Investigation of the Brittle-Plastic Behavior of Asphalt Mixtures by Use of an Impact Device

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Because much of the longitudinal cracking that develops in asphaltic concrete pavements throughout Connecticut cannot be attributed to base or subgrade failures, one hypothesis is that the cracking is due, in part, to the brittleness of the pavement at low temperatures. The purpose of this laboratory investigation was to study the relative brittle-plastic behavior of some asphalt mixtures. The pendulum-hammer impact device used was able to define the transition temperature ranges for the asphalt cements and the medium-cure asphalt used. The temperature range of -10 to 140 F was investigated. The effects of change in size, aggregate gradation, velocity of impact, and asphalt content were also considered.

For the paving grade asphalts studies, the transition temperature ranges shifted toward the colder temperatures as the penetration increased. The transition temperature range for the liquid asphalt studies was the lowest. The energy-absorbed values increased linearly with increasing impact velocity. Asphalt content had a significant effect on failure energy for samples tested at relatively high temperatures but had only a negligible effect at lower temperatures. A statistical model was developed for prediction of the energy-absorbed values through knowledge of the environmental temperature and asphalt content.

•SOME of the longitudinal cracking that develops in asphaltic concrete pavements apparently cannot be attributed to base or subgrade failures. A possible explanation is that, since asphalt is highly temperature-susceptible, it becomes somewhat rigid and therefore brittle at low temperatures. As a consequence it cannot resist the tensile stresses induced by wheel loads. Therefore, working on the hypothesis that longitudinal cracking of asphalt pavements is due, in part, to the brittleness of the pavement at low temperatures, it is the purpose of this investigation to study the relative brittle-plastic behavior of some asphalt mixtures.

Some research on the behavior of asphalt materials under dynamic loading has been conducted by researchers in an attempt to learn the detailed mechanisms of deformation and fracture. Such work as has been done was usually performed with the material at room temperature. Very little work has been done at temperatures below freezing. Also, the work that has been conducted at temperatures below freezing was usually performed under static or slowly applied loading. Notable among this work is that of Rader (1) and Breen (2).

Since pavements are subjected to moving loads, a dynamic loading test would seem appropriate. To investigate the relative brittle-plastic behavior of a pavement, the authors felt that a new approach might be beneficial.

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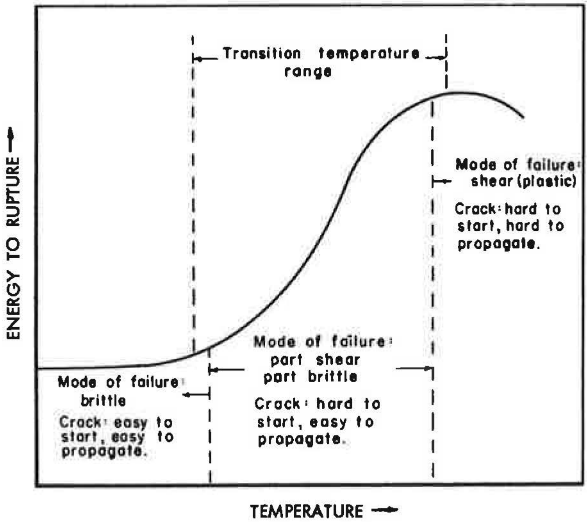

Figure 1. Variation of energy to rupture with temperature for metals.

Impact tests performed on certain metals have demonstrated that temperature has, among other things, a very marked effect on the strength and ductility of the material. For a particular metal, below a specific temperature, the failures are brittle with low energy absorption. Above a specific temperature, the failures are ductile with energy absorption that may be many times that in the brittle-fracture range. Between these temperatures is what has been termed the "transition-temperature range," where the character of the fracture may be mixed. This variation of energy absorbed with temperature is shown in Figure 1, adapted from Davis, Troxell, and Wiskocil (3).

Assuming that asphalt behaves in a similar manner when subjected to an impact load, it should be possible to determine the temperature below which pavement will fail in a brittle fashion. Four different types of asphalt, five asphalt contents, and an environmental temperature range from -10 to 140 F are the variables considered in this study.

While impact tests have provided valuable information about the relative brittle-plastic nature of metals and plastics subjected to a wide temperature range, they have provided little, if any, similar information on the behavior of asphalt mixtures. Many researchers (4, 5, 6) have shown the transitions between plastic and brittle behavior of many different steels and alloys. Other researchers (7, 8, 9) have shown the temperature variation of many types of plastics. Even though a definite transition region does not exist with the plastic materials, these variations do indicate, in general, an increase in impact energy as the temperature increases to a point, then a decrease as the temperature continues to increase. Gordon (10) has investigated the dynamic properties of high polymers. His results on the mechanical energy absorption with temperature variation for ball impact on polymethyl methacrylate indicate that the "dynamic glass-transition" point for this particular polymer is about 160 C. While primarily a study on the minute molecular chain segments of this polymer, the general variation of energy absorbed with temperature is apparent.

All these investigations, however, have one thing in common. Each indicated that as the temperature was decreased the material exhibited an increased susceptibility to fail in a brittle manner.

Some work on the impact resistance of bituminous materials has been conducted by Pfeiffer (11), Smith (12), Manton and Wren (13), Tregoning (14), Lethersich (15), and Rader (1). With the exception of Rader's work, though, no direct information is available relating the effect of temperature variation with energy absorption. Much of the research was conducted on asphalt or mineral filler-asphalt mixtures and not on mixtures actually used for road construction. Therefore, a need exists for this investigation of the temperature-impact variation.

This investigation was based on a "fixed variable" statistical design (16). The analysis of variance and multiple regression analysis (17) were performed on a IBM 7040 computer at the University of Connecticut's Computer Center. A detailed discussion of the significance of the results appears in a later section.

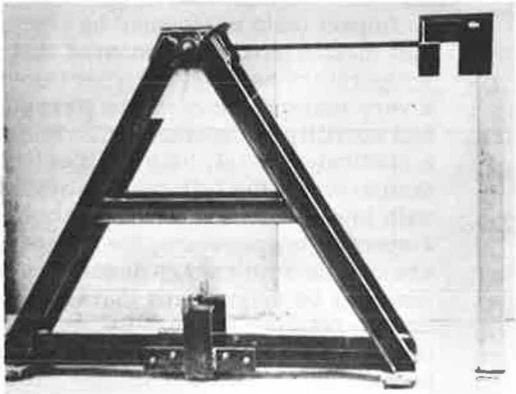

Figure 2. Impact device with pendulum-hammer set at an angle of 90 deg from vertical, ready to be released.

TABLE 1

SAND SHEET GRADATION

Sieve Size	Percent Retained	Weight Used (grams)
½-in.	0	0
⅜-in.	7.5	82.5
No. 4	12.5	55.0
No. 8	20.5	88.0
No. 16	32.5	132.0
No. 30	55.0	247.5
No. 50	77.5	247.5
No. 100	90.0	137.5
No. 200	95.0	55.0
Pan	100.0	55.0

THE PENDULUM IMPACT TESTER

After consideration of the various types of impact devices, the Standard Page Impact Tester, Izod, and Charpy testers, it was felt that a modified Charpy pendulum device offered the most practical advantages. The device used is shown in Figure 2. The pendulum hammer weighed 9.02 lb with its center of percussion at the center of the striking edge. The impact tester has a maximum potential energy of 244.27 in.-lb, and a maximum velocity at impact of 163.3 ips.

It is recognized that there are several losses inherent in this type of impact test, but since the primary objective of this investigation is to determine the relative impact values of the several types of asphalt mixtures, the losses will for the present only be mentioned. The impact values are affected by (a) air drag, (b) energy absorbed by friction in the machine bearing and by the indicator arm, and (c) energy used in moving the broken test piece. A more complete discussion of these losses is given later.

MATERIALS AND SAMPLE PREPARATION

The aggregates used in this investigation, obtained from local river terrace gravel, were washed, dried, sieved into respective sizes, and recombined by weight in the proportions given in Table 1. This gradation was used throughout the investigation. The mineral filler was obtained from material passing the number 200 sieve.

Asphalt

Three paving grades of widely varying penetration and one liquid asphalt were used in the investigation. A 30 penetration, 85-100 penetration, and 180-200 penetration asphalt cement (the crude from Panuco, Mexico) were supplied by Mobil Oil Corporation. The liquid asphalt, designated an MC-5, was supplied by the Chevron Oil Company's Asphalt Division. The properties of the asphalt cement and liquid asphalt are given in Tables 2 and 3.

Asphalt Mixtures

The aggregate and asphalt were heated separately and then combined in a mixing operation. The asphalts and aggregate were heated in separate ovens for a period of one hour at a temperature of 300 F. The aggregate and asphalt were weighed and then mixed in a mechanical mixer for 2 minutes; 1100 grams of aggregate, and the percentage of asphalt based on the total weight, were used for each sample. The mixture was placed in a 1 by 5 by 7-in. rectangular steel mold in three layers, each rodded 30 times. The mixture in the mold was then subjected to a double plunger compactive load of 14,000 pounds. The samples were extruded and cured for 6 days at room temperature, 77 ±3 F. The samples were then cut into three 1 by 1¼ by 7-in. rectangular specimens and tested the seventh day (Fig. 3).

TABLE 2

PROPERTIES OF ASPHALT

Property	Grade		
	30	85-100	180-200
Penetration, 100g, 5 sec, 77 F	30	93	224
Soft point, F	139	117	105
Flash point, C. O. C. F	585	520	490
Viscosity est. at 275 F	890	375	215
300	510	220	125
350	150	81	55
Ductility 5 cm/min, 77 F	110+	110+	110+
Specific gravity, 60 F/60 F	1.069	1.050	1.041
Solubility in CCl_4, %	99.9	99.8	99.8
Thin film loss, % wt	0.13	0.41	2.20

Testing

Each specimen was placed in the desired temperature environment for 30 minutes before being tested. A water bath was used for temperatures in the range from 40 to 140 F. Between 40 and -10 F a cold-air environment was used. The specimens subjected to a water environment were wiped dry and tested in the impact tester. For all testing in the main investigation, the pendulum hammer was released from an angle of 90 deg. In preliminary tests, the effect of varying velocity was studied by releasing the pendulum hammer from different heights as discussed later. The specimens were supported as simple beams with an unsupported length of 4½ in. The specimens were not notched. A final angle reading was taken in each case and subtracted from the original angle. This difference was then multiplied by the weight and distance to the center of gravity of the pendulum hammer to give an energy absorption value. With no specimens in the device, the pendulum hammer would swing freely to a final angle of 90 deg. Generally, for specimens subjected to the colder temperatures, 40 and -10 F, the maximum final angle recorded was 85.5 deg. For specimens subjected to the warmer temperatures, from about 80 to 140 F, the maximum final angle recorded was 63.5 deg. With specimens in the device, the final angle varied in the range from 63.5 to 85.5 deg.

PRELIMINARY TESTING AND RESULTS

Before the main investigation, preliminary tests were conducted on a limited series to ascertain the effect certain variables had on the impact values. These variables—effect of gradation and area, effect of impact velocity, and temperature duration—are described below.

Effect of Gradation and Area

The effect of gradation on the impact values was examined at two temperatures, 50 and 80 F, with impact velocity constant at 137 ips. Three gradations were used: surface course grading No. 2 (19), sand sheet (20), and fine sheet (20). The asphalt used was a 60-70 penetration. As is evident from Figure 4, gradation had little effect on impact values. There appears to be no definite relationship between a change in gradation and impact values. This conclusion was based on a limited amount of data. Also from this figure, the effect of a change in cross-sectional area of the impact specimen on the energy values can be observed. As the cross-sectional area increases (width of specimen held constant), the impact values increase more and more rapidly. These tests were conducted at temperatures of -2, 23, 50, 80, and 140 F. At all temperatures,

TABLE 3

PROPERTIES OF LIQUID ASPHALT MC-5

Furol viscosity at 180 F, sec		548	
Flash point, C. O. C. F		270	
Distillation test	Temperature F		% of Total Distillate
	437		0
	500		4.97
	600		43.0
Percent residue		89.2	
Penetration of residue, 100g, 5 sec, 77 F		165	
Ductility of residue, 5 cm/min, 77 F		109	
Solubility of residue, CCl_4, percent		99.9	

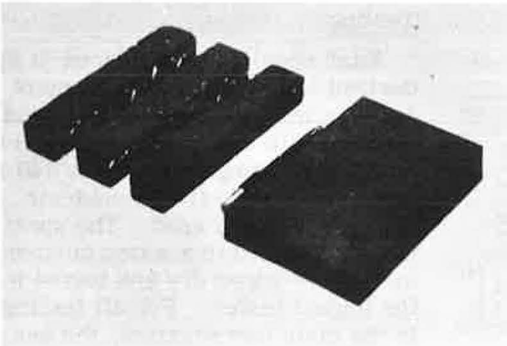

Figure 3. Impact specimens.

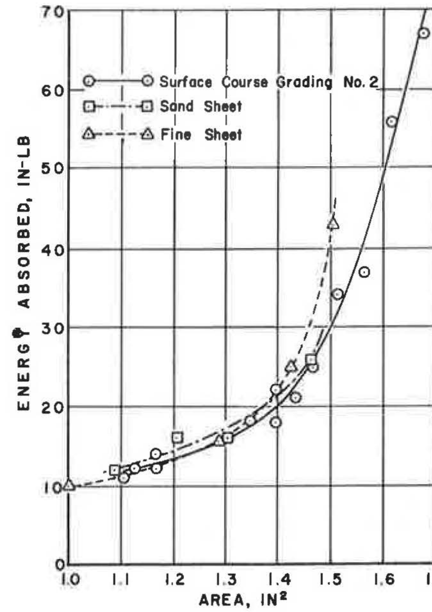

Figure 4. Plot of energy absorbed vs area for impact specimen at 50 F and 60-70 penetration asphalt.

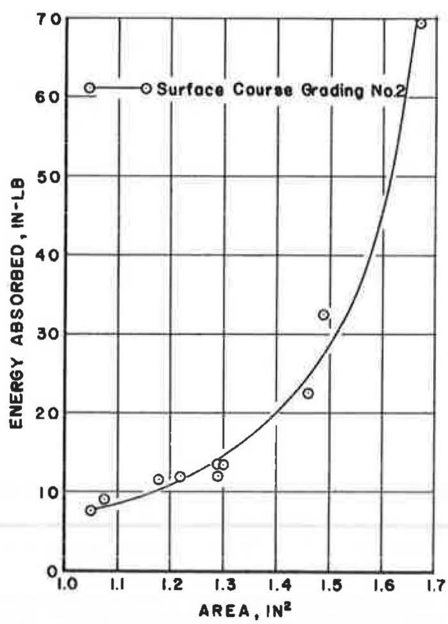

Figure 5. Plot of energy absorbed vs area for impact specimen at -2 F and 60-70 penetration asphalt.

impact values increased with temperature at an increasing rate. Fiugres 4, 5, and 6 are representative of the results.

Effect of Velocity

Using gradation A and 60-70 penetration asphalt, the effect of velocity at impact was examined at 0, 50 and 80 F. Velocities of 51.0, 74.0, 96.8, 137.0, and 163.3 ips were tested. These velocities correspond to initial angle release of 30, 45, 60, 90, and 115 deg respectively. The results appear in Figure 7. The relationship between energy absorbed and velocity at impact for each temperature increases linearly. This supports the apparent linear zone of Lethersich's (15) theoretical analysis of the relationship between impact energy and impact velocity. Lethersich theorized that this relationship, based on an equivalent mechanical circuit representing the behavior of bitumen under stress, would vary as shown in Figure 8. Hoppmann (21) called the point at which the energy value decreased sharply the "critical velocity."

The intent of this test series was to determine experimentaly if a "critical velocity" existed in the range of velocities possible. If so, more detailed studies of velocities would be required to insure that all materials would be tested in the same portion of the velocity-energy curve. None was found. However, Figure 7 does show the displacement of energy with temperature.

Temperature Duration

Initially there was some concern as to whether the 30-minute temperature conditioning period was sufficient for the impact specimens subjected to the cold-air environment

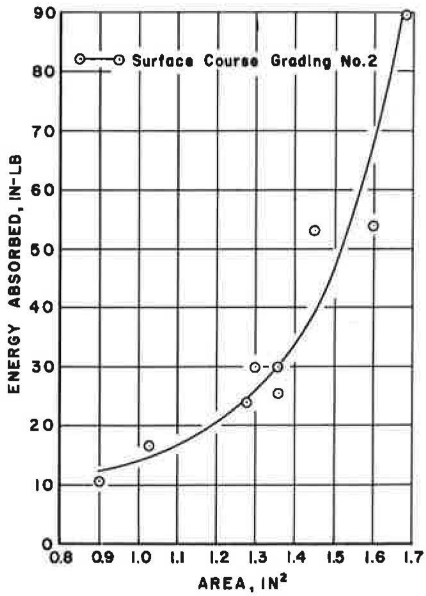

Figure 6. Plot of energy absorbed vs area for impact specimen at 140 F and 60-70 penetration asphalt.

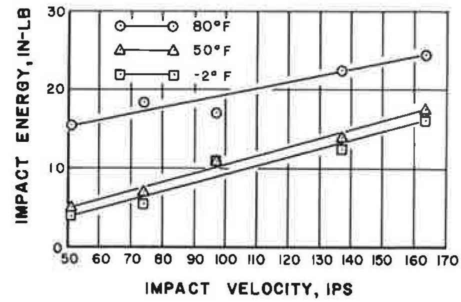

Figure 7. Plot of impact energy vs impact velocity for surface course grading No. 2, 6 percent AC, and 60-70 penetration asphalt.

to reach constant temperature throughout their interior. To evaluate conditioning time, a short series was conducted with specimens left in a 0 F air environment for periods of 15 minutes, 1 hour, and 1 day, and compared to the tentative 30-minute test period. At 15 minutes the impact value was 4.8 percent above that at 30 minutes. At 1 hour and 1 day the impact values were the same as the 30-minute value. Therefore, the 30-minute environment temperature duration before testing was deemed adequate.

Summary of Preliminary Testing

The "sand sheet" gradation, 137.0 ips impact velocity, and 30-minute test temperature duration were selected for the main investigation.

For the small cross-section used, unduly large aggregate could seriously affect individual energy values measured. In addition, large aggregate made molding 1-in. specimens without large voids very difficult. The lack of sensitivity to velocity made possible the selection of a velocity for ease of energy computation practical. Because no change in impact value was found for conditioning beyond 30 minutes, this time was used.

TEST RESULTS AND DISCUSSION

Figures 9, 10, 11, and 12 show the variation of energy absorbed with temperature for the four types of asphalt used. In these figures, each point represents the average of three tests. Of the five asphalt contents tested, only the 6 and 10 percent curves are shown in each figure because the 7, 8, and 9 percent curves would merely plot between these two. The transition range for each asphalt is clearly evident. For the 30 penetration asphalt, the transition range of approximately 100 to 132 F is the highest magnitude of the four types. The 85-100 penetration has a transition range from approximately 70 to 100 F, and the 180-200 penetration from 55 to 100 F. The MC-5 range, from 40 to 80 F, represents the lowest in magnitude. The abrupt transitions in the energy-temperature curves indicates that changes of state in the asphalt from an elastic, "rigid structure" state to an "elastic-viscous" state to a "mainly viscous" state are taking place. These pronounced rheological differences can possibly be explained in terms of the change in molecular structure of the asphalts as temperature changes.

Because the three paving grades were obtained by vacuum distillation of Panuco, Mexico, crude oil, a characteristic of this asphalt is its relatively high degree of oc-

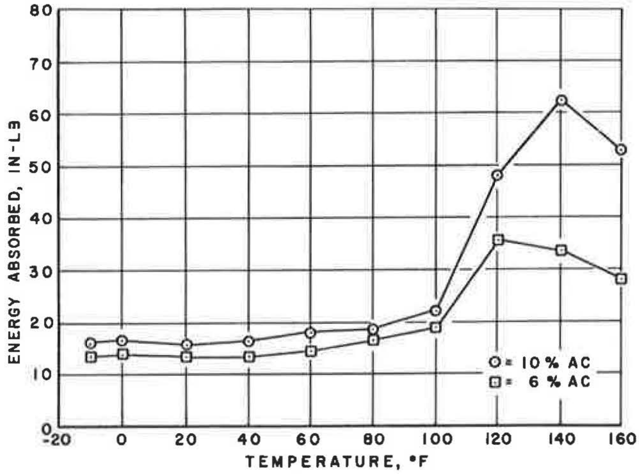

Figure 8. Relationship between impact energy to cause failure and impact velocity, after Lethersich (15).

currence of micelle formation. This micelle formation is in the direction of accretion of resinous matter onto asphaltene particles at ambient temperature (22). Micelles increase in size and content as an asphalt approaches the solid condition at lower temperatures. This gives rise to the formation of a rigid molecular structure and as such to a definite elastic-behaving material. Brittleness may then be the result of this appearance of elasticity with failure at corresponding low energy-absorbed values. At elevated temperatures the situation is reversed, with less strongly absorbed resins going into the outer (oil) phase in varying degrees, depending on the type of hydrocarbon and its chemical constitution. With a temperature rise beyond the peaks of the curves the kinetic energy of the molecules destroys the relatively weak forces (van der Waals forces) of attraction between asphaltenes and resins. As a consequence most of the elastic structure in the asphalt is broken up with the viscous condition predominating. Low energy-absorbed values can then be expected.

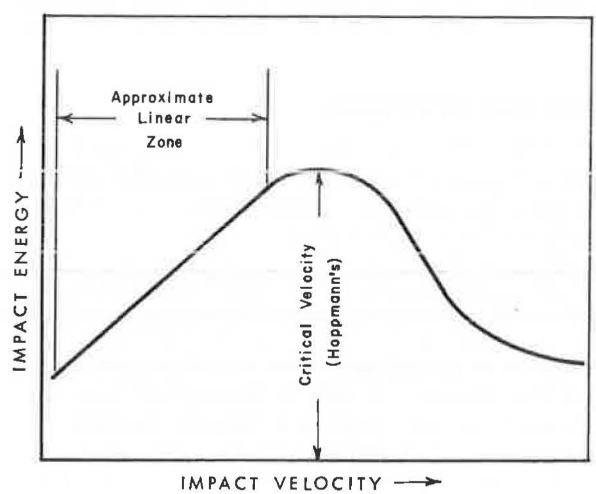

Figure 9. Average energy absorbed vs temperature for 30 pen asphalt mix.

In the transition temperature ranges, while the degree of micelle formation (elastic structure) is possibly being reduced, viscous effects are becoming more pronounced. The result is an asphalt in a relatively plastic state. In this state, the energy-absorbed values might tend to increase.

In a composite drawing, Figure 13, only the 10 percent asphalt content of each type is shown, but clearly evident is the shift of the transition range to the lower temperatures as the penetration is increased. It is apparent from Figure 13 that the maximum energy-absorbed values for each asphalt type are approximately equal in magnitude if tangent lines are drawn from the two extreme sloping lines of the 30 and 85-

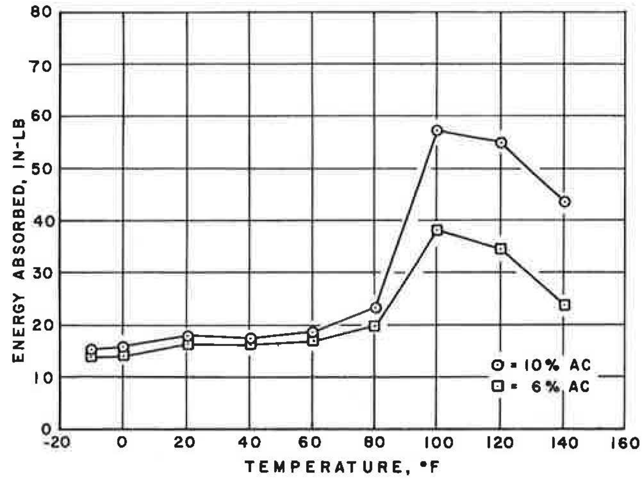

Figure 10. Average energy absorbed vs temperature for 85-100 pen asphalt mix.

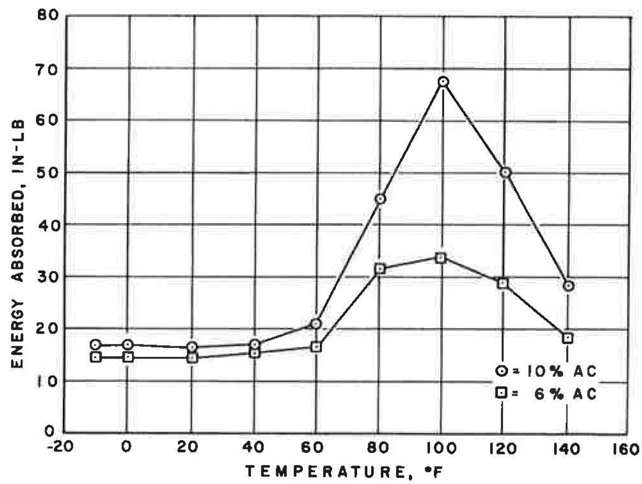

Figure 11. Average energy absorbed vs temperature for 180-200 pen asphalt mix.

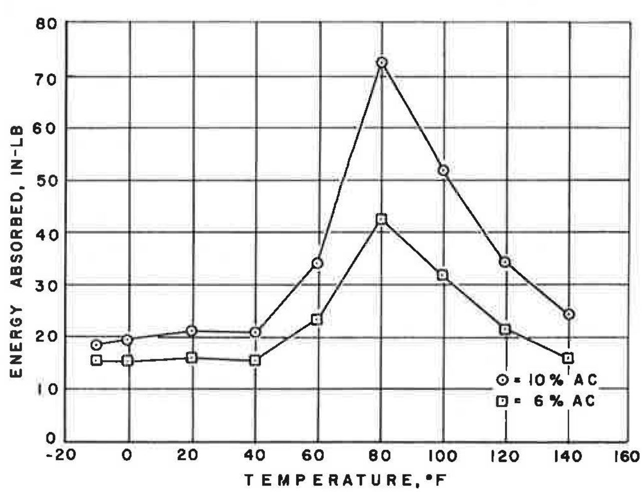

Figure 12. Average energy absorbed vs temperature for MC-5 asphalt mix.

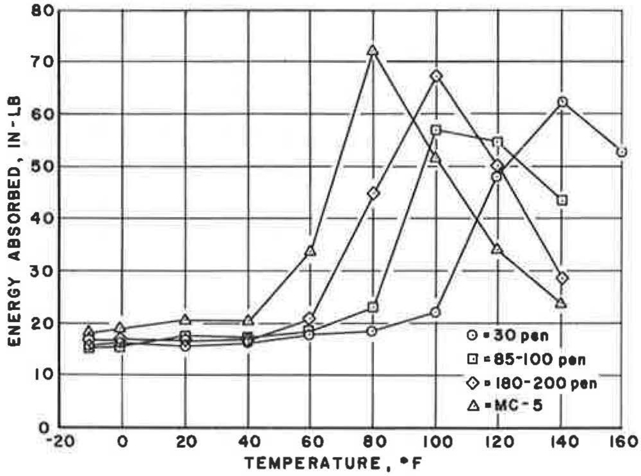

Figure 13. Average energy absorbed vs temperature at 10 percent AC.

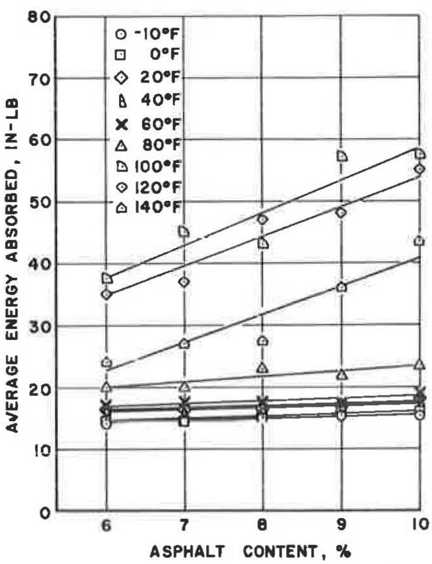

Figure 14. Plot of average energy absorbed vs percent asphalt content for 85-100 penetration asphalt.

100 penetration asphalt. This possibly indicates that maximum energy absorbed is a function of absolute viscosity and at these critical temperatures the viscosity for all four asphalts is the same. Also from Figure 13, the relative energy-absorbed values for the three paving grades are fairly constant over a temperature range of -10 F to approximately 40 F, whereupon they begin to diverge into their respective transition regions. This seems to indicate that there is no advantage when using a particular paving grade in this temperature region. In other words, because the three paving grades yield approximately the same energy-absorbed values in this region, they possess the same degree of elastic structure and its associated brittleness. The MC-5 shows a marked increase in energy-absorbed values over the same temperature range and even in its transition range. Because the MC-5 is a liquid asphalt, its asphaltenes are much more highly dispersed in the oil medium because of increased solvent power of the latter. In this state, even at low temperatures, its degree of micelle formation (and its elastic structure) is not as great as the three paving grades, and as such is probably more plastic in nature. It appears then that use of this particular liquid asphalt would tend to minimize the brittle tendencies of an asphalt pavement.

From Figure 14, which is representative of the other three asphalts tested, the effect of asphalt content on the energy-absorbed values is evident. An increase in asphalt content in the temperature range -10 to 40 F has only a slight effect on the impact values. But as the temperature increases, the effect of content becomes more pronounced. The energy-absorbed values increase substantially with an increase in asphalt content at the critical (maximum energy-absorbed) temperature. The slight effect

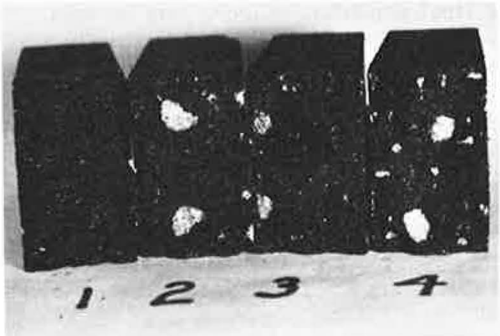

Figure 15. Four typical cross section failures.

of content at low temperatures seems reasonable. In this temperature environment, the asphalt is rigid and possesses a high coefficient of viscosity, which is essentially constant. Because the asphalt is rigid, the amount of deformation for fracture is extremely small. Increasing the asphalt content will produce only a slight increase in deformation for fracture and a very small increase in the energy-absorbed value. At the higher temperatures associated with the transition range, the amount of deformation for fracture at one content is much greater, resulting in high energy-absorbed values. When the content is increased, the associated deformation for fracture is increased substantially, giving rise to much higher energy-absorbed values.

Figure 15 shows typical cross section failures. All impact specimens failed by fracture. The first failure in Figure 15 was designated an asphalt interface failure, no broken aggregate. Referring to Figures 9 through 12, this type of failure first appeared in the transition range and was entirely the case throughout the plastic region for all asphalts. A small percentage of these failures was evident, however, in the brittle region. The remaining failures in Figure 15 occurred mainly in the lower portions of the transition and brittle regions with again a very small percentage occurring in the plastic region. It seems evident that the asphalt interface failures are indicative of a strong adhesiveness of asphalt to aggregate rather than a cohesiveness between the particles of asphalt. In the brittle region where numerous cracked aggregate was prevalent the adhesiveness of the asphalt to aggregate was fully substantiated.

The authors' initial expectation that the size of aggregate would affect the energy values was not borne out by the data. The energy-absorbed values for specimens in which fractured aggregate appeared in the failure plane showed no correlation with those specimens that failed through the asphalt interface. This would seem to indicate that the energy was absorbed by the asphalt.

It is realized that the energy required to break the specimen is in reality the sum of the energies consumed by several mechanisms (23). In general they would include:

1. The energy to initiate fracture of the specimen;
2. The energy to propagate the fracture across the specimen;
3. The energy to deform the specimen plastically;
4. The energy to throw the broken ends of the test specimens; and
5. The energy lost through vibration of the apparatus and its base, and through friction.

Referring again to the impact-transition temperature curve (Fig. 1) the three areas of significance yield valuable information dealing with the initiation and propagation of a crack. Specimens falling into the category at the right or plastic region are those in which it is hard to start a crack and hard to keep it going. Into the area at the left or the brittle region fall those specimens in which it is easy to start a crack and easy to keep it going. In the middle area or the transition region fall the specimens where it is hard to start a crack, but once started it is easy to keep it going.

Craggs' work (24) on the propagation of a crack in an elastic-brittle material presents the conclusion that the force required to maintain a steady rate of extension of the crack decreases as the rate increases. In the present investigation, it can be said that the crack propagates through the specimen with a velocity that is basically dependent upon the average velocity imparted by the pendulum hammer. This average velocity is a result of the initial pendulum velocity, before impact, and the final pendulum velocity, after fracture. During the tests in which the initial velocity was constant, the pendulum hammer was always released from the same position. The final pendulum velocity is a function of environmental temperature and composition and size of the specimen.

Since the size of the specimen was constant, the final pendulum velocity can be said to be a function of temperature and mix composition. Because velocity is directly related to energy, the energy then becomes a function of temperature and composition. In the plastic region relatively high energy values were obtained since the average velocity through the specimen or rate of propagation of the crack decreased significantly. In the brittle region the decrease in average velocity or rate of propagation was slight, therefore yielding relatively smaller energy values. The energy values in the transition region also support Craggs' conclusion.

The authors feel that this initiation and propagation of a crack criterion is indicative of present pavement behavior, especially since the pavement is an elastic-brittle type material when subjected to the 0 to 40 F temperature range. Through use of the impact tester, these crack conditions are quite apparent.

High-speed photography was used to estimate the energy transformed into rotation and displacement of the fractured samples. The photographs indicate that all samples were displaced to the same magnitude. For the comparative charts, energy losses due to air drag, friction, and sample friction have not been deducted from the absorbed-energy values. The comparisons would not be altered by such corrections.

Pavement Applications

It is apparent from the results of this investigation that certain factors are necessary to determine whether or not brittle failure is imminent. Considered in question form, they are:

1. What is the minimum anticipated service temperature? The lower the temperature, the greater the susceptibility to brittle failure. Through the entire late fall, winter, early spring season, the temperature varies from about 0 to 40 F in the New England area. As seen in Figure 13, the paving grades would then be in a brittle condition. Even taking the year-round average temperature for this area of approximately 50 to 55 F, the paving grades are still in the brittle region. It would seem then that a mixture should be designed with more consideration given to this temperature range rather than the summer conditions now accepted as critical. The MC-5 mixture shows promise in this respect.
2. Are tension stresses involved? Brittle failure can occur only under conditions of tensile stress. As temperature decreases, the surface course tends to become increasingly rigid and as such resists stresses by beam action.
3. Are stress concentrations present? The presence of stress concentrations increases susceptibility to warrant brittle failure. Marshall stability tests (25) were determined for each asphalt type. A voids analysis was also performed. It is theorized that a high percentage of voids means a potentially high stress concentration in an asphalt mixture, thereby tending to cause an inherent brittle condition in the resulting pavement. The basis for this hypothesis may be attributed to Griffith's crack theory (26). If the asphalt-aggregate complex can be considered as a continuous body and the air voids as the discontinuities, Griffith's theory may be applicable. When a load is applied to a body in which there are discontinuities, such as air voids, the stress has a much higher than average value near the void. Fracture results when the applied stress causes cracks from these voids to grow to macroscopic size. Asphalt has a coefficient of contraction and expansion that is much higher than that of aggregate, 0.0006 vs 0.0000060 in. per degree F respectively. It is realized that at high environmental temperatures, the high coefficient of expansion of the asphalt permits a sufficient amount of plastic flow to occur in the asphalt, thereby relieving the areas of stress concentration around the voids. But at low environmental temperatures the asphalt is very stiff. Therefore, plastic flow is essentially nonexistent and the relatively high internal stresses in the asphalt surrounding the voids still exist. In other words, at the colder temperatures the pavement may have areas of high stress concentration. In pavements with a high percentage of voids, impending fracture might be more prevalent. But because voids are directly related to asphalt content, evaluating the effect of voids separately is somewhat complex. Nevertheless, the effect of voids on the energy-absorbing capability of a pavement should not be eliminated from consideration.

4. Is loading applied at a high rate? It is realized that increasing the rate of loading increases the brittle behavior of a material as well as affecting the transition range. The maximum velocity of impact for the pendulum hammer corresponds to a possible rate of strain of approximately 60 in./in./sec. The assumptions leading to this value are (a) that velocity of deflection of the specimen is equal to the velocity of impact, and (b) that elastic beam theory is applicable. The majority of tests to determine the transition temperature ranges were carried out using an impact velocity of 137 ips, which corresponds to a rate of strain of 50 in./in./sec. As was evident from Figure 7, the absorbed-energy values increased linearly with increasing impact velocity at constant temperature. This implies that transition temperature ranges are dependent on rate of strain.

For pavements in the field, a value for rate of strain would be computed based on an assumed maximum radius of curvature of the pavement, an automobile speed, a distance from zero strain to maximum strain, and a pavement thickness. The radius of curvature would be obtained from pavement deflection measurements. The computation of field strain rate might also be based on elastic beam theory. But no one value of rate of strain can be computed, because automobile speeds vary, pavement thicknesses vary, and, depending on the stiffness of the asphaltic concrete surface course, the radius of curvature varies.

Therefore, it is extremely important to know what the conditions are in the field before a meaningful calculation of rate of strain can be made. Thus, one might ask the following question: Based on the impact and field values for rate of strain, can the transition temperature ranges obtained by the impact device be applied to the field conditions? While the authors feel that they can, they are unable to cite any work done in this area that would either substantiate or disprove this claim. The authors leave this problem to future research.

Finally, it must be realized that one of the most critical conditions under which paving asphalt must function is at low temperatures with high rates of loading. It seems then that under these conditions an impact test could serve quite satisfactorily as an acceptance test for brittle behavior.

STATISTICAL ANALYSIS

From the statistical analysis conducted, the significance of temperature, type, content, and their interactions on the energy-absorbed values were determined. Fisher's (15) distribution and 95 percent confidence limits were set as the test criteria. From the significance tests it was evident that:

1. Type, temperature, and content each had a significant effect on the energy-absorbed values. The relative importance of each variable, as determined from a comparison of the ratios of the mean squares, indicates that, while type had a significant effect on the energy-absorbed value, 48.3 > 3.07, it was not as important as the effect that content had on the energy-absorbed values, 128.6 > 2.68. Nor were these as important as the significance that temperature had on the energy-absorbed values, 605.5 > 2.09.
2. The interaction between temperature and type had a significant effect on the energy-absorbed values, 128.1 > 1.659.
3. The interaction between temperature and content also had a significant effect on the energy-absorbed values, 10.01 > 1.659.
4. The interaction between type and content had a slight effect on the energy-absorbed values, 2.10 > 1.910. Comparing the relative significance of the interactions in 2, 3, and 4, it is evident that the interaction between temperature and type is of greater importance than that between temperature and content, while the interaction between type and content is of little importance.
5. The interaction between temperature, type, and content also had a slight effect on the energy-absorbed values, 2.93 > 1.43.

A multiple regression analysis was conducted in an attempt to obtain a mathematical model that would explain the variation in the observed data (energy-absorbed values)

for an asphalt when subjected to changing temperature and content. The basic model, as developed for the 85-100 penetration asphalt, consisted of 11 terms:

$$E = K_0 + K_1C + K_2T + K_3T^2 + K_4T^3 + K_5CT + K_6(CT)^2 + K_7(CT)^3 + K_8\sin(T/15) + e$$

This model gave a multiple correlation coefficient of 0.95787. This corresponds to an R^2 of 0.9174; in other words, approximately 92 percent of the variation in the observed data was explained by the model.

This model was then tried on the 30 and 180-200 penetration asphalts, and on the MC-5 liquid asphalt with varying results. It gave multiple correlation coefficients of 0.93263, 0.91787, and 0.88646 respectively. These multiple correlation coefficients correspond to R^2's of 0.8700, 0.8440, and 0.7870 respectively.

The interactions between content, C, and temperature, T, CT, $(CT)^2$, $(CT)^3$, had the highest degree of association with energy absorbed; these were followed closely by the temperature terms, T, T^2, T^3, for each asphalt. Content, C, had the least degree of association with energy absorbed.

CONCLUSIONS

From the results of this investigation, the following conclusions are apparent:

1. The change in gradation had little or no effect on the energy-absorbed values. The energy is absorbed primarily by the asphalt.
2. The asphalt specimens are susceptible to changes in velocity. As the impact velocity increased up to about 160 ips, the energy-absorbed values increased linearly.
3. For the asphalt mixtures tested, there is a definite temperature transition range from viscous-plastic behavior to brittle behavior. And this transition range shifts as a function of viscosity toward the lower temperature, as the penetration of the particular asphalt type increases.
4. In the brittle temperature region, the energy-absorbed values for the three paving grades are essentially constant up to their respective transition temperature regions. The liquid asphalt, an MC-5, in the same region shows consistently higher energy-absorbed values. Therefore, use of this particular liquid asphalt would tend to minimize the brittle tendencies and thus the potential crack susceptibility of an asphalt pavement.
5. Asphalt content has little effect on the energy-absorbed values in the brittle temperature region, while it has a pronounced effect in the transition region and part of the plastic temperature region.
6. For the 10 percent asphalt content mixes the maximum energy absorption values varied over a range of less than 20 percent with the greater penetration asphalts having the larger values. At the 6 percent asphalt content the maximum energy absorption values varied over a range of less than 10 percent, with the single exception of the 180-200 penetration specimens, which were lower by 20 percent.

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