Premature Asphalt Concrete Pavement Distress Caused by Moisture-Induced Damage

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Cases of premature pavement distress have recently occurred in Northern California. The distress has mainly been manifested in the form of cracking (alligator and longitudinal). Also, rutting, raveling, and bleeding have occurred at various locations. Field observations and laboratory tests performed by the California Department of Transportation indicated that the primary cause of this distress is moisture-induced damage (stripping). Stripping was extensive at many locations. Sections that exhibited more severe pavement deterioration showed more stripping damage. Sections that showed more severe stripping were those that received a chip seal treatment, had an asphalt concrete overlay over an existing chip seal, or were constructed with pavement reinforcing fabrics. Many core samples also revealed high air voids and high ratios of fines to asphalt. Various laboratory tests were conducted, including the moisture-induced damage test (AASHTO T283), which included the effect of lime and BA2000 antistripping additives; surface abrasion (CT 360); the moisture vapor susceptibility test (CT 307); and density analysis and extraction tests. It was concluded that using lime in a slurry form or using a liquid antistripping agent in combination with lowering the level of air voids and reducing the ratio of fines to asphalt could minimize stripping. Also, among the tests evaluated, AASHTO T283 appears to have the best potential to identify moisture-susceptible mixes. The other tests did not appear to possess this potential.

A significant number of premature asphalt concrete (AC) pavement failures in Northern California (District 2) have occurred in the last few years. The distress has mainly been manifested in the form of cracking (alligator, longitudinal, and transverse) in varying degrees. Rutting, raveling, bleeding, and potholes also occurred at various locations. These failures generally have occurred 2 to 5 years after construction.

The extent of these problems was reason for concern and warranted an investigation. Therefore, the Division of New Technology, Materials and Research (NTM&R) of the California Department of Transportation (Caltrans), in cooperation with District 2 embarked on an investigation that involved taking core and jackhammer samples and performing material tests on core and laboratory fabricated specimens. This work was conducted with the hope of identifying the causes and remedies of the problems.

Initially, 30 projects were reviewed and 18 of them were selected as representative for sampling as shown in Table 1. Of the 18 projects four were considered to be in fairly good condition. These projects are located on Interstate 5 and on Routes 3 and 97. The projects consisted of AC overlays over existing AC and portland cement concrete pavements. The rehabilitation strategies on these projects included the use of pavement reinforcing fabrics and chip seals. Some projects included bases constructed using asphalt-treated permeable materials.

On the basis of initial findings, stripping was suspected to be a possible cause of distress, and a sampling program was conducted to verify this hypothesis. The results of this effort are presented in this paper, which include a diagnosis of the causes of the premature distress along with recommendations for remedial measures.

INITIAL OBSERVATIONS

The pavement sections were surveyed and then core and jackhammer samples were taken. The following were the initial findings.

1. Moisture damage (stripping) was extensive at many locations. Sections that exhibited more severe pavement deterioration (alligator and longitudinal cracking) showed more stripping damage.
2. Sections that had received a chip seal treatment or had an AC overlay over an existing chip seal showed more stripping damage.
3. Sections constructed with pavement reinforcing fabrics showed more stripping damage.
4. Many core samples revealed low densities (high air voids).
5. Sections in which the aggregate was lime treated did not show significant improvements in performance over untreated sections.
6. In sections in which the aggregate was lime treated, the lime treatment was not according to specifications, which called for the use of lime in a slurry form. The lime was actually added to wet aggregates. Thus, lime may not have been uniformly distributed on the surfaces of the aggregates.

TESTING

Core and jackhammer samples were obtained from the various pavement sections that are shown in Table 1. NTM&R and District 2 laboratories performed tests on these samples and on mixes fabricated using representative aggregates that were used on these projects.

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TABLE 1 Pavement Sections and Field Sampling Information

Section[a,b]	Core Location[c]	Year Rehabilitated	Aggregate Source
301	3-36.65EBLN2	87	Grenada
301	3-37.55WBLN2	87	Grenada
301	3-37.6WBLN2	87	Grenada
302	3-41.4EBLN2	88	Grenada + Lime
501	5-.4SBLN2	84	Clear Creek
501	5-.9NBLN2	84	Clear Creek
504	5-10.2NBLN2	88	Grenada + Banhart
505	5-16.8SBLN1	86	Grenada
505	5-16.8SBLN2	86	Grenada
505	5-18.5NBLN2	86	Grenada
506	5-20.9NBLN2	88	Grenada + Lime
506	5-22.0NBLN2	88	Grenada + Lime
507	5-24.6NBLN2	86	Grenada
507	5-23.8NBLN2	86	Grenada
508	5-26.5NBLN2	85	Kidder Creek
508	5-28.3NBLN2	85	Kidder Creek
509	5-37.8NBLN2	83	Kidder Creek
509	5-38.2SBLN2	83	Kidder Creek
510	5-44.5NBLN2	84	Kidder Creek
510	5-49.0SBLN2	84	Kidder Creek
512	5-59.1NBLN2	87	Rogue River
512	5-60.3SBLN2	87	Rogue River
512	5-67.2NBLN3	87	Rogue River
512	5-67.75NBLN3	87	Rogue River
513	5-62.45NBLN2	84	Clear Creek
513	5-62.65SBLN2	84	Clear Creek
9702	97-16.55NBLN2	87	Grenada
9702	97-16.55SBLN2	87	Grenada
9702	97-16.55SBLN1	87	Grenada
9703	97-29.7NBLN2	88	(Grenada + Banhart)+Lime
9703	97-32.3SBSHL	88	(Grenada + Banhart)+Lime
9703	97-32.3NBLN1	88	(Grenada + Banhart)+Lime
9703	97-32.35SBLN2	88	Grenada + Banhart
9704	97-35.8SBLN2	84	Grenada
9704	97-37.9SBLN2	84	Grenada
9705	97-47.25SBLN1	89	Truax + Lime
9706	97-51.5NBLN1	88	Truax + Lime
9706	97-53.05NBLN2	88	Truax + Lime
9707	97-53.3SBLN2	88	Truax + Lime
9707	97-53.35NBLN2	88	Truax + Lime

[a] Sections with numbers starting with 3,5 or 97 are on Route 3, Interstate 5 or Route 97, respectively.
[b] All sections are in Siskiyou County except 513 which is in Shasta County.
[c] Locations marked such as 3-36.65EBLN2 indicate Route 3, Post Mile 36.65, Eastbound, Lane two. Locations marked such as 97-32.3SBSHL indicate Route 97, Post Mile 32.3, Southbound, Shoulder.

Field Sample Testing

Field samples were brought to NTM&R and District 2 laboratories. Core specimens were remolded and tested to determine their stabilometer values by California test (CT 366) and the following other tests were conducted.

Density (CT 308-C)

The bulk specific gravity was measured by weighing each specimen in air and then weighing it in water. The air voids were then computed using the bulk specific gravity and the measured maximum theoretical specific gravity using the Rice method (AASHTO T209). The relative compaction was computed as the ratio between the bulk specific gravities of the core and remolded core specimens.

Extraction Testing (CT 310, CT 202, and CT 380)

The in-place asphalt contents were determined using the hot solvent extraction test (CT 310), and extracted gradations were performed using CT 202. The asphalt was recovered using the Abson recovery test (CT 380).

Aggregate Source Testing

Aggregates from six different sources were sent to the NTM&R laboratory. These aggregates were representative of those used on the projects. The testing was conducted to determine whether the observed stripping could be related to the mix and aggregate properties and, if so, which test Caltrans should use in the future as a basis to detect moisture-susceptible mixes. New mix designs were conducted on these aggregates using Chevron AR-4000 asphalt. In addition, the following tests were performed.

Moisture Vapor Susceptibility (CT 307)

The moisture vapor susceptibility (MVS) test is used to determine the effect of moisture vapor on asphalt concrete. This effect is assessed on the basis of the reduction in the stabilometer value after conditioning. In this test the bottom of the specimen is placed on top of a wet felt pad and the top is sealed by an aluminum cap to prevent the escape of vapor. The test is performed by placing the assembly in a 60°C (140°F) oven for 75 hr. The sample is then removed and the stability is measured using CT 366.

Surface Abrasion (CT 360 and Modified CT 360)

The abrasion resistance of asphalt concrete surfaces is generally thought to be related to parameters such as the asphalt content, aggregate type, surface texture, and grade of binder. In this study the surface abrasion test was performed to investigate the effect of aggregate type on the stripping potential. In this method cylindrical samples are stored in water at 4.5°C (40°F) for 24 hr and then placed in a mechanical shaker. During the test steel balls bounce on the top surface of the sample in the presence of water for 15 min at 4.5°C (40°F). The surface abrasion is then measured by weighing the loss of material from the surface of the specimen.

The abrasion testing was performed on both laboratory fabricated specimens and field core specimens, each tested by a different method. For the laboratory specimens, the method used was CT 360 in which 35 g is considered to be the maximum tolerable loss. For the core specimens, a modified version of CT 360 was used. In the modified CT 360, the surface exposed to the bouncing balls is less and the maximum tolerable loss is 21 g.

Resistance to Moisture-Induced Damage (AASHTO T283)

A test to measure resistance to moisture-induced damage was used to assess the moisture damage potential of the aggregate sources on these projects and to evaluate the effect of treating these aggregates with hydrated lime and BA2000 (a liquid antistripping agent) to reduce their moisture damage susceptibility.

This test was developed originally by Lottman (*1*), who used the indirect tensile strength test to evaluate moisture damage potential. During the test, six specimens are prepared, and three of them are subjected to vacuum saturation followed by a freeze-thaw cycle. The reduction in tensile strength caused by this conditioning, which is expressed as the tensile strength ratio (TSR), is used to measure moisture damage. Lottman indicated (on the basis of a 5-year investigation) that a value of TSR greater than 0.80 would provide adequate level of service with respect to moisture damage. Another researcher (*2*), using modified versions of the test, has recommended TSR values of 0.70 or greater in combination with a visual assessment of stripping of the failure plane area of 20 percent or less.

Other Tests

Other properties were obtained using tests that included aggregate absorption (CT 206), coarse durability and fine durability (CT 229), sand equivalency (CT 217), Los Angeles Rattler (CT 211), CKE (Kc and Kf indexes) (CT 303), and moisture absorption (CT 370). Each of these tests is briefly described.

Moisture absorption was obtained using Method of Determining Moisture Content of Asphalt Mix or Mineral Aggregate using Microwave Ovens (CT 370). After running the MVS test (CT 307) for the stabilities, the moist asphalt mixture was weighed and then placed in a microwave oven for drying. The moisture absorption was then computed after reweighing.

Aggregate absorption (CT 206) is performed by weighing a representative sample of 5000 g of coarse aggregate, soaking it in water for a minimum of 15 hr, and then weighing it in a saturated condition. The sample is then dried to a constant weight. The aggregate absorption was computed from the dry weight and the saturated surface dry weight.

Coarse durability (coarse aggregate) and fine durability (fine aggregate) (CT 229) are indexes that provide a measure of the relative resistance of an aggregate to produce clay-size fines when subjected to prescribed methods of interparticle abrasion in the presence of water. The fine materials (passing No. 4 sieve) and the coarse materials (retained on No. 4 sieve) are subjected to shaking separately.

The sand equivalency test (CT 217) provides a measure of the relative proportions of detrimental dust or clay-like material in fine aggregates. The material is subjected to agitation in a calcium chloride solution in a graduated cylinder and then left undisturbed for 20 min. The percent ratio between the clay reading (top of sediment column) and the sand reading (resting position of weight foot) is termed the sand equivalent. A minimum acceptance value of 50 is specified in the Caltrans standard specifications for Type A AC.

The Los Angeles Rattler test (CT 211) is used to determine the resistance of coarse aggregate to impact in a rotating cylinder containing metallic spheres. The loss is the percent difference between the original weight of the sample and the weight retained on the No. 12 sieve after the specified number of revolutions divided by the original weight. The standard specifications value after 500 revolutions is 45 maximum for Type A AC.

The Kf and Kc indexes are obtained by Test for Centrifuge Kerosene Equivalent and Approximate Bitumen Ratio (CT 303). The indexes are thought to indicate the relative particle roughness and surface capacity of the aggregate on the basis of porosity. A maximum value of 1.7 is considered acceptable in the standard specifications for both Kf and Kc indexes.

EVALUATION OF TEST RESULTS

The results from the various major tests were evaluated. The evaluation was performed on core and laboratory mixtures as follows.

Densities

The air voids of the core specimens are shown in Figure 1. This figure shows a substantial number of cores with air voids of more than 7.0 percent. This value is rather high, considering that these sections already have experienced several years of traffic. High air voids can have detrimental effects on moisture susceptibility. In regions where there are aggregates with stripping potential and high moisture conditions, lower air voids should be recommended after placement.

The relative compaction results (Figure 2) showed values of 95 percent and more for the majority of the specimens. Some specimens had 100 percent relative compaction. It is very likely that the relative compaction data shown in the

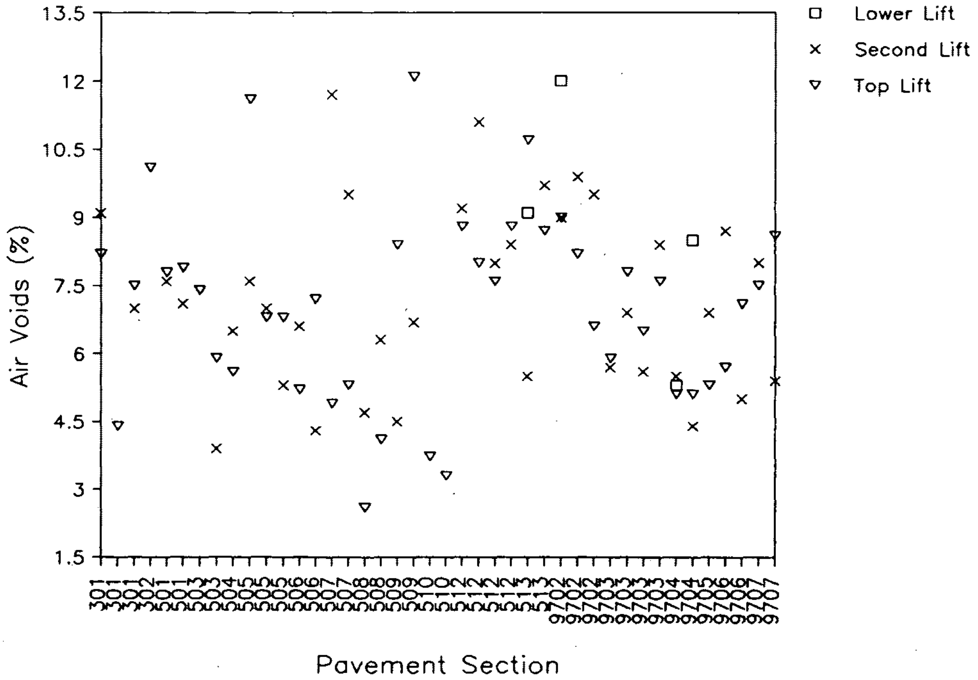

FIGURE 1 In-place air voids versus pavement section.

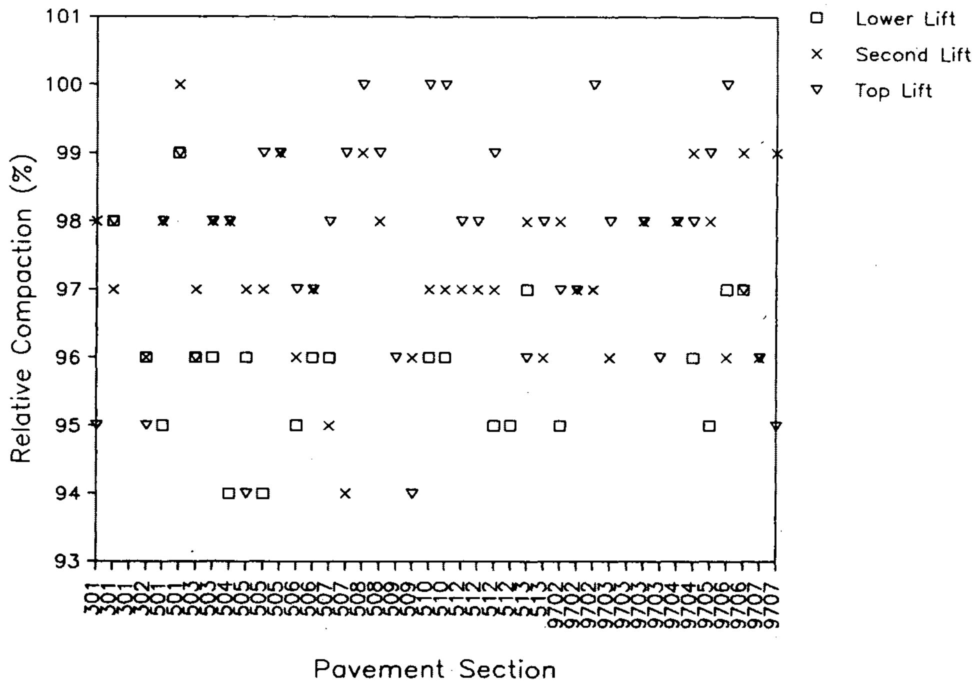

FIGURE 2 Relative compaction versus pavement section.

figure are lower than they were originally because of further compaction by traffic after placement. The mixes were initially placed with lower relative compaction levels (higher air voids), which probably allowed an excessive amount of water to infiltrate the asphalt concrete pavement, resulting in an increase in the rate of stripping.

Extractions

The extracted binders from core specimens were tested for their properties, and the majority of the data were considered to be within the normal range. The extracted gradations from the core specimens showed general conformity with the standard specifications, except for the fines (the fraction passing the No. 200 sieve) where they exceeded the maximum specification range (3 to 8 percent) by an average of 2 percent. This value is rather high and can be a contributing factor to the poor performance. Table 2 shows the extracted fines and extracted asphalt contents for the sections evaluated. These values were then used to compute the ratios of fines (dust) to asphalt as shown in Table 3. This table shows high ratios of fines to asphalt, which exceed the range of 0.6 to 1.2 as recommended by the FHWA Advisory T5040.27 (*3*). Excessive fines or low asphalt content, or both, can lead to stripping and premature pavement distress. The excessive fines content may be attributed partly to a breakdown of the aggregates as a result of repeated traffic loading.

Resistance to Moisture-Induced Damage Test (AASHTO T283)

Table 4 shows the TSR values for mixes using the various aggregate sources. These results were obtained by both NTM&R and District 2 laboratories. (The testing was performed on ½-in. maximum-size aggregates by NTM&R and on ¾-in. maximum-size aggregates by District 2.) It appears that the differences in the maximum sizes have contributed significantly to the values of tensile strength (Table 5).

TABLE 2 Extracted Asphalt and Fines for the Sections Evaluated

	Extracted Asphalt (%)			Extracted Fines (%)[a]			
Section	Top[b]	Second	Lower	Top	Second	Lower	Average
301	6.3	4.9	-[c]	12	6	-	9
302	5.3	6.1	5.1	12	12	6	10
501	4.7	5.2	6.0	9	9	9	9
504	5.8	5.8	5.4	11	11	9	10
505	5.4	6.0	5.9	10	10	10	10
506	5.7	6.1	5.7	10	12	-	11
507	5.8	5.6	5.8	10	10	11	10
508	4.8	5.4	4.4	10	9	8	9
509	4.6	-	5.7	9	-	10	10
510	4.7	-	5.2	10	-	11	11
512	5.2	-	5.2	10	9	10	10
513	4.6	5.3	5.5	9	9	8	9
9702	5.3	5.1	5.4	10	8	8	9
9703	6.2	5.7	-	11	11	11	11
9704	5.8	5.6	-	9	9	-	9
9705	5.0	5.2	-	10	11	-	11
9706	5.6	5.4	5.6	11	10	9	10
9707	5.4	5.5	5.8	11	10	10	10

Average of Fines = 10% with a Standard Deviation of 1.3.

[a] Fines is the fraction passing sieve #200.
[b] Top, 2nd and Lower refer to the pavement lifts.
[c] Test was not performed.

TABLE 3 Ratios of Fines[a] to Asphalt

	Pavement Lifts			
Section	Top	2nd	Lower	Average
301	1.90	1.22	-[b]	1.56
302	2.26	1.97	1.18	1.80
501	1.91	1.73	1.50	1.71
504	1.90	1.90	1.67	1.82
505	1.85	1.67	1.69	1.74
506	1.75	1.97	-	1.86
507	1.72	1.79	1.90	1.80
508	2.08	1.67	1.82	1.86
509	1.96	-	1.75	1.86
510	2.13	-	2.12	2.13
512	1.92	-	1.92	1.92
513	1.96	1.7	1.45	1.70
9702	1.89	1.57	1.48	1.65
9703	1.77	1.93	-	1.85
9704	1.55	1.61	-	1.58
9705	2.00	2.12	-	2.06
9706	1.96	1.85	1.61	1.81
9707	2.04	1.82	1.72	1.86
Average	1.92	1.77	1.68	1.80
St. Dev.	0.16	0.21	0 .23	0.22[c]

[a] Fines is the fraction passing sieve #200.
[b] Test was not performed.
[c] The stand. dev. of all values in this table.

Table 4 shows that the NTM&R and District 2 tests have resulted in high TSR values for the Truax (0.80 and 0.95). Tests on Edsell indicate values of 0.70 and 0.61 for the two laboratories, respectively. If a TSR of 0.70 were selected as a minimum criterion, the Truax would be considered good quality. The Edsell would be considered acceptable but borderline by the NTM&R results and unacceptable by District 2 results. According to the information supplied by District 2, the Edsell aggregate does not have a good field performance record in terms of moisture susceptibility. The Stukel aggregate performed poorly with TSR values of 0.63 and 0.56 for both laboratories, respectively. The Kidder Creek aggregate provided contradictory TSR values of 0.55 by NTM&R and 0.87 by District 2. According to District 2 personnel, the Kidder Creek aggregate is believed to have provided good field performance. The Banhart and Grenada aggregates consistently performed poorly, with TSR values of 0.52 and 0.50 by NTM&R and 0.54 and 0.59 by District 2. These values, according to District 2 personnel, are consistent with the field performance records of these two aggregates. Examination of the test data shows that the AASHTO T283 appears to have the potential to assess moisture damage susceptibility of AC mixtures, but more testing is needed to verify the results.

Testing Using Hydrated Lime and BA2000 Additives

Test method AASHTO T283 was used to assess the effectiveness of hydrated lime and BA2000. The hydrated lime was used to treat the aggregates in a slurry form (3 parts water, 1 part lime). The amount of lime used was 2 percent by dry weight of aggregate. The BA2000 was blended with the asphalt before mixing with the aggregate. The amount used was 0.5 percent by total weight of the mixture.

TABLE 4 Aggregate Source Test Results

Test	Aggregate Source Truax	 Edsell	 Stukel	 K. Creek	 Banhart	 Grenada
1/2"Max. Size (TSR)[a]	0.80	0.70	0.63	0.55	0.52	0.50
3/4"Max. Size (TSR)	0.95	0.61	0.56	0.87	0.54	0.59
MVS Reduction (%)[b]	-15	-[c]	-21	-5	+3	-12
Surf. Abrasion (grams)	13.2	-	32.0	42.0	21.9	15.2
Agg. Abso. (%)	1.33	1.08	2.54	-	-	1.70
Moist. Abso. (%)	0.5	-	0.9	0.6	0.3	0.4
Kc Index	1.5	1.3	1.7	1.1	1.4	1.5
Kf Index	1.3	1.2	1.2	1.2	1.1	1.3
Coarse Durability	-	-	86	91	91	-
Fine Durability	84	73	67	77	81	82
Sand Equivalency	82	72	65	72	70	64
LA Rattler (%loss)	-	-	-	14.9	36.9	36.6

[a] TSR is Tensile Strength Ratio.

[b] The percent in stability using the Moisture Vapor Susceptibility Test.

[c] Test was not performed.

The results of these tests are shown in Table 5 and in Figures 3 and 4. These tests were performed by NTM&R. When lime and BA2000 were used, most of the TSR values increased to over 0.80 (Figure 3). Exceptions were the Stukel aggregate with lime and the Kidder Creek aggregate with BA2000. These mixes exhibited increases, but the increases were not substantial. For the Stukel, the TSR increased from 0.63 to 0.69 when lime was used and to 0.91 when BA2000 was used. For the Kidder Creek, the TSR increased from 0.55 to 0.83 when lime was used and to 0.66 when BA2000 was used. From these data it can be concluded that using either lime or BA2000 can result in improvements in the TSR values. The degree of improvement is dependent on the type of aggregate.

The data also indicate that there can be a substantial improvement in the strength of the mixes using either lime or BA2000 for both conditioned and unconditioned samples. Figure 4 shows the improvements in strength as a percentage for conditioned specimens with lime and BA2000. The figure shows that some of the mixes experienced increases in strength that were higher than 100 percent, such as the Truax and Grenada mixes. The other mixes showed increases, but they were not as high.

Abrasion Resistance

The average abrasion losses for the laboratory mixes using CT 360 were 42 g for the Kidder Creek, 32 g for the Stukel, 21.9 g for the Banhart, 15.2 g for the Grenada, and 13.3 g for the Truax aggregates (Table 4). These values did not appear to correlate with observed field performance. The Kidder Creek aggregate showed the highest loss even though it is considered to be a good-quality aggregate in terms of its resistance to stripping on the basis of its field performance. However, the AASHTO T283 results at the NTM&R showed poor performance for Kidder Creek aggregate in terms of its TSR values (Figure 3). The Truax experienced the lowest loss, which is in agreement with the results from the AASHTO T283 in which it showed high TSR values. This aggregate does not have a known performance history. The Banhart and Grenada aggregates showed low material losses, but in the AASHTO T283 they performed poorly. These two aggregates have poor performance history in terms of moisture susceptibility.

The core specimens did not experience high losses as shown in Figure 5. These results are from the modified CT 360, in

TABLE 5 Indirect Tensile Strength Values (kPa) from Moisture-Induced Damage Test (AASHTO T283)

Testing	Aggregate Source Truax	 Edsell	 Stukel	 Kidder Creek	 Banhart	 Grenada
1/2" Max. Size						
Unconditioned						
Control	758[a]	1102	1300	1183	1295	1118
Lime	1153	1615	1426	1167	1217	1229
BA2000[b]	1424	1247	1265	1334	_[c]	1334
Conditioned						
Control	606	772	811	643	675	556
Lime	1073	1894	1394	983	971	1210
BA2000	1316	1109	1151	877	_	1197
3/4" Max. Size (Control)						
Uncond.	1702	1840	1509	2494	2081	2163
Cond.	1612	1116	841	2177	1116	1275

[a] Units are in kilopascals, kPa (1 psi = 6.89 kPa).

[b] BA2000 is a liquid anti-stripping agent.

[c] Test was not performed.

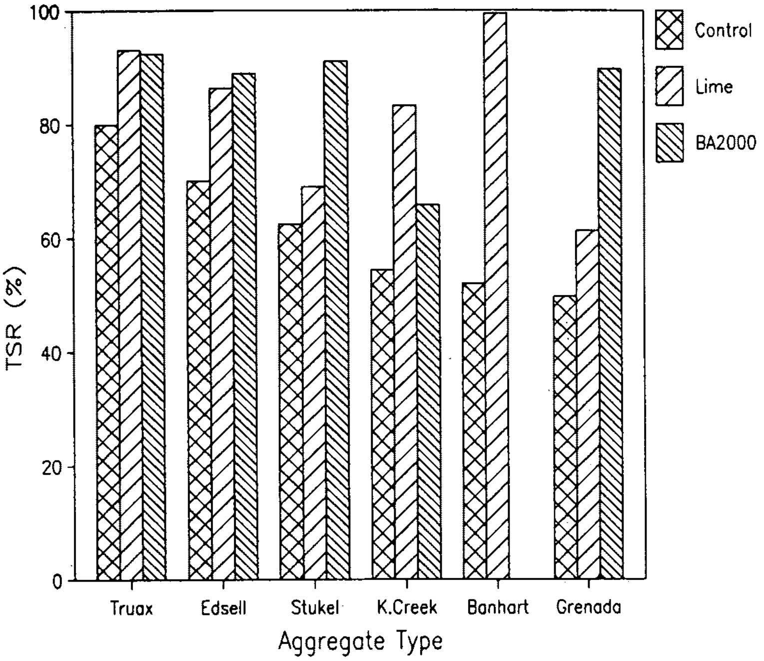

FIGURE 3 TSR versus aggregate type.

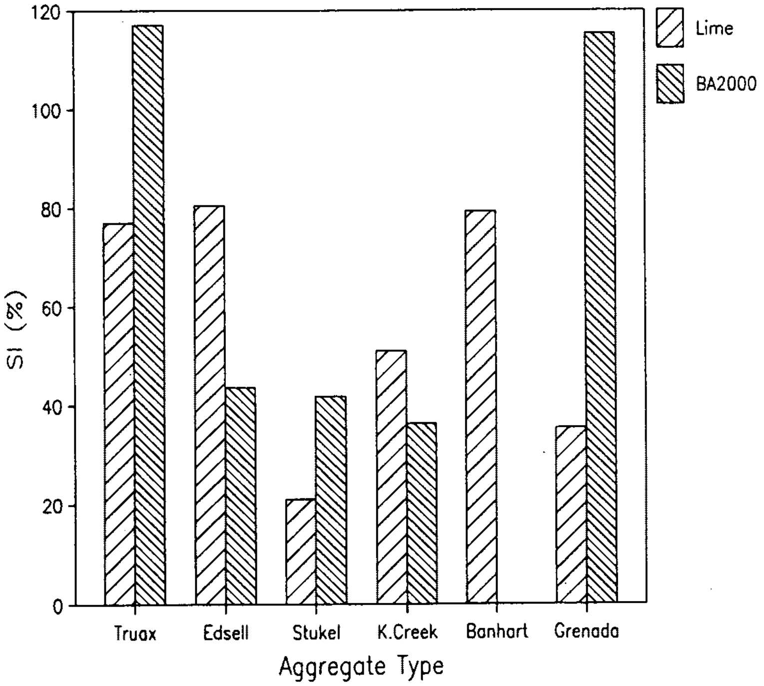

FIGURE 4 Strength improvement (SI) in conditioned specimens due to addition of lime and BA2000.

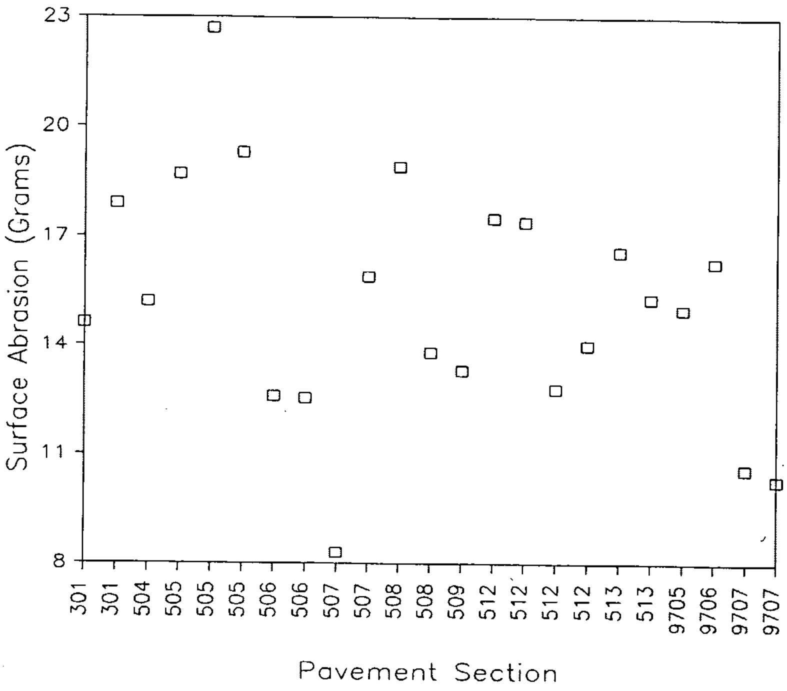

FIGURE 5 **Surface abrasion of core samples versus pavement section.**

which the maximum allowable loss is 21 g. Only one sample from Section 505 exceeded that criterion. It appears that abrasion loss is not a good indicator of moisture susceptibility. Because this test abrades the surface of the core, the abraded surface conditions could affect the results. On the basis of field survey and sampling, the pavement surfaces on most of the roadways that were subject to this study appeared to be overly rich. This was probably a result of (a) a slight migration of asphalt to the surface caused by stripping in the lower AC layers and (b) previous maintenance surface treatments such as fog seals.

MVS (CT 307)

Laboratory-fabricated specimens were tested using the MVS test. The stability values after MVS conditioning were compared with the mix design stabilities and are shown in Table 4.

The results indicate that the Banhart and the Kidder Creek aggregates did not show significant changes (+3 percent and −5 percent, respectively). These changes are within the variability range of the stability test. The Grenada, Stukel, and Truax aggregates exhibited larger changes in stabilities (−12, −21, and −15 percent, respectively). The Edsell aggregate was not tested because of insufficient material.

Although the specimen stabilities showed a reduction after MVS conditioning, they still met the minimum standard specification requirement of 30 for Type A AC. Therefore, this test did not prove to be a satisfactory indicator for detecting moisture-susceptible mixes.

Other Material Properties

The percent wear using the Los Angeles Rattler for the Kidder Creek, Banhart, and Grenada aggregates was 14.9, 36.9, and 36.6 percent, respectively (Table 4). These values do not exceed the maximum loss recommended by the specifications. The other aggregates were not tested. The Kc values ranged from 1.1 to 1.7, and the Kf values ranged from 1.1 to 1.3 for all sources tested, which is at or below the specified maximum of 1.7. The fine durability, coarse durability, and sand equivalent results are also shown in Table 4. These values all met the minimum specification requirements.

The moisture absorption values as shown in Table 4 ranged from 0.3 to 0.9 percent. Table 4 shows reductions in stability that corresponded to these values. Although the high moisture absorption of 0.9 percent for the Stukel material corresponded to the highest stability reduction of 21 percent, this trend does not appear to be consistent. For example, the Truax aggregate has a moisture absorption of 0.5 percent, corresponding to 15 percent reduction in stability, whereas the Kidder Creek aggregate had a 0.6 percent moisture absorption, corresponding to only 5 percent reduction in stability. All of the MVS stability values were considered acceptable and were within the specifications. The moisture absorption values also do not correlate well with the AASHTO T283 TSR values. For instance the Banhart material had an average TSR value of 0.53 (poor) that corresponded to 0.3 percent moisture absorption and no reduction in MVS stability.

The aggregate absorption values in Table 4 ranged from 1.08 to 1.77. These data show Stukel to have the highest aggregate absorption, followed by Grenada. Stukel also showed a high moisture absorption of 0.9, a 21 percent MVS stability reduction, 0.63 TSR, 1.7 Kc, 1.2 Kf, and an abrasion loss of 32 g. All of these properties point in one direction; that is, the Stukel having low-quality characteristics. This pattern, however, is not present for other aggregates. The Grenada aggregate, for example, had the lowest TSR at 0.5, an MVS stability reduction of 12 percent, an aggregate absorption of 1.7 percent, abrasion loss of 15.2 g, and moisture absorption of 0.4 percent. It appears that the moisture absorption test, the MVS test, and the aggregate absorption test are not good indicators of moisture susceptibility.

DISCUSSION OF RESULTS

Field and visual observations of core and jackhammer samples revealed extensive stripping at many locations. Stripping is a moisture-induced damage and occurs when the asphalt becomes detached from the aggregate surface in the presence of water. Stripping results in a loss of the structural integrity of the asphalt concrete and causes rapid deterioration. Problems such as rutting and fatigue cracking have been associated with stripping.

The distress of the evaluated sections was generally manifested in the form of alligator and longitudinal cracking, which may be related to stripping. When a layer strips it loses some structural strength, which causes an increase in the tensile strains in the upper layers. These high strains result in cracking that propagates upward. This mode of failure is evident from the core samples gathered during this investigation. There were no significant rutting problems.

Locations that were identified as having severe stripping were those with pavement reinforcing fabrics and chip seals. In almost all cases, in the areas in which these fabrics were used, the bond between the fabric and the layer beneath it was nonexistent. Generally, moisture and stripping occurred in the layers above and below the fabric. In some cases cracks were observed to extend from the fabric to the surface. It appeared that most of these cracks were not reflecting up through the fabric from the underlying layers.

As mentioned above, sections that received chip seal treatments experienced higher stripping problems. It appears that the chip seals accelerated the deterioration probably caused by moisture entrapment. A chip seal can block the water vapor from escaping through the surface and can retain water infiltrating through the surface in locations where a dense-graded AC overlay is placed on top of it. These characteristics result in a prolonged exposure to moisture. When it is combined with aggregates that are susceptible to stripping, this situation becomes detrimental. Some of the aggregates used in District 2 are believed to be susceptible to moisture damage. Some are described as being soft and highly absorptive and contain volcanic materials. The laboratory results from the Resistance to Moisture-Induced Damage Test Method (AASHTO T283) have confirmed this problem. Therefore, the use of chip seals and pavement reinforcing fabrics should be reevaluated in areas where moisture-susceptible aggregates exist.

The tests during this study consisted of density analysis, extractions, surface abrasion, MVS, and moisture-induced damage test (AASHTO T283), which included the effect of lime and BA2000 antistripping additives. The density analysis was performed on new mixes, cores, and recompacted cores. A substantial number of in-place air voids were found to be more than 7.0 percent. This number is a cause for concern when aggregates that are susceptible to stripping are used. An effort should be made to reduce the level of in-place air voids. The results showed the relative compaction to be generally higher than 95 percent. These values can be misleading because the pavements probably exhibited even higher air voids at the time of placement. The relative compaction relates the in-place density at the time of this investigation to the density of recompacted core specimens. This means that the relative compaction at the time of construction was probably much lower than these values (i.e., higher in-place air voids). High air voids reduce material strength and increase the exposed surface to moisture. These features can result in stripping and may cause premature pavement deterioration. Many researchers have recognized the effect of air voids on stripping. Kennedy and Anagnos (*4*), for example, indicated that air voids of more than 7.0 percent would allow the water to readily penetrate the mixture. These authors concluded that adequate compaction should produce air voids of less than 7.0 percent to reduce the continuity of the air void system, which would reduce the potential for stripping.

Caltrans prefers to design mixes that result in in-place air voids within the 7.0 to 10.0 percent range to prevent rutting problems caused by high truck traffic. The reasoning comes from a rehabilitation standpoint, which considers sealing the cracks an easy alternative, resulting in longer pavement use. On the other hand, rutting is considered hazardous, and major rehabilitation would be needed immediately to correct the situation. Therefore, Caltrans prefers to have the pavements fail in fatigue rather than in rutting.

The extraction results showed high ratios of fines to asphalt for the sections evaluated. Excessive fines or low asphalt contents, or both, can be detrimental to the resistance of AC mixtures to stripping and can result in premature pavement distress. The amount of fines exceeded the standard specifications range by an average of 2 percent. An effort should be made to reduce the ratio between the fines and asphalt content.

On the basis of the above discussion and because of the severity of stripping, modification of mix design standards and field compaction is needed. A second look at the density requirements is necessary, especially because of these current moisture damage problems. The use of antistripping additives in conjunction with lower air voids and lower ratios of fines to asphalt can provide significant improvements.

The AASHTO T283 results showed that there were improvements in the TSR values and in the tensile strength when either lime or BA2000 was used. Also, the ¾-in. maximum-size aggregates exhibited significantly larger strength values than the ½-in. maximum-size aggregates, but there were no significant changes in the TSR values. These findings are because the TSR is only an indicator of the relative strength loss after conditioning, which is influenced by the bond between the aggregate particles in the AC mix.

Other tests were performed, such as the surface abrasion and the MVS to identify AC mixtures that have stripping potential, but the results were not satisfactory. Therefore, among the tests evaluated in this study, only the moisture-induced damage test was found to have a potential to identify moisture damage susceptibility. Tests that should be evaluated in the future should include the environmental conditioning system, which was developed as a result of the Strategic Highway Research Program.

CONCLUSIONS

During this investigation it was found that the high rate of deterioration in AC pavements in Northern California was generally related to stripping. Sections that exhibited severe distress (alligator and longitudinal cracking) showed more stripping damage. The following are some of the conclusions.

1. Stripping was related to the use of moisture-susceptible aggregates in AC mixtures. Many of the aggregates tested showed high susceptibility to stripping.
2. High ratios of fines to asphalt may have contributed to stripping. Excessive fines or low asphalt contents can decrease the stripping resistance of good-quality mixtures.
3. High in-place air voids may have contributed to stripping. High air voids reduce the strength, trap water, and accelerate the rate of deterioration.
4. Stripping was more severe in pavements that had chip seals and pavement reinforcing fabrics. The use of chip seals and pavement reinforcing fabrics as interlayers can increase moisture damage because they trap water in the pavement.
5. Moisture damage testing should be part of the mix design procedure, and an effort should be made to select a moisture damage test. The surface abrasion test (CT 360B) and the moisture vapor susceptibility test (CT 307) did not adequately identify moisture-susceptible mixes, but the Resistance to Moisture-Induced Damage Test (AASHTO T283) showed promising results.
6. Hydrated lime in a slurry form or liquid antistripping agents can be effective in reducing moisture damage to AC mixes. The degree of their effectiveness depends on the type of aggregate.

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REFERENCES

1. Lottman, R. P. *NCHRP Report 246: Predicting Moisture-Induced Damage to Asphaltic Concrete-Field Investigation.* HRB, National Research Council, Washington, D.C., 1968.
2. Hazlett, D. G. *Evaluation of Moisture Susceptibility Tests for Asphaltic Concrete.* Report 3-C-2-102. State Department of Highways and Public Transportation Material and Tests Division, Texas, Aug. 1985.
3. *Asphalt Concrete Mix Design and Field Control.* Technical Advisory T 5040.27. FHWA, U.S. Department of Transportation, March 10, 1988.
4. Kennedy, T. W., and J. N. Anagnos. *Lime Treatment of Asphalt Mixtures.* Report 253-4. Center for Transportation Research, The University of Texas at Austin, July 1983.

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