PRINCIPAL COMPONENT AND CLUSTERING ANALYSIS IN MOISTURE DAMAGE EVALUATION OF HMA

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Adriana Vargas-Nordcbeck, Ph.D.
(Corresponding author)
National Laboratory of Materials and Structural Models (LanammeUCR)
University of Costa Rica, P.O. Box 11501-2060, UCR, San José, Costa Rica
E-mail: adriana.vargasnordcbeck@ucr.ac.cr

Fabricio Leiva-Villacorta, Ph.D.
National Laboratory of Materials and Structural Models (LanammeUCR)
University of Costa Rica, P.O. Box 11501-2060, UCR, San José, Costa Rica
E-mail: fabricio.leiva@ucr.ac.cr

José P Aguiar-Moya, Ph.D.
National Laboratory of Materials and Structural Models (LanammeUCR)
University of Costa Rica, P.O. Box 11501-2060, UCR, San José, Costa Rica
jose.aguiar@ucr.ac.cr

Luis G Loria-Salazar, Ph.D.
National Laboratory of Materials and Structural Models (LanammeUCR)
University of Costa Rica, P.O. Box 11501-2060, UCR, San José, Costa Rica
E-mail: luis.loriasalazar@ucr.ac.cr

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ABSTRACT

Moisture damage in asphalt concrete mixtures can be evaluated through several laboratory tests, many of which compare the results of conditioned specimens to those of dry specimens. While the results from ratios of conditioned to unconditioned specimens may provide an adequate pass/fail criteria, a more comprehensive evaluation of mixture performance should include the specific values obtained (tensile strength, dynamic modulus or flow number), as these are also related to pavement performance. The objective of this study was to provide a comprehensive evaluation of the moisture susceptibility of different asphalt mixtures through principal component and clustering analysis. Twelve mixtures were designed and produced in the laboratory using a single aggregate source for nominal maximum aggregate sizes of 9.5 mm and 12.5 mm. Each of the sizes included a control mix, an SBS modified mix, mixtures that contained antistripping agents (liquid antistrip or hydrated lime), and mixtures that combined both SBS and antistripping agents. All mixtures used the same PG 70-22 binder source. Results from the Modified Lottman Indirect Tension Test Procedure, dynamic modulus and flow number tests for conditioned and unconditioned specimens were used as inputs for the analysis. The analysis indicated that principal components can be used to explain the variation in the results and to calculate an overall performance score to rank the mixtures based on selected variables. Cluster analysis was used to group mixes and to identify characteristics that affect their performance. It was found that mixtures that combined SBS and an antistripping agent ranked highest in overall performance.

INTRODUCTION

Moisture damage is a widespread problem that can cause premature failure in asphalt concrete mixtures. This type of damage can occur due to a loss of bond between the asphalt binder and the aggregate, or because moisture permeates and weakens the mastic, making it more susceptible during cyclic loading (*1-6*).

For decades, asphalt technologists and state highway agencies have been in pursuit of a laboratory test procedure that can reliably predict moisture resistance of asphalt pavements in the field (*7*). There are many tests that can be used to evaluate moisture susceptibility of raw materials and mixtures with different types of results (qualitative and quantitative). However, they often fail to account for differences in laboratory and field-produced mixtures (*8*).

The AASHTO T283 Test Method (*9*), also known as the Modified Lottman Indirect Tension Test Procedure, was adopted by the Superpave system as the required test for determination of moisture damage and is currently the most commonly specified test procedure for determination of moisture damage potential (*7, 8*).Nonetheless, this test method is empirical and is performed under conditions that differ significantly from those in the field: its conditioning procedure does not include dynamic loading, and it uses strength, a parameter that is not directly used in pavement design, to determine whether unacceptable moisture damage will occur in the field (*3*).This often results in false positives or false negatives in the prediction of moisture susceptibility (*7*).

Simple performance tests (SPTs) have been used as an alternative to evaluate moisture susceptibility of asphalt mixtures with promising results (*10-13*). Similar to AASHTO T283, test parameters from the dynamic modulus and flow number tests can be calculated by comparing the results of conditioned specimens to those of dry specimens. The use of multiple conditioning cycles has also been included during testing to provide a more accurate simulation of field performance (*13*).

While the results from ratios of conditioned to unconditioned specimens may provide an adequate pass/fail criterion, a more comprehensive evaluation of mixture performance should include the specific values obtained (tensile strength, dynamic modulus or flow number), as these are also related to pavement performance. Multivariate statistical techniques such as principal components analysis (PCA) and clustering can be useful tools to assess mixture performance using a more robust data set.

OBJECTIVES AND SCOPE OF WORK

The objective of this study was to provide a comprehensive evaluation of the moisture susceptibility of different asphalt mixtures through principal component and clustering analysis. Results from the Modified Lottman Indirect Tension Test Procedure (AASHTO T283), dynamic modulus and flow number tests for conditioned and unconditioned specimens were used as inputs for the analysis.

METHODOLOGY

Mix Designs

Twelve mixtures were designed and produced in the laboratory using a single aggregate source for nominal maximum aggregate sizes (NMAS) of 9.5 mm and 12.5 mm. Each of the sizes included a control mix, as well as the following variations: 2% SBS modified mix by total weight of binder, mixtures that contained 0.5% liquid antistrip (LAS) by total weight of binder and 1% hydrated lime by total weight of aggregate, a mixture that combined 2% SBS and 1% lime, and a mixture containing 2% SBS and 0.5% liquid antistrip. All mixtures used the same PG 70-22 binder source. Table 1 shows the gradations for the two aggregate sizes and Table 2 shows the volumetric properties of all the mixtures used in this study.

TABLE 1 Mixture Gradations

Sieve Size	% Passing	
	9.5 NMAS	12.5 NMAS
3/4"	100	100
1/2"	100	95.4
3/8"	95.0	78.3
N° 4	60.0	43.3
N° 8	40.0	28.9
N° 16	25.0	20.0
N° 30	17.0	14.8
N° 50	10.0	10.9
N° 100	7.0	8.0
N° 200	5.0	5.8

TABLE 2 Mixture Volumetric Properties

Mixture	% Design AC	%VMA	% VFA	Dust Proportion
9.5 Control	6.5	15.5	73.7	1.0
9.5 SBS	6.5	15.8	74.3	1.0
9.5 LAS	6.5	15.9	72.7	1.0
9.5 SBS+LAS	6.3	15.4	72.9	1.0
9.5 Lime	6.7	16.3	74.4	0.9
9.5 SBS+Lime	6.6	16.0	74.4	1.0
12.5 Control	7.0	15.8	74.5	1.1
12.5 SBS	6.5	15.1	73.3	1.2
12.5 LAS	6.5	14.7	72.7	1.2
12.5 SBS+LAS	5.9	13.1	69.9	1.5
12.5 Lime	6.0	14.0	71.5	1.3
12.5 SBS+Lime	6.3	14.3	72.0	1.3

Laboratory Testing

For each of the mixtures, the Modified Lottman Indirect Tension Test, dynamic modulus (E*) and flow number (FN) tests were conducted for dry (unconditioned) specimens and specimens subjected to 6 freeze/thaw cycles, to simulate more aggressive field conditions. For all tests, one cycle of conditioning consisted of subjecting vacuum-saturated specimens to a temperature of -18°C for 16 hours, followed by a 60°C water bath for 24 hours.

The dynamic modulus and flow number tests were performed in accordance to AASHTO TP79 (*14*). E* data used in the analysis correspond to the measurements made at 20°C and 10 Hz (typical pavement operating conditions).

RESULTS AND DISCUSSION

Tensile strength

Figure 1 shows the average tensile strength for all mixtures for dry and conditioned specimens. In general, mixtures containing SBS have higher tensile strengths within each of the nominal maximum aggregate sizes. However, antistripping additives (liquid or lime) are required to prevent the tensile strengths from decreasing excessively after conditioning (i.e. maintain a high tensile strength ratio).

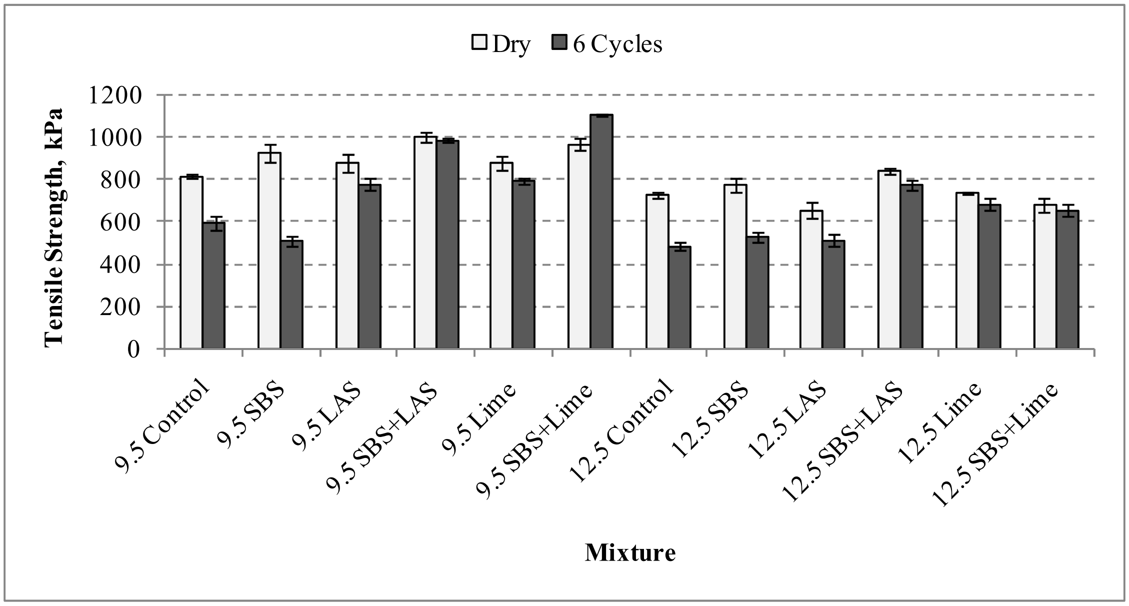

FIGURE 1 Average tensile strengths.

Dynamic Modulus

Figure 2 shows the average dynamic modulus for all mixtures. The trend is similar to the one observed for tensile strengths, but in this case the ratios of conditioned to unconditioned specimens tend to be lower, especially for mixtures that do not contain antistripping agents.

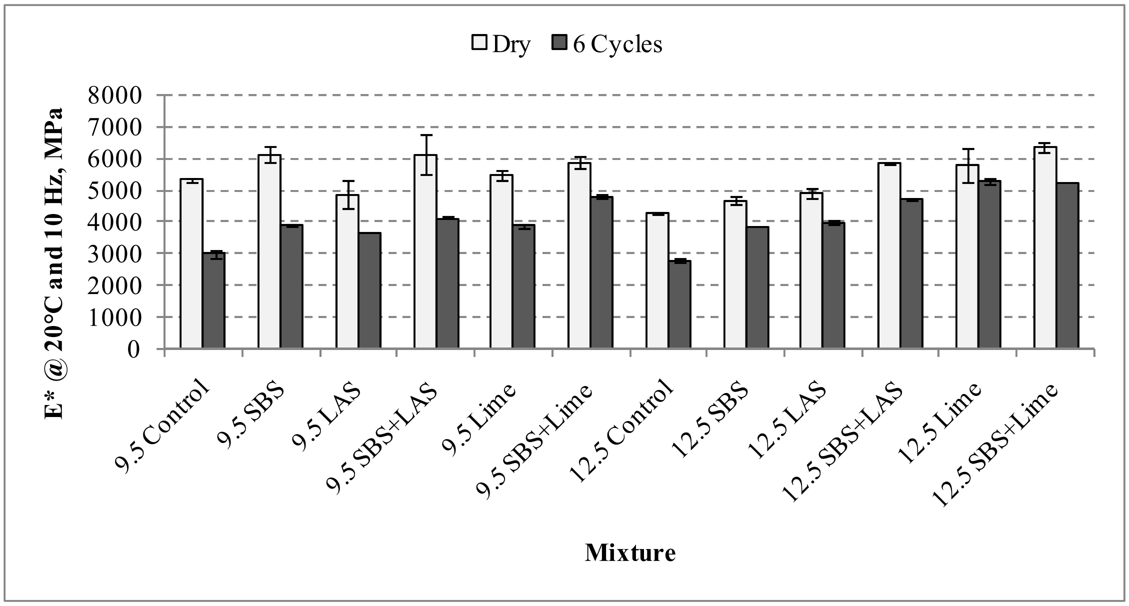

FIGURE 2 Average dynamic modulus at 20°C and 10 Hz.

Flow Number

The average flow number results are shown in Figure 3.It can be observed that SBS modified mixtures tend to be more resistant to permanent deformation, but antistripping agents are required to maintain a similar performance after conditioning. It should be noted that the results from the flow number test exhibit higher variability compared to the tensile strength and dynamic modulus results.

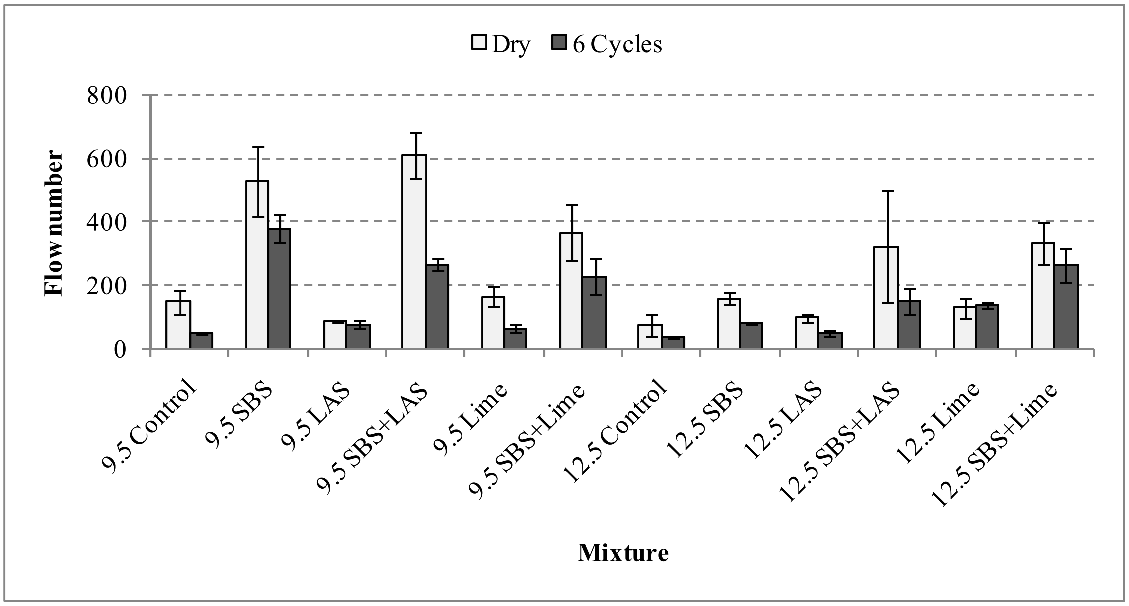

FIGURE 3 Average flow number.

Figure 4 summarizes the conditioned to unconditioned specimens ratio for all three tests performed. The results are highly variable, and given a minimum required value, a mixture may or may not pass, depending on which test is used. In general, the observed trend indicates that moisture resistance is improved with the addition of antistripping agents. However, this assessment is based solely on the shown ratios, and does not consider the specific values for the measured properties, which also affect mixture performance. For example, the 9.5 LAS mixture has a FN ratio of 0.91, meaning it does not deteriorate significantly after conditioning. However, the individual flow number values are under 100, so this mixture is more susceptible to rutting compared to others in this study, and may not be adequate for high traffic applications.

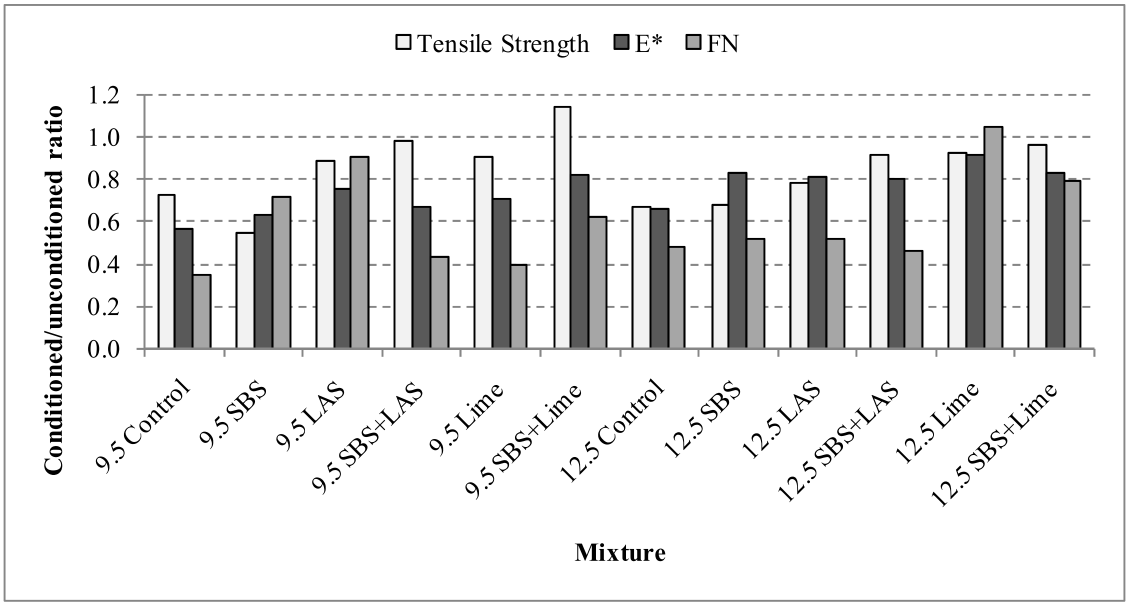

FIGURE 4 Ratio of conditioned to unconditioned specimens.

Principal component analysis and clustering can integrate all the results to provide a more comprehensive evaluation and identify groups of mixtures based on their overall performance, so that a mixture can be selected according to specific project needs.

Principal Component Analysis

A principal component analysis (PCA) is a procedure that explains the variance-covariance structure of a set of variables through a few linear combinations of these variables, called principal components. The main objectives of PCA are data reduction and interpretation. A detailed description of the procedure can be found elsewhere (*15*).

In this study, six variables were included for each of the mixtures: dry and conditioned tensile strength ($S_{t\ dry}$, $S_{t\ cond}$), dry and conditioned dynamic modulus (E_{dry}, E_{cond}) and dry and conditioned flow number (FN_{dry}, FN_{cond}). These variables were standardized to calculate the principal components, since they are measured in different scales. Table 3 shows the eigenvalues and the proportion of variation explained by the principal components. The eigenvalues represent the estimated variances of the respective principal components. It can be observed that the first three principal components explain 95.6% of the variation, therefore, only these components were used in the evaluation.

TABLE 3 Variance Decomposition

Principal component	Eigenvalue	Proportion	Cumulative
1	3.649	0.608	0.608
2	1.229	0.205	0.813
3	0.860	0.143	0.956
4	0.131	0.022	0.978
5	0.089	0.015	0.993
6	0.042	0.007	1.000

Table 4 shows the coefficients of the first three principal components. From these results, it can be seen that the first principal component is strongly correlated with the dry dynamic modulus, and the dry and conditioned flow numbers. The second principal component is correlated primarily with the dry tensile strength and the conditioned dynamic modulus, while the third principal component is mostly correlated with the conditioned tensile strength. The positive sign of the coefficients indicates that the principal component increases with an increase in the corresponding variable, while a negative sign means that the principal component increases with a decrease in the variable.

TABLE 4 Principal Component Coefficients

Variable	PC1	PC2	PC3
1 - $S_{t\ dry}$	0.352	0.645	0.025
2 - $S_{t\ cond}$	0.352	0.330	0.676
3 - E_{dry}	0.471	-0.285	-0.019
4 - E_{cond}	0.310	-0.600	0.456
5 - FN_{dry}	0.473	0.099	-0.380
6 - FN_{cond}	0.458	-0.153	-0.435

The scores of the principal components for each of the asphalt mixtures are calculated as follows:

$$\mathrm{Y_i = a_{i1}X_1 + a_{i2}X_2 + \cdots + a_{ip}X_p} \quad (1)$$

where

Y_i = ith principal component (i = 1, 2, 3)

X_p = variable (p = 1, 2,.. ,6)

a_{ip} = linear combination coefficients from Table 4

For example, the score for the first principal component is given by Equation 2:

$$Y_1 = 0.352S_{t\,dry} + 0.352S_{t\,cond} + 0.471E_{dry} + 0.310E_{cond} + 0.473FN_{dry} + 0.458FN_{cond} \quad (2)$$

An overall performance score (Y) can be calculated as a weighted value using the proportions shown in Table 3:

$$Y = 0.608Y_1 + 0.205Y_2 + 0.143Y_3 \quad (3)$$

The scores for the three principal components as well as the overall performance score are shown in Table 5. A higher value of Y indicates better performance. In general, it can be observed that SBS modified mixtures exhibit better performance, especially if combined with an antistripping additive.

TABLE 5 Principal Component Scores and Overall Performance

Mixture	Y_1	Y_2	Y_3	Y
9.5 Control	-1.416	0.757	-0.396	-0.762
9.5 SBS	2.045	-0.017	-2.266	0.916
9.5 LAS	-1.016	1.040	0.685	-0.307
9.5 SBS+LAS	2.971	1.270	-0.207	2.037
9.5 Lime	-0.312	0.698	0.721	0.057
9.5 SBS+Lime	2.368	0.760	1.255	1.775
12.5 Control	-2.997	0.662	-0.665	-1.782
12.5 SBS	-1.641	0.004	-0.271	-1.036
12.5 LAS	-2.110	-0.905	-0.015	-1.470
12.5 SBS+LAS	0.878	-0.374	0.437	0.520
12.5 Lime	0.011	-1.628	0.906	-0.198
12.5 SBS+Lime	1.219	-2.267	-0.185	0.250

Cluster Analysis

Cluster analysis consists on grouping objects into classes so that there is some similarity between the objects in a given class (*15*). There are several methods for measuring the similarity between objects as well as algorithms for sorting objects into groups. This study used the Euclidian distance as the similarity measure and Ward's method for creating the groups. A maximum of three clusters was selected so that the resulting groups would contain more than one object.

Table 6 shows the cluster assignment for the mixtures, along with the rank from the principal component analysis. The grouping resulting from the cluster analysis is mostly in agreement with the results from the principal component analysis. The dendogram shown in Figure 5 is a visual representation of how mixtures were combined using the same variables as the principal component analysis.

TABLE 6 Mixture Rank and Cluster Distribution

Mixture	Rank	Cluster
9.5 SBS+LAS	1	2
9.5 SBS+Lime	2	2
9.5 SBS	3	2
12.5 SBS+LAS	4	3
12.5 SBS+Lime	5	3
9.5 Lime	6	1
12.5 Lime	7	3
9.5 Antistrip	8	1
9.5 Control	9	1
12.5 SBS	10	1
12.5LAS	11	1
12.5 Control	12	1

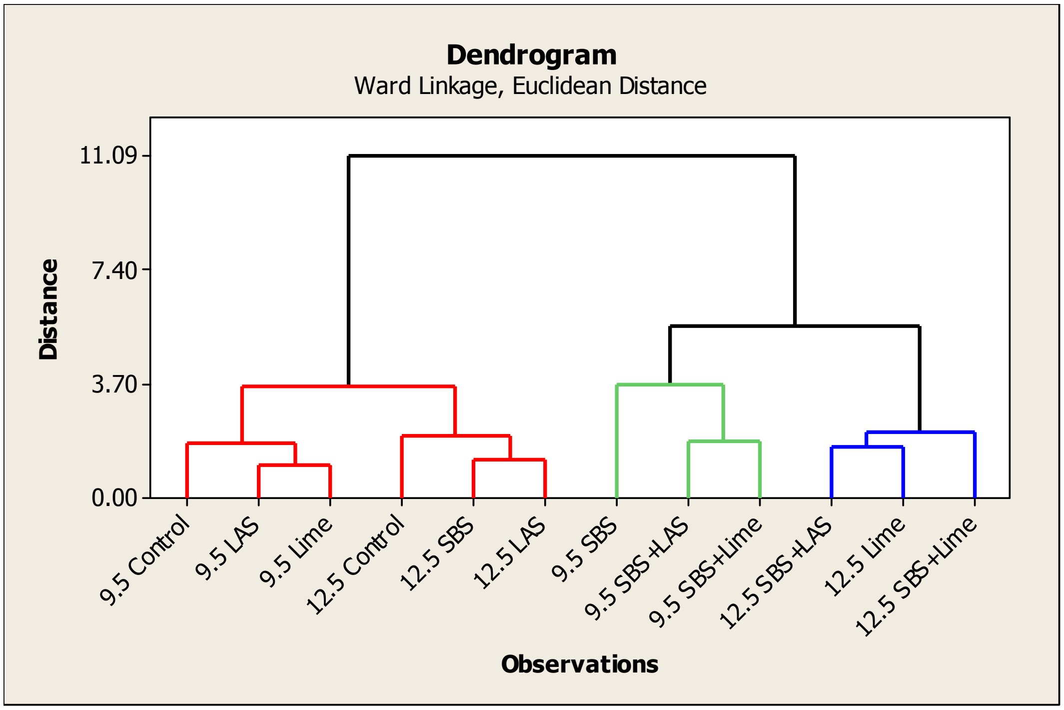

FIGURE 5 Dendogram for mixture performance.

A summary of the properties for each of the clusters is given in Tables 7 and 8.The first cluster has intermediate values for dry tensile strength, but exhibits the greater reduction for this parameter after conditioning. It also has the lowest values for dynamic modulus and flow number (dry and conditioned), so mixtures in this cluster can be considered the ones with the poorer performance. They include both nominal maximum aggregate sizes, one has SBS modified binder, and about half of the mixtures in the group were treated with antistripping aid. This group did not include any mixtures combining SBS and antistripping agents.

The second cluster has the highest tensile strengths and flow numbers. Although it also exhibits the highest dry dynamic modulus, this value has the greater reduction after conditioning. All mixtures in this group have a 9.5 mm NMAS and contain SBS modified binder. In some cases SBS is combined with antistripping agents. The mixtures in this cluster can be considered the best performing mixtures.

Finally, the third cluster has intermediate values for all the parameters measured under the dry condition, but are the least affected after being subjected to conditioning. All mixtures in this group have a 12.5 mm NMAS and contain either liquid antistrip or lime, some of them combined with SBS. This group exhibits intermediate performance.

TABLE 7 Descriptive Statistics of the Clusters

Test result	Cluster 1, n = 6		Cluster 2, n = 3		Cluster 3, n = 3	
	Avg.	St. Dev.	Avg.	St. Dev.	Avg.	St. Dev.
$S_{t\ dry}$, kPa	787.0	86.8	963.4	39.0	750.3	81.0
$S_{t\ cond}$, kPa	614.5	138.2	865.7	314.6	701.1	61.9
E_{dry}, MPa	4915.2	448.1	6030.0	138.6	5990.8	303.6
E_{cond}, MPa	3538.5	509.1	4273.4	473.4	5084.9	323.6
FN_{dry}	122.3	40.1	501.3	125.0	261.0	113.6
FN_{cond}	61.1	18.2	291.4	78.9	183.4	70.3

TABLE 8 Mixture Characteristics of the Clusters

Mixture characteristics	Cluster 1	Cluster 2	Cluster 3
NMAS	9.5, 12.5	9.5	12.5
Asphalt binder	Neat, SBS modified	SBS modified	Neat, SBS modified
Antistripping aid	None, LAS, lime	None, LAS, lime	LAS, lime
Polymer combined with antistripping aid	No	Yes	Yes

CONCLUSIONS

The objective of this study was to provide a comprehensive evaluation of the moisture damage performance of asphalt mixtures using multivariate analysis tools. Based on the previous results, the following conclusions were made:

- Testing protocols that compare ratios of conditioned to unconditioned specimens can be useful to establish a pass/fail criteria regarding moisture damage resistance. However, results vary depending on which test is used.
- Principal component analysis determined that for the mixtures included in this study, three linear combinations of the variables (principal components) explain most of the variation in the results. The first principal component, which explains roughly 61% of the variation, is strongly correlated with the dry dynamic modulus, and the dry and conditioned flow numbers.
- An overall performance score can be calculated for each mixture as a weighted value using the selected principal components. These scores indicate how the mixtures rank in terms of performance, taking into account six different variables.
- Clustering analysis identified three groups of mixtures according to their performance. Best and intermediate performing mixtures (clusters 2 and 3) contained polymer modified binder and/or antistripping aid. Mixtures that combined SBS and an antistripping agent ranked high in overall performance.
- In general, mixtures in the best performing group have the highest average values for the variables (with the exception of the conditioned dynamic modulus). However, they don't necessarily have the highest conditioned to unconditioned ratios.

The type of analysis performed in this study using multivariate techniques is a good option for classifying mixtures according to their performance. The mixtures used had two gradations, each with several variations, resulting in similar volumetric properties. The analysis could be extended to include more mixtures with different gradations and materials, and mixture properties may be included as variables to determine their influence in performance. It is also recommended that the results be validated with field performance data.

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