Determination of Age Hardening Tendencies And Water Susceptibility of Paving Asphalt By the Sonic Method

FRANKLIN P. ABBOTT and WILLIS G. CRAIG, The Lubrizol Corp., Cleveland, Ohio

This paper presents data on (a) progressive hardening and embrittlement of the asphalt cement with aging; (b) loss of adhesion of the asphalt cement to the aggregate with the resultant lower compressive strengths due to water displacement of the asphalt binder at the asphalt-aggregate interface; (c) progressive loss of water resistance of the asphalt cement as the asphalt hardens; and (d) progressive loss of the ability of the asphalt binder to re-adhere to the aggregate after displacement by water.

The action of effective anti-stripping additives in ameliorating these causes of road deterioration is shown to be in the direction of reducing the magnitude of the last three of these deteriorative factors.

● THE DETERIORATING effect of water on bituminous paving mixes has long been recognized as a serious cause of service failure, but there is still a wide divergence of opinion regarding the causes of this deterioration and, more particularly, the means by which this deterioration can be evaluated in accelerated tests. In a previous paper (1), W.G. Craig pointed out the major variables of static water immersion tests and has shown that the asphalt is as great a variant as the aggregate. It was also shown that the utility of adhesion improving additives is limited by their temperature stability and/or their degree of reactivity with the asphalt under test. The test methods used to demonstrate these variables were largely based on the Massachusetts State Highway Department stripping test (2) which includes 24-hr elevated temperature (350 F) storage of the asphalt-additive blend prior to aggregate coating, curing and immersion in water.

EFFECT OF PROLONGED HEATED STORAGE OF ASPHALT-ADDITIVE BLENDS

At the time this earlier paper was presented, a question was raised regarding the validity of the method in determining the long-term effectiveness of additives at road temperatures by means of this short-term, high temperature test. Because of this question, a long-term, moderate temperature test was started. The test procedure was as follows:

1. The four additives evaluated in the previous paper were blended with two geographically different paving asphalt cements at 0.5 percent by weight in the manner prescribed by the Massachusetts stripping test (2). This level of additive treatment was sufficient to allow all four additives to pass the stripping test without a heating period prior to coating and immersion.
2. Immediately after blending, a portion of each blend was tested according to the procedure of the Massachusetts stripping test.
3. The balance of eight samples was placed in tightly sealed cans and stored in a constant temperature oven held at 140 F.
4. After 1, 3, 6, and 12 months of oven storage, the samples were removed and the stripping tests repeated. The results of this test are shown in Figure 1.

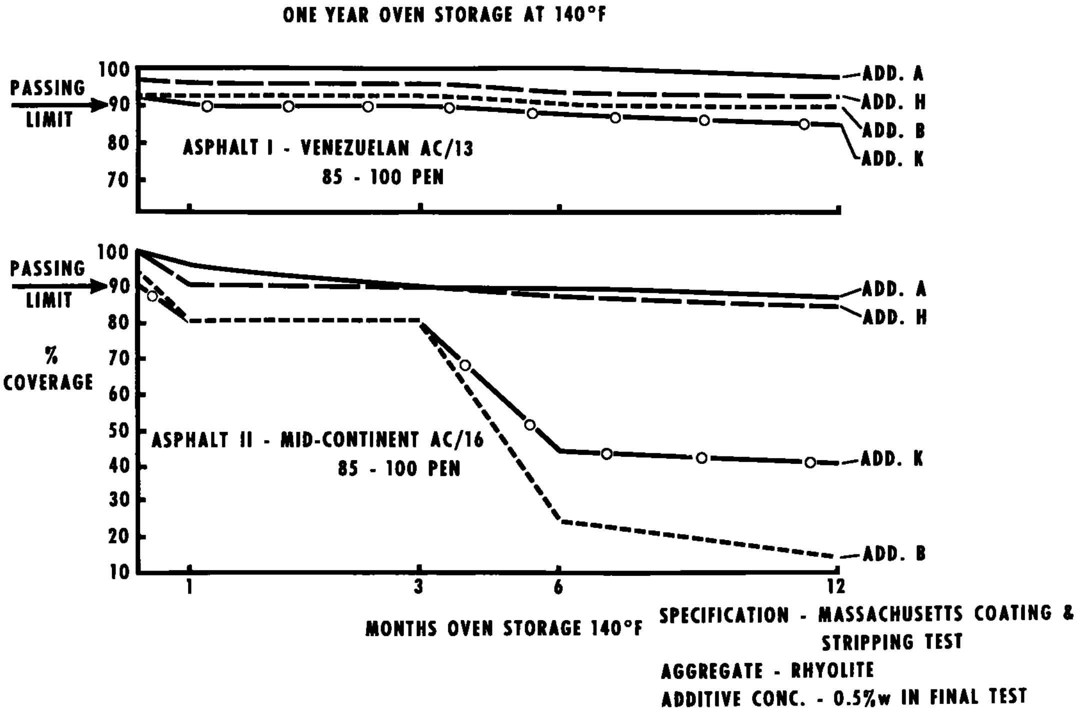

Figure 1. Variation of additive effectiveness in two geographically different asphalts.

Asphalt I has excellent susceptibility to treatment with anti-stripping agents. The data show that in this long-term, moderate temperature test, Additive A is most effective, Additive H somewhat less, Additive B is borderline, and Additive K fails between three and six months. This is exactly the same relative performance of these four additives in this asphalt as was obtained in the standard Massachusetts, 350 F, 24-hr heat test. The Massachusetts test, however, caused a greater degree of deterioration in Additives H, B, and K than is shown here.

Asphalt II is much more difficult to treat. Additives A and H were still performing at close to specification levels at the end of the year, while B and K were well below specification level after only one month of oven exposure. This is also in line with our previous results obtained from the Massachusetts heat stability test with this asphalt and these additives, although again, the regular Massachusetts test is somewhat more severe than the test reported here.

The data clearly indicate that the performance of adhesion improving additives is markedly affected by the asphalts with which they are blended, and that with unstable additives the stripping resistance may be lost during summer road exposure as well as during refinery handling and storage at elevated temperatures, as is demonstrated by the conditions of the standard Massachusetts test.

EVALUATION OF STRIPPING CHARACTERISTICS BY MEANS OF THE SONIC METHOD

Inasmuch as none of the static methods of determining stripping of cutbacks from aggregates uses the wide gradation of aggregate found in a typical paving mix, it was decided to determine if the sonic method (3) was applicable to open gradation aggregate-asphalt test beams prepared with cutback asphalt.

Test beams, 12 by 2½ by 2½ in., were prepared by vibratory compaction of an aggregate mix containing 6.5 percent by weight binder as either RC-2 or MC-3 cutbacks.

The mix design and method of compaction resulted in test samples with substantially uniform voids content. This open mix design was chosen to allow rapid water penetration into the test beams. (See Appendix B for details of mix design and method of compaction.)

Freshly prepared beams were much too plastic to yield reliable data by the sonic test method. Attempts to cure the test specimens at 140 F resulted in slumping of the specimens at edges and ends. Because of this, test specimens were allowed to cure at room temperature in the laboratory and their loss of weight as the solvent evaporated was closely followed by periodic weighing. After each weighing the fundamental frequency of the test beam was determined and the sonic modulus calculated. The results are shown in Figure 2 where the sonic modulus and the solvent weight loss of the test beams are plotted against curing time.

The loss of solvent from both the RC and MC bars was very slow. After 12 weeks the rate of solvent loss dropped to practically zero, although there was a very slow increase in the sonic modulus of the samples between 12 and 21 weeks. The sonic modulus at the end of this period was still well below that of a fresh sample prepared from molten asphalt, which served as a baseline, and it was decided to accelerate the cure by heating to 140 F inasmuch as the samples now appeared to be firm enough to withstand this temperature without slumping. One week of exposure at 140 F caused enough additional solvent to evaporate from the RC specimens to bring their sonic moduli into the range of similar beams prepared from the same asphalt by hot-mixing, although weighings showed that the aged specimens still retained approximately 35 percent of their original solvent content.

The MC series, as would be expected, did not respond as readily to the forced drying. After one week at 140 F about 50 percent of the original solvent content still remained in these beams, and their sonic moduli were not as high as those of the RC specimens.

The data in Figure 2 clearly show that even in these specimens of small cross-section which were open to the air on three sides, the loss of solvent was very slow. In a road section of comparable depth (2½ in.), evaporation could take place only at the surface and therefore solvent escape would be even slower.

The increase in sonic modulus in comparison to the solvent evaporation rate is interesting. Apparently there is a marked increase in the "body" of the asphalt which is not entirely attributible to solvent loss, inasmuch as the RC beams with 35 percent

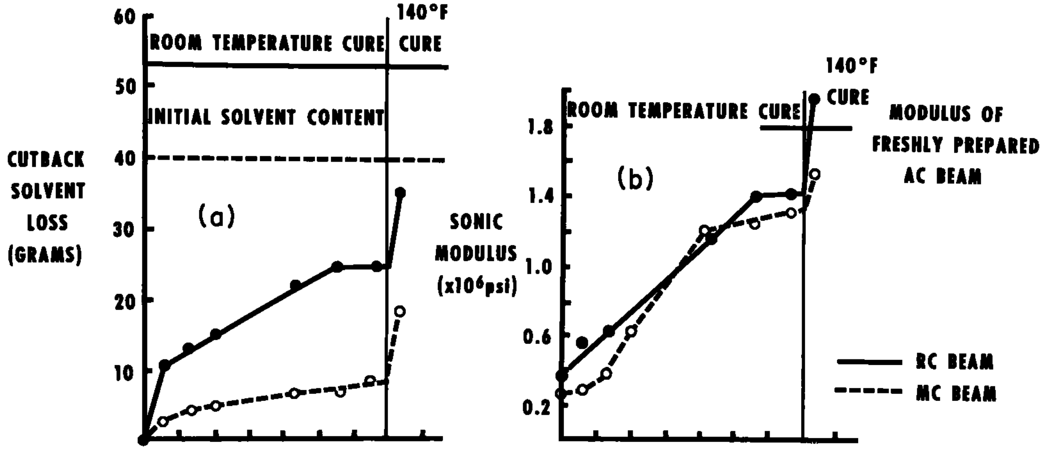

Figure 2. Changes during curing of RC and MC cutback beams showing (A) rate of cutback solvent loss and (B) sonic modulus increase.

of their initial solvent content remaining were as resilient as a freshly prepared AC beam. This can only mean that, during the long drying period, changes in the asphalt have occurred which have hardened it to such an extent that, although the asphalt is partially solvated, these beams have reached the elasticity of a standard hot-mix specimen.

To determine the effect of water and adhesion-improving additives on the sonic moduli, the cured RC and MC beams were immersed in water at 140 F, as recommended by Goetz (4), for 15 days and their decrease in sonic modulus was followed.

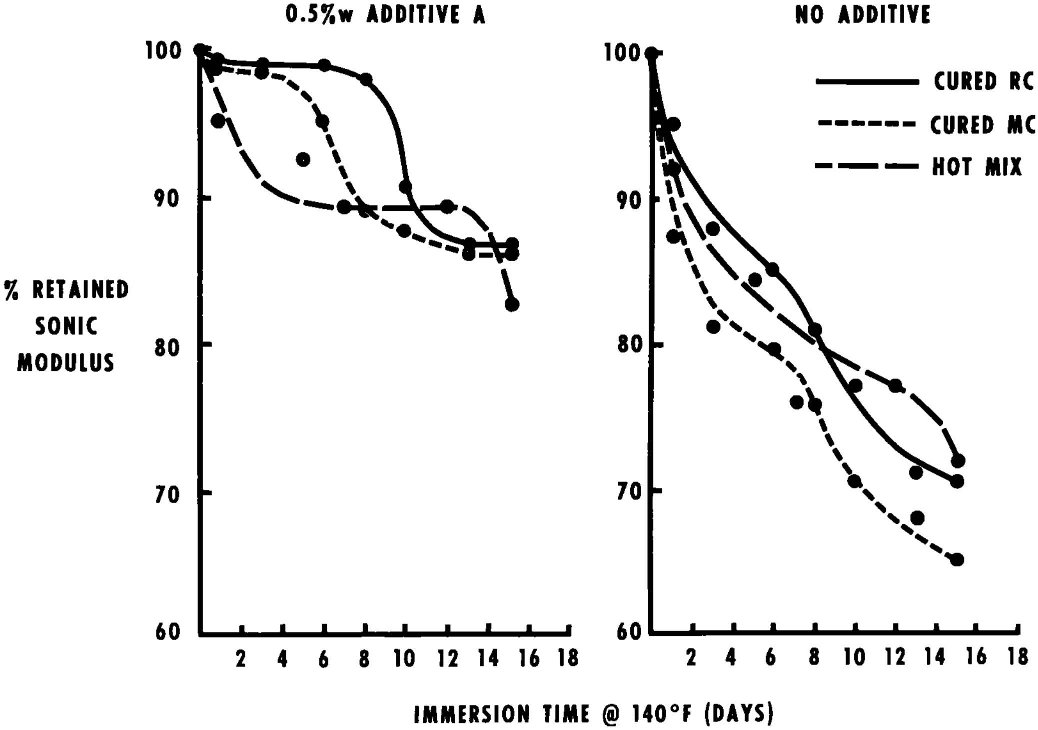

Figure 3. Effect of additive on sonic modulus during water immersion of cutback and hot mix beams.

An additional set of test specimens was prepared from the same mix design by hot-mixing with the same asphalt cement as was used in preparing the cutback samples, and immersed and tested in the same manner. The results are shown in Figure 3.

From Figure 3 it can be seen that there is a marked reduction in sonic modulus at the end of the first day of immersion, followed by a somewhat slower decline throughout the test. In the case of the untreated test samples, the loss of modulus on extended water immersion is very pronounced, and is especially severe with the untreated MC specimens which are the most plastic of the group. The left-hand group of curves in this illustration demonstrates the effectiveness of this particular additive (Additive A) in retarding the change in modulus during water immersion.

Figure 3 shows that the water resistance of non-additive cutback paving mixes and of similar paving mixes prepared from asphalt cement was substantially the same after the cutback mix had reached the same elasticity (as shown by equivalent sonic moduli) as the AC. However, the time required for an RC mix to reach this state in actual service is very long, and it is thus susceptible to severe stripping during this period.

Effective additive treatment, however, will protect against this deterioration and, in the cutback mixes, will markedly improve their stripping resistance over that which can be obtained with a treated AC. Just why the additive should be more effective in protecting the samples prepared from cutback asphalt than it is with the AC samples is not known. It may well be that this increase in effectiveness is caused by the lower viscosity of the cutback asphalt at the time of mixing of the samples, as the degree of effectiveness of the additive is greatest for the lower viscosity RC cutback sample. The lower viscosity of the cutback binders at the time of mixing, together with the surface activity of the additive, may enable them to wet out better on the aggregate and thus provide more complete and uniform coverage than can be obtained with asphalt cement by hot-mixing.

EFFECT OF AGING, WATER IMMERSION, AND DRYING ON COMPACTED BITUMINOUS MIXES

Since it had been shown by means of the Massachusetts test that asphalt-additive blends were deteriorated by long-term storage at 140 F, and that the sonic method was effective in showing differences between untreated and additive-containing asphalt during water immersion of compacted aggregate paving mixtures, the next step was to combine the two in a single test which would introduce the effects of both long-term aging at 140 F and of aggregate gradation on water resistance.

A large number of open-mix sonic test beams, prepared in the same manner as the foregoing, were made from an untreated 85-100 penetration Lloydminster asphalt and from the same asphalt containing 0.5 percent by weight of four commercial, heat stable, adhesion-improving additives. All freshly prepared beams were chilled to 40 F and their sonic values determined. One set was immersed in water immediately and the balance of the test beams were placed in a large, forced draft oven maintained at 140 F. At intervals of 1, 3, and 6 months, beams of each mixture were withdrawn and their fundamental frequencies at 40 F redetermined.

After each particular oven aging cycle, beams of each mixture were immersed in 140 F water for 15 days and the decrease in their sonic moduli was followed. At the end of the 15-day immersion period the test beams were removed from the water and allowed to dry at room temperature. The increase in sonic modulus as the beams dried was followed periodically for 20 days. After this time the beams had returned to nearly their original weight, indicating essentially complete drying.

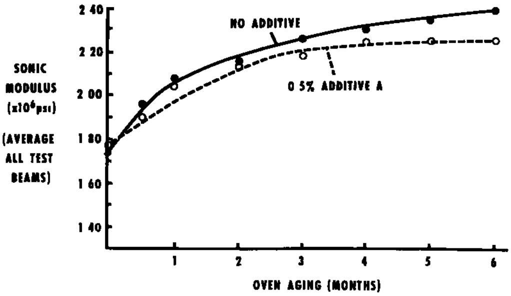

Figure 4. Sonic modulus changes occurring in Lloydminster AC-rhyolite beams during aging at 140 F.

On completion of sonic evaluation after each aging, immersion, and drying cycle, beams of each mixture were carefully sawed into two, 5-in. long sections, the ends capped with plaster-of-Paris, and the two samples crushed in unconfined compression by means of a Marshall Compression Tester, modified to operate 0.05 in. per min per inch of beam height in accordance with ASTM Specifications (Appendix C). The asphalt from the crushed specimens was recovered by the ASTM D-402-55 method for penetration testing.

Figure 4 shows the effect of oven aging at 140 F on the sonic modulus of beams prepared from the 85-100 penetration Lloydminster asphalt and from the same asphalt treated with 0.5 percent of a commercial anti-stripping agent. Here it will be seen that there is a fairly rapid increase in the moduli during the first month, followed by a somewhat slower, relatively constant increase during the balance of the test.

Figure 5 shows the results of the aging, water immersion, and drying test for the untreated asphalt sample, and for the sample treated with 0.5 percent of Additive A,

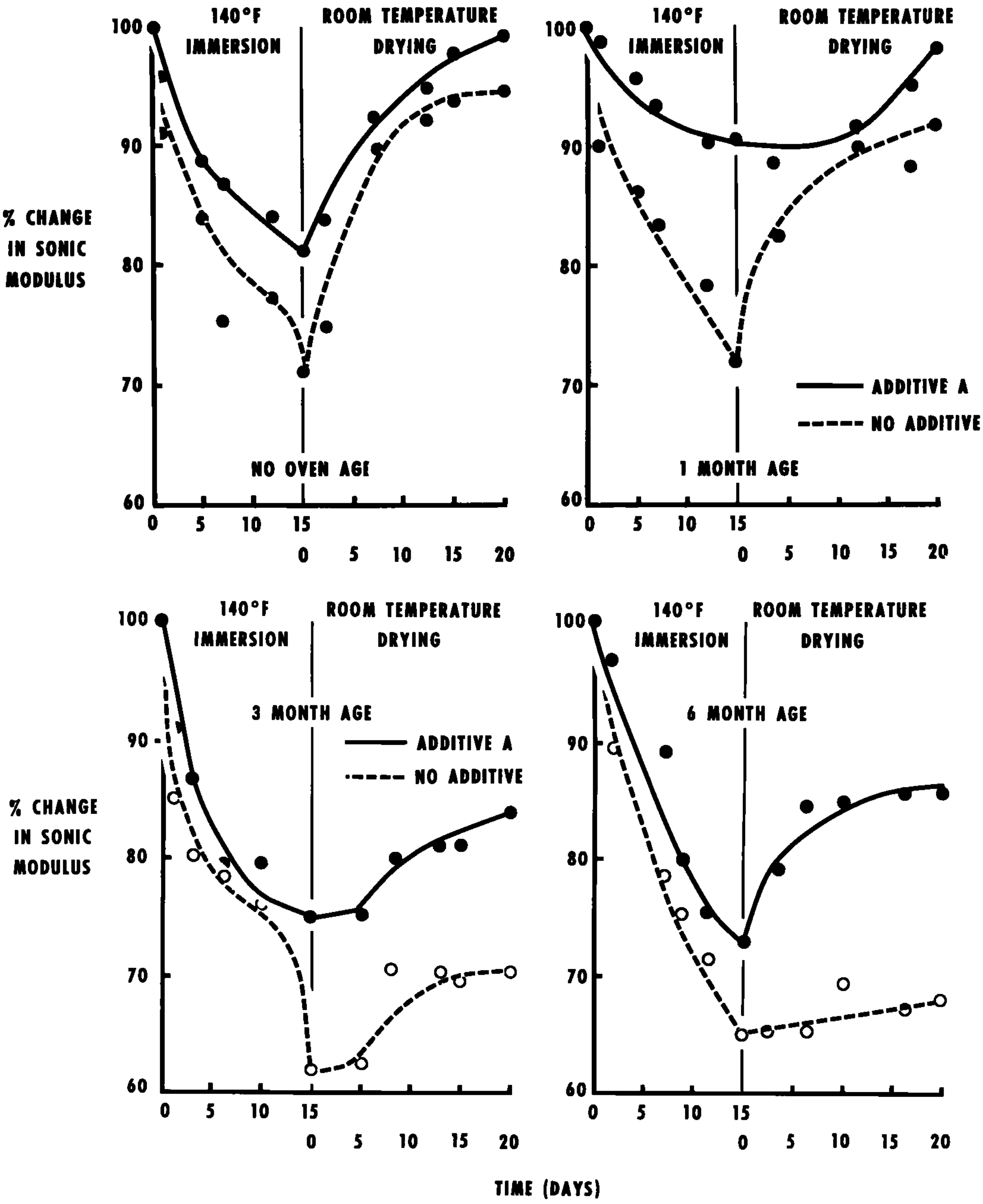

Figure 5. Sonic modulus changes during water immersion and drying of Lloydminster AC-rhyolite beams after various periods of oven aging.

which was the most effective of the four additives. Because oven aging caused the sonic moduli of the test beams to increase with time of exposure, samples removed from the oven after the various test times had different moduli at the time they entered the soaking and drying cycle. For this reason the data have been presented as the "percentage change" of modulus during this cycle. From these curves it can be seen that both the treated and untreated test beams became progressively more susceptible to changes in their sonic moduli during immersion as their test age increased. After the first month of aging at 140 F, the changes in sonic moduli during the soaking and drying cycle were not markedly different from the unaged beams, but after three and six months of aging, pronounced reductions in the retention of sonic moduli during water immersion are shown for both the treated and untreated test beams. The loss of sonic moduli of additive-treated beams is, however, noticeably less than that of the untreated specimens at all periods of aging.

The most interesting information gained from these tests is to be found in the recovery of sonic modulus on drying. After one month of aging, the recovery of the additive-treated beam was substantially 100 percent, and the untreated beam regained almost 95 percent of its original modulus. As aging progressed and the asphalt hardened, the "healing", or re-establishment of bond between asphalt and aggregate as the water evaporated, became less and less. The effect of the additive, while appreciable, was not enough to bring the moduli of the beams back to their original values. This is especially evident after six months of aging. At this time the recovery of sonic modulus of the untreated beam is only 65 percent of its original age-hardened value, whereas the beam containing Additive A showed recovery to 85 percent of its original value. Apparently, during the aging of the test beams, the asphalt has hardened enough so that it is no longer sufficiently plastic to re-establish its bond to the aggregate once it has been displaced by water.

The water immersion test data show little change in the stripping characteristics during the first month of aging, although there has been a rapid increase in sonic modulus during this period (Fig. 4). It is thought that this initial rapid increase in sonic modulus may be due to "structure formation" or gelling of the asphalt rather than to chemical changes due to oxidation and/or polymerization, and that actual age hardening is not apparent until after the first month, after which time this hardening continues at a constant rate depending on the susceptibility of the system.

Because the sonic moduli of the test beams are increasing with the test age of the specimens, it is logical to suspect that the compressive strength of the specimens is also increasing if the increase of sonic moduli is a function of the hardening of the asphalt. Figure 6 confirms this, as it will be noted that when the unconfined compressive strength of the test specimen is plotted against the oven aging time, the general shape of the curves obtained are similar to those of Figure 4. Therefore, a reasonably good correlation appears to exist between the unconfined compressive strength and the sonic moduli of these specimens. This correlation is confirmed by Figure 7, where sonic modulus is plotted against compressive strength. This gives a straight-line plot with only modest scatter of the data. The exact relationship of sonic modulus to unconfined compressive strength shown in this figure is, of course, applicable only to this particular mix design and asphalt.

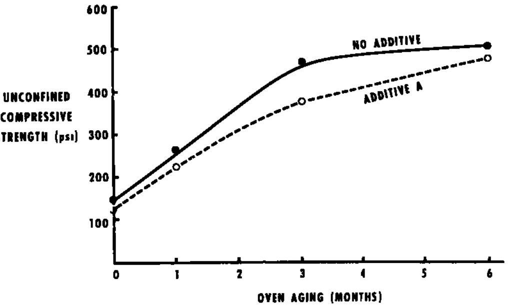

Figure 6. Changes in unconfined compressive strength of Lloydminster-rhyolite beams after various periods of oven aging at 140 F.

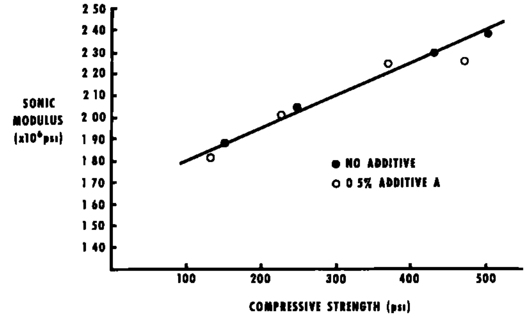

Figure 7. Sonic modulus and strength relationship during 6-month age hardening of Lloydminster AC-rhyolite beams.

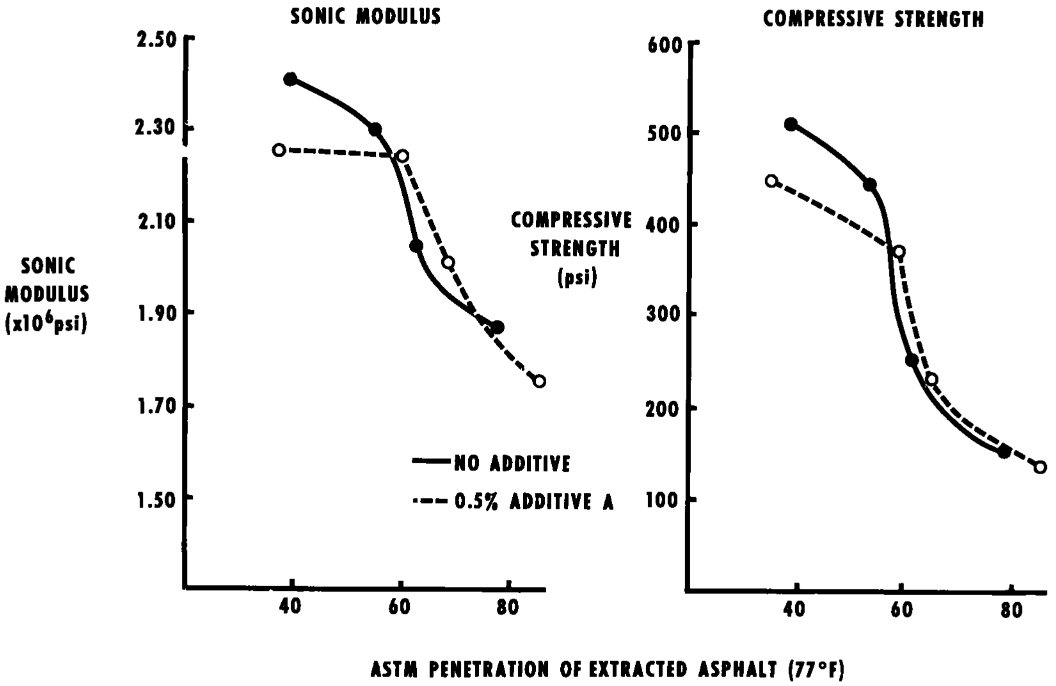

Figure 8. Relationship of penetration of extracted asphalt with sonic modulus and compressive strength of beams during oven aging cycle.

The relationship of the sonic modulus and the unconfined compressive strength of the test specimens to the penetration of the asphalt extracted from them, is shown in Figure 8. Starting from the lower right, each point on a curve is the value obtained at 0, 1, 3, and 6 months of oven aging, respectively. The curves show a uniform increase of both sonic modulus and strength, with decreasing penetration up to the three months' aging period when the asphalt has hardened from its original 78-87 penetration range to a 55-60 penetration range. After this point neither the sonic modulus nor the compressive strength change as rapidly as the penetration. This would seem to indicate that between 60 and 40 penetration, changes take place in the asphalt structure which markedly affect the ASTM penetration value without adding greatly to the elasticity or the strength of the test specimen as measured by these tests.

This anomaly can be explained by assuming that a high degree of "structure formation" or gelation occurs in the asphalt during the first few months of aging, and that this "structure," once formed, does not change appreciably as the asphalt hardens further. This "structure" could contribute appreciably both to the elasticity (sonic modulus) and the unconfined compressive strength of the specimen. It would be broken during the extraction procedure used to recover the asphalt for the penetration tests, and therefore the penetration values would not be a true indication of the rheological characteristics of the asphalt as it was when in situ during the sonic and compression tests.

It may well be, however, that when the asphalt reaches a hardness near 60 penetration, there is a reduction in the interfacial forces of adhesion between the asphalt and the aggregate which affects both the elasticity and the strength values of the specimen in these tests so that their increase is not proportional to the hardness of the asphalt. This supposition is reinforced by the data on water immersion of aged bars, where it was shown (Fig. 5) that the aged bars were more subject to the deterioration of sonic values on water immersion than were freshly prepared bars. This would indicate that the asphalt, during aging, gradually loses adhesion to the aggregate and is now more readily displaced from the surface of the aggregate by water penetration at the interface.

The data derived from test beams that were aged, immersed in water for 15 days, and then dried at room temperature for 20 days, are shown in Figure 9 (right). Freshly prepared beams regained a substantial portion of their original moduli and strength on drying, with the additive treated samples showing almost complete recovery. The difference between the fresh samples and those aged for one month is somewhat more pronounced than in the immersion test, and the benefit of the additive in promoting rehealing shows up strongly in the strength recovery. After three and six months, however, the "healing," particularly in regard to regaining strength lost during water immersion, is very minimal.

From these data it is apparent that the prolonged effect of water on aged bituminous concrete pavement is very deleterious, much more so than on a fresh pavement, and that once such a pavement is so exposed the damage is permanent.

CONCLUSIONS

From the data presented, the following conclusions can be drawn:

1. The long-term storage of asphalt-additive blends at 140 F (a temperature which often occurs in roads) confirms the results previously published (1) regarding the variability in results which can be obtained with a series of asphalt-additive blends. The previous work was based on an accelerated heat test with 24-hr storage of the blends at 350 F. Present data confirm the supposition that the same differences would be shown by long, low temperature storage as is obtained in the accelerated test. It also indicates that deterioration of the effectiveness of anti-stripping agents can occur over long periods in the road as well as at elevated temperature in asphalt processing, and shows that an accelerated heat stability test is desirable in specifying anti-strip additives which will be effective in the particular asphalt to be used for construction.

2. The sonic test method is not an effective tool for evaluating the stripping characteristics of cutback paving mixes because of the long time required for the sample to reach an elastic state by evaporation of solvent. The data show, however, that cold paving mixes prepared from RC cutback will eventually reach the same elastic state as freshly prepared AC mixes even though 35 percent of their initial solvent content still remains in the mix. This can be explained by the increasing hardness of the asphalt due to oxidation and/or polymerization during the long drying period.

The water resistance of cold-mix and hot-mix pavements is substantially the same after the cold-mix paving has evaporated enough of its solvent to approach the viscosity of the hot mix. Prior to this time, cold-mix pavements are much more susceptible to stripping. MC cold-mix pavements require much longer cure times to approach the nature of AC paving than do RC mixes, and hence are susceptible to severe stripping for a longer time. Anti-stripping additives are very effective in preventing stripping of cold-mix pavements during their long period of curing, and once a cutback paving containing anti-strip additive has cured, it is more resistant to water deterioration than a hot-mix paving containing the same additive.

3. Aging compacted bituminous paving mixtures in a forced circulation hot air oven results in hardening of the paving. This hardening can be readily followed by the increase in the sonic moduli of the test specimens. The increase in sonic modulus parallels the increase in unconfined compressive strength. For a given mix design, and a given asphalt, a straight-line plot of sonic modulus versus compressive strength can be obtained.

4. Water susceptibility of hot-mix pavements can be readily determined by the sonic method and the effectiveness of adhesion promoting additives evaluated. Hardening of asphalts during aging results in lessened resistance to stripping, a phenomenon which cannot be demonstrated by the usual static stripping tests. In addition, the method enables an evaluation of the degree of re-adhesion of the asphalt to the aggregate on drying—a factor which may be of great importance to road durability.

5. Sonic modulus, unconfined compressive strength, and the ASTM penetration of the asphalt recovered from the test specimens are parallel functions up to a point. After about three months of oven aging, the penetration value of the asphalt changes more rapidly than either the compressive strength or the modulus. The more rapid

increase of strength and sonic modulus in relation to the decrease in ASTM penetration during the first three months of oven exposure is thought to be due, in part, to development of "structure" or gelation within the asphalt.

6. Measurement of the unconfined compressive strength of compacted test samples after aging and soaking, confirms the loss of adhesion shown by the decrease in sonic modulus. On very long soaking, the decrease in the compressive strength is greater than the decrease in sonic modulus.

7. Adhesion improving additives are effective in reducing the magnitude of change in both sonic modulus and in unconfined compressive strength during water immersion of fresh and aged paving samples. They are also effective in promoting the "healing" or regaining of these values as the sample dries.

8. A major cause of road deterioration lies in the hardening of the asphalt during aging and the additives become less effective as the age and hardness increases. In order to further improve the quality of asphaltic paving cements, additive utilization and efficiency, research should be directed toward devising means of retarding the hardening of the asphalt during exposure.

REFERENCES

1. Craig, W.G., "Variables of the Static Asphalt Stripping Test." The Lubrizol Corp., Cleveland, Ohio.
2. "Specification for Anti-Strip Additive." Commonwealth of Massachusetts, Dept. of Pub. Works (March 1955).
3. Goetz, W.H., "Sonic Testing of Bituminous Mixtures." AAPT Proc., Vol. 25 (1955).
4. Andersland, O.B., and Goetz, W.H., "Sonic Test for Evaluation of Stripping Resistance in Compacted Bituminous Mixtures." AAPT Proc., Vol. 25 (1956).
5. Bawa, K.S., "Sonic Studies of Bituminous Mixtures." M.S. Thesis, Purdue Univ. (Jan. 1953).
6. Yong, R.N.U., "The Physical Significance of Sonic Test on Bituminous Mixtures." M.S. Thesis, Purdue Univ. (June 1954).

Appendix A

MODIFIED[1] MASSACHUSETTS HIGHWAY SPECIFICATION

Test Procedure

1. Additives tested were blended into the two representative asphalt cements (85-100 pen.) at a concentration of 0.5 percent w at a temperature of 200-250 F and stored for a period of one year at 140 F in tightly sealed ½ pint paint cans. After 1, 3, 6, and 12 months of storage, samples were removed for anti-strip evaluation.

2. An RC-2 cutback was prepared by diluting 75 parts of each sample with 25 parts of Varnish Makers and Painters Naphtha.

3. Rhyolite stone was graded so that 100 percent passes a ⅜-in. sieve and is retained on a No. 4 sieve. The aggregate was washed in distilled (ph 6-7) water and oven dried at 270-300 F.

Coating and Stripping Test

One hundred grams of washed and dried Rhyolite aggregate was wetted with two grams distilled water and coated with six grams of the prepared cutback by thoroughly mixing for 5 min. The coated aggregate was then air-cured for 1 hr at room temperature. Initial coverage was noted.

The coated aggregate was then immersed in distilled water at room temperature and, after 24 hr, inspected for percent coverage. (At least 90 percent coverage after the immersion period is necessary to pass this test.)

---

[1] Extended heat storage at 140 F.

ASPHALT SPECIFICATIONS

Asphalt Type:	Lloydminster	Asphalt I	Asphalt II
Specific gravity at 77 F	1.0351	1.019[a]	0.9945
Softening point (R and B)	115 F	113 F	120 F
Pen. at 77 F (100g, 5 sec)	97	92	94
Saybolt furol vis, 210 F	1220	-	-
Ductility, 5cm/min at 77 F	150+	-	150+
Loss on htg. 325 F, 50g, 5 hr	0.07%	0.7%	0.005
Pen. at 77 F on residue from loss on heating test	88	87	95
Flash, C.O.C., deg F	535	535	595
% CCl_4 soluble	99.92	-	99.85
% CS_2 soluble	99.94	-	99.90
% 86 deg Baume naph insoluble	23.1	-	18.00
% Sulphur	5.2	-	-
Oliensis spot test	Neg	Neg	Neg

---

[a] Specific gravity at 60 F.

Appendix B

MIX DESIGN

Standard open-gradation aggregate mix was used in the preparation of all sonic beams. This design was so chosen to produce specimens of relatively high voidage to enhance both permeability of air during oven aging, thereby promoting hardening, and to accelerate the effect of water to promote stripping. Mixed aggregates—rhyolite as coarse, Ohio bank sand as fine, and either limestone dust or hydrated lime as filler—and 6.5% w binder (based on total weight) composed the mix design.

Rhyolite aggregate (as received) was washed thoroughly with tap water to remove dust and finally with distilled water (pH 6-7), then dried overnight in a forced air oven at 300-325 F. Ohio bank sand and inorganic fillers were used as received, omitting the washing step, but were oven dried prior to screening. The aggregates were then individually sieved and the various sized components stored for batch blending.

The asphalt for test was received in 5-gal. pails, and to appropriately sample, the pails and contents were carefully heated to 200-225 F in a forced air oven with their lids intact so as to exclude excess air. Samples of asphalt were transferred to one-pint cans, in an amount sufficient to prepare two test beams. Additive, at a concentration of 0.5% w based on AC, was mixed with the samples of asphalt at 175-200 C for 1-2 min. Blends were then set aside in closed cans until used in beam preparation.

Cutback asphalt blends (RC-2 and MC-3 types) were prepared in a similar manner, except that pint samples of cutback were first prepared using either V.M. and P. Naphtha (RC solvent) or Bronoco 529 (MC solvent), and then mixed with additive at 120-140 F.

PREPARATION OF SONIC TEST BEAMS PREPARED FROM HOT MIXES

All sonic beams prepared in this program were compacted from individual 2,500 gram batches of bituminous mix. The blended aggregates and container of prepared asphalt were brought to a temperature of 275 ± 5 F in a forced air oven prior to mixing together. A stainless steel mixing bowl, trowel, and beam mold were simultaneously heated to this temperature. After heating, the nescessary amount (6.5% w) of asphalt was added to the hot aggregate mix and stirred vigorously by hand for approximately 2 min or until a visually homogeneous mix was obtained. Temperature of the mix after this time was 255-260 F. The hot mix was then immediately troweled into the preheated, specially-constructed portable beam mold, tamped slightly to level

SIEVE ANALYSIS OF AGGREGATES

% Passing

Sieve Size:	1/2	3/8	# 4	# 8	# 50	# 100	# 200
Rhyolite	100	99	70	5	0	0	0
Ohio Sand	100	100	95	81	20	3.5	1.5
Limestone Dust	100	100	100	100	100	100	85
Hydrated Lime	100	100	100	100	100	100	100
Median of Spec	100	95	70	32	7.5	4.5	3.5

ADJUSTED MIX DESIGN (BLEND PROPORTIONS)
(For Hot Mix Beams*)

% Passing

Sieve Size		1/2	3/8	# 4	# 8	# 50	# 100	# 200
Rhyolite	64.5%	64.5	64.5	45.3	3.2	-	-	-
Ohio Sand	32.0%	32.0	32.0	31.0	27.0	6.4	1.0	0.5
Limestone Dust	3.5%	3.5	3.5	3.5	3.5	3.5	3.5	3.0
Total		100	100	79.8	33.7	9.9	4.5	3.5
Median of Spec		100	95	70	32	7.5	4.5	3.5

BATCH WEIGHTS (% OF TOTAL MIX)

Hot Mix

Rhyolite (60%)	- 1500g
Ohio Sand (30%)	- 750g
Limestone Dust (3.5%)	- 87.5g
Asphalt (6.5%)	- 162.5g

Cold Mix

Rhyolite (60%)	- 1500g
Ohio Sand (30%)	- 750g
Limestone Dust (1.5%)	- 37.5g
Hydrated Lime (2.0%)	- 50.0g
AC (as Cutback) (6.5%)	- 162.5g

Total
2500g

* Adjusted mix design for cutback beams uses 1.5%w Limestone Dust and 2.0%w Hydrated Lime.

RHYOLITE-LLOYDMINSTER RC-2 AND MC-3 BEAMS

Physical Properties

Beam No.		Weight After Cure Gms	Lbs	Overall Solv Loss Gms	(%)	Theo. Solv. Content (gms) Before Cure	Beam Dimensions (Length = 12") Breadth Inch	Thickness Inch	Density*	%v Solids	%v Voids	Theo. Vol. Air Voids cc
RC-2	(1)	2468	5.46	34	(64.4)	53.3	2.45	2.53	2.025	86.8	13.2	161
	(2)	2471	5.46	36	(68.2)	53.5	2.49	2.53	1.995	85.5	14.5	180
MC-3	(3)	2502	5.54	19	(47.3)	40.2	2.47	2.52	2.045	87.8	12.2	149
	(4)	2501	5.54	23	(57.2)	40.2	2.49	2.52	2.027	86.8	13.2	163

* Max theo. Specific Gravity of Mix (after Cure): RC-2 Beams, 2.333
MC-3 Beams, 2.33 (3), 2.336 (4)

RHYOLITE-LLOYDMINSTER AC BEAMS

Physical Properties

(1) Beams Containing No Additive

Beam No.	Oven Dry Wt. Gms	Oven Dry Wt. Lbs	Dimensions (Length = 12") Breadth Inch	Dimensions (Length = 12") Thickness Inch	Vol. cc	Density*	%v Solids	%v Voids	Theo.Vol, Air Voids (cc)
1	2479	5.46	2.55	2.52	1263	1.962	82.7	17.3	218
2	2478	5.46	2.54	2.52	1259	1.969	83.0	17.0	214
3	2477	5.46	2.54	2.52	1259	1.968	83.0	17.0	214
4	2475	5.46	2.55	2.53	1268	1.951	82.3	17.7	224
5									
6	2482	5.47	2.55	2.53	1268	1.957	82.5	17.5	222
7	2482	5.47	2.53	2.53	1258	1.972	83.1	16.9	213
8									
9	2482	5.47	2.54	2.52	1258	1.972	83.1	16.9	213
10	2480	5.47	2.53	2.52	1253	1.978	83.4	16.6	208
11	2477	5.46	2.53	2.52	1253	1.976	83.3	16.7	209
12	2482	5.47	2.55	2.52	1263	1.964	82.8	17.2	217

* Max. Theo. Sp. Gr. of Mix = 2.372 (based on densities of aggregates and binder)

Physical Properties

(2) Beams Containing Additive "A"

Beam No.	Oven Dry Wt. Gms	Oven Dry Wt. Lbs	Dimensions (Length = 12") Breadth Inch	Dimensions (Length = 12") Thickness Inch	Vol. cc	Density*	%v Solids	%v Voids	Theo.Vol, Air Voids (cc)
13	2480	5.47	2.54	2.53	1263	1.963	82.8	17.2	217
14	2484	5.47	2.55	2.52	1263	1.966	82.9	17.1	216
15	2483	5.47	2.54	2.53	1263	1.965	82.8	17.2	217
16	2480	5.46	2.54	2.53	1263	1.963	82.8	17.2	217
17	2479	5.46	2.54	2.52	1258	1.970	83.1	16.9	212
18									
19	2492	5.49	2.54	2.52	1258	1.980	83.5	16.5	207
20	2486	5.48	2.54	2.53	1263	1.968	83.0	17.0	214
21									
22	2488	5.48	2.55	2.53	1268	1.962	82.7	17.3	219
23	2488	5.48	2.55	2.53	1268	1.962	82.7	17.3	219
24	2485	5.48	2.54	2.53	1263	1.967	82.9	17.1	216

* Max. Theo. Sp. Gr. of Mix = 2.372

the mix, and compacted by means of an air-driven, hand vibrator containing a steel base which fit loosely into the mold. The temperature immediately prior to compaction was 225-235 F. Control of degree of compaction of the mixes was easily afforded by applying vibrational force until the mix level reached a measured depth in the mold. Specimens compacted in this manner had a variable breadth dimension of 2.50-2.55 in., the thickness and length dimensions being fixed at 2.5 in. and 12 in., respectively.

After compaction, which normally took about 3 min, the beam mold was cooled by a stream of cold water, disassembled immediately, and the beam removed and marked with suitable identification. Beams were then oven-dried for 24 hr at 140 F and their breadth and thickness dimensions determined prior to sonic testing.

PREPARATION OF SONIC BEAMS FROM MIXES CONTAINING CUTBACK ASPHALT

Cold-mix bituminous beams containing RC and MC cutback asphalt were prepared using the batch method described in the section on "Preparation of Sonic Test Beams Prepared from Hot Mixes" with the exception that preheating of the aggregates and cutback was at a lower temperature to prevent solvent loss during the over-all operation. Preheating of the mix ingredients and implements, including beam mold, did not exceed 175 F and the temperature at time of compaction was between 140-150 F. After compaction, beams were removed from the mold without water-cooling applied, and carefully set aside to cure at room temperature after proper measurement to determine breadth and thickness dimensions.

Appendix C

DETAILS OF THE SONIC METHOD

Determination of the Fundamental Frequency of Vibration

The first step in calculating the sonic modulus of the beam was determining its fundamental frequency of vibration at one specific temperature, 40 F. This was accomplished by chilling each beam to 40 ± 1 F in either a melting ice bath for specimens undergoing water immersion or in a cold chest when dry beams necessary for oven aging were desired. At least 2 hr chilling time was required to reduce beams to the desired 40 F.

The sonic apparatus used in this study consisted of a Type 208-B Dumont cathoderay oscillograph, a Model 655, Jackson audio oscillator, a modified ST-104 Jensen Speaker used as a driver, and a VM-1 Brush Vibromike used as a signal pick-up. For obtaining frequencies of a beam at 40 F, it was placed horizontally on the driver stand with one side in contact with the driver, and with the pick-up placed on the approximate center of the beam, the output frequency of the oscillator was varied until a peak of maximum amplitude was registered on the oscilloscope. The frequency at which this condition exists is denoted as the fundamental frequency.

To insure that the frequency determined was the true fundamental frequency, a quick check was made for existence of nodal points. These nodes should be located a distance of 0.224 L from either end of the beam with length L, vibrating transversely in a free-free condition. Nodal point check was made by feeding the oscillator signal directly to the X-plates of the oscilloscope as well as to the driver. The signal detected by the pick-up was fed to the Y-plates. When these signals were of the same frequency and in phase, a Lissajous circle was seen on the tube screen. At the point of maximum trace height, zero amplitude of vibration was shown on the Y-plates after moving the pick-up to the theoretical location of the nodal points. When the pick-up was moved to either left or right of the nodal point, the Lissajous circle showed inclinations in opposite directions indicating reversal of signal phasing.

SONIC EVALUATION OF HOT-MIX AND CUTBACK BEAMS

After determination of physical properties of hot-mix beams, those beams which were chosen to undergo an oven-age cycle were placed on a flat steel tray containing perforations to allow circulation of air and this set-up put into a forced draft oven regulated at 140 ± 2 F.

Periodically, beams were removed from the oven, chilled to 40 F in a cold chest, and their fundamental frequencies obtained and recorded. Beams subjected to oven storage were tested in this manner for periods of one, three and six months.

After completion of each aging cycle, the appropriate set of beams (usually two of each asphalt blend composition) underwent a water immersion cycle in a constant temperature water bath at 140 ± 2 F for a 15-day period. Frequencies of vibration were again obtained after intervals by removing beams from the water bath and placing them in a melting ice bath adjusted at 40 F for a 2-hr period prior to frequency determination. A 20-day drying cycle at room temperature followed, with similar periodic frequency measurement.

For cutback specimens, frequencies were similarly determined during a 5½ month cure period. This served to follow transition of beams from a plastic to a progressively more elastic state. Solvent loss was also followed. Approximately five months' cure was conducted at room temperature, after which time solvent loss and frequency of vibration ceased to change. Inasmuch as both RC and MC beams possessed plastic character after this time, it was decided to hasten solvent loss by curing at 140 F.

After one week of additional curing at 140 F, both RC and MC beams lost considerably more solvent and showed greater elastic properties (rise of frequency values).

These "cured" beams then underwent a 15-day water immersion cycle similar to hot-mix specimens.

Calculation of Sonic Modulus of Elasticity

The following equation, derived by Bawa (5) and Yong (6), was used in the computation of the modulus of elasticity:

$$E = CWn^2$$

$$C = 0.00323\ l^3/bt^3$$

in which E = Young's Modulus of Elasticity in psi;
C = a constant dependent on beam dimensions in inches;
W = weight of each beam in pounds;
n = fundamental frequency in cps at 40 F;
l = length of beam (inch);
b = breadth of beam (inch); and
t = thickness of beam (inch).

Sample Calculation of Sonic Modulus

Example cited herein used data obtained from Sonic beam No. 10.

Beam weight	5.47 lb
Breadth (width)	2.53 in.
Thickness	2.52 in.
Length	12.0 in.
Fundamental frequency (n)	1460 cps

$$C = 0.00323 \times \frac{(12)^3}{2.53 \times (2.52)^3} = 0.1379$$

$$E = CWn^2$$

$$E = 0.137 \times 5.47 \text{ lb} \times (1460)^2$$

$$E = 1.61 \times 10^6 \text{ psi}$$

Reliability of Fundamental Frequency Measurements and Sonic Modulus Data

The major factor governing the confidence limits of the reported fundamental frequency values is the temperature of the beams at the time of measurement. Because 40 F is the point determined by Goetz (3) at which elastic properties of asphalt beams exist, it is very important that this temperature does not significantly vary during the time required to measure the frequency. This depends wholly on technique of the experimenter, and with a little practice reasonably accurate frequencies can be obtained within 30 to 45 sec. Throughout this program, care has been taken to carefully regulate the temperature of ice baths and cold boxes to 40 ± 1 F and allow beams to reach an equilibrium before testing. Thermocouples were imbedded in the beams to determine the length of time required to reach 40 F. It was found that 1.75 to 2.0 hr cooling was necessary to reduce a beam from 140 F to 40 F, and approximately 0.75 hr to cool from room temperature to 40 F.

Reproducibility of frequency measurements for any given set of beams was very good considering minor differences in size of the beams, a normal variation inherent in the method of vibratory compaction.

For the most part, frequency data obtained was reliable to within about 1.5 percent. It was found that occasional beams having identical frequencies had slightly different sonic moduli. This is caused by the slight variations in the breadth and thickness dimensions which affect the constant, C, in the calculation of sonic modulus. Apparently, there is a limit in the accuracy of the instruments or method itself to depict the differences in frequencies of beams of slightly different size. Variation in beam weights of from 5.45 to 5.48 lb does not significantly change the sonic modulus at a given frequency and is therefore not a factor affecting the accuracy of test data.

Determination of Unconfined Compressive Strength of Sonic Beams

After completion of a particular cycle (aging, immersion, drying) of sonic testing, beams were sawed into two pieces, each 5 in. in length, and a cap of plaster-of-Paris, approximately $^1/_{16}$ in. thick carefully applied to each end to form flat, parallel bearing surfaces. Unconfined strength of each piece was then determined according to ASTM Procedure Des. D-1074-55T (77 F, rate of vertical deformation, 0.05 in./min/in. of specimen height). A motor-driven Marshall Stability Testing Machine with variable speed gear reducer installed, operated in accordance with ASTM rate, was used to determine strengths reported. Variation of strength between the two sections of the beams did not vary by more than 5 psi units, and an average of the two values was reported for each beam.

Extraction of Asphalt From Sonic Beams for ASTM Penetration Determination

Immediately after strength data were obtained, one section of each beam, with plaster caps removed, was immersed in water-white commercial xylol, and after 2 hr the resulting xylol-asphalt solution decanted from the aggregates and filtered to remove included fines. The solution was then stripped of xylol and the asphalt recovered according to ASTM Des. D-402-55. Approximately 60 grams of recovered asphalt was obtained, and penetration (ASTM Des. D-5-52) at two temperatures, 40 F and 77 F, determined. Penetration values reported herein are those determined at 77 F.