Upgrading of Marginal Aggregates for Improved Water Resistance of Asphalt Concrete

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Work done at Pennsylvania State University on the upgrading of marginal aggregates in asphalt concrete mixtures in order to improve the water resistance of the mixtures is reported. A number of alternate approaches or treatment classes that show promise for improving the water resistance of asphalt concrete mixtures were identified. Typical treatments from each class were used with six marginal aggregates that have performed unacceptably in the field. The water resistance of treated and untreated mixtures was studied by using a freeze-soak conditioning procedure and resilient modulus, E-modulus, and tensile-strength test procedures. Test procedure variability, effect of treatment on mixture properties, and effectiveness of the treatments in improving water resistance are discussed. It is concluded that a variety of approaches should be considered for improving the water resistance of asphalt concrete mixtures. These include the use of conventional antistripping additives, surfactants, hydrated lime, aggregate pretreatment, aggregate coatings, and modified binders. It was found that the effectiveness of the treatments varied with the different aggregates and that the treatments must be selected according to the mechanism responsible for moisture damage. The treatments affected the mechanical properties (stiffness and strength) of the mixtures to varying degrees.

The resistance of an asphalt concrete mixture to the effects of water is influenced by the properties of the aggregate, the composition and consistency of the asphalt, and the properties of the mixture. A number of aggregate properties, such as surface chemistry, surface texture, weathering, dust coatings, and surface abrasion, affect the resistance of asphalt mixtures to water. The literature has been reviewed by others (1,2) and is much too extensive to summarize here, except to note that the classic stripping mechanisms may be inadequate to explain many stripping problems in the field. For example, the classic stripping mechanisms do not account for the moisture damage caused by such factors as dust coatings or alteration resulting from weathering.

Laboratory studies have shown that asphalt properties can also affect the water resistance of asphalt mixtures. More viscous asphalts may improve water resistance, but this improvement is not always reflected in the field (3,4). Dohaney (4) has reported that asphalt composition can affect water resistance. Others (5) suggest that the importance of chemical composition is related to specific aggregate-asphalt combinations. Maupin (6) has, on the other hand, found no significant difference in laboratory stripping tests performed with asphalts from different sources. Finally, mixture properties play an important role in determining water resistance. For example, asphalt concrete mixtures with high permeability and low asphalt content are more susceptible to moisture damage than denser mixtures with high asphalt contents (1).

The resistance to water of a mixture made with a moisture-sensitive aggregate may be improved by treating the aggregate, treating the asphalt, or changing the mixture design. The addition of antistripping additives to the asphalt is routinely specified by many agencies. For maximum effectiveness, these additives must be matched to the particular aggregate being used; moreover, their effectiveness has been found to vary with the asphalt source (7) and the pH of the water present (8). Although antistripping additives may improve moisture resistance in the laboratory, similar improvements have not always been obtained in the field (5). This may be attributable to the heat stability of the additives or may reflect the inadequacy of present laboratory test procedures. In some instances, antistripping additives have been found to change the physical properties of asphalt cements and to greatly increase loss on heating (ASTM D1574) (9,10).

Additives applied directly to the aggregate may also improve the moisture resistance of some asphalt-aggregate mixtures. Heavy metal ions dissolved in a sodium oleate solution and added to the aggregate have been shown to improve the wetability of asphalt on aggregate surfaces (3). Fromm (11) determined that heavy metal cations, when applied to aggregate surfaces, could improve moisture resistance. Ferric napthanate was found to be particularly effective. Sodium dichromate has also been effective when added to the aggregate in an aqueous solution.

The effectiveness of hydrated lime for improving the resistance of certain asphalt mixtures has been known for many years. Hydrated lime is often added as a mineral filler, but it is more effective as an antistripping additive if it is added as a slurry and allowed to cure for several days. Recent research suggests that the hydrated lime absorbs carboxylic acids in the asphalt, which results in a more water-resistant asphalt-aggregate bond (12). Hydrated lime has also been found to change the mechanical properties of asphalt mixtures (13).

RESEARCH APPROACH

The objective of the research described in this paper was to identify alternative approaches to improving the water resistance of asphalt concrete mixtures made with marginal aggregates. Based on a review of the general problem, a number of approaches appeared to be valid:

1. Traditional antistripping additives--surfactants added to the asphalt to provide a physical-chemical bond between the asphalt and the aggregate;
2. Metal ions--surfactants added directly to the aggregate surface that change the surface charge of the aggregate;
3. Hydrated lime--an additive that alters the chemical composition of the asphalt;
4. Sulfur-extended asphalt--modification of the binder;
5. Acid wash--acid treatment of the aggregate to remove surface contaminants and, if possible, to alter the surface chemistry of the aggregate; and
6. Epoxy coating--total encapsulation of the aggregate to isolate it from the asphalt.

Typical treatments representing each of these approaches were used on six marginal aggregates that have given unacceptable field performance. The water resistance of the treated and untreated mixtures was evaluated by using resilient-modulus and tensile-strength testing procedures. Moisture damage was induced by means of a freeze-soak conditioning procedure. Test variability, the effect of the treatments on mixture properties, and the effectiveness of the treatments in improving the water resistance of the mixtures were determined. The scope of the research project required that off-the-shelf materials be used for the treatments, and no attempt was made to optimize the various treatments.

Asphalts

The asphalts were supplied by those states that indicated that the source of an asphalt can influence its resistance to water. Otherwise, an AC-20 asphalt selected by the researchers was used. The properties of the asphalts used in the study are given in Table 1.

Aggregates

Each of the aggregates used in the study is described below. Source and other pertinent data for each of the aggregates are given in Table 2.

1. The Grayson, Georgia, granite is a coarse-grained, partially metamorphosed crushed granite with loosely bonded grains on factured faces.
2. Granite from the Piedmont region of southeastern Virginia is coarse-grained, crushed granite. Compared with the Grayson granite, the Piedmont granite exhibits a much higher degree of interlocking between grains and contains less silica.
3. Colorado gravel is a crushed, siliceous river gravel from a heterogeneous deposit that consists of granites, cherts, and quartzites.
4. Roseburg, Oregon, basalt is a crushed, homogeneous basalt from the Mt. Nebo formation that weathers rapidly, forming a surface with a dust coating, and is typical of many coastal Oregon basalts. The source of the asphalt reportedly influences the water resistance of this aggregate.
5. Gravel from Pocatello, Idaho, is composed of uncrushed, rounded particles that are mainly quartzites and some basalt, limestone, and metamorphic material. The asphalt source reportedly influences the water resistance of this aggregate.
6. Holbrook, Arizona, gravel is a crushed river gravel composed mainly of siliceous materials that range from cryptacrystalline particles to sandstones. Some of the particles tend to expand and disintegrate when exposed to water. The asphalt source reportedly influences the water resistance of this aggregate.
7. The minus-4.75-mm (No. 4) sieve material (fine aggregate) used in all mixtures is a blend of sand and mineral filler. The sand is a washed, siliceous river sand from Montoursville, Pennsylvania, that has a good performance record in asphalt mixtures. The filler is a ground dolomitic limestone.

Mixture Design

The mixtures were proportioned by using the Marshall method of mixture design with 50-blow compaction. The gradations of the mixtures met the limits of ASTM D3515-77 for a 3A binder mixture and in most cases approximated the gradations used by the supplying agencies. The intent of the mixture design procedure was to proportion the mixtures to meet gradation and voids-in-mineral-aggregate requirements and to contain 4.5 ±1 percent air voids. Gradation and asphalt content were the same for the treated and untreated (control) aggregates except for the epoxy-coated aggregates. The gradation of the epoxy-coated aggregates was corrected for specific gravity, and the asphalt content was reduced to account for reduced asphalt absorption. Additional information about the mixture design is given elsewhere (14).

Test Procedures

A freeze-thaw procedure recently proposed by Lottman (15) was used to induce moisture damage in the compacted specimens. The specimens were vacuum saturated at room temperature, frozen at -17.8°C (0°F), and then soaked for 24 h in a 60°C (140°F) water bath.

Moisture damage resulting from the conditioning procedure was evaluated by performing E-modulus, tensile-strength (16), and resilient-modulus (17) tests on untreated and treated triplicate specimens before and after conditioning. The testing schedule used in the study is shown in Figure 1. Details of the test procedures can be found elsewhere (16,17). In addition to the mechanical testing, the broken surfaces of each specimen subjected to the tensile-strength test were examined visually to evaluate the degree of stripping of the coarse aggregate.

TREATMENT METHODS

Six modifications were made to the asphalt concrete mixtures to improve their resistance to water damage. These treatments modified either the aggregate or the binder. As a result of limited aggregate supplies, all treatments were not used with all aggregates. The asphalt-aggregate treatment combinations used in the study are given in Table 3. Only the coarse (plus-4.75-mm) aggregate was treated with epoxy, hydrated lime, acid wash, and sodium dichromate treatments. Specific details of the treatment methods can be found elsewhere (14).

Epoxy Encapsulation

Epon 828, a diglycidyl ester of disphenol A, manufactured by Shell, was used to encapsulate the aggregates. Both the specific gravity and absorption (Table 2) of the aggregate were lowered as a result of the coating. The coating was so thick that much of the surface texture of the aggregate was lost and the surfaces acquired a smooth, glasslike texture.

Hydrated Lime

A high calcium-hydrated lime was applied to individually batched coarse-aggregate fractions (plus 4.75 mm) in slurry form. Approximately 1.0 percent hydrated lime (based on the weight of the coarse aggregate) was added to the coarse aggregate. The mineral filler content of the mixture was reduced by the amount of hydrated lime added to the mixture--approximately 0.5 percent by weight of the total mixture.

Acid Wash

A commercially available material, composed primarily of sulfuric acid, was used in treating the coarse-aggregate surfaces. The acid wash removed loosely bound surface material from the Georgia and Arizona aggregates and caused foaming on the surfaces of the Georgia, Virginia, and Oregon aggregates. The surfaces of the Georgia and Virginia aggregates were abraded during the acid-wash procedure, and they were thus smoother and less angular than the untreated aggregate. The physical properties of the treated aggregates were essentially unchanged (Table 2), except that absorption by the Oregon aggregate was reduced from 3.5 to 2.8 percent, primarily because of the removal of dust coatings.

Table 1. Physical properties of asphalts.

Property	Asphalt AC-20	120-150	AR 4000	AR 2000
Original				
Penetration at 25°C, 100 g, 5 s	56	109	140	84
Softening point (°C)	48.9	45.3	43.3	44.2
Specific gravity	1.028	1.024	–	–
Dynamic (60°C) viscosity (P)	1941	495	1142	1128
Kinematic (135°C) viscosity (cSt)	365	175	338	194
TFOT loss (%)	0.05	0.34	0.84	0.21
TFOT residue				
Penetration at 25°C, 100 g, 5 s	28	57	79	56
Softening point (°C)	53.9	49.2	49.7	47.2
Dynamic (60°C) viscosity (P)	5843	1586	3322	2010
Kinematic (135°C) viscosity (cSt)	562	289	577	265
Specific gravity	–	–	1.034	1.019
Rostler composition				
Asphaltenes (%)	19.1	22.2	16.0	38.7
Nitrogen base (%)	30.6	14.6	42.2	28.9
Acidiffins (%)				
First	19.3	22.3	14.7	19.4
Second	10.5	24.0	19.0	10.7
Paraffins (%)	20.5	11.9	8.1	2.3
Rostler parameter	1.61	1.03	2.10	3.72

Notes: t°C = (t°F - 32)/1.8; 1 P = 0.1 Pa·s; 1 cSt = 0.01 cm^2/s.
TFOT = thin-film oven test.

Table 2. Properties of aggregates.

Aggregate	Untreated Bulk Specific Gravity	Untreated Absorption (%)	Epoxy Coated Bulk Specific Gravity	Epoxy Coated Absorption (%)	Acid Wash Bulk Specific Gravity	Acid Wash Absorption (%)
Georgia granite	2.615	0.6	2.510	0.5	2.622	0.5
Virginia granite	2.631	0.5	2.450	0.8	2.625	0.5
Colorado gravel	2.598	1.0	2.510	0.8	2.600	0.9
Oregon basalt	2.711	3.5	2.581	0.5	2.724	2.8
Idaho gravel	2.587	0.9	2.508	0.8	2.566	1.0
Arizona gravel	2.569	1.3	2.490	0.9	2.541	1.6
Sand	2.530	2.8	–	–	–	–
Filler	2.816[a]	–	–	–	–	–

Note: Properties determined by using ASTM C127-77.
[a]Apparent specific gravity measured in kerosene.

Surface Active Agent

The surface active agent used was amine, a commonly used asphalt antistripping additive, which was mixed directly into the asphalt cements at a concentration of 0.5 percent by weight of the asphalt cement. The results of the consistency tests performed on the treated asphalts are given in Table 4. The addition of the amine had no measurable effect on either the AR-2000 or A-4000 asphalt; however, noticeable hardening did occur with the AC-20 asphalt. Although no firm conclusions can be drawn from the small amount of data presented here, it appears that the addition of antistripping agents may affect the properties of the asphalt.

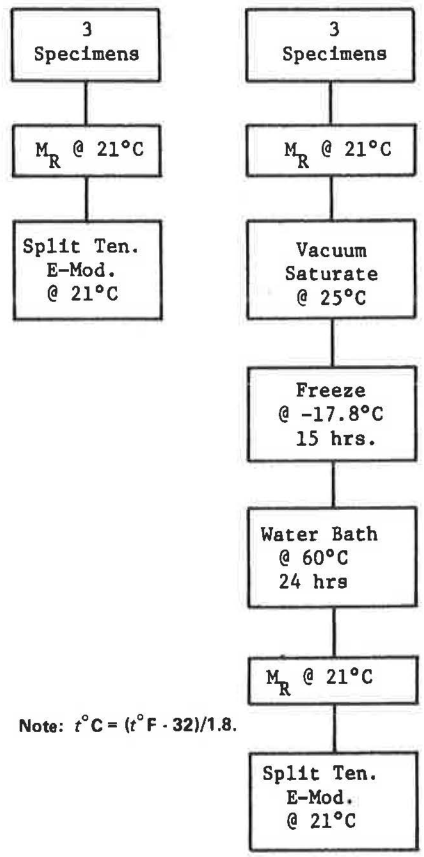
Sodium Dichromate

The coarse aggregate was moistened with a 2 percent (by weight) aqueous sodium dichromate solution. Sufficient solution was added to yield a 0.025 percent sodium dichromate residual (by weight of aggregate) on the dried coarse-aggregate surfaces.

Sulfur-Extended Asphalt

The sulfur-extended asphalts were prepared by adding elemental sulfur to the AC-20 asphalt cement, which was heated to 135°C (275°F). Properties of the sulfur-extended asphalt are given in Table 4.

Figure 1. Conditioning sequence for test specimens.



Note: t°C = (t°F - 32)/1.8.

EFFECT OF TREATMENTS ON THE MECHANICAL PROPERTIES OF UNCONDITIONED MIXTURES

The sample mean, standard deviation, and coefficient of variation were computed before and after moisture conditioning for each mixture-treatment-test combination. To provide a comparison of the variability between the different test procedures, coefficients of variation were averaged for each mixture-treatment-test combination. The coefficient of variation for Marshall stability and tensile strength was 9.7 percent, and the average coefficient of variation for resilient modulus (M_R) was 18.2 percent. Although the variability of the resilient-modulus results was similar before and after conditioning (19.2 versus 17.2 percent), the variability of the tensile-strength results nearly doubled after conditioning (6.7 versus 12.6 percent). An increase in variability after conditioning might be expected because differences in the test samples should be amplified by the conditioning procedure. We consider the increased variability to be a reflection of the sensitivity of the tensile-strength test.

Throughout the study it was noted that the treatments not only affected the water resistance of the mixtures but also affected the mechanical properties of the mixtures before moisture conditioning. The effect of each treatment on the mechanical properties of the mixtures before conditioning was evaluated by dividing the average test parameter for the treated mixture by the

Table 3. Aggregate-asphalt treatment combinations used in the study.

Aggregate	Untreated	Epoxy Coating	Acid Wash	Hydrated Lime	Amines	Sodium Dichromate	Sulfur-Extended Asphalt 15 Percent	Sulfur-Extended Asphalt 30 Percent
Georgia granite	1	1	1	1	1	1	1	1
Virginia granite	1	1	1	1	–[a]	–[a]	–[a]	–[a]
Colorado gravel	1	1	1	1	1	1	–[a]	–[a]
Oregon basalt	1,2	2	2	2	2	2	1	1
Idaho gravel	1,3	3	3	3	3	3	1	1
Arizona gravel	1,4	4	4	4	4	4	1	1

Note: 1 = AC-20 asphalt, 2 = Oregon (AR-4000) asphalt, 3 = Idaho (120-150 pen) asphalt, and 4 = Arizona (AR-2000) asphalt.
[a]Not tested.

Table 4. Physical properties of treated asphalts.

Asphalt	Treatment	Penetration at 25°C	Softening Point (°C)	Viscosity Dynamic, 60°C (P)	Viscosity Kinematic, 135°C (cSt)
AC-20	Untreated	56	48.9	1941	365
	Amines	46	49.4	2630	414
	Sulfur-extended asphalt				
	15 percent	105	44.7	698	143
	30 percent	61	45.6	744	167
120-150	Untreated	109	45.3	495	175
	Amines	121	42.8	572	192
AR-4000	Untreated	140	43.3	1142	338
	Amines	135	42.5	1149	338
AR-2000	Untreated	84	44.2	1128	194
	Amines	85	43.9	1118	193

Note: $t°C = (t°F - 32)/1.8$; 1 P = 0.1 Pa•s; 1 cSt = 0.01 cm^2/s.

average test parameter for the corresponding untreated mixture. The resulting ratios are given in Table 5. Ratios greater than 1.0 indicate an increase in the test parameter as a result of the treatment. The treatments reduced the resilient modulus to a greater degree than the tensile strength, which indicated that the treatments had a greater effect on stiffness than on strength.

Epoxy Coating

The epoxy coating increased the flow values and lowered the tensile strength and resilient modulus of all the mixtures. These effects were attributable to the smooth surface texture created by the epoxy coating. In contrast, except in the case of the Arizona aggregate, Marshall stability values were little affected by the epoxy coating. The epoxy reacted with the Arizona aggregate (14) so that some of the particles decomposed when exposed to water. On the basis of these observations, we suggest that the surface texture of coated aggregates should be considered in the development of new coating procedures. Potential coating-aggregate reactivity and durability should also be considered.

Hydrated Lime

The effect of hydrated lime on the mechanical properties of the aggregates varied. The hydrated lime decreased the resilient modulus of the Virginia mixture by 64 percent but increased the resilient modulus of the Oregon mixture by 64 percent. Other investigators (13) have noted that the addition of hydrated lime to asphalt concrete mixtures reduces the resilient modulus and that this reduction varies with aggregate type and asphalt source. Further research on additional aggregates and asphalts is needed to determine the effects of hydrated lime.

Table 5. Ratios of treated to untreated mixture properties.

Treatment	Test	Aggregate Georgia	Virginia	Colorado	Oregon	Idaho	Arizona
Epoxy coating	M_R	0.35	0.33	0.57	0.37	0.37	0.21
	Tensile strength	0.77	0.76	0.76	0.55	0.63	0.47
	Stability	1.00	1.08	1.09	0.99	1.33	0.46
	Flow	1.31	1.21	1.27	1.21	1.33	1.13
Hydrated lime	M_R	0.51	0.46	1.14	1.64	1.00	0.84
	Tensile strength	0.84	1.02	1.19	1.05	1.03	0.90
Acid wash	M_R	0.43	0.31	0.73	1.00	0.61	0.63
	Tensile strength	0.86	0.86	1.00	0.97	0.99	0.85
Amines	M_R	0.51	–	0.65	0.88	0.57	0.51
	Tensile strength	0.75	–	–	0.99	1.07	0.93
Sodium dichromate	M_R	0.77	–	1.05	0.88	0.56	0.58
	Tensile strength	0.82	–	–	1.09	–	0.89
Sulfur-extended asphalt							
15 percent	M_R	0.46	–	–	0.56[a]	0.39[a]	0.53[a]
	Tensile strength	0.64	–	–	0.70	0.70	0.69
30 percent	M_R	0.40	–	–	0.61[a]	0.44[a]	0.86[a]
	Tensile strength	0.61	–	–	0.75	0.78	0.87

[a]Computed with respect to the AC-20 asphalt.

Acid Wash

The acid-wash treatment reduced the resilient modulus and tensile strength of all mixtures. The effect on resilient modulus was more pronounced. The surfaces of the Georgia and Virginia aggregates were abraded by the acid-wash procedure, which caused those aggregates to be smoother and more rounded than the untreated aggregates. This abrasion may be the cause of the lower resilient modulus and tensile strength of these mixtures.

Amine

The addition of an amine to the asphalts lowered the resilient modulus of the mixtures but lowered the tensile strength only of the Georgia mixture. The various aggregates and asphalts responded differently to the amine treatment and the testing procedures, and no trends could be identified.

Sodium Dichromate

The addition of sodium dichromate to the aggregates followed the same pattern observed for the amines, lowering the resilient modulus of the mixtures but lowering the tensile strength only of the Georgia mixture. Both of the treatments are of the surfactant type, but the amines were added to the asphalt cements and the sodium dichromate was added to the aggregates.

Sulfur-Extended Asphalt

The sulfur-extended asphalt changed the resilient modulus and the tensile strength of the mixtures. The 15 percent replacement ratio resulted in a decrease in the modulus and tensile strength of the mixtures investigated. Except for the Georgia aggregate, the mixtures containing the 30 percent sulfur-extended asphalt had a higher modulus and tensile strength than those containing the 15 percent sulfur-extended asphalt. This agrees with the findings of others (18,19). This effect is the result of changes in the consistency of the sulfur-extended asphalt, which is a function of replacement percentage.

EFFECT OF TREATMENTS ON MOISTURE SENSITIVITY

The effectiveness of the treatments for improving the water resistance of the mixtures was evaluated by making comparisons of the data and by visually examining fractured surfaces of the conditioned specimens for stripping. The results of the visual examination are given in Table 6. All of the untreated mixtures were severely damaged by the moisture conditioning procedure. The effectiveness of the treatments varied with the different mixtures and treatment types.

Retention ratios were calculated for each mixture-treatment-test combination by dividing the average test parameter after conditioning by the average test parameter before conditioning. Retention ratios for resilient modulus and tensile strength are given in Table 7 and represent the fraction of the test parameter retained after conditioning. Improvement ratios were calculated for each mixture-treatment-test combination by dividing the treated test parameter obtained after conditioning by the untreated test parameter obtained after moisture conditioning. These ratios are given in Table 8.

An analysis of variance was performed by using the retention and improvement ratios as dependent variables. Aggregate source, treatment method, and test method were considered as independent variables. Test methods included in the analyses were resilient modulus (17), tensile strength (15), and E-modulus (15). A series of full factorial models was constructed based on the aggregate-asphalt-treatment combinations given in Table 3. Results for a typical analysis-of-variance model are given in Table 9. The statistical analyses indicated that the treatments varied in their effectiveness and that the effectiveness of each treatment varied with the different aggregates. The structure of the models is as follows: Retention ratios = aggregate + treatment + test + all second-order interactions + error. The formulas for the null hypothesis (H_0) and the alternative hypothesis (H_1) are given below (R^2 = 0.947). For H_0,

$$\mu_1 = \mu_2 = \ldots = \mu_n \qquad F^* \leq F(\alpha, \upsilon_1, \upsilon_2) \tag{1}$$

For H_1,

$$\mu_1 \neq \mu_2 \neq \ldots \neq \mu_n \qquad F^* > F(\alpha, \upsilon_1, \upsilon_2) \tag{2}$$

The effectiveness of the treatments, as measured by improvement and retention ratios, was dependent on the type of test. In general, tensile strength was affected differently than stiffness (E-modulus and resilient modulus). Improvements in tensile strength were not necessarily associated with improvements in stiffness and vice versa. The second-order interactions were significant for most of the models, indicating that, as measured by the improvement and retention ratios, (a) the different aggregates reacted differently to the different treatments, (b) the different test procedures gave different measures of the effectiveness of the different treatments, and (c) the different test procedures gave different measures of treatment effectiveness for the different aggregate sources.

Epoxy Coating

Encapsulation of the aggregates with epoxy provided some degree of moisture improvement in all of the mixtures, but the effect was particularly evident for Georgia aggregate. It is surprising that all of the treated aggregates did not have similar retention ratios because they were all totally encapsulated in epoxy. The most likely explanation is the differences in the shape and surface texture of the coated aggregates. The epoxy-coated aggregates did show visual evidence of stripping and, if further research is done with aggregate coatings, particular attention should be paid to the compatibility of the coating with asphalt as well as the thickness of the coating and the texture of the coated aggregate.

Hydrated Lime

Both the improvement and retention ratios were significantly improved by the addition of hydrated lime to the mixtures. Based on visual examination (Table 6), the use of hydrated lime reduced the stripping on all aggregates investigated, but this was not always reflected in the improvement or retention ratios. In view of this and the improvement in the mechanical properties of the mixtures, the hydrated lime was the most successful of the treatments investigated.

Acid Wash

The acid wash produced slight improvements in the moisture resistance of the Arizona and Oregon mixtures but lowered the moisture resistance of Virginia, Colorado, and Idaho mixtures. Although loose surface material was removed from the Georgia and Oregon aggregates, the remaining surfaces were sensitive to stripping, as Table 6 indicates.

Amines

The addition of amines to the asphalts improved the retention ratios and improvement ratios of the mixtures investigated. All of the amine-treated mixtures exhibited less stripping than the untreated mixtures (Table 6). Although the amines did significantly improve the water resistance of the aggregates, none of the treated mixtures can be considered successful based on a 0.75 tensile-strength retention ratio as recommended for field acceptance (6,15).

Sodium Dichromate

Both the improvement and retention ratios increased for all the mixtures treated with sodium dichromate. The improvement in moisture resistance was approximately the same as it was for the amine-treated mixtures. Based on visual examination of stripping, all of the sodium-dichromate-treated mixtures stripped to a lesser extent than the untreated mixtures. The observed stripping also

Table 6. Observed stripping in freeze-soak-conditioned specimens.

Treatment	Aggregate Georgia	Virginia	Colorado	Oregon	Idaho	Arizona
Untreated	H	H	H	H	H	H
Epoxy coating	M	M	L	L	M	M
Hydrated lime	L	L	L	L	L	L
Acid wash	H	H	H	M	H	H
Amines	L	-	M	L	L	M
Sodium dichromate	L	-	L	M	L	M
AC-20 asphalt	-	-	-	H	H	H
Sulfur-extended asphalt						
15 percent	H	-	-	H	H	H
30 percent	H	-	-	H	H	H

Note: H = high (>70 percent stripping on coarse aggregate), M = medium (30-70 percent stripping on coarse aggregate), and L = low (<30 percent stripping on coarse aggregate).

Table 7. Average retention ratios for different treatments.

Treatment	Test	Aggregate Georgia	Virginia	Colorado	Oregon	Idaho	Arizona
Untreated	M_R	0.08	0.14	0.27	0.21	0.21	0.21
	Tensile strength	0.27	0.39	0.46	0.45	0.43	0.39
	Stability	0.47	0.68	0.60	0.35	0.26	0.28
Epoxy coating	M_R	0.96	0.58	0.49	0.52	0.59	0.49
	Tensile strength	0.75	0.67	0.80	0.77	0.66	0.72
	Stability	1.13	0.57	0.53	0.44	0.42	0.61
Hydrated lime	M_R	0.72	0.63	0.54	0.62	0.41	0.46
	Tensile strength	0.62	0.69	0.59	0.72	0.59	0.70
Acid wash	M_R	0.27	0.19	0.19	0.42	0.06	0.31
	Tensile strength	0.24	0.27	0.33	0.66	0.12	0.53
Amines	M_R	0.34	-	-	0.53	0.53	0.29
	Tensile strength	0.58	-	-	0.66	0.57	0.46
Sodium dichromate	M_R	0.41	-	-	0.37	-	0.42
	Tensile strength	0.63	-	-	0.49	-	0.58
Sulfur-extended asphalt							
15 percent	M_R	0.02	-	-	-[a]	0.03[b]	0.11[b]
	Tensile strength	0.06	-	-	0.19[b]	0.07[b]	0.30[b]
30 percent	M_R	0.08	-	-	0.02[b]	0.06[b]	0.04[b]
	Tensile strength	0.23	-	-	0.50[b]	0.19[b]	0.16[b]

[a] Too weak to test.
[b] Computed with respect to AC-20 mixtures.

followed the same trends as those for the amines.

Sulfur-Extended Asphalt

Neither of the sulfur-extended asphalts improved the moisture resistance of the mixtures investigated. This observation is based on the values of the retention and improvement ratios as well as observed stripping in the mixtures (Table 6). Based on measurements recorded during the mechanical testing, mixtures made with the sulfur-extended asphalt tended to expand more than the other mixtures and tended to turn slightly brownish when subjected to the freeze-soak conditioning procedure. Fromm (11) noted that the presence of a brownish coloration in an asphalt-aggregate mixture that was subjected to water signified the formation of an expanding asphalt-water emulsion that was highly sensitive to water. This type of emulsion may have formed in the conditioned sulfur-extended-asphalt specimens. The claim that sulfur-extended asphalts in general show high resistance to water (20) does not seem to be justified on the basis of the findings of this study.

Table 8. Average improvement ratios for conditioned samples.

Treatment	Test	Aggregate Georgia	Virginia	Colorado	Oregon	Idaho	Arizona
Epoxy coating	M_R	4.22	1.39	1.04	0.89	1.03	0.49
	Tensile strength	2.09	1.30	1.31	0.93	1.10	0.86
	Stability	2.40	0.91	0.97	1.24	2.18	1.01
Hydrated lime	M_R	4.59	2.11	2.30	3.02	1.92	1.86
	Tensile strength	1.90	1.81	1.54	1.68	1.63	1.61
Acid wash	M_R	1.42	0.43	0.50	1.96	0.17	0.93
	Tensile strength	0.97	0.60	0.72	1.41	0.32	1.16
Amines	M_R	2.19	-	1.18	2.18	1.40	0.72
	Tensile strength	1.57	-	1.44	1.45	1.63	1.10
Sodium dichromate	M_R	3.93	-	1.95	1.51	1.04	1.17
	Tensile strength	1.88	-	1.64	1.18	1.48	1.33
Sulfur-extended asphalt							
15 percent	M_R	0.10	-	-	-[a]	0.37[b]	0.79[b]
	Tensile strength	0.15	-	-	1.09[b]	0.26[b]	1.06[b]
30 percent	M_R	0.42	-	-	0.47[b]	1.10[b]	0.48[b]
	Tensile strength	0.51	-	-	0.30[b]	0.75[b]	0.72[b]

[a] Too weak to test.
[b] Computed with respect to AC-20 mixtures.

Table 9. Typical analysis of variance for retention ratios.

Source	df	SS	MS	F*	$F_{\upsilon_1, \upsilon_2}$ $\alpha = 0.1$	$\alpha = 0.01$
Aggregate	3	0.158	0.527	8.03	2.23	4.31
Treatment	7	2.94	0.420	64.22	1.87	3.12
Test method	2	0.752	0.376	57.44	2.44	5.18
Aggregate x treatment	21	0.448	0.213	3.26	1.60	2.35
Aggregate x test method	6	0.0619	0.010 3	1.58	1.93	3.29
Treatment x test method	14	0.295	0.021 1	3.22	1.67	2.54
Error	40	0.262	0.006 54	-	-	-

SUMMARY AND CONCLUSIONS

Inadequate resistance to the effects of water is a problem with many asphalt concrete mixtures. To improve the performance of many aggregates in current use and to upgrade aggregates that are currently unacceptable, new treatment methods and procedures need to be developed. Traditional antistripping additives cannot be expected to upgrade all problem aggregates because of the variety of mechanisms that are responsible for moisture damage. A classification scheme that considers various moisture-damage mechanisms should be developed so that treatments can be selected on a rational basis.

In this study, a number of approaches to the upgrading of water-sensitive aggregates were identified. Further study is needed to optimize the various treatment approaches and to develop a rational procedure for matching the treatment with particular aggregates and aggregate-asphalt mixtures. Based on the results of this study, the following conclusions can be made:

1. A variety of mechanisms influence the resistance of asphalt mixtures to the effects of water, and this must be recognized in the process of selecting an appropriate upgrading procedure.
2. Upgrading procedures can affect the mechanical behavior of mixtures. Strength and stiffness may be increased or decreased.
3. Different test procedures (tensile strength, E-modulus, or resilient modulus) provide different measures of treatment effectiveness, and improvements in retained strength are not always accompanied by equivalent improvements in retained modulus and vice versa.
4. The effectiveness of a particular treatment may depend on the properties of both the aggregate and the asphalt.
5. Several of the treatment approaches show promise for improving water resistance and should be studied further.

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