Evaluation of Effectiveness of Antistrip Additives Using Fuzzy Set Procedures

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Asphalt concrete pavement layers are sometimes weakened by moisture when the adhesive bond between the aggregate surface and the asphalt cement is broken. The problem of stripping, or disbonding of asphalt cement from aggregates in asphaltic concrete mixtures, has produced serious pavement distress, has increased pavement maintenance, and has resulted in poor pavement performance. Use of antistrip additive is often necessary to prevent stripping in asphaltic concrete pavements. The selection of an appropriate antistrip additive for a particular project is not an easy task because of the many factors involved. Most highway agencies perform tests on an asphaltic concrete mixture to determine its moisture-susceptibility performance. Some of these tests may include indirect tensile strength, resilient modulus test, boiling test, and moisture-susceptibility tests (e.g., Lottman or Tunnicliff-Root). The results obtained from some or all of these tests are used to determine the moisture susceptibility of a mixture. However, depending upon the agency or individuals involved, each test property may be evaluated differently. Therefore, fuzzy set theory is introduced for selecting the best-performance antistrip additive based on the performance of several asphaltic concrete mixture properties. The Tunnicliff-Root procedure was used to evaluate the effect of antistrip additives on the strength of 960 Marshall specimens. The average dry and wet indirect tensile strength ratio, visual stripping, and the price of the antistrip additives were used in a computer program developed to analyze the data using the fuzzy set theory. In this research project, it was shown that fuzzy sets can be successfully used for evaluating the effectiveness of antistrip additives in asphaltic concrete mixtures.

In recent years, more highway agencies have been requiring the use of antistrip additives because of increasing awareness of asphaltic concrete pavement failures caused by moisture damage. Antistrip additives are primarily used to reduce stripping and to increase mixture strength in the presence of moisture. Stripping involves disbonding of asphalt cement from aggregate surfaces, often in the presence of moisture.

Many antistrip additives (ASAs) are on the market. Performance of these ASAs in asphaltic concrete mixtures varies depending on many factors (e.g., the source of asphalt cements and aggregates used). There is, therefore, a need to identify the best-performing ASA for each asphaltic concrete mixture.

Many methods are available, for example, Tunnicliff-Root (*1*) and Lottman (*2*), to measure the performance and moisture susceptibility of asphaltic concrete mixtures. The Tunnicliff-Root procedures recommend saturating a Marshall sample between 55 and 80 percent by applying a vacuum (20 in. Hg, for 5 min). The sample is then placed in water (77°F) for 1 hr, and the indirect tensile strength of the specimen is determined. The ratio of moisture-conditioned specimen to dry-conditioned (stored for 24 hr, 77°F) specimen is determined and is referred to as tensile strength ratio (TSR).

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Although methods are available to examine a particular mixture property that is known to be a measure of ASA performance, comprehensive evaluation of ASA performance requires the consideration of many properties. For example, in these evaluations, the interrelationship of tensile strength (TS) ratio (wet TS/dry TS) and visual stripping rating is not clear.

Because the interrelationship among properties is vague, the comparison of one property with another is "fuzzy." Sometimes, comparison of the same property among different mixtures is also fuzzy. For example, because TSR is a function of the TS of dry- and wet-conditioned mixtures, a mixture of lower wet TS can have a higher TSR than a mixture with higher wet TS. In such a case, comparison of TSR alone does not yield meaningful results. Even though it is generally known that stripping has some correlation with weakening of tensile strength (*3,4*), some stripped mixtures show higher strength values than unstripped mixtures. Therefore, an unstripped mixture does not necessarily exhibit high tensile strength. Detailed examples are explained in a subsequent section.

Organizing information for many properties in the way that will lead to a conclusive performance evaluation may involve many subjective judgments. Especially, because interrelation of data is ambiguous, rating individual value and weighing each factor for integration of information are difficult. The result of using conventional methods or simple numerical-ranking comparison for this type of problem may still be ambiguous. The major advantage of using fuzzy procedure is that the result is easy to understand, because fuzzy weighted average operation can quantify the ambiguous values and translate them into illustrative expressions. Therefore, fuzzy set procedures have been applied to the evaluation of the potential performance of antistrip additives.

In this research, fuzzy sets were used to determine the moisture susceptibility of laboratory-prepared Marshall specimens. The materials (aggregates, asphalt cements, and ASAs) used in the lab were typical of those widely used in South Carolina. Four AC-20 ashalt cement sources, designated as I, II, III, and IV, were used. In addition, three liquid ASAs, designated as 1, 3, and 4, and a hydrated lime, designated as 2, were used to evaluate the effectiveness of ASAs on indirect tensile strength (ITS) of Marshall specimens. Aggregates used in this research (designated as A, B, and C) were typical of those used for Type 3 surface mixtures in South Carolina.

Aggregates A and C were predominantly crushed granitic aggregates; Aggregate B consisted of siliceous coastal plains sand and gravel (*3*).

FUZZY SET THEORY

Zadeh, in 1965, introduced the notion of fuzzy sets (*5*). Zadeh (*6*) suggested that the closer one investigates a "real-life" complex problem, the fuzzier the manner of solution becomes. He therefore developed the theory of fuzzy sets to obtain meaningful solutions to complex problems.

The mathematics of fuzzy sets were developed over a decade. However, only a few applications of the approach were implemented. In recent years, fuzzy sets have been used in engineering, medicine, and other areas of science as a tool for the expression of professional judgments (*7–11*). The following sections briefly explain the mathematics involved with fuzzy set theory.

A set is defined as a collection of objects having a general property, for example, a set of asphaltic concrete mixtures or a group of paving contractors. If an engineer works as a paving contractor (i.e., belongs to a group of contractors), then he or she has a membership of 1 in the set of paving contractors. However, if he or she is not a paving contractor, his or her membership is 0 and he or she does not belong to the set. Therefore, in general, the set has a clear and crisp boundary. A fuzzy set, on the other hand, is a set with members having a continuum of grades of membership from 0 to 1, rather than having discrete membership of 0 or 1 (*12*).

Let U denote a space of objects. A fuzzy set A in U is set of

$$A = \{x, \mu_A(x)\}, \qquad X \subset A \quad \text{and} \quad A \in U \tag{1}$$

in which $\mu_A(x)$ is the grade of membership of x in A ($0 \leq \mu_A(x) \leq 1$). Practical expressions for two fuzzy sets (e.g., A and B) are as follows (*13*, p. 192).

$$A = \{x(i)|i; 1 < i < n\} \tag{2}$$

$$B = \{y(j)|j; 1 < j < n\} \tag{3}$$

where

i, j, and n = domain elements, expressed as integers, and
$x(i)$ and $y(j)$ = membership functions that characterize A and B, respectively.

Fuzzy Weighted Average Operation

The fuzzy weighted average (FWA) is defined as follows (*13*, p. 192):

$$R = \frac{\Sigma(R_i \times W_i)}{\Sigma W_i} \tag{4}$$

where

R = fuzzy set that represents the overall rating of an alternative,
R_i = fuzzy set that represents rating of an alternative based on a particular criterion, and
W_i = fuzzy set that represents the weight assigned to the particular criterion.

The fuzzy operations—addition, multiplication, and division—for the two fuzzy sets A and B, are defined as

Addition: $A + B$

$$= \{\min[x(i), y(j)]|(i + j); 1 < i, j < n\} \tag{5}$$

Multiplication: $A * B$

$$= \{\min[x(i), y(j)]|(i * j); 1 < i, j < n\} \tag{6}$$

$$\text{Division: } A/B = \{\min[x(i), y(j)]|(i/j); 1 < i, j < n\} \tag{7}$$

For practical use, the result of the fuzzy division defined in Equation 7 can be rearranged according to the Clements algorithm. The Clements algorithm involves two assumptions: (a) any division of (i/j) that does not result in an integer is deleted, and (b) any division that results in a quotient greater than n is discarded (*14*).

Whether or not the fuzzy normalization is required must be determined after each fuzzy operation. Normalization gives more reasonable results in the fuzzy set operations (*13,15*). The fuzzy normalization, NOR, for a fuzzy set X is defined as follows:

$$\text{if } Z = \text{NOR}(X), \qquad \text{then } Z = \{[z(i)]/i; 1 < i < n\} \tag{8}$$

$$\text{where } z(i) = x(i)/\max[x(i), 1 < i < n]. \tag{9}$$

The normalization for the fuzzy set obtained after each operation (addition, multiplication, or division) should be conducted by Equations 8 or 9 if max $x(i)$ does not equal max $z(i)$.

Ranking Index

Expression of FWA result is not by a single numerical value, but by a set that contains a series of domain element and degree of support for each element. The set from FWA operation can be graphically expressed for visual evaluation, or quantitatively expressed with ranking index (RI) for numerical evaluation.

RI can be defined to represent a quantitative measure of the fuzzy set (R in Equation 4) for each alternative. In this study, the RI was defined to increase as the alternative becomes better. The arithmetic expression of the RI is (*14*):

$$\text{RI} = a_l - a_r + c \tag{10}$$

where

a_l = area enclosed to the left of the membership function,
a_r = area enclosed to the right of the membership function, and
c = a constant that is the area enclosed by the universe.

Figure 1 (top) illustrates a_l and a_r. In Figure 1 (bottom), for example, RI for the fuzzy set of $X = \{0|4, 0.5|5, 1.0|6, 0.5|7,$

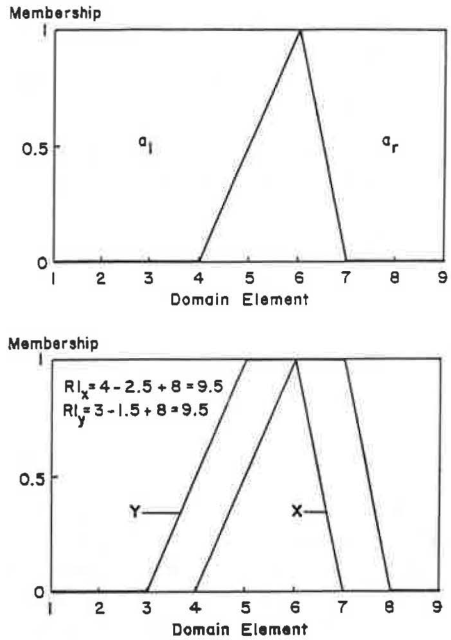

FIGURE 1 Illustration of ranking index for Fuzzy Sets X and Y.

0|8} is the same as that for fuzzy set Y = {0|3, 0.5|4, 1.0|5, 1.0|6, 1.0|7, 0.5|8, 0|9}, where values of a_l for fuzzy set X and Y are 4 and 3, and values of a_r for X and Y are 2.5 and 1.5, and value of RI is 9.5, respectively.

TESTING PROCEDURES

The Tunnicliff-Root (*1,16,17*) procedure was used to evaluate the effect of ASAs on the strength of asphaltic concrete mixtures. This procedure recommends an air voids content of 7 ± 1 percent for each specimen. After several trials, it was found that a compactive effort of 20 blows per face produced the recommended degree of air voids and saturation (55 to 80 percent). An automatic recording Marshall machine (which conforms to ASTM D1559) was used to measure the ITS of all specimens (*18*). The rate of deformation was 2 in./min and the test temperature was 77 ± 2°F. TSRs of the specimens were calculated. Immediately after tensile strength tests were completed, the surface condition of the exposed aggregates was examined. The visual strip rating (S) was calculated by obtaining the mean value of C and F, percentage of stripping for coarse (C) and fine (F) aggregates, respectively. Values of C and F are defined in Table 1.

TABLE 1 VALUES OF COARSE AND FINE AGGREGATES

Aggregate	Value	Definition
C	1	Less than 10% stripping
	2	10–40% stripping
	3	More than 40% stripping
F	1	Less than 10% stripping
	2	10–25% stripping
	3	More than 10% stripping

EXPERIMENTAL RESULTS

A total of 960 Marshall specimens were made and tested. The means and standard deviations of dry and wet ITS and TSR values for all specimens are shown in Tables 2–5. These tables indicate that the specimens made with Aggregate A and various asphalt cements and ASAs produced the highest values of dry ITS compared with specimens prepared with other aggregate sources. However, the TSR values of the same specimens generally produced lower values than specimens made with Aggregates B and C.

The following examples will demonstrate the fuzziness of the data. For Mixture A0 in Table 2, TSR was found to be 65.7 percent and its wet ITS was 44.1 psi. However, for Mixture B4, TSR was more than 100 percent and its wet ITS was 44.8 psi, which is approximately the same value of wet ITS for Mixture A0 (44.1). Therefore, in this case, simply comparing numerical values of TSR between the two mixtures is not meaningful to comparing mixture performance.

Another fuzzy example can be shown with Aggregate B in Table 3. When only the values of TSR were compared, TSR for Mixture B4 (88.7 percent) appeared to be improved (because an antistrip additive was used), compared with TSR of Control Mixture B0 (87.0 percent). However, ITS wet of B4 (45.8) was actually lower than that of B0 (47.1).

In addition, Table 4 indicates that the values of ITS dry for Aggregate A were, in general, higher than those for Aggregate B. However, TSR values for Aggregate A were lower than those for Aggregate B. Based on this result, neither wet ITS nor TSR gives clear comparison of ASA performance in the mixtures. This result may suggest an analogy that Aggregate A produced stronger mixture than Aggregate B, but was more moisture-susceptible than Aggregate B.

APPLICATION OF FUZZY SETS FOR EVALUATION OF BEST-PERFORMING ANTISTRIPPING ADDITIVE

In this section, the application of fuzzy set for evaluating ASAs is illustrated using several examples. It is important to note that the fuzzy sets selected in this study to define the rating scale and weighing for each criterion are arbitrary. Criteria for fuzzy evaluation are also selected arbitrarily. These ratings and evaluations were selected only for demonstration purposes. Any other fuzzy set can be defined and applied for similar cases.

Selection of Fuzzy Sets

Fuzzy sets A, B, C, D, and E were defined to represent ratings of excellent, very good, good, fair, and poor, respectively. Each fuzzy set was defined with only three membership functions (0, 0.5, or 1) over a domain of 9 elements (n = 9 in Equations 2 and 3) for easy computation. Fuzzy sets A, B, C, D, and E are arithmetically expressed in Equations 11–15 and are illustrated in Figure 2.

$$A = \{0|1, 0|2, 0|3, 0|4, 0|5, 0|6, 0|7, 0.5|8, 1.0|9\} \quad (11)$$

TABLE 2 STATISTICAL RESULTS OF ANALYSES FOR MARSHALL SPECIMENS MADE WITH ASPHALT CEMENT I

Aggregate Source	ANTISTRIP AGENT	ITS DRY (PSI)	STD. DEV. (PSI)	ITS WET (PSI)	STD. DEV. (PSI)	TSR (%)	STD. DEV. (%)
A	0	67.7	8.4	44.1	4.8	65.7	7.9
	1	65.2	7.5	57.3	10.3	87.8	10.4
	2	62.3	8.7	55.8	11.0	89.2	10.5
	3	65.0	11.0	58.3	14.8	89.3	12.6
	4	65.7	9.3	52.6	11.4	79.7	10.5
B	0	50.5	6.8	45.1	4.2	90.3	12.0
	1	51.7	9.7	46.3	4.7	92.4	20.0
	2	48.8	9.6	46.2	8.2	97.5	24.8
	3	52.4	6.9	41.4	18.5	77.8	32.4
	4	44.9	7.1	44.8	5.8	102.3	25.1
C	0	58.9	10.2	29.4	8.2	52.0	22.7
	1	57.9	11.4	51.0	8.7	89.8	17.9
	2	62.6	6.8	65.4	5.7	105.7	15.0
	3	57.6	6.8	48.5	8.1	83.9	5.7
	4	57.4	9.5	42.1	8.4	75.5	20.9

Note: Each Cell is Based on an Average of Eight Specimens.

TABLE 3 STATISTICAL RESULTS OF ANALYSES FOR MARSHALL SPECIMENS MADE WITH ASPHALT CEMENT II

Aggregate Source	ANTISTRIP AGENT	ITS DRY (PSI)	STD. DEV. (PSI)	ITS WET (PSI)	STD. DEV. (PSI)	TSR (%)	STD. DEV. (%)
A	0	69.3	15.8	46.2	9.8	68.7	16.3
	1	73.3	9.4	60.8	10.2	82.9	8.3
	2	71.4	12.7	61.4	9.1	87.2	12.8
	3	71.6	12.7	64.8	9.2	91.6	11.9
	4	63.1	8.4	59.3	10.3	94.1	11.6
B	0	54.7	8.7	47.1	5.6	87.0	9.6
	1	56.0	8.1	53.7	7.8	97.2	16.5
	2	55.3	6.3	46.9	9.8	85.4	19.3
	3	54.9	8.2	51.3	3.5	94.9	12.2
	4	52.2	7.1	45.8	9.3	88.7	17.5
C	0	66.3	8.2	26.2	3.7	40.2	7.8
	1	67.8	10.3	56.8	8.1	84.8	12.6
	2	64.3	11.9	61.9	9.8	97.7	15.8
	3	65.3	8.7	53.1	6.0	81.7	7.0
	4	58.6	12.6	53.5	7.0	94.6	22.7

Note: Each Cell is Based on an Average of Eight Specimens.

TABLE 4 STATISTICAL RESULTS OF ANALYSES FOR MARSHALL SPECIMENS MADE WITH ASPHALT CEMENT III

Aggregate Source	ANTISTRIP AGENT	ITS DRY (PSI)	STD. DEV. (PSI)	ITS WET (PSI)	STD. DEV. (PSI)	TSR (%)	STD. DEV. (%)
A	0	81.9	5.3	61.2	7.8	74.8	8.8
	1	86.3	12.9	75.2	9.9	87.5	6.9
	2	81.9	14.6	74.3	9.4	92.7	17.1
	3	85.6	11.6	72.0	10.7	85.0	13.1
	4	73.7	12.4	68.0	9.3	93.1	9.1
B	0	58.4	5.9	57.8	7.1	99.1	9.1
	1	63.6	10.2	66.3	8.5	105.3	14.3
	2	64.9	9.9	63.3	5.2	98.8	10.8
	3	64.6	9.8	58.2	11.3	89.8	8.9
	4	60.3	8.5	56.6	5.9	95.4	15.1
C	0	72.2	13.9	45.9	5.2	64.9	8.9
	1	71.9	10.4	63.9	8.9	90.4	16.4
	2	72.6	12.9	71.6	9.0	100.6	16.6
	3	71.5	9.9	64.5	6.0	91.5	11.9
	4	68.0	11.6	62.0	6.9	93.2	16.6

Note: Each Cell is Based on an Average of Eight Specimens.

TABLE 5 STATISTICAL RESULTS OF ANALYSES FOR MARSHALL SPECIMENS MADE WITH ASPHALT CEMENT IV

Aggregate Source	ANTISTRIP AGENT	ITS DRY (PSI)	STD. DEV. (PSI)	ITS WET (PSI)	STD. DEV. (PSI)	TSR (%)	STD. DEV. (%)
A	0	76.5	14.4	61.6	12.8	82.3	18.8
	1	78.0	11.6	71.2	6.8	92.9	14.4
	2	78.9	15.2	73.4	8.1	95.4	15.7
	3	76.2	14.7	77.9	7.5	104.9	16.5
	4	79.8	17.0	66.4	12.9	84.5	13.9
B	0	61.2	12.6	58.0	9.9	96.4	14.9
	1	61.2	12.8	63.9	7.8	107.5	20.3
	2	66.5	14.9	55.4	6.3	86.6	16.9
	3	56.0	10.9	58.1	11.9	104.7	16.0
	4	57.8	11.9	57.0	8.1	101.3	18.7
C	0	73.5	17.2	35.7	3.8	50.9	12.9
	1	74.6	17.8	63.8	8.6	90.5	27.5
	2	77.6	13.3	73.1	9.9	95.4	13.9
	3	71.9	17.3	68.9	10.1	101.2	30.2
	4	68.5	11.8	59.7	6.3	89.9	20.8

Note: Each Cell is Based on an Average of Eight Specimens.

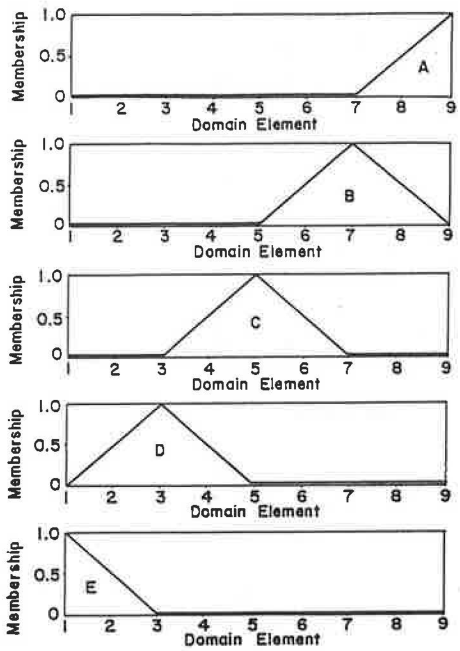

FIGURE 2 Graphical illustration of Fuzzy Sets *A*, *B*, *C*, *D*, and *E*.

$$B = \{0|1, 0|2, 0|3, 0|4, 0|5, 0.5|6, 1.0|7, 0.5|8, 0|9\} \quad (12)$$

$$C = \{0|1, 0|2, 0|3, 0.5|4, 1.0|5, 0.5|6, 0|7, 0|8, 0|9\} \quad (13)$$

$$D = \{0|1, 0.5|2, 1.0|3, 0.5|4, 0|5, 0|6, 0|7, 0|8, 0|9\} \quad (14)$$

$$E = \{1.0|1, 0.5|2, 0|3, 0|4, 0|5, 0|6, 0|7, 0|8, 0|9\} \quad (15)$$

The weight or relative importance of one criterion to the other, expressed as W_i in Equation 4, was also defined as fuzzy sets A, B, C, D, and E to represent weights for extremely important, very important, important, less important, and unimportant, respectively. The same fuzzy sets, previously defined for rating each alternative, were used for each of the five weights for easy computation. Ranking indexes for the five fuzzy sets, defined as A, B, C, D, and E, are 15, 12, 8, 4, and 1, respectively (Figure 2). The ranking index of the FWA for any two of the five fuzzy sets can be calculated by Equations 4–15.

Criteria for Fuzzy Evaluation of ASA Performance

Many properties can be used for evaluation of ASA performance in an asphaltic concrete mixture. Properties used here (for demonstration purposes only) for evaluating performance of ASAs include (a) dry tensile strength (DTS), (b) tensile strength of wet-conditioned mixtures (WTS), (c) tensile strength ratio [$TSR = 100\% \times (WTS/DTS)$], and (d) visual strip rating of the mixture (VSR). The price (P) of additive may be important from an economic point of view. Therefore, in some examples, the price was added as the fifth major criterion.

If several different sources of aggregates with one asphalt cement are used for a project and an ASA needs to be selected for the entire project, the aggregate can be used as subcriteria. If several asphalt cements are used with one aggregate and an ASA needs to be selected for the entire project, the asphalt cements can be used as subcriteria. However, if an ASA for each aggregate or asphalt cement is to be selected, there is no need to use aggregates or asphalt cement as subcriteria.

Converting Real Values to Fuzzy Data

Real data (mean value of each group) collected for the major and subcriteria must be converted to the fuzzy rating system (i.e., fuzzy sets A, B, C, D, or E). The rating scale and weight for each criterion and subcriterion can be selected on the basis of relative comparison of mean values, variation of data, or the engineer's judgment. This is explained more in example problems.

A computer program was developed to compare the test results for several asphaltic concrete mixtures to determine the mixture that produced the best results (higher TSR, lower value of visual strip rating, lowest cost, etc.). This program produces numerical values of RI for each alternative so that the engineer can obtain the order of mixture performance from the best to the worst. A simplified flow chart of the computer program developed for this study is illustrated in Figure 3.

Example Problems

Several example problems using the fuzzy sets defined previously are illustrated in the following sections. Data in this study were based on three aggregates, five ASAs (including control) and four asphalt cements, as shown in Tables 2–5. Aggregates were used as subcriteria for each of the first four major criteria for example problems 1–4, and asphalts were used as subcriteria for Example Problem 5. For Example Problems 1–4, the input data were organized as following major criteria and subcriteria. For Example Problem 5, four asphalt cements were used as subcriteria instead of three aggregates.

Major Criterion 1: DTS
  Subcriterion a: Aggregate A
  Subcriterion b: Aggregate B
  Subcriterion c: Aggregate C
Major Criterion 2: WTS
  Subcriterion a: Aggregate A
  Subcriterion b: Aggregate B
  Subcriterion c: Aggregate C
Major Criterion 3: TSR
  Subcriterion a: Aggregate A
  Subcriterion b: Aggregate B
  Subcriterion c: Aggregate C
Major Criterion 4: VSR
  Subcriterion a: Aggregate A
  Subcriterion b: Aggregate B
  Subcriterion c: Aggregate C
Major Criterion 5: Price (P)
  No Subcriteria

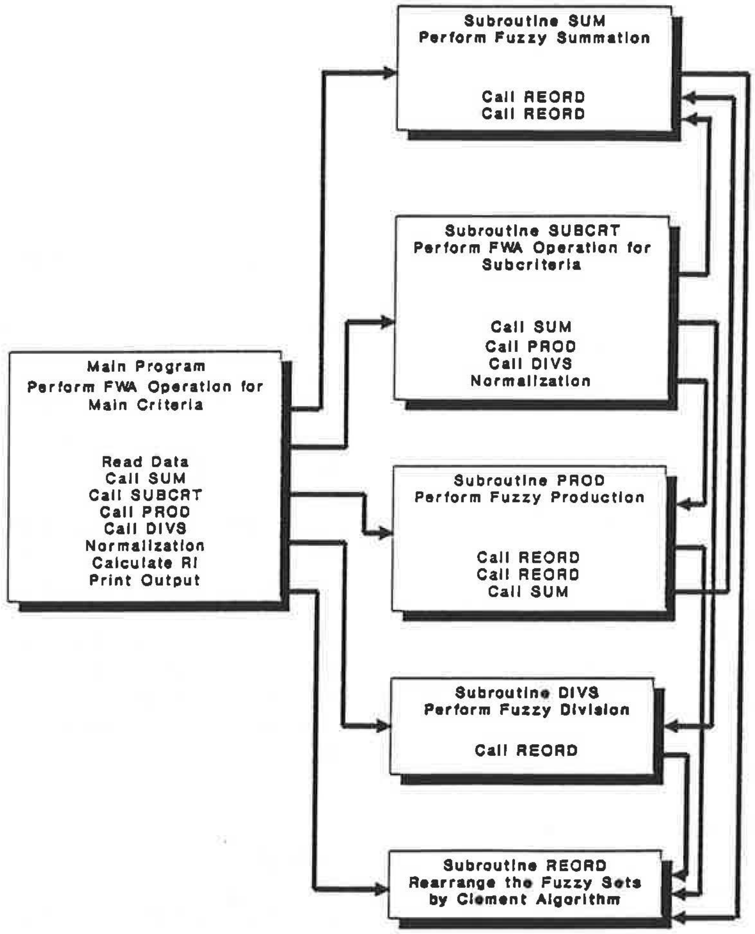

FIGURE 3 Simplified flow chart of computer program developed for example problems.

A control (denoted as 0) and four additives (denoted as 1, 2, 3, and 4) were compared using the FWA operation to select the best-performing additive. In Example Problems 1–4, the data shown in Table 2 (Asphalt Cement I and Aggregates A, B, and C) were used. However, for Example Problem 5, the data for Aggregate C and the four asphalt cements mentioned in Tables 2–5 were used. The arbitrarily selected rating scale for each criterion for this study is shown in Table 6. The relative importance of one criterion to the others (weight) can be assigned by the engineer. Therefore, if a criterion is considered more important than the others, then a higher weight (e.g., *A*) can be given to that criterion. Several different weights were assigned in each example analysis to show the effect on the results. The developed computer program was used to obtain the RI values and the ranking of ASAs for each example problem (Figure 3).

Example Problem 1

Five asphaltic concrete mixtures containing five ASAs (including control) made with three different aggregate sources were evaluated based on DTS, WTS, TSR, and VSR. The value for each criterion and rating converted by the rating scale in Table 6 is listed in Table 7. The value for each criterion in Table 7 is the mean value of eight laboratory-prepared specimens. An equal weight *A* was assigned for all the criteria and subcriteria in this example for illustration purposes.

Rating values are represented by numerical values of 1 through 5, which correspond to the fuzzy sets of *A* through *E*, respectively. The RI values obtained by the result of the FWA operation are shown in Table 7. ASAs 1, 2, and 3 tied as the best choice (RI = 12.75 out of possible maximum of 15); control (0) was the worst choice (RI = 8.5) in this case.

Example Problem 2

For this example problem, the same data used in example problem 1 were used, except for different weights for the main criteria. WTS and VSR are weighted as extremely important (*A*), because the purpose of using an ASA is to reduce stripping (VSR) and, at the same time, to improve WTS of the mixture. Weight *B*, very important, was assigned to DTS because DTS is the base of TSR and is the mixture's intrinsic strength that is not affected in the presence of moisture or ASA. Weight *C*, important, is given to TSR because, even though the higher the TSR the better the moisture susceptibility of mixtures, the magnitude of TSR is sometimes less important in evaluating performance of an asphaltic concrete

TABLE 6 RATING SCALE FOR MAIN CRITERIA

Rating	Criteria: DTS, WTS	TSR	VSR[1]	Price[2]
A	R[3] > 0.9	> 90%	1.0 - 1.50	P = 0
B	0.8 < R < 0.9	90 - 80%	1.50 - 2.50	P = 1
C	0.7 < R < 0.8	80 - 70%	2.50 - 3.50	1 < P < 2
D	0.6 < R < 0.7	70 - 60%	3.50 - 4.50	2 < P < 3
E	R < 0.6	< 60%	> 4.50	P > 3

1. VSR: 1.0: S = 1.0; 2.0: S = 1.5C, 1.5F; 3.0: S = 2, 2C, 2F; 4.0: S = 2.5C, 2.5F; 5.0: S = 3

   where, S = (C + F) /2; value of C and F, coarse and fine aggregate stripping, respectively are defined as:

   Value of C
   1 = less than 10% stripping
   2 = 10-40% Stripping
   3 = greater than 40% stripping

   Value of F
   1 = less than 10% stripping
   2 = 10-25% Stripping
   3 = greater than 25% stripping

2. P = price / (cheapest price of the additives (except for control)) For one ton of asphaltic concrete mixture

3. R = (Tensile Strength) /(Max. Tensile Strength)

TABLE 7 INFORMATION FOR FWA INPUT AND RESULTS FOR EXAMPLE 1

FWA Input Information

Main Criteria (Weight)	ASA No.	Subcriteria: Agg A Mean	Agg A Rating	Agg B Mean	Agg B Rating	Agg C Mean	Agg C Rating
	0	67.7*	1	50.6	2	58.9	2
	1	65.2	1	51.7	3	58.0	2
DTS (psi)	2	62.3	1	48.8	3	62.6	1
(A)	3	65.0	1	52.4	3	57.6	2
	4	65.7	1	45.0	4	57.4	2
Weight for Subcriteria			A		A		A
	0	44.1	4	45.1	4	29.4	5
	1	57.3	2	46.3	3	51.0	3
WTS (psi)	2	55.8	2	46.2	3	65.4*	1
(A)	3	58.3	2	47.6	3	48.6	3
	4	52.6	2	44.8	4	42.1	4
Weight for Subcriteria			A		A		A
	0	65.7	4	90.3	1	52.1	5
	1	87.8	2	92.4	1	89.8	2
TSR (%)	2	89.3	2	97.5	1	105.7	1
(A)	3	89.3	2	91.0	1	83.9	2
	4	79.7	3	102.3	1	75.5	3
Weight for Subcriteria			A		A		A
	0	4.13	4	2.38	2	1.88	2
	1	1.63	2	1.88	2	1.00	1
VSR	2	1.13	1	2.00	2	1.13	1
(A)	3	1.25	1	1.86	2	1.00	1
	4	2.50	2	1.88	2	1.13	1
Weight for Subcriteria			A		A		A

Result of FWA Operation

ASA	0	1	2	3	4
RI value	8.5	12.75	12.75	12.75	10.50

*: highest value in each criterion

mixture. A high value of TSR does not necessarily mean high strength of the wet mixture if DTS is low to begin with. Therefore, a lower weight (*C*) was assigned to TSR than to the other three criteria.

It was expected that ratings based on criteria WTS and VSR would be the dominant factors in the evaluation because of the high weights assigned to these two criteria. A different result, compared with Example Problem 1, was obtained (Table 8). ASA 2 showed the highest RI value, ASAs 1 and 3 showed the second highest, and control (0) showed the lowest. The results of this example problem indicate the importance of assigning weight for each criterion to determine the RI.

Example Problem 3

In this example problem, the price of ASA was added as a criterion to the FWA operation. Market price of ASA for 1 ton of asphaltic concrete mixture was used for the price criterion. No subcriteria were given to the price main criterion. The price for ASAs 1, 3, and 4 was assumed to be \$0.50/ton of mixture; the price for ASA No. 2 was taken as \$1.50/ton of mixture. The price of control, ASA 1, was zero. Because prices of the ASA are small compared with the prices of other materials such as asphalt cement and aggregate, a weight *E*, unimportant, was assigned to the price in this example.

Rating for the price was determined based on the scale shown in Table 6. Table 9 shows the input information and the results obtained for this example problem. Because the price of ASA 2 was the highest (lowest rating), RI for ASA 2 was reduced from 12.75 to 12.25. RI values for ASAs cheaper than ASA 2 were somewhat increased (from 11.75 to 12 for ASA 1 and 3, from 8.5 to 10.75 for ASA 0, and from 11 to 11.25 for ASA 4) even though a weight of *E* was assigned to

TABLE 8 INFORMATION FOR FWA INPUT AND RESULTS FOR EXAMPLE 2

FWA Input Information

Main Criteria (Weight)	ASA No.	Subcriteria Agg A Mean	Agg A Rating	Agg B Mean	Agg B Rating	Agg C Mean	Agg C Rating
	0	67.7*	1	50.6	2	58.9	2
	1	65.2	1	51.7	3	58.0	2
DTS (psi)	2	62.3	1	48.8	3	62.6	1
(B)	3	65.0	1	52.4	3	57.6	2
	4	65.7	1	45.0	4	57.4	2
Weight for Subcriteria			A		A		A
	0	44.1	4	45.1	4	29.4	5
	1	57.3	2	46.3	3	51.0	3
WTS (psi)	2	55.8	2	46.2	3	65.4*	1
(A)	3	58.3	2	47.6	3	48.6	3
	4	52.6	2	44.8	4	42.1	4
Weight for Subcriteria			A		A		A
	0	65.7	4	90.3	1	52.1	5
	1	87.8	2	92.4	1	89.8	2
TSR (%)	2	89.3	2	97.5	1	105.7	1
(C)	3	89.3	2	91.0	1	83.9	2
	4	79.7	3	102.3	1	75.5	3
Weight for Subcriteria			A		A		A
	0	4.13	4	2.38	2	1.88	2
	1	1.63	2	1.88	2	1.00	1
VSR	2	1.13	1	2.00	2	1.13	1
(A)	3	1.25	1	1.86	2	1.00	1
	4	2.50	2	1.88	2	1.13	1
Weight for Subcriteria			A		A		A

Result of FWA Operation

ASA	0	1	2	3	4
RI value	8.5	11.75	12.75	11.75	11.00

*: highest value in each criterion

the price. Therefore, the difference between the highest RI and the lowest RI was reduced. However, ASA 0 was still the worst and ASA 2 was the best. If a higher weight is assigned to the price, a different result, which may show better RI values for lower-priced ASA, would be expected.

Example Problem 4

For this example problem, all information is the same as given in example problem 3 except for different weights assigned for each of the three subcriteria. The weight for each subcriterion (aggregate) in each main criterion can be determined based on the value of the coefficient of variation (CV), and the weighing scale can be selected arbitrarily.

The CV of DTS, WTS, and VSR ranged up to more than 60 percent. Weight *A* was given for the first 15 percent of CV, *B* for the next 15 percent, and so forth for *C*, *D*, and *E*. Therefore, the following scales were defined to assign the weight to each subcriterion (aggregate) based on CV.

A: CV ≤ 15%,
B: 15% < CV ≤ 30%,
C: 30% < CV ≤ 45%,
D: 45% < CV ≤ 60%, and
E: CV > 60%.

TABLE 9 INFORMATION FOR FWA INPUT AND RESULTS FOR EXAMPLE 3

FWA Input Information

Main Criteria (Weight)	ASA No.	Subcriteria Agg A Mean	Agg A Rating	Agg B Mean	Agg B Rating	Agg C Mean	Agg C Rating
	0	67.7*	1	50.6	2	58.9	2
	1	65.2	1	51.7	3	58.0	2
DTS (psi)	2	62.3	1	48.8	3	62.6	1
(B)	3	65.0	1	52.4	3	57.6	2
	4	65.7	1	45.0	4	57.4	2
Weight for Subcriteria			A		A		A
	0	44.1	4	45.1	4	29.4	5
	1	57.3	2	46.3	3	51.0	3
WTS (psi)	2	55.8	2	46.2	3	65.4*	1
(A)	3	58.3	2	47.6	3	48.6	3
	4	52.6	2	44.8	4	42.1	4
Weight for Subcriteria			A		A		A
	0	65.7	4	90.3	1	52.1	5
	1	87.8	2	92.4	1	89.8	2
TSR (%)	2	89.3	2	97.5	1	105.7	1
(C)	3	89.3	2	91.0	1	83.9	2
	4	79.7	3	102.3	1	75.5	3
Weight for Subcriteria			A		A		A
	0	4.13	4	2.38	2	1.88	2
	1	1.63	2	1.88	2	1.00	1
VSR	2	1.13	1	2.00	2	1.13	1
(A)	3	1.25	1	1.86	2	1.00	1
	4	2.50	2	1.88	2	1.13	1
Weight for Subcriteria			A		A		A
	0			0	1		
	1			0.5	2		
Price (E)	2			1.5	4		
($/ton)	3			0.5	2		
	4			0.5	2		

Result of FWA Operation

ASA	0	1	2	3	4
RI value	10.75	12.00	12.25	12.00	11.25

*: highest value in each criterion

The input information and results are shown in Table 10. In this example problem, RI values for ASA 1, 2, and 3 were the same as for example problem 3. However, RI for ASA 0 was improved to fourth place and RI for ASA 4 was moved to the last choice. ASA 2 was determined to be the best choice.

Example Problem 5

In this example problem, FWA operation was conducted based on five main criteria, used previously, with four subcriteria (four asphalt cements), instead of three aggregates. Weighing for the five main criteria was the same as for Example Problem 4. Weighing for subcriteria was based on CV, which is the same procedure explained in Example Problem 4.

The input information and FWA operation results are shown in Table 11. Similar results to the previous example problems were obtained: ASA 2 was the best choice and ASA 0 was the last.

TABLE 10 INFORMATION FOR FWA INPUT AND RESULTS FOR EXAMPLE 4

FWA Input Information

Main Criteria (Weight)	ASA No.	Subcriteria Agg A Mean	Agg A Rating	Agg B Mean	Agg B Rating	Agg C Mean	Agg C Rating
	0	67.7*	1	50.6	2	58.9	2
	1	65.2	1	51.7	3	58.0	2
DTS (psi)	2	62.3	1	48.8	3	62.6	1
(B)	3	65.0	1	52.4	3	57.6	2
	4	65.7	1	45.0	4	57.4	2
Wt for Subcr.	CV	13.4	A	16.4	B	15.1	B
	0	44.1	4	45.1	4	29.4	5
	1	57.3	2	46.3	3	51.0	3
WTS (psi)	2	55.8	2	46.2	3	65.4*	1
(A)	3	58.3	2	47.6	3	48.6	3
	4	52.6	2	44.8	4	42.1	4
Wt for Subcr.	CV	21.7	B	13.4	A	29.7	B
	0	65.7	4	90.3	1	52.1	5
	1	87.8	2	92.4	1	89.8	2
TSR (%)	2	89.3	2	97.5	1	105.7	1
(C)	3	89.3	2	91.0	1	83.9	2
	4	79.7	3	102.3	1	75.5	3
Wt for Subcr.	CV	16.4	B	20.0	B	29.9	B
	0	4.13	4	2.38	2	1.88	2
	1	1.63	2	1.88	2	1.00	1
VSR	2	1.13	1	2.00	2	1.13	1
(A)	3	1.25	1	1.86	2	1.00	1
	4	2.50	2	1.88	2	1.13	1
Wt for Subcr.	CV	60.5	E	19.9	B	34.5	C
	0			0	1		
	1			0.5	2		
Price (E)	2			1.5	4		
($/ton)	3			0.5	2		
	4			0.5	2		

Result of FWA Operation

ASA	0	1	2	3	4
RI value	11.75	12.00	12.25	12.00	11.00

*: highest value in each criterion

TABLE 11 INFORMATION FOR FWA INPUT AND RESULTS FOR EXAMPLE 5

FWA Input Information

Main Criteria (Weight)	ASA No.	Subcriteria Asp I Mean	Asp I Rating	Asp II Mean	Asp II Rating	Asp III Mean	Asp III Rating	Asp IV Mean	Asp IV Rating
	0	58.9	3	66.3	2	72.2	1	73.5	1
	1	58.0	3	67.8	2	71.9	1	74.6	1
Dts (psi)	2	62.6	2	64.3	2	72.6	1	77.7	1
(B)	3	57.6	3	65.3	2	71.5	1	71.9	1
	4	57.4	3	58.7	3	68.0	2	68.6	2
Wt for Subcr.	CV	15.1	B	16.2	B	15.9	B	20.7	B
	0	29.4	5	26.2	5	45.9	4	35.7	5
	1	51.0	4	56.8	3	64.0	2	63.8	2
WTS (psi)	2	65.4	2	61.9	2	71.6	1	73.0	1
(A)	3	48.6	4	53.1	3	64.5	2	68.9	1
	4	42.1	5	53.5	3	62.0	2	59.7	2
Wt for Subcr.	CV	29.7	B	28.5	B	18.0	B	25.4	B
	0	52.1	5	40.2	5	64.9	4	50.9	5
	1	89.8	2	84.5	2	90.4	1	90.5	1
TSR (%)	2	105.7	1	97.7	1	100.7	1	95.4	1
(C)	3	83.4	2	81.7	2	91.5	1	101.2	1
	4	75.5	3	94.6	1	93.2	1	89.9	2
Wt for Subcr.	CV	30.0	B	31.3	C	20.9	B	32.4	C
	0	1.88	2	1.88	2	1.63	2	2.13	2
	1	1.00	1	1.00	1	1.00	1	1.00	1
VSR	2	1.13	1	1.00	1	1.00	1	1.00	1
(A)	3	1.00	1	1.00	1	1.00	1	1.00	1
	4	1.13	1	1.00	1	1.00	1	1.00	1
Wt for Subcr.	CV	34.5	C	38.0	C	35.9	C	47.1	D
	0			0	1				
	1			0.5	2				
Price (E)	2			1.5	4				
($/ton)	3			0.5	2				
	4			0.5	2				

Result of FWA Operation

ASA	0	1	2	3	4
RI value	9.50	10.50	13.50	12.75	12.50

*: highest value in each criterion

DISCUSSION AND CONCLUSIONS

Using the fuzzy set analysis method, a procedure for evaluating the effectiveness of ASAs for asphaltic concrete mixtures was presented. The procedure uses selected mixture properties (e.g., dry and wet tensile strength, TSR, VSR) that can be obtained by simple laboratory testing. Because of the vague interrelationship among the mixture properties, a simple comparison of one value to another is fuzzy and sometimes does not give a clear answer. Moreover, selecting the best-performing mixture by comparing many factors (criteria) is not achieved simply, because subjective judgments are involved in organizing much of the data. Therefore, the fuzzy set theory was introduced, and it was shown that it can be successfully incorporated into a solution procedure.

From example problems, it was shown that the best-performing ASA can be selected from among many additives. This was accomplished from FWA operation based on real data, arbitrarily selected fuzzy sets, and weighing scales determined by the engineer's judgment.

The selection of the best-performing ASA is based on a reasonable performance evaluation of the mixtures because the fuzzy weighted average is a combined result of the following considerations:

1. The mean values of engineering properties and moisture susceptibility of each group of mixtures for rating,
2. The engineer's judgment for weight of main criteria, and
3. The variation of the data for weight of each subcriterion.

More properties such as resilient modulus and fatigue resistance modulus can be added to the main criteria, if available. In addition, field mixtures can be used to evaluate the performance of ASAs in the field. In that case, if samples are collected from extensive sections of highway, construction quality and traffic condition can be made additional criteria to obtain a more reasonable result.

It should be noted that fuzzy sets used in this study were arbitrarily selected. Other fuzzy sets can be established for similar types of problems with any number of criteria and subcriteria.

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Publication of this paper sponsored by Committee on Nonbituminous Components of Bituminous Paving Mixtures.