses laid down by current paving equipment. Also, recommendations are made for measuring the rheologic behavior of asphalt concrete at low temperatures utilizing relatively simple equipment.

Justification

Procedures have been developed to measure directly the loading time and temperature dependence of mixtures by testing in compression, tension, and flexure. The types of tests include creep, stress relaxation, and constant rate-of-strain tests and the more complicated dynamic tests that apply sinusoidal loadings to a specimen or the repeated, or pulse-type, loading that simulates vehicle velocity. But whether the equipment utilized in a test is a simple compression machine applying a three-point beam load, a flexural-fatigue machine, or a console-mounted materials testing system with digital processor and analog computer, it is necessary to use a specimen that has "real-life" characteristics and is reproducible within an acceptable index of precision. A literature review indicates that some researchers have been disappointed in what they felt was a high coefficient of variation in test results, especially in flexural-fatigue work. Perhaps some of the deviations were caused by testing beams with nonuniform densities throughout their cross sections.

Because flexural stresses were to be applied to asphalt concrete in subsequent cold-temperature testing, a beam of rectangular cross section was chosen as the geometric form for the specimens. Also, when cutting samples from existing pavements for laboratory correlation, a beam shape is the most suitable for sawing and testing. Under ideal conditions, a bituminous pavement does not act as a beam but rather as a mat on an elastic foundation. Its layered system depends on its base course and subbase to spread traffic loads to the subgrade. But sometimes in the early spring when the wearing course is still frozen and the supporting elements are saturated, the stiffer surface layer resists most of the wheel loads and does indeed act as a beam.

Compaction by static, vibratory, and impact methods was rejected because the resulting beams were not acceptable from the standpoint of proper and uniform densities, particle orientation, and excessive aggregate degradation. Earlier works of beam testing at low temperatures by Davidson (1) and Stauss (2) were handicapped by the inability to produce beams that had uniform densities throughout the cross sections.

Equipment

The California kneading compactor (Fig. 1) was used to form the beams. Monismith (3), Kallas (4), and Hong (5) did pioneer work with the compactor and reported favorable results. The machine applies a kneading action to the hot, loose asphaltic mixture and simulates construction and traffic compaction. Mounted on the mechanical compactor is a sliding plate assembly that laterally moves the steel mold beneath a tamping foot (Fig. 2). Compaction is accomplished by applying a "kneading-like" pressure to the asphaltic mixture in the mold through the tamping foot by means of a controlled slow-speed dynamic force, a balancing air pressure, and the cushioning action of a helical spring. The tamper travels up and down through a distance of about 4 in., alternately applying and releasing a pressure on the mix in a time cycle of 2 sec per stroke. The load exerted by the tamper is regulated by air pressure in the oil reservoir.

Materials

Two types of aggregates were used: a crushed gravel containing a mixture of limestone and igneous material and a crushed stone of dolomite composition. Their grain-size accumulation curves are shown in Figure 3. The gradations were kept constant. The gravel meets Wisconsin specifications and has an acceptable service record in

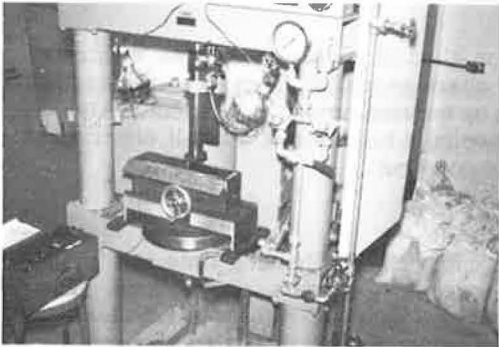Figure 1. California kneading compactor.

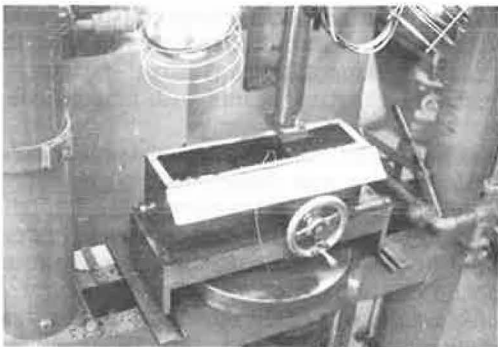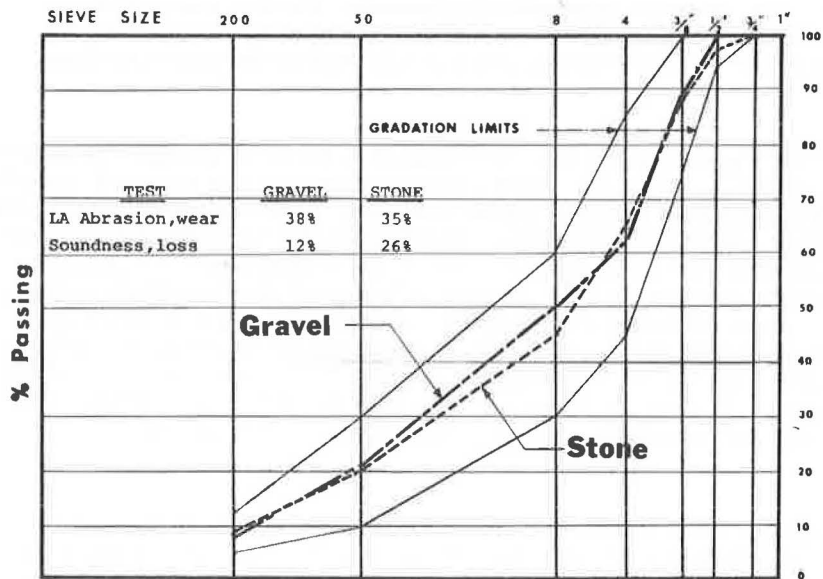

Figure 2. Beam mold assembly.

Figure 3. Grain-size accumulation curves.

asphalt pavements in Wisconsin. The crushed stone was rejected as an asphalt concrete aggregate because it failed the five-cycle sodium sulfate soundness test with a weighted loss of 26 percent. Standard specifications of the Wisconsin Division of Highways state that the weighted loss shall not exceed 18 percent, unless 12 percent is specified by special provision. This stone was used in beam making to test the effects of the kneading compactor on aggregate degradation.

Five different asphalt cements were used, ranging from the stiff 40 to 50 penetration grade to the very soft 200 to 300 penetration grade, including 60 to 70, 85 to 100, and 150 to 200 penetration grades. Because viscosity control was used during mixing and compacting operations, the penetration properties of the cements at the standard 77 F were "equalized" during the beam-making process. Mixing was done at the temperature that produced a viscosity of 170 ± 20 cs. This was analogous to mean temperatures varying from 315 F for the 40 to 50 penetration grade to 272 F for the 200 to 300 penetration grade asphalt. Compacting of the mixture was done at 500 ± 50 cs, which corresponds to mean compacting temperature of 275 F for the 40 to 50 penetration grade and 234 F for the 200 to 300 penetration grade asphalt. The higher compaction viscosity is a departure from the present 280 ± 30 cs of ASTM D 1559 (Marshall test). The works of Kallas (6) and Bahri and Rader (7) support the use of the higher compaction viscosity. The range of mixing temperatures and compacting temperatures corresponding to the 170 ± 20 cs and 500 ± 50 are best determined from the plot of log temperature versus log-log viscosity for each asphalt cement. A typical curve is shown in Figure 4.

LABORATORY RESULTS

The finished beams, made by the proposed standard method shown in the Appendix, were examined for acceptable densities, for homogeneity throughout their cross sections, and for particle orientation.

The frequency distribution of the bulk specific gravities of 72 beams is shown in Figure 5. A plot of the accumulative "less than" percentage distribution of the densities on probability graph paper indicates that the data fit the pattern of a normal curve. Using normal curve theory, we found that about 97.5 percent of the beams formed by the proposed procedures had air voids between 2 and 6 percent (Wisconsin Division of Highways' specifications), about 2 percent had less than 2 percent air voids, and 0.5 percent of the beams had more than 6 percent air voids. The mean density of all of the beams was 149.25 lb/ft^3, with a standard deviation of 1.25 lb/ft^3, or, as a better measure, a coefficient of variation of 0.84 percent.

The Pearsonian coefficient of skewness of -0.15 indicates a slight tendency toward producing more beams on the "heavy" side (lower air voids content).

The internal dispersion of densities of the beam was checked by cutting into sixths each of the 72 beams—sawed in half along their lengths and transversely at the third points—and obtaining their bulk specific gravities. Here a slightly greater spread of densities was found, with a standard deviation of 1.40 lb/ft^3 and a coefficient of variation of 1.1 percent.

A visual nonquantitative scrutinization of many sawed faces showed that most of the large aggregates were embedded in the mixture with their short axes in the vertical direction. This indicates that the kneading action of the compactor does indeed produce specimens whose particle orientation is similar to that produced in "real life" in pavements.

For a quantitative approach to determine the distribution of coarse aggregates within a beam, a densitometer was utilized. This plotter automatically reads closely spaced optical density gradations of film. The measurements are translated into levels of 10 percent increments that are digitally printed by an electric typewriter. The film reader, consisting of the light source and photodetector, is mounted on top of the typewriter carriage. Output is a voltage directly proportional to the optical density of the film, and an exponential converter linearizes the information on the film. Beams were transversely sawed at four random points, their cross sections were photographed, and the films were enlarged to 8- by 10-in. sheets. At 10 characters per second and 168 units of resolution per square inch, the outputwriter prints out the film densities in 10 incre-

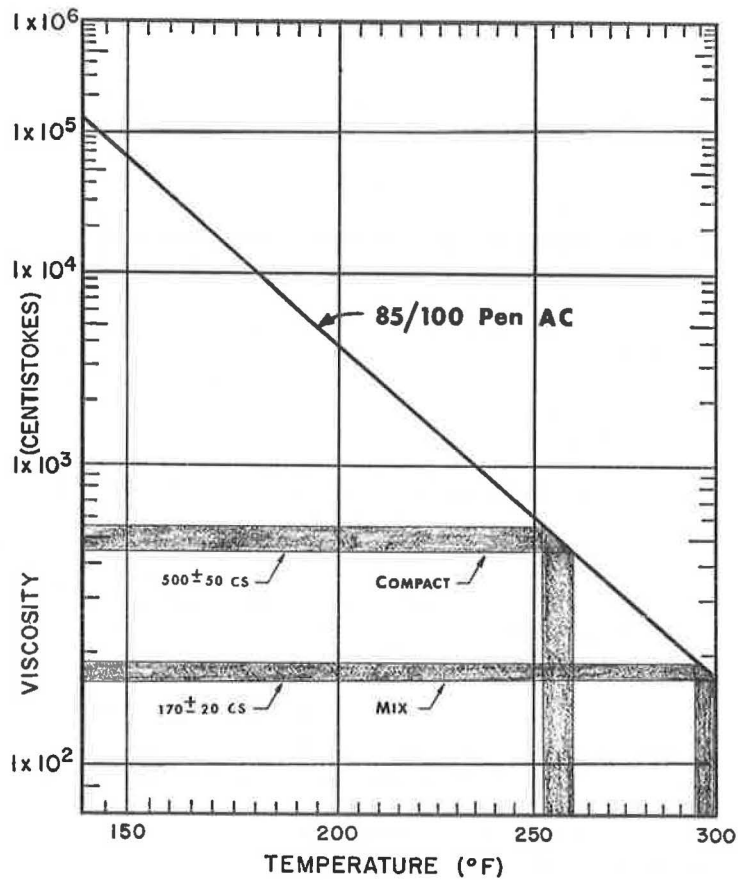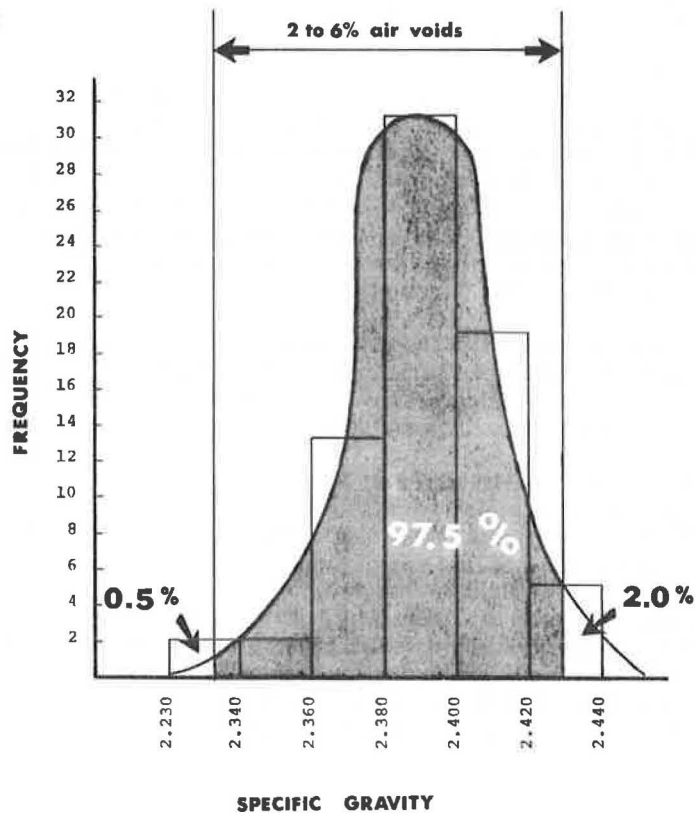Figure 4. Mixing and compacting temperatures.

Figure 5. Frequency distribution of specific gravities.

ments from 1 to 0; 1 is white and 0 is black. The light aggregate sections are shown
in high contrast within the dark asphaltic binder background, so contouring the course
aggregates and obtaining the proportion of their areas to the binder can be readily ac-
complished. Figure 6 shows a typical beam cross section, and Figure 7 shows its
digital densitometer printout.

Readings of the printouts from the four beam cross sections indicated that the coarser
aggregates (retained on the No. 8 sieve and larger) occupied 34, 37, 35, and 39 percent
of the sawed surface areas. The symbol density of 14 characters per horizontal inch
and 12 characters per vertical inch precluded the identification of finer aggregates. The
uniformity of the coarse aggregate distribution, as measured by densitometer measure-
ments, suggests that a relatively homogeneous beam was produced.

Specifications dictate that the hot mixture be compacted at a viscosity of 500 ± 50 cs.
The heat loss of the mixture during the 11 min required to complete one beam was de-
termined by burying a copper-constantan thermocouple in the hot mix and plotting the
millivolt (temperature) versus time curve (Fig. 8). In 11 min, the temperature of the mix
dropped 9 F. Referring to Figure 4, the viscosity-temperature curve of the asphalt
cement used, the temperature range that corresponds to the viscosity range of 550 to
450 cs is from 253 to 262 F. This means that the beam was compacted entirely within
the recommended viscosity limits. It should be noted that asphalt cements of greater
temperature sensitivities (steeper slopes) would have smaller temperature tolerances
to maintain the 500 ± 50 cs. Figures 1 and 2 show a pair of infrared lamps clamped
above the beam apparatus. It was found that the envelope of heat from the two 275-watt
bulbs surrounding the mold materially reduced temperature losses during compaction.

The maximum dynamic pressure applied to the mixture during compaction is 300 psi,
and, although the tamper blow is cushioned by a spring and is less severe than that from
standard impact hammers, some degradation of aggregate does occur. The severity of
the degradation was tested by forming beams with acceptable crushed-gravel aggregate
and with a rejected crushed stone. A modified extraction process was used to extract
and sift the aggregates. The "before and after" curves are shown in Figures 9 and 10.
The gravel showed little disintegration, but the crushed stone broke down at all frac-
tions, the percentage finer than the No. 200 sieve increasing from 8½ to 19 percent.
The grain-size accumulation curves show that the compacting forces, although produc-
ing beams of high densities, are responsive to the strength characteristics of the ag-
gregates.

The specifications state that the beam should be made in two lifts and that three
separate and different compactive efforts should be applied to their surfaces as follows:

    1. Bottom layer—40 tamps at 75 psi, 40 tamps at 100 psi, and 40 tamps at 200 psi;
    2. Top layer—40 tamps at 75 psi, 40 tamps at 100 psi, 40 tamps at 200 psi; and
60 tamps at 300 psi; and
    3. Top layer—400 psi static load.

The effects of the three accumulative forces on a beam density, as measured by air
voids, are shown in Figure 11. The significance of the static load is evident. It is not
merely a cosmetic treatment to the top surface for smoothing the imprints left by the
tamping action, but it acts to increase the densities of both layers. More importantly,
the static load minimizes the inevitable density differences between top and bottom lay-
ers and reduces the relative variations within the beam. In the finished beam, the ends
and middle sections of the top layer have air voids contents that vary from the mean by
about 0.04 percent; in the bottom layer the deviation is 0.03 percent. Overall, the coef-
ficient of variation among the six segments of the whole beam is approximately 1 per-
cent.

RECOMMENDATIONS

The HRB Committee on Design of Bituminous Paving Mixtures emphasized the im-
portance of bituminous pavements being designed to resist cracking and stated that "the
desirability of nonbrittleness at low temperatures in a bituminous pavement has been
recognized for many years and is considered to be fully as important as stability from
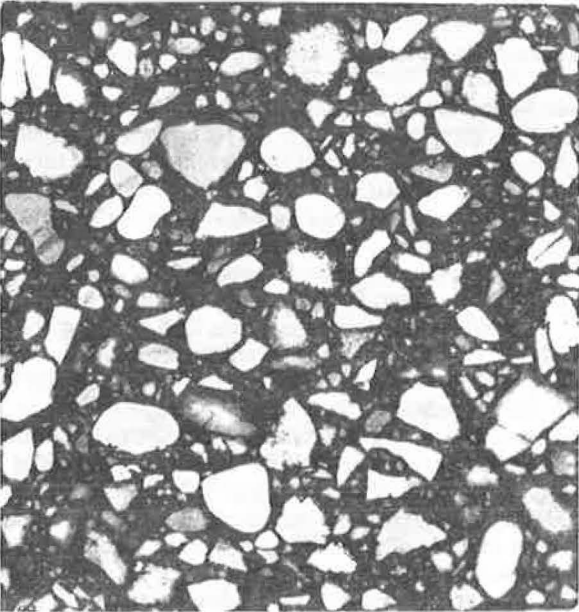
Figure 6. Typical beam cross section.

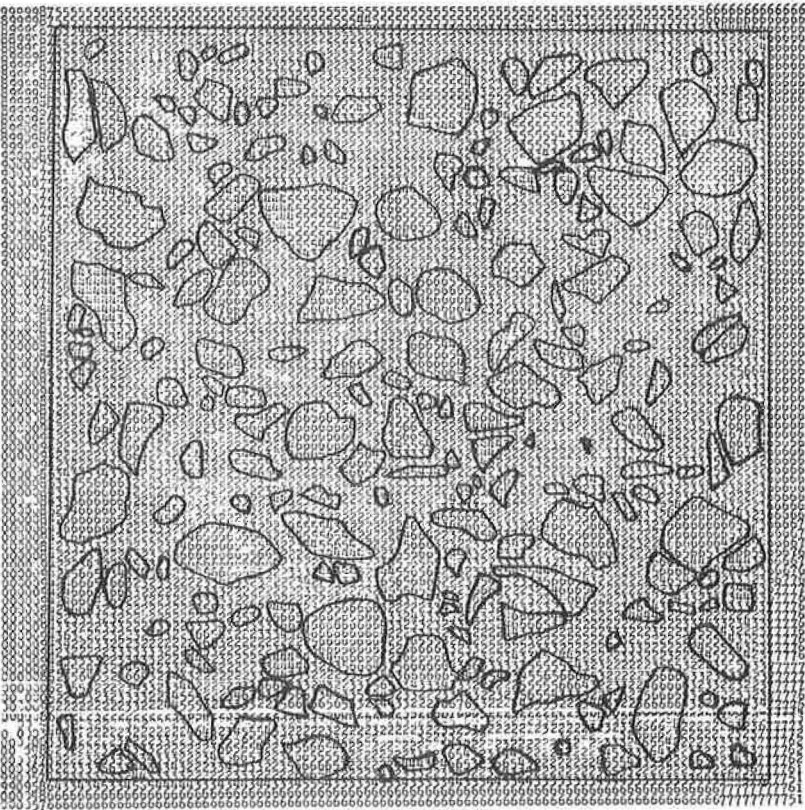**Figure 7. Digital densitometer printout of Figure 6.**

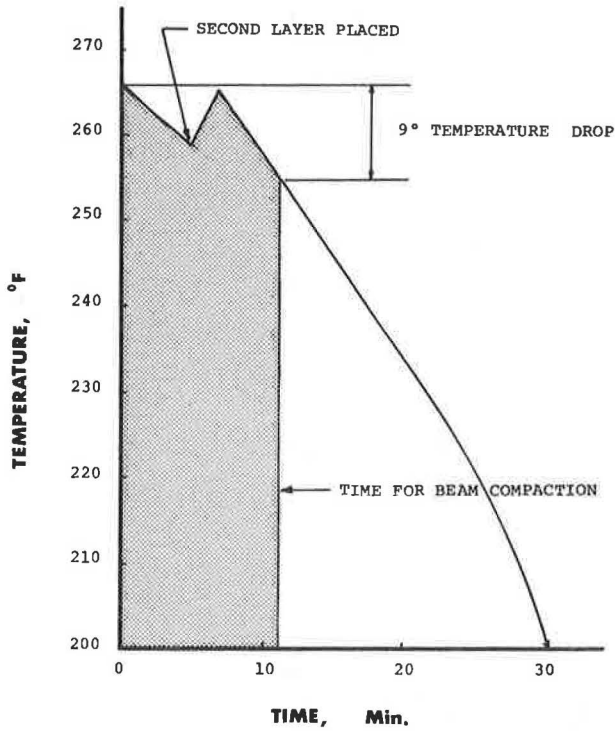**Figure 8. Heat loss during compaction.**

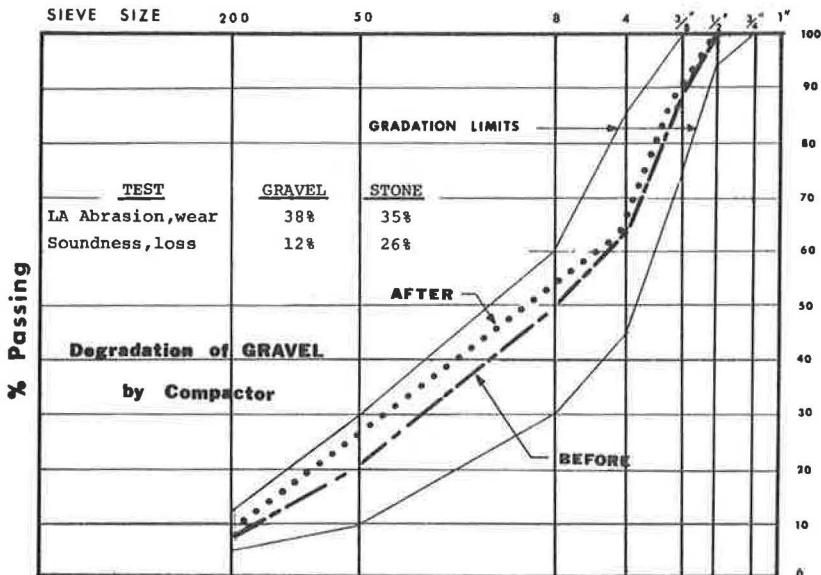**Figure 9. Grain-size accumulation curves (degradation of gravel).**

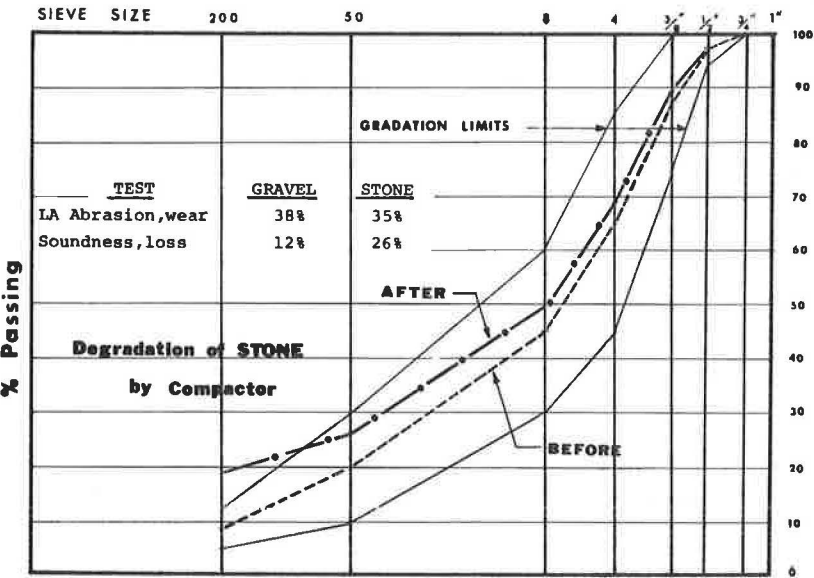**Figure 10. Grain-size accumulation curves (degradation of stone).**

Figure 11. Effects of compact loadings on beam density.

I Loadings

40 tamps @ 75 psi
40 " @ 100
40 " @ 200

AV = 5.22%   AV = 5.00%   AV = 4.78%

x̄=5.00%
CV=4.05%
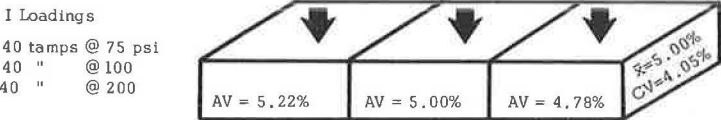
BOTTOM LAYER (tamping load)

II Loadings

40 tamps @ 75 psi
40 " @ 100
40 " @ 200
60 " @ 300

5.89%   5.80%   5.98%

3.98%   3.77%   4.07%

x̄=5.89%
CV=1.40%
x̄=3.94%
CV=3.60%
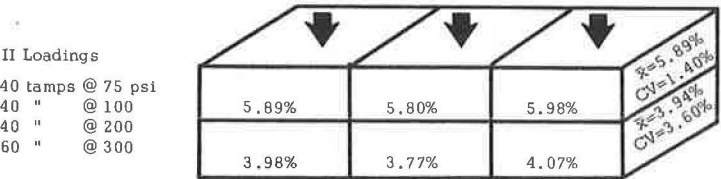
AV = Air Voids
x̄ = Mean
CV = Coeff. of Variation

TOP LAYER (tamping load)

III Loadings

Static load of
400 psi @ 0.25"/min.
held for 1 min.

3.42%   3.38%   3.46%

3.25%   3.25%   3.20%

x̄=3.42%
CV=1.06%
x̄=3.23%
CV=0.80%
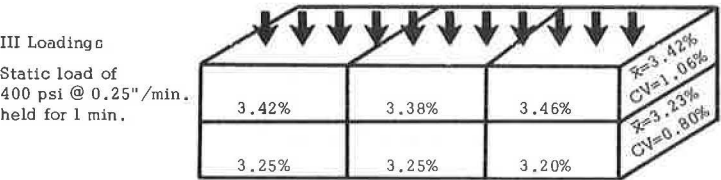
TOP LAYER (static load)

the standpoint of maintaining desirable physical characteristics and rendering good service. Flexural tests conducted on beams of bituminous paving mixtures at low temperatures to establish the modulus of rupture and modulus of elasticity were suggested as possible tests methods. These methods have not received wide acceptance, probably due to a variety of factors, not the least of which is the relative difficulty in preparing suitable specimens." Because it was felt that a method of "preparing suitable specimens" had been devised, the testing of mixtures at low temperatures followed.

Some 37 years ago, Rader (8) wrote: "Quantitative data obtained from low temperature tests should aid engineers in solving problems relating to control of cracking." In 1968, Haas and Topper (9) noted that "The appreciation of this need seems to have lain relatively dormant though until the markedly increased attention given to low-temperature cracking during the past five years." Except for some recent work in Alberta, design supplements for bituminous concrete pavements in cold climates have not been developed.

Current methods of designing paving mixtures seek an end product that has a certain minimum stability at an expected maximum summer temperature, a deformation or flow within limits at the same high temperature, and specified ranges of air voids and voids in the mineral aggregate. Also, various physical and chemical constraints are placed on the asphalt cements and aggregates. In concert, these are supposed to bear some relation to the in-service performance of the asphalt-aggregate system. But most of the criteria are high-temperature oriented and are little related to the range of environmental conditions that the pavement will be subjected to—especially in cold climates. There seems to have been the assumption that high-temperature stability and deformation were the most important considerations and that, because stability increases rapidly with decreasing temperatures, the requirements for design criteria were taken care of.

The search then is for a predictive technique that can foretell the condition of an asphalt paving mixture under a specific low-temperature condition. This procedure should apply to mixtures of different combinations from different sources and having different types of asphalt cement.

From flexural tests on asphalt concrete beams, the moduli of elasticity and moduli of rupture can be calculated. These indexes measure stiffness and bending strengths at the conditions that exist during testing. Formulas from the elastic theory are permissible in the calculations because the specimens are in an elastic state at low temperatures. The full-sized beam (15 by $3\frac{1}{4}$ by $3\frac{1}{2}$ in.) is used. Some researchers have been sawing the beam into quarters, $1\frac{1}{4}$- by $1\frac{1}{4}$-in. cross sections; however, Kallas and Puzinauskas (10) found that, by using full-sized beams, the variability of their flexural fatigue tests was reduced. Correlation coefficients ranging from 0.91 to 0.99 were obtained for stress-fracture life and strain-fracture life regression lines.

Busby and Rader (11) have developed procedures for predicting the stiffness of asphalt concrete mixtures at low temperatures. The aggregate gradation was kept constant for any one family of curves, and the beams were formed of mixtures made with various grades of asphalt cements. At some low temperatures (+25, -5, -35 F), the beams were tested in flexure by three-point loadings (loading at center) at a constant rate of strain. The deflection and load at failure together with the geometrics of the beam were used to calculate the moduli of rupture and stiffness. The rupture moduli remained fairly constant at temperatures below -5 F, and a minimum modulus of 800 psi at -5 F was suggested as a design standard for cold-weather areas. Curves of stiffness moduli and temperature were plotted for each mixture, and regression analyses showed high correlation between stiffness and temperature. From the conclusions of McLeod (12) and Phang (13) and working through Van der Poel's stiffness nomographs, it was determined that (for these mixes) cracking could be expected at a flexural stiffness modulus of 300,000 psi minimum. A flexural stiffness modulus of 250,000 psi maximum, which allows for experimental error and in-service hardening, was recommended as a design guide. By placing the limiting 250,000-psi line on the stiffness-temperature curves, the minimum design temperature for thermal crack prevention can be determined for each mixture. From these data, another curve of minimum design temperature and original penetration at 77 F of asphalt cement can be used to

check the minimum penetration grade of asphalt cement that could safely be specified according to the anticipated low temperature of the area. The highest penetration grade cement consistent with high-temperature stability should be selected.

Busby and Rader (14) have also suggested that the slope of the flexural stiffness-temperature curve be used to identify cements that cause premature cracking at low temperatures. This temperature susceptibility slope (TSS), which measures the tendency for a cement to crack, is taken from the -20 F to +20 F segment of the curve and is measured in psi per degree F. A maximum allowable TSS of 6,000 psi/deg F is proposed for a densely graded surface course.

CONCLUSIONS

Upon examining and testing random samples of the finished product, it is evident that the proposed standard method can consistently produce homogeneous beams of acceptable densities and aggregate arrangement. These results are the efforts of two operators working independently in the same laboratory. A series of exercises in several laboratories would more rigorously put the process to the test.

It appears feasible that the forming and testing of beams to determine some of the rheological characteristics of paving mixtures could be conducted in the materials laboratories of state highway departments and municipal and commercial organizations. The equipment described is at hand in laboratories or available at no great cost. Departments could design bituminous pavements to resist low temperatures by working directly with the aggregates and asphalt cements common to the area. Perhaps some asphalt cements that now meet specifications but are deficient in low-temperature considerations would be eliminated from use in surface courses. Some asphalt cements equally graded at 140 F viscosity were shown to behave erratically at low temperatures, and their different susceptibilities could be known only by testing them in mixes. Regional curves could be developed that would restrict bitumens with high sensibilities to thermal variation, and the acceptable asphalt cements could be selected from their temperature-penetration grade relations.

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APPENDIX

BEAM-FORMING METHOD

This method covers the preparation of beams of bituminous paving mixtures by means of a mechanical compactor that imparts a kneading action compacting the beam by a series of individual impressions made with a ram.

Apparatus

The following equipment is used in the method:

1. California kneading compactor—a mechanical kneading compactor in accordance with ASTM D 1561;
2. Compactor foot—a ram 2.0 by 3.0 in.;
3. Mold—a beam mold with inside dimensions of 15 in. long, $3\frac{1}{4}$ in. wide, and $4\frac{1}{2}$ in. high;
4. Sliding base assembly—an assembly attached to kneading compactor with a hand wheel for moving mold laterally during compaction;
5. Extraction assembly—a beam specimen extraction assembly;
6. Paper—sheets of heavy paper $3\frac{1}{4}$ by 15 in.;
7. Ovens—electric ovens capable of maintaining temperatures of 200 to 325 F ± 5 F;
8. Testing machine—a comparison testing machine having a minimum capacity of 50,000 lb;
9. Balance—a balance having a capacity of 5 kg or more and sensitive to 1.0 g or less; and
10. Miscellaneous apparatus—thermometer, spatulas, spoons, gloves, metal pans, and mechanical mixer.

Test Specimens

Approximately 6,800 g of the bituminous mixture shall be prepared in accordance with ASTM D 1560, sections 3.1, 3.2, and 3.3 except for specific requirements given in this Appendix.

The beam test specimens shall have a rectangular cross section $3\frac{1}{4}$ in. wide, $3\frac{1}{2}$ in. deep, and 15 in. long.

Procedure

The mixing temperatures shall be those corresponding to an asphalt viscosity of 170 ± 20 cs. Compaction temperatures shall be those corresponding to an asphalt viscosity of 500 ± 50 cs.

Heat the mold to the compaction temperature specified previously. Lightly oil the mold and tamping foot. Place three sheets of $3\frac{1}{4}$- by 15-in. paper on the mold base-plate. The compactor foot is maintained sufficiently hot to prevent the mixture from adhering to it. Place one-half of the required amount of mixture for one specimen in the mold in a uniform layer. When applying tamping blows to the mixture, turn the base assembly handwheel one-quarter revolution to move the mold laterally $1\frac{1}{2}$ in. after each tamping blow. Apply 40 tamping blows at a foot pressure of 75 psi, followed by 40 blows at 100-psi and 40 blows at 200-psi foot pressure. Place the remaining half of the mixture in the mold and apply 40 tamps at 75 psi to settle the loose mix. Follow with 40 blows at 100-psi, 40 blows at 200-psi, and 60 blows at 300-psi foot pressure. If unstable material is involved and there is undue movement of the mixture under the compactor foot, the foot pressure shall be reduced until the kneading compaction can be accomplished.

Immediately after compaction in the California kneading compactor, place the heated and slightly oiled leveling bar on top of the specimen. Using a compression testing machine, apply a static load on the specimen at the rate of 0.25 in. per min until an applied pressure of 400 psi is reached. Maintain the applied pressure for a period of 1 min and then slowly release the pressure. After the compacted specimen

has cooled sufficiently so that it will not deform on handling, remove it from the mold by means of the extraction assembly. Place the specimen on a smooth, flat surface and allow to cool to room temperature.

Some of the diverse beam fabrication procedures by others are given in Table 1.

Table 1. Beam-making methods.

Study	Layer	Compactive Effort	Mixing Temperature (deg F)	Compaction Temperature (deg F)
A	1 2	30 tamps at 200 psi 45 tamps at 200 psi, 45 tamps at 300 psi	250 to 300	230
B	1 2 3	20 tamps at 145 psi 25 tamps at 290 psi 20 tamps at 145 psi, 50 tamps at 290 psi	250	Not available
C	1 2 3	20 tamps at "low pressure" 45 tamps at 400 psi 20 tamps at "low pressure," 45 tamps at 400 psi, 75 tamps at 400 psi	250	230
D	1, 2	40 tamps at 50, 120, 190, 260, 330, 400 psi	250 to 300	230
E	1, 2 3	45 tamps at 400 psi 115 tamps at 400 psi	250	250
F	1, 2 3	25 tamps at 400 psi 100 tamps at 400 psi	250	250

Note: Static leveling load for studies A, C, D, and E was 400 psi; for study B it was 300 psi; and for study F it was 350 psi.