EFFECT OF TEMPERATURE, FREEZE-THAW, AND VARIOUS MOISTURE CONDITIONS ON THE RESILIENT MODULUS OF ASPHALT-TREATED MIXES

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Any material property, such as the resilient modulus (M_R), that can be used directly in the elastic layer calculation for pavement structural design should be determined under test conditions that simulate or reflect the actual conditions to be expected in the pavement. This study explored the effects of realistic variations of temperature, moisture, and freeze-thaw conditions on the M_R of a representative spectrum of asphalt-treated mixes, some of which contain lime or cement. A method is proposed that allows the M_R to be estimated at any temperature from -20 to 140 F from 2 M_R measurements. Suggestions are made on how the various findings can be used in pavement design procedures with a minimum of testing.

• THE THICKNESS required of each layer in the highway structure to limit fatigue failure or overstressing of the subbase can be estimated by using multiple elastic layer calculations if the effective elastic modulus of each layer of material is known. The resilient modulus (M_R) test gives a suitable elastic modulus for asphalt-treated materials. Any such test, however, must be determined under test conditions that simulate or reflect actual conditions. This study explored the effects of realistic variations of temperature and moisture conditions on the M_R of a representative spectrum of asphalt-treated mixes, some of which contained lime or cement.

The study considered M_R changes as the temperature varied from -20 to 140 F on both dry and water-saturated asphalt-treated mixes. Also considered were the effects of single and repeated freeze-thaw cycling on the M_R over the same temperature range. The M_R of asphalt-treated mixes in equilibrium with air at moderate and high humidities also was investigated.

SPECIMEN PREPARATION AND MEASUREMENT OF M_R

The effect of various environmental conditions on material performance can be studied most effectively with a nondestructive test that efficiently measures functional properties. These requirements are met by a diametral M_R test (1) on 4-in.-diameter, 2¾-in.-thick, asphalt-treated specimens made by a kneading compactor built to ASTM D 1561-65. These M_R measurements are made at $^1/_{10}$-second pulse durations repeated every 3 seconds.

Three aggregates were studied—crushed Bristol silica from Oregon; Apex calcite, which is a nearly pure limestone from Nevada; and Cache Creek gravel obtained from a pit near Sacramento, California, which was used most extensively. X-ray diffraction and emission spectrograph analysis of these aggregates are given in Tables 1 and 2. All aggregates were graded according to the I curve shown in Figure 1. This gradation was chosen because it has a high mineral surface area and because it gives specimens with voids contents that are high enough to permit both rapid water saturation and rapid drying. Both hot mixes and asphalt emulsion mixes contained 5 percent

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Table 1. X-ray diffraction analysis of aggregates.

Aggregate	Silica (SiO_2)	Feldspar ($NaAlSi_3O_8$)	Calcite ($CaCO_3$)	Chlorite [$Mg_5Al_2Si_3O_{10}$, $(OH)_8$]	Mica [$KMg_3(Si_3AlO_{10})(OH)_2$]
Bristol silica	100				
Apex calcite limestone			100		
Cache Creek gravel	60	25		10	5

Table 2. Emission spectroscopy analysis of aggregates.

Aggregate	Component						
	SiO_2 (percent)	Al_2O_3 (percent)	Fe_2O_3 (percent)	MgO (percent)	CaO (percent)	Na_2O (percent)	K_2O (percent)
Bristol silica	98.0	0.2	<0.1	<0.6	0.8	<0.1	<0.1
Apex calcite limestone	2.0	0.6	0.2	0.9	>50.0	<0.1	0.3
Cache Creek gravel	74.0	8.0	5.0	2.0	1.0	2.0	0.8

Note: Values do not total to 100 percent because water and CO_2 are not included.

Figure 1. Gradation of aggregate.

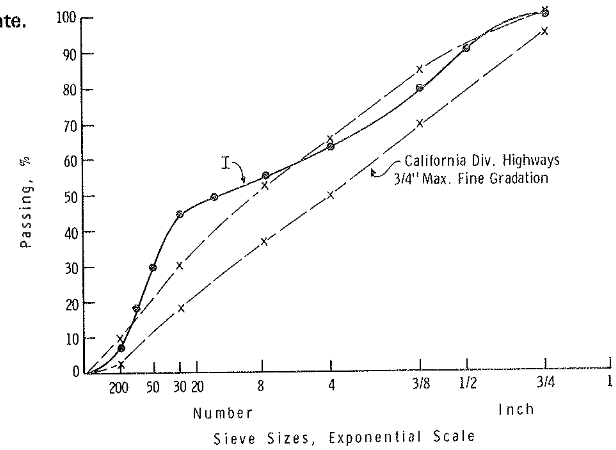


Table 3. Properties of asphalts used in tests.

Type	Boscan 40-50	Boscan 85-100	Boscan 200-300	Midway 85-100
Original asphalt				
Penetration at 77 F	39	83	244	91
Viscosity at 140 F, kP	8.75	2.25	0.56	1.14
Viscosity at 275 F, cs	883	462	246	212
Glass transition temperature, deg F	-20	-27.5	-37	-17
Residue from rolling thin film oven exposure				
Penetration at 77 F	25	50	127	—
Viscosity at 140 F, kP	—	6.35	1.62	1.90
Viscosity at 275 F, cs	—	744	401	270
Residue recovered from specimens[a]				
Penetration at 77 F	24	48	108	52
Softening point temperature, deg F	149.5	131.5	115.5	132.2
Viscosity at 140 F, kP	28.2	6.1	1.7	5.2
Viscosity at 275 F, cs	1427	690	421	637

[a]Recovered from typical Cache Creek hot-mix specimens.

asphalt. Three of the asphalts used (40-50, 85-100, and 200-300 penetration grades) were made from Boscan (Venezuelan) crude oil. Also included in some tests was an 85-100 penetration grade Midway asphalt made from a California Central Valley crude oil. Boscan asphalts are low wax, high asphaltene asphalts that are not very temperature sensitive. The Midway asphalt is a low wax, low asphaltene asphalt that is highly temperature sensitive. ASTM SS-1 emulsions were made from the same 4 asphalts. Properties of these asphalts are given in Table 3.

Hot asphalt-treated mixes (ATM) containing lime (L-ATM) or cement (C-ATM) were prepared by adding the lime or type I cement as a slurry to the aggregate just before it was heated in an oven. One and three-tenths percent lime or cement was used. This amount previously was found to be effective in providing these mixes with excellent resistance to water damage (2).

All hot ATM, L-ATM, and C-ATM intended for temperature susceptibility for freeze-thaw studies were first vacuum saturated and then soaked at 73 F for 24 hours, air dried for 10 days, and finally vacuum desiccated at about 20 torr to constant weight. We followed this procedure to ensure that the lime or cement in the hot mixes had a reasonable chance to wet cure before testing and, accordingly, afford a more realistic comparison with the cement-modified asphalt emulsion-treated mixes (C-ETM). Asphalt emulsion-treated mixes (ETM) and C-ETM were allowed to air dry at 73 F and about 50 percent relative humidity (RH) until they reached constant weight (60 days).

TEMPERATURE SENSITIVITY OF M_R

Experimental Measurement

All of the dried specimens were allowed to equilibrate for approximately 24 hours in a chamber controlled at the test temperature. While they were in the temperature-controlled cabinet, their resilient moduli were determined diametrally (1). The M_R device was operated in the chamber through armholes equipped with long rubber gloves. An interior view of this device, installed in the cabinet, is shown in Figure 2. Also shown, in the lower part of the figure, is an electronic system that permits direct read-out of specimen deformation without use of recorders.

When wet or partially wet specimens were to be tested, they were kept in the chamber in double plastic bags. The specimens were removed from the bags for testing and then quickly returned to the bags. Little change in moisture content occurred during the short exposure.

Dry, Hot ATM

The M_Rs of dried, untreated ATM mixes made from Cache Creek aggregate containing 5 percent asphalt were tested over a temperature range of -20 to 140 F. As shown in Figure 3, at temperatures above 50 F the logarithm of M_R varied linearly with 1/K. This simple Arrhenius relationship also was found at these temperatures for plots of viscosity versus temperature.

The M_R of specimens made with the highly temperature-susceptible Midway asphalt, as expected, had a high temperature sensitivity. The 3 specimens made with the 3 different grades of Boscan asphalts generated parallel curves. These results, together with previous tests made on asphalts extracted from similar mixes after M_R testing (3), further illustrate the dependence of M_R on asphalt viscosity.

The resilient moduli of these mixes approached a limiting value of about 4 to 6 $\times 10^6$ psi as the temperature dropped to levels approaching the glass transition temperature (Table 3) of the asphalts used (4). Heukelom and Klomp's work (11), together with Van Draat and Sommer's modifications (12), suggests a limit of 2 to 9 $\times 10^6$ psi for wide differences in mix composition.

All of these dry mixes could be cycled from 0 to 73 F without apparent damage. No abrupt change in the M_R at any temperature was evident over the range from -20 to 140 F. That is, with dry mixes, no freeze-thaw damage was incurred.

Although the data are not given, lime- or cement-treated hot mixes were shown to have M_R versus temperature characteristics almost identical to those of untreated hot mixes. No freeze-thaw damage was evident in these treated mixes, either.

Figure 2. Resilient modulus test device.

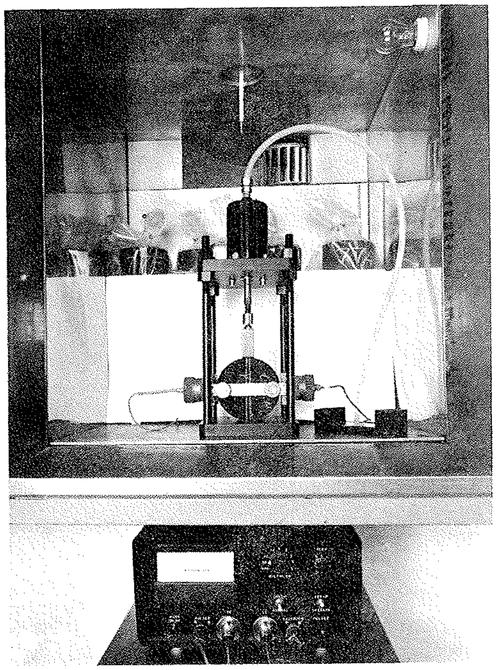


Figure 3. Temperature sensitivity of dry ATMs.

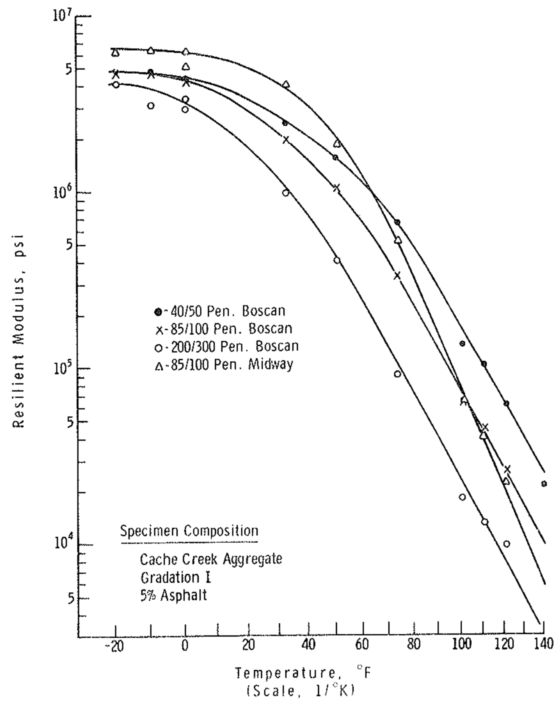


Figure 4. Comparison of temperature sensitivity of hot mix, ETM, and C-ETM.

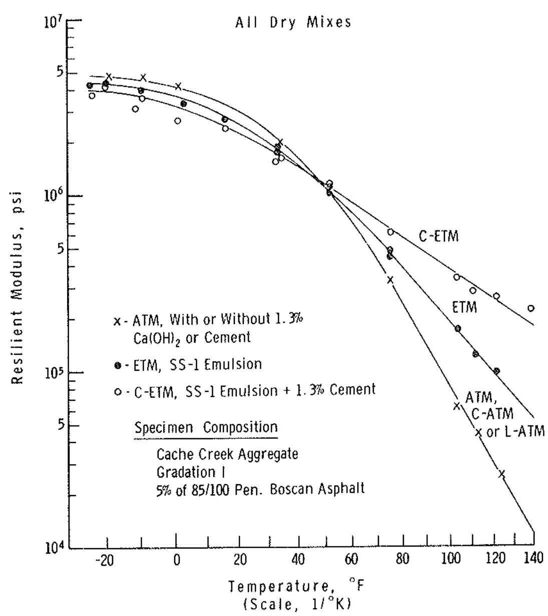
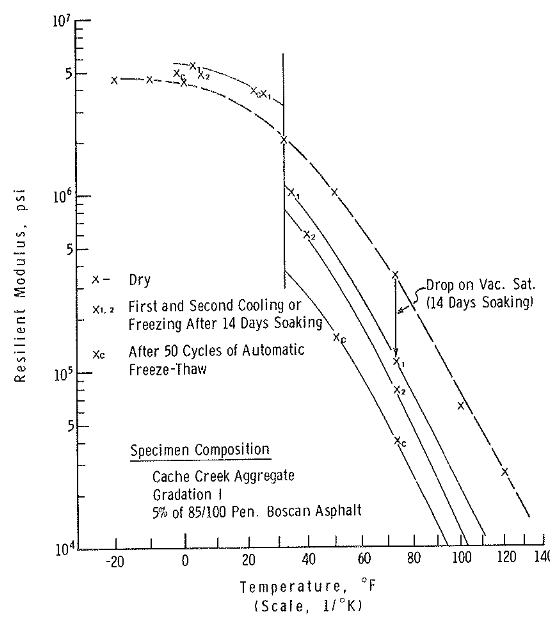


Figure 5. Freeze-thaw behavior of ATMs.



Dry ETM

An ETM made with the same aggregate and with an ASTM SS-1 asphalt emulsion containing the same 85-100 penetration Boscan asphalt had less temperature sensitivity than was found with the ATM as shown in Figure 4. The ATM made with the 85-100 penetration Boscan asphalt is also shown in Figure 4. At low temperatures, the M_R values for both mixes approached a similar limiting value of about 5×10^6 psi. However, at higher temperatures, the M_R value of this ETM was higher than that of the ATM. For example, at 140 F the ATM had an M_R value of 10,000 psi; the ETM made with the same asphalt had an M_R value of 50,000 psi. This 5 to 1 difference in M_R was obtained without an increase in the stiffness at low temperatures.

Other similar emulsion-treated mixes made with 40-50 or 200-300 penetration grade emulsified asphalt behaved in the same way except that the M_R level shifted to correspond with the hardness of asphalt used. All of the M_R values approached 5×10^6 psi as the temperature dropped below 0 F.

All of these dry ETMs could be cycled repeatedly through the freeze-thaw temperature range without apparent damage.

Dry C-ETM

A dried C-ETM (1.3 percent cement) made with the same aggregate and asphalt as the ATM and ETM discussed above is also shown in Figure 4. The C-ETM was less temperature sensitive than either ATM or ETM. The M_R values of the C-ETM at elevated temperatures were higher than those of the ETM and much higher than those of the ATM (with or without lime or cement). For example, the C-ETM had an M_R at 140 F of 250,000 psi; the ETM had an M_R of 50,000 psi.

Again, other similar C-ETMs made with 40-50 and 200-300 penetration asphalt behaved in the same way as the C-ETM made with the 85-100 penetration grade asphalt. The only apparent change was that the M_R levels were shifted by the asphalt hardness. These dry C-ETM's showed no change in M_R characteristics on repeated cycling through the freeze-thaw temperature range.

Wet ATM and Wet ETM

The response of M_R to freeze-thaw conditions, as shown in Figure 5, was quite different if the ATMs were thoroughly wet by vacuum saturation. Not only did water saturation lower the M_R at temperatures above freezing but there was also an abrupt increase in the M_R as the water in the specimen froze. The parallel nature of M_R versus temperature lines (dry and wet) indicates water soaking had not changed the temperature sensitivity of the M_R.

Below freezing, the M_R was significantly higher than it was in the dry specimen. As shown by Schmidt and Graf (3), the decrease in M_R of an ATM during water soaking is related to the length of time the saturated specimen is soaked before testing. When tested 13 days after saturation, the M_R had dropped from 346,000 to 105,000 psi. A repeat of the testing through the freeze-thaw range caused an additional drop in the M_R levels above freezing. Repeated automatic freeze-thaw cycles between 0 and 73 F reduced the M_R still further. The greatest decrease was noted above freezing. The automatic freeze-thaw sequence was 3 hours at 73 F, a $1\frac{1}{2}$-hour transition to 0 F, 6 hours at 0 F, and a $1\frac{1}{2}$-hour transition to 73 F.

These effects are even more clearly illustrated by the ETM behavior shown in Figure 6. Although the data for the ATM and ETM (Figs. 5 and 6) cannot be compared directly because they were soaked for different periods of time before the freeze-thaw cycles, the trends are similar. Not only was the initial drop in M_R on soaking distinct but also the added loss in M_R that resulted from each freeze-thaw cycle was clearly evident. The result of prolonged freeze-thaw cycles is also shown. The M_R drop, shown in Figure 5 for the ATM, was slightly less than is shown in Figure 6 for the ETM because the ATM was soaked for only 14 days compared to 42 days for the ETM.

Also shown in Figure 6 is the consequence of redrying the ETM. After it had been exposed to 50 freeze-thaw cycles, it had dropped to 6 percent of its original M_R. On

Figure 6. Freeze-thaw behavior of ETMs.

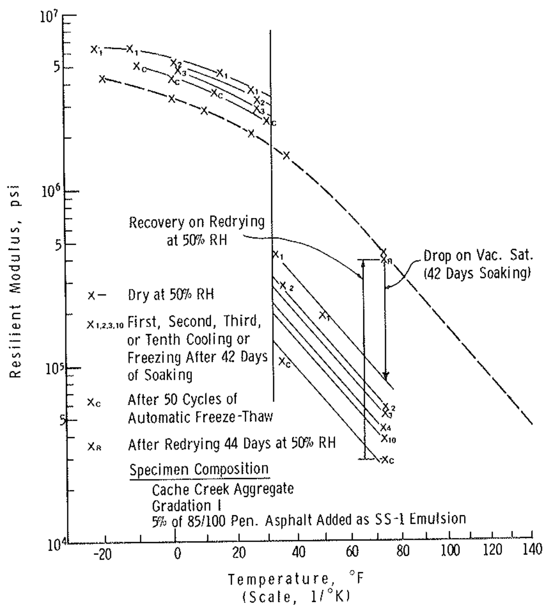


Figure 7. Freeze-thaw behavior of L-ATMs.

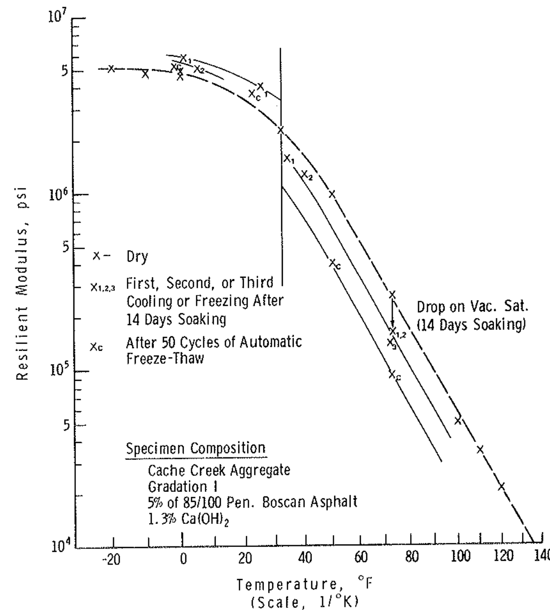


Figure 8. Freeze-thaw behavior of C-ATMs.

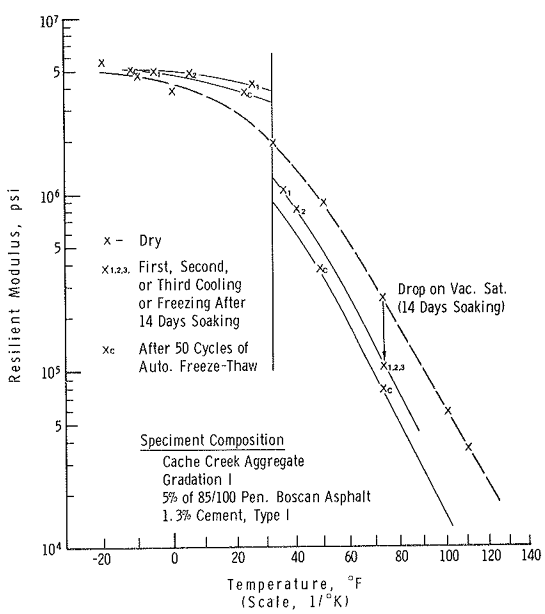
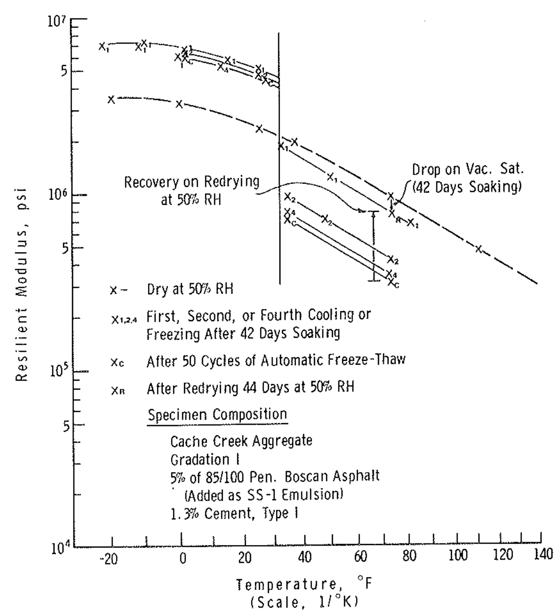


Figure 9. Freeze-thaw behavior of C-ETMs.



redrying at 73 F and 50 percent RH for 44 days, the specimen recovered to nearly the same M_R as was found on the original dry M_R.

The ability of ATMs to recover their strength on redrying is a most important characteristic. If it did not exist, the average life of asphalt pavements would be quite limited.

Wet Lime- or Cement-Treated Mixes

The behavior of water-saturated, hot L-ATM or C-ATM and water-saturated C-ETM is changed markedly from similar mixes not containing these modifiers. L-ATM and C-ATM as shown in Figures 7 and 8 were much less affected by 14 days of water saturation than the unmodified ATM. Subsequent repeated freeze-thaw cycles also were less damaging to these mixes than to the untreated ATM.

C-ETM as shown in Figure 9 changed only slightly on 42-day vacuum saturation. However, subsequent freeze-thaw cycles produced additional change. A comparison of Figure 9 with Figure 6 shows that the C-ETM was damaged much less than the unmodified ETM both by water saturation and by subsequent freeze-thaw cycles.

Also shown in Figure 9 is the consequence of drying the C-ETM specimen (73 F and 50 percent RH), which had been exposed to 50 cycles of freeze-thaw. This specimen recovered on redrying to 77 percent of the dry M_R value. Its actual recovered value was 730,000 psi; that of the ETM was 360,000 psi. Also, after the 50 cycles of freeze-thaw, the C-ETM only dropped to 310,000 psi compared to 29,000 for the ETM and 40,000 for ATM. Had the ATM been soaked 60 days instead of 14 days, its M_R value after freeze-thaw would have been lower.

EFFECT OF DRYING WET ATM AT DIFFERENT HUMIDITIES

Several investigators (3, 4, 5, 6, 7, 8, 9, 10) have used vacuum saturation to force water into asphalt-treated specimens. These investigators soaked or subjected the specimens to freeze-thaw cycles after saturation. These severe conditions were needed to simulate, in a short period of time, the most severe pavement deterioration likely to occur in the field.

This approach is useful principally to limit the extent of water sensitivity of acceptable materials. For example, Lottman's procedure (5, 6, 7, 8, 9, 10) reveals water-sensitive aggregates. Also, the moisture vapor sensitivity test (California Division of Highways Test Method 307-D) and the immersion compression test (ASTM D 1075-68, AASHO T 165-55) are used routinely to limit use of excessively moisture-sensitive aggregates. This section explores the extent of variation in M_R that the design engineer might expect under extreme as well as mild field conditions.

Although the exposure of water-saturated pavements to freeze-thaw cycles severely reduces the M_R, these extreme conditions seldom exist for long. Usually, intermediate moisture conditions prevail. The M_R on mixes when they are at equilibrium at about 50 percent and 95 percent RH should provide values that reflect relatively dry and near-saturated ground vapor conditions. These conditions are intermediate to the extreme dry conditions and those exposed to freeze-thaw cycles while saturated.

To investigate this, we vacuum saturated ATM specimens, soaked them for 7 days, and then air dried them at about 50 percent and 95 percent RH. We noted both the weight and M_R as they dried.

As expected, 2 specimens of a vacuum-saturated, soaked, Cache Creek, hot ATM as shown in Figure 10 lost water at 73 F and 50 percent RH at a faster rate than when they were dried at 73 F and 95 percent RH. Also, different equilibrium moisture contents (0.45 percent and 1.3 percent) were found in specimens dried under these conditions. No free water was present. If free water were present, even under an asphalt film, drying would have continued at both humidities until the free water disappeared.

As shown in Figure 11, the M_R increased more rapidly in the 50 percent RH than in the 95 percent RH. Although both specimens reached an equilibrium moisture content, the M_R of neither specimen stopped increasing. A comparison in Figure 11 of these 2 drying curves to a plot of M_R versus time of a dry ATM made with the same asphalt and aggregate suggests that at least some of the increase in M_R after moisture equilibrium

Figure 10. Equilibrium moisture content of ATM.

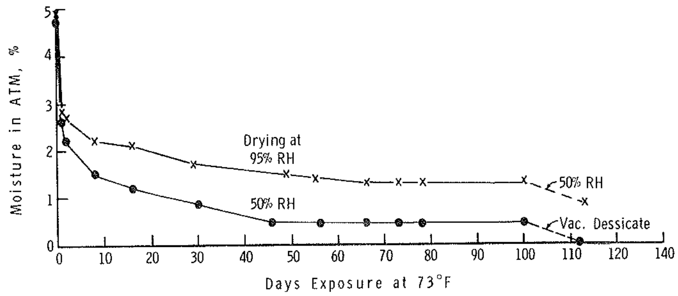


Figure 11. Level of ATM M_R.

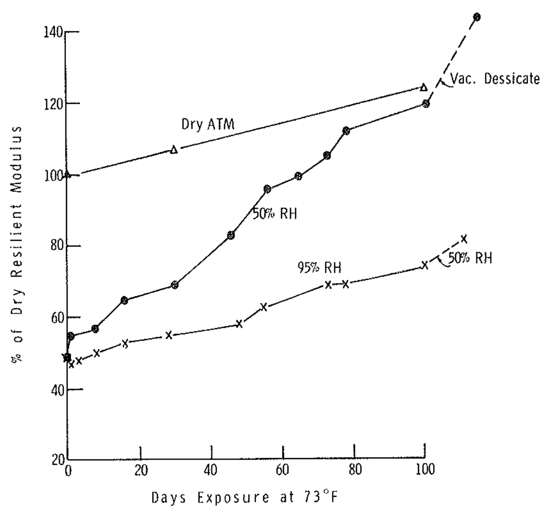
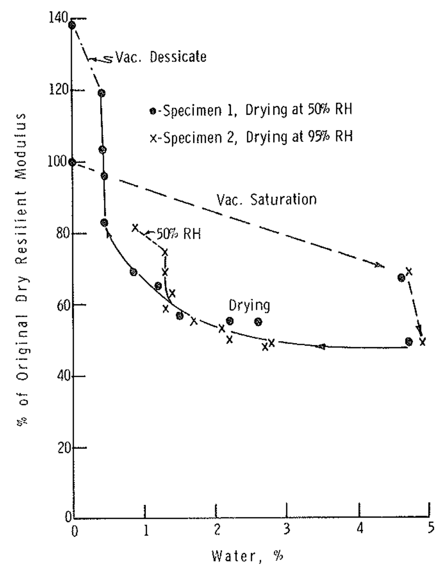


Figure 12. Effect of humidity during drying on water content and M_R of ATM.



can be accounted for by the hardening of the asphalt in the specimen (that is, for the continued increase in M_R after 45 days and 65 days for the 50 percent and 95 percent RH cases).

Shown in Figure 12 are the M_R versus water content of specimens as they are first vacuum saturated and subsequently dried at 50 percent or 95 percent RH. As the specimens dried, the M_R changed very little until the moisture content dropped below about 2.5 percent, possibly until all free, unassociated, or excess water was lost. Between 2.5 percent and 1.4 percent water content, both curves are superimposed. However, at 1.3 percent the 2 curves diverge. The M_R of the specimen dried at 95 percent RH rose first and gradually continued to increase its M_R as long as it remained at 95 percent RH, whereas the specimen dried at 50 percent RH continued to dry to 0.45 percent water and gradually increased its M_R to a much higher value. A possible explanation for the divergence of these curves is that more oxidation of the asphalt took place in the specimen exposed to 95 percent RH during the longer period it took to dry to the same moisture content than did the specimen in the 50 percent RH atmosphere.

Results of similar experiments on ATM specimens made with the same gradation of Bristol silica or Apex calcite aggregates and with the same asphalt are given in Table 4. Also given are the consequences of pretreating these aggregates and the Cache Creek aggregate previously discussed. Pretreatments included 1.3 percent lime (as a slurry) or 0.1 percent solution of silane in benzene for an adhesion aid.

The general behavior of all of these aggregate systems, whether pretreated or not, was the same; they all dried more rapidly at 50 percent RH and reached a higher equilibrium moisture content at 95 percent RH than when they were dried at 50 percent RH. When the 95-percent-RH-equilibrated specimens were placed in air at 50 percent RH, they all approached the condition of the corresponding 50-percent-RH-cured specimens. All silane-treated specimens behaved very nearly the same as the untreated specimens except that, on vacuum saturation, the silane-treated silica and calcite specimens were more water resistant.

Lime treatment increased the equilibrium moisture content on all aggregate mixes about 0.2 percent to 0.3 percent. This extra residual water was likely combined chemically in the reaction product of the lime and aggregate. Also, lime-treated ATM dried at 95 percent RH attained the same or higher equilibrium M_R than it did when dried at 50 percent RH. These higher M_R values were evident even though the specimens contained about twice as much residual moisture when they were dried at the higher RH.

SIMPLIFIED METHOD FOR DEVELOPING TEMPERATURE VERSUS M_R CURVES

When the structural design (thickness of layer) is determined by the M_R value assigned to the pavement mixture, the most representative temperature under which the M_R of ATM is tested must be chosen.

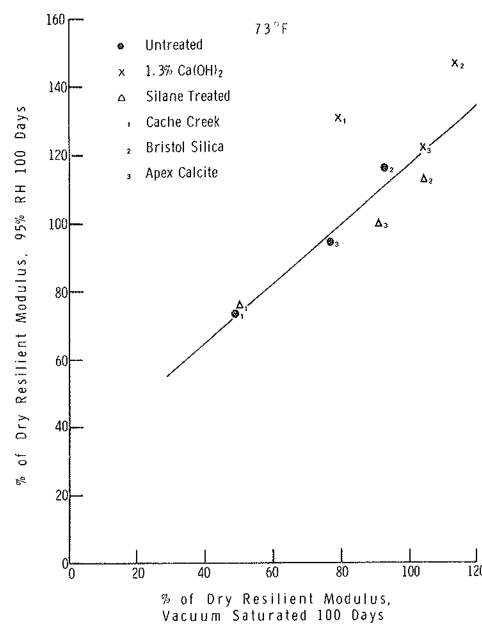
M_R estimates can be made over the entire range of temperature from measurements made at 2 separate temperatures above 73 F. This greatly simplifies testing. Most conveniently, 1 measurement is made at room temperature and the other at about 100 F to 120 F. The appropriate M_Rs can then be taken from a plot constructed from these 2 points. M_R values of most ATMs at very low temperatures (below about 0 F) can be taken as about 5×10^6 psi. Between 0 and about 73 F, additional experimentally determined values should be obtained. However, a French curve laid tangentially to and touching at 73 F the line describing the M_R above 73 F and laid tangentially to and touching at 0 F a horizontal line made at 5×10^6 psi allows estimation of intermediate values. These intermediate values appear to be within a factor of 2 of the experimentally measured values. This method of estimation is certainly more convenient and possibly more accurate than the method of Heukelom and Klomp (11) as modified by Van Draat and Sommer (12).

Once the total M_R versus temperature curve is estimated, the M_R can be determined at various levels in the pavement structure in accordance with the yearly or, preferably, monthly average temperature existing at that level. These temperatures can be estimated from the climatic conditions by methods such as those of Christison and Anderson (13); Straub, Schenk, and Przybycien (14); Croney and Bulman (15); or Barber (16). The

Table 4. Drying of ATM at moderate and high humidities.

Aggregate and Treatment	Original Dry Specimen: M_R (psi), 24 Hours at 73 F	Original Dry Specimen: M_R (psi), Vacuum Dessication	Original Dry Specimen: Density (pcf), 24 Hours at 73 F	Original Dry Specimen: Density (pcf), Vacuum Dessication	7 Days' Soaking After Vacuum Saturation: M_R (psi)	7 Days' Soaking After Vacuum Saturation: Dry M_R (percent)	Equilibrium After 100 Days: M_R (psi)	Equilibrium After 100 Days: Dry M_R (percent)	Equilibrium After 100 Days: Water (percent)
50 Percent Relative Humidity									
Cache Creek gravel	224,000	321,000	142.2	142.0	110,000	49	267,000	119	0.44
Plus 1.3 percent $Ca(OH)_2$	199,000	308,000	142.4	142.5	157,000	79	285,000	143	0.87
Silane-treated	314,000	385,000	143.1	142.9	157,000	50	311,000	99	0.52
Bristol silica	77,000	108,000	137.7	—	71,000	92	115,000	150	0.28
Plus 1.3 percent $Ca(OH)_2$	179,000	200,000	140.1	—	204,000	113	268,000	149	0.47
Silane-treated	92,000	100,000	137.6	—	97,000	105	119,000	129	0.20
Apex calcite	342,000	302,000	143.6	—	263,000	77	389,000	114	0.36
Plus 1.3 percent $Ca(OH)_2$	275,000	388,000	146.6	—	286,000	104	410,000	148	0.55
Silane-treated	311,000	277,000	143.3	—	285,000	91	358,000	118	0.35
95 Percent Relative Humidity									
Cache Creek gravel	284,000	—	141.5	—	141,000	49	211,000	74	1.30
Plus 1.3 percent $Ca(OH)_2$	278,000	—	142.7	—	211,000	75	364,000	131	1.89
Silane-treated	323,000	—	142.0	—	152,000	47	243,000	76	1.19
Bristol silica	87,000	—	137.1	—	79,000	91	102,000	118	1.10
Plus 1.3 percent $Ca(OH)_2$	179,000	—	140.1	—	190,000	106	266,000	148	1.45
Silane-treated	104,000	—	138.0	—	98,000	94	118,000	113	1.27
Apex calcite	381,000	—	143.7	—	287,000	72	357,000	94	0.95
Plus 1.3 percent $Ca(OH)_2$	412,000	—	145.0	—	367,000	89	500,000	121	1.10
Silane-treated	386,000	—	145.0	—	306,000	79	386,000	100	0.75

Figure 13. Predicting M_R in equilibrium at 95 percent RH from M_R of 7-day vacuum-saturated ATMs.



M_Rs estimated at these various levels are then used in the multilayer elastic design calculations by methods such as those described by Kasianchuk, Monismith, and Garrison (17) or by the Asphalt Institute (18).

METHOD FOR INCLUDING EFFECTS OF MOISTURE IN PAVEMENT DESIGN

Design of an efficient pavement structure depends, in part, on the use of realistic stiffness values for the composites. As seen herein, the stiffness, as measured by M_R, varies not only with temperature but also with moisture. This latter effect has been largely ignored except to the extent that material tests have been used that are designed to prevent use of those exceptionally water-sensitive materials (3, 5, 6, 7, 8, 9, 10) occasionally responsible for catastrophic pavement failures.

The extent of variation of M_R within the range of moderate moisture conditions is as significant as the effect of rather large changes in the average pavement temperature. For example, 4 percent water in an ATM made from a good aggregate can cause as much change in M_R as a 50 F change in the average pavement temperature (3). As shown earlier, the M_R of ATM drops nearly as much when in equilibrium with 95 percent RH vapor, a common condition under pavements. For example, the drop in M_R at 95 percent RH can be equal to about a 40 F rise in the average pavement temperature.

The actual drop in M_R observed at 95 percent RH on mixes made with a variety of aggregates as shown in Figure 13 was related to the M_R drop observed in the same mixes after vacuum saturation and soaking. Although this relationship was conservative for lime-treated mixes, the relationship showed that actually measuring the M_R of mixes in equilibrium at 95 percent RH is unnecessary. Measurement after vacuum saturation and soaking gave sufficient information to estimate the 95 percent RH M_R.

Also, measurement of M_R in equilibrium at 50 percent RH appears unnecessary. This value, given in Table 4, was at least as high as the original dry M_R (because of the asphalt hardening that takes place).

The total variation of M_R with field conditions can be assessed by using the following sequence:

1. Measure the M_R of the freshly made ATMs or ETMs as soon as they reach constant weight when dried at room temperature or when dessicated under vacuum;
2. Measure the M_R again after it has been vacuum saturated and allowed to stand under water at 73 F for at least 7 days; and
3. Measure the M_R after about 10 freeze-thaw cycles of 73 to 0 to 73 F. (This can be omitted when pavements are not frozen.)

If 95 percent RH is a condition similar to one prevailing in the pavement, the 95 percent RH M_R can be estimated by increasing the vacuum-saturated M_R by a factor of 1.25.

Although these tests allow the projected effective M_Rs to be estimated for the probable range of moisture conditions, there still remains to be estimated the proportion of time the projected pavement will be under each of these conditions. No such procedure is presently available so this judgment must still be made by the engineer.

CONCLUSIONS

Emulsion-treated mixes are less temperature susceptible than hot ATM made with the same asphalts and aggregates.

Cement-modified, asphalt emulsion-treated mixes have temperature susceptibilities substantially lower than ETM and greatly lower than ATM. Both improved high-temperature M_Rs are attained without an increase in the low-temperature M_R. Thus, the ETMs and, more particularly, the C-ETMs should have higher structural values at summer temperatures than do ATMs. They also should be more resistant to traffic consolidation and surface bleeding.

Dry ATM, which has been lime- or cement-pretreated, has almost the same M_R and M_R temperature susceptibility as dry, untreated ATM.

Although the M_R values of ATMs are lower when wet than when dry, the temperature susceptibilities of wet and dry ATM are nearly the same. This relationship is also true for ETMs.

No damage appears to occur on prolonged freeze-thaw cycling to dry, hot asphalt or treated or untreated asphalt emulsion-treated mixes.

Repeated cycling between a frozen and a thawed condition sharply drops the M_R of all water-saturated, hot asphalt or asphalt emulsion-treated mixes. After 50 freeze-thaw cycles, little further damage is apparent. Most of the damage occurs in the first 10 cycles. However, drying at room temperature reverses this freeze-thaw damage. Damage resulting from simple soaking after saturation is also reversible.

Damage occurring to water-saturated, cement- or lime-modified, hot ATMs as a result of freeze-thaw cycling is substantially less than that which occurs when similar unmodified ATMs are freeze-thaw cycled. Also, the damage sustained is largely reversed by drying.

Of particular importance is the greatly reduced freeze-thaw damage of water-saturated C-ETMs. Most of this damage is also temporary and is recovered after drying.

Saturated samples of ATMs made with Cache Creek, silica, or calcite aggregate dry to moisture contents in equilibrium with the humidity of the drying air. Moisture contents as high as 1.3 percent are found in equilibrium with 95 percent RH. Water contents in excess of about 2 percent exist as free or excess water. Pretreatment of either Cache Creek, silica, or calcite (pure limestone) aggregate with a silane had almost no effect on the equilibrium moisture contents. Pretreatment of these same aggregates with lime slurry increased the equilibrium moisture content but at the same time greatly increased the M_R at these equilibrium conditions.

The M_R of dry or wet mixes can be estimated from 73 to at least 140 F from a straight line constructed by plotting 2 experimentally determined points as the logarithm of M_R versus the reciprocal of the temperature in kelvins. At temperatures below 0 F, an M_R value of 5×10^6 psi for most mixes can be assumed to be without an error greater than ±50 percent.

Although they are easily determined directly by the diametral M_R device, values on dry mixes at intermediate temperatures (0 to 73 F) can be estimated by placing a smooth curve tangent to and touching the above limit at 0 F. The other end of the curve is tangent to and touching at about 73 F the line described by the logarithm of M_R versus 1/K. This method of estimation is more convenient and is possibly more accurate than other methods of estimating the M_R.

The M_R versus temperature curve on wet mixes above freezing can be estimated by drawing a curve through a measured point at room temperature parallel to the estimated dry curve. The curve below freezing intercepts the 32 F temperature at about 4×10^6 psi and extends to lower temperatures as a curve parallel to the dry curve.

M_R values determined dry, 7 days (or more, if convenient) after vacuum saturation of specimens, and, when necessary, after 10 cycles of freeze-thaw while specimens are saturated, are sufficient to give reasonable indications of the range of M_R that can be obtained in the actual pavements.

Methods still must be developed for estimating the proportion of the time the various layers of asphalt-treated mixes exist at the various moisture levels explored.

REFERENCES

1. Schmidt, R. J. A Practical Method for Measuring the Resilient Modulus of Asphalt-Treated Mixes. Highway Research Record 404, 1972, pp. 22-32.
2. Schmidt, R. J., Santucci, L. E., and Coyne, L. D. Performance Characteristics of Cement-Modified Asphalt Emulsion Mixes. Presented at Annual Meeting of AAPT, Houston, Texas, 1973.
3. Schmidt, R. J., and Graf, P. E. The Effect of Water on the Resilient Modulus of Asphalt-Treated Mixes. Proc. AAPT, Vol. 41, 1972, pp. 118-162.
4. Schmidt, R. J., and Santucci, L. E. A Practical Method for Determining the Glass Transition Temperature of Asphalts and Calculation of Their Low Temperature Viscosities. Proc. AAPT, Vol. 35, 1966, p. 61.
5. Lottman, R. P. Debonding Within Water-Saturated Asphalt Concrete Due to Cyclic Effects. Symposium on The Science of Asphalt in Construction, American Chemical Society, 1972.

6. The Moisture Mechanism That Causes Asphalt Stripping in Asphaltic Pavement Mixtures—Phase 1. First Annual Report, Eng. Exp. Station, Univ. of Idaho, Nov. 1968.
7. The Moisture Mechanism That Causes Asphalt Stripping in Asphaltic Pavement Mixtures—Phase 2. Second Annual Rept., Eng. Exp. Station, Univ. of Idaho, Dec. 1969.
8. The Moisture Mechanism That Causes Asphalt Stripping in Asphaltic Pavement Mixtures—Quarterly Progress Rept. Eng. Exp. Station, Univ. of Idaho, March 1970.
9. The Moisture Mechanism That Causes Asphalt Stripping in Asphaltic Pavement Mixtures—Quarterly Progress Rept. Eng. Exp. Station, Univ. of Idaho, June 1970.
10. The Moisture Mechanism That Causes Asphalt Stripping in Aspahltic Pavement Mixtures—Quarterly Progress Rept. Eng. Exp. Station, Univ. of Idaho, Sept. 1970.
11. Heukelom, W., and Klomp. A. J. G. Road Design and Dynamic Loading. Proc. AAPT, Vol. 33, 1964, pp. 92-115.
12. Van Draat, W. E. F., and Sommer, P. Ein Gerät zur Bestimmung der Dynamischen Elastizitätsmoduln von Asphalt. Strasse und Autobahn. Vol. 35, 1966.
13. Christison, J. T., and Anderson, K. O. The Response of Asphalt Pavements to Low Temperature Climatic Environments. Proc. Third Internat. Conf. on Structural Design of Asphalt Pavements, Vol. 1, 1972, p. 41.
14. Straub, A. L., Schenck, H. N., Jr., and Przybycien, F. E. Bituminous Pavement Temperature Related to Climate. Highway Research Record 256, 1968, pp. 53-77.
15. Croney, D., and Bulman, J. N. The Influence of Climatic Factors on the Structural Design of Flexible Pavements. Proc. Third Internat. Conf. on Structural Design of Asphalt Pavements, Vol. 1, 1972, p. 67.
16. Barber, E. S. Calculation of Maximum Pavement Temperatures From Weather Reports. Highway Research Bull. 168, 1957, pp. 1-8.
17. Kasianchuk, D. A., Monismith, C. L., and Garrison, W. A. Asphalt Concrete Pavement Design—A Subsystem to Consider the Fatigue Mode of Distress. Highway Research Record 291, 1969, pp. 159-172.
18. Full Depth Asphalt Pavements for Air Carrier Airports. In Construction Manual on Airports, The Asphalt Institute, MS-11, 1973.