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AGGREGATE TOUGHNESS/ ABRASION RESISTANCE AND DURABILITY/SOUNDNESS TESTS RELATED TO ASPHALT CONCRETE PERFORMANCE IN PAVEMENTS

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ABSTRACT

Numerous tests have been developed to empirically characterize aggregate without, necessarily, a strong relationship with the performance of the final products incorporating these aggregates. This seems to be particularly true for aggregate “toughness and abrasion resistance” and “durability and soundness.” The purpose of this research was to identify and evaluate toughness/abrasion resistance and durability/soundness tests for characterizing aggregate used in asphalt concrete and to determine those test methods that best correlate with field performance. Based on a review of literature and specifications, laboratory tests for characterizing aggregate toughness/abrasion resistance and durability/soundness were selected. Sixteen aggregate sources with poor to good performance histories were identified for evaluation with the selected suite of tests. Performance histories of pavements containing these aggregates in asphalt concrete layers were established through personal contacts with state transportation agencies and performance evaluation questionnaires.

Aggregate properties from laboratory tests were correlated with field performance. The Micro-Deval and magnesium sulfate soundness tests provide the best correlations with field performance of asphalt concrete, and are recommended for characterizing aggregate toughness/abrasion resistance and durability/soundness.

KEYWORDS: Aggregate, toughness/abrasion resistance, durability/soundness, asphalt concrete, pavement performance.

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INTRODUCTION

The properties of aggregates used in asphalt concretes are very important to the performance of the pavements in which the asphalt concretes are used. Often pavement distress, such as stripping and rutting, can be traced directly to the aggregates used. Clearly, proper aggregate selection is necessary for attaining desired performance.

Many tests have been developed to empirically characterize aggregate properties without, necessarily, strong relationships to the performance of final products incorporating an aggregate. This seems to be particularly true for aggregate “toughness and abrasion resistance” and “durability and soundness.” The objective of this research is to select tests for characterizing aggregate toughness/abrasion resistance and durability/soundness that are related to the performance of asphalt concrete pavements.

Toughness/Abrasion Resistance

Aggregates must be tough and abrasion resistant to prevent crushing, degradation, and disintegration when stockpiled, fed through an asphalt plant, placed with a paver, compacted with rollers, and subjected to traffic loadings. These properties are especially critical for open or gap graded asphalt concrete mixtures (such as open-graded friction courses and stone matrix asphalt) which do not benefit from the cushioning effect of the fine aggregate and where coarse particles are subjected to high contact stresses.

Aggregates which lack adequate toughness and abrasion resistance may cause construction and performance problems. Degradation occurring during production can affect the overall gradation and, thus, widen the gap between properties of the laboratory designed mix and field produced mix.

A review of literature and state transportation agency specifications revealed a number of available test methods, but only a few that are widely used. The survey of specifications indicated that 94 percent of the states use the Los Angeles abrasion test or some variation. Only two states have a degradation requirement from some other type tests. The majority of the states have a maximum allowable loss of 40 or 45 percent. Loss criteria become more restrictive as exposure and loading conditions increase in severity, i.e., criteria are more restrictive for surface courses than for base courses.

Durability/Soundness

In addition to toughness and abrasion resistance, aggregates must be resistant to breakdown or disintegration when subjected to wetting and drying and/or freezing and thawing. If the asphalt cement coating remains intact, these weathering cycles do not significantly affect the asphalt concrete mixture. However, water can penetrate the aggregate particles if some degradation of the asphalt concrete mixture has occurred during construction. Soft or weak particles that breakdown during compaction provide convenient access for water. Water can also penetrate if the asphalt concrete mixture has experienced stripping. Therefore, it is essential to use durable and sound aggregates to maintain the integrity of the asphalt concrete mix during service. Raveling, stripping and, in extreme cases, rutting of asphalt concrete pavement can result from the use of aggregate which is not resistant to weathering.

The review of literature and state transportation agency specifications revealed a number of available test methods, but only a few that are widely used. The survey of specifications show that 53 percent of the states have a requirement for sodium sulfate soundness, 19 percent magnesium sulfate soundness, 10 percent a freeze-thaw loss requirement, 2 percent (1 state) the Durability Index Test, and 16 percent no soundness requirement. Maximum allowable sodium sulfate soundness loss ranges from 5 to 25 percent with an average of about 14 percent. Range and average for magnesium sulfate soundness are 10 to 30 percent and 16 percent, respectively.

TEST METHODS

Aggregate toughness and abrasion resistance are closely related to and often considered simultaneously with, durability and soundness. However, in this study separate suites of test methods were selected to evaluated each properly. Toughness/abrasion resistance are associated with mechanical degradation and durability/soundness are associated with degradation due to weathering.

Toughness/Abrasion Resistance

The following test methods were selected for characterizing aggregate toughness/abrasion resistance:

- Los Angeles Abrasion (AASHTO T 96)
- Aggregate Impact Value (British)
- Aggregate Crushing Value (British)
- Micro-Deval Abrasion (French/Canadian)
- Degradation in the SHRP Gyratory Compactor

Although widely used, the predictive capability of the LA abrasion test was rated only fair by the researchers and project consultants. Early development studies, Woolf [1], Shelburne [2] and Shergold [3], indicated good correlations with performance, but there is a paucity of subsequent studies that confirm a strong, definitive correlation. This may be due to specifications that eliminate troublesome aggregate or construction practices that can accommodate aggregate with low toughness and abrasion resistance. Examples of such practices are wasting of baghouse fines, better construction quality control, and adjustment of compaction procedures to minimize aggregate breakdown.

Performance predictability of the two British tests, impact and crushing, is unknown although they are standard tests. Bullas and West [4] reported the aggregate impact value did not, but the aggregate crushing value did separate suitable and unsuitable aggregate for bitumen macadam roadbase. Fookes, Gourley and Ohikere [5] recommended that combinations of physical tests such as impact, crushing and abrasion resistance be used to assess aggregate durability.

The Micro-Deval abrasion test was developed in France during the 1960's. It is a wet ball mill test. A 1.5 kg graded aggregate sample (retained on the 9.5 mm sieve), 2 L of water and a 5 kg charge of 5 mm diameter steel balls are placed in a stainless steel jar mill and rotated for 2 hours. Loss is the amount of material passing the 1.18 mm sieve expressed as a percent of the original sample mass. Extensive evaluation has been done in the provinces of Quebec and Ontario, Canada. Senior and Rogers [6] correlated test results with field performance of asphalt concrete pavements and recommended the Micro-Deval tests for evaluating aggregate quality. The SHRP gyratory compactor is becoming readily available with implementation of the Superpave^{TM} mix design and analysis system. Gyratory compactors are gaining acceptance because of their purported realistic simulation of asphalt concrete compaction during construction and in service. A logical extension of the use of SHRP gyratory compactors for asphalt concrete mix design and analysis is to also use them to evaluate aggregate degradation during compaction. Moavenzadeh and Goetz [7] used the Corp of Engineers gyratory testing machine to determine factors affecting the degradation of aggregates in asphalt concrete mixes. The gyratory testing machine was used to simulate the compaction of asphalt concrete mixes and subsequent exposure to traffic. The study showed potential for the gyratory compactor to evaluate the toughness and abrasion resistance of aggregate through interparticle abrasion and grinding action.

Durability/Soundness

The following test methods were selected for characterizing aggregate soundness and durability:

- Sodium and Magnesium Sulfate Soundness (AASHTO T 104)
- Freezing and Thawing Soundness (AASHTO T 103)
- Aggregate Durability Index (AASHTO T 210)
- Canadian Freeze-Thaw Test

The performance prediction capability of the sulfate soundness tests was considered fair by researchers and project consultants, although they are widely utilized. Some early studies, Paul [*8*], report good correlations with performance while others, Garrity and Kriege [*9*], report poor correlations. Later studies, Gandhi and Lytton [*10*], Papaleontiou et al [*11*], Hasan et al [*12*], Rogers et al [*13*] and Senior and Rogers [*6*] also report mixed reviews for performance prediction. Lack of precision is also mentioned as a problem.

The strength of relationships between the performance of asphalt concrete pavement layers and aggregate durability/soundness measured with the AASHTO freeze thaw test or the durability index are unknown. They are not used extensively in specifications, 10 % of the states have freeze thaw requirement and 2% (1 state) has a durability index requirement, and little research was found in the literature review. The durability index test has been used primarily in western states for identifying weathered basalt containing interstitial montmorillonite that will not maintain strength when used as unbound aggregate base.

The Canadian freeze-thaw test was developed by the University of Windsor and the Ontario Ministry of Transportation. The procedure is similar to the AASHTO freeze-thaw test except a 3% NaCl solution is used to simulate the influence of deicing salts. Senior and Rogers [*6*] report the Canadian freeze-thaw test is marginally better than the magnesium sulfate soundness test for evaluating aggregate for asphalt concrete.

AGGREGATE SELECTION

Contacts were made with state transportation agencies to identify sixteen aggregate sources for study. The basis for selection was to provide a wide range of performance levels in asphalt concrete. Table 1 identifies the aggregate sources and the initial performance rating used in the selection process. The following subjective pavement performance evaluation criteria were used:

Pavement Performance Rating	Description
Good	Used for many years with no significant degradation problem during construction and no significant popouts, raveling or potholes during service life
Fair	Used at least once where some degradation occurred during construction and/or some popouts, raveling, and potholes developed, but pavement life extended for over 8 years
Poor	Used at least once where raveling, popouts, or combinations developed during the first two years, severely restricting pavement

Table 1. Pavement Performance Rating for Aggregate Sources

Rock Type and State	Initial General Rating Used for Source Selection	Performance Rating Based on Toughness /Abrasion	Performance Rating Based On Durability /Soundness	Overall (worst case) Performance Rating
1. Traprock, NY	G	G	G	G
2. Granite, GA	G	G	G	G
3. Steel Slag, IN	G	G	G	G
4. Gravel, MN	G	G	G	G
5. Gravel, NV	G	G	G	G
6. Limestone, IA	G	G	G	G
7. Granite, SC	F	F	G	F
8. Gravel, MN	F	F	F	F
9. Limestone, IA	F	F	G	F
10. Gravel, PA	F	P	P	P
11. Limerock, FL	P	P	N	P
12. Limestone,TX	P	P	P	P
13. Sandstone, PA	P	P	P	P
14. Limestone, MN	P	N**	P	P
15. Siltstone, VA	P	N	N	N
16. Basalt, OR	P	N**	P	P

Notes:
G = Good pavement performance; F= Fair pavement performance; P = Poor pavement performance; N = Not a factor in assessing pavement performance; * = Test results compared with criteria for several durability/soundness tests indicate fair performance might be expected; ** = Test results compared with criteria for several toughness/abrasion resistance tests indicate fair performance might be expected.

Additional data was collected to refine the pavement performance rating. Pavement performance evaluation questionnaires were sent to agencies. Visits were made to several states to observe pavement conditions and discuss performance with state transportation agency personnel. Based on the additional data each aggregate was rated independently in terms of both toughness /abrasion resistance and soundness/durability and these ratings are also shown in Table 1. The lowest or worst case of these ratings are also tabulated as indicators of overall pavement performance.

Source 10, Pennsylvania gravel and source 15, Virginia siltstone, are examples that illustrate the difficulties encountered in establishing reliable indications of pavement performance. Source 10 was selected based on expected fair performance. However, after testing was completed and analyses started the characterization as a fair performer became questionable. Additional contacts with both Pennsylvania DOT and contractor personnel revealed sufficient problems had been experienced with pavements constructed with the source to change the rating to poor. Several projects were identified that had required sealing within four years.

Source 15 was selected based on expected poor performance. However all test results, both toughness/abrasion resistance and durability/soundness, indicated pavement constructed using the aggregate in asphalt concrete should perform well. A site visit and conversations with Virginia DOT field personnel indicated that pavements constructed with the aggregate do indeed frequently perform poorly, but not because of deficiencies in aggregate toughness, abrasion resistance, durability or soundness. Rutting appeared to be the primary distress mode associated with source 15. Speculation was that flat and elongated particles result in mix rutting susceptibility that can be very sensitive to asphalt content and in some particle breakdown during compaction. Therefore, source 15 was excluded from the analyses.

Usage levels of various rock types and climate conditions were also considered during aggregate selection. The sixteen aggregates include five carbonate sources, four gravels (varying composition), two granites, one traprock, one siltstone, one sandstone, one basalt and one steel slag. Ten of the aggregates were from the SHRP wet-freeze region [*14*] where weathering conditions are most severe.

DATA ANALYSIS

Three replicates for each of the nine tests (five toughness/abrasion resistance and 4 soundness/durability) enumerated previously were performed on aggregate from the sixteen sources described in Table 1. Average from the three replicates were combined with performance ratings to establish relationships between aggregate properties and performance.

Graphic Comparisons

The first analysis approach was to plot test results and performance rating and examine these plots for trends. Figure 1 is a plot for LA abrasion loss and performance based on toughness and abrasion resistance. This plot indicates no separation or grouping of performance rating by LA abrasion loss. Figure 2 is a plot for Micro-Deval abrasion and shows three groupings for aggregate with good, fair and poor performance ratings. Solid horizontal lines at the average for each group are in the proper order. The dashed horizontal line at loss of 18% separates poor from fair and good performing sources. The Micro-Deval test was the only one of the five toughness/abrasion resistance tests that delineated performance ratings.

Figures 3 and 4 are, respectively, plots of sodium and magnesium sulfate soundness versus performance based on soundness/durability. No trends of groupings are obvious for sodium sulfate but magnesium sulfate groups sources with good, fair and poor performance. The solid horizontal lines through averages for each group are in proper order and the dashed horizontal line at 18% loss separates poor from fair and good performing sources. The magnesium sulfate soundness test was the only one of the four soundness/durability tests that delineated performance ratings. However, when Micro-Deval test results are combined with soundness/durability ratings in Figure 5, the proper groupings are noted. This is thought due to the inclusion of water in the Micro-Deval test which provides some indication of weathering susceptibility as well as resistance to mechanical degradation.

Micro-Deval abrasion and magnesium sulfate soundness appear to be the two tests most strongly related to asphalt concrete performance in pavements. These two aggregate properties are combined with overall (worst case) performance ratings in Figure 6. Vertical and horizontal lines at 18 percent loss for the magnesium sulfate soundness and Micro-Deval abrasion tests separate the figure into quadrants. All fair and good performers fall in one quadrant and all poor performers (except the Virginia siltstone as noted previously) fall in one quadrant. No sources fall in either of the two other quadrants where there would be conflicts between the tests.

Rock Source	Description	Rock Source	Description	Rock Source	Description	Rock Source	Description
1	Traprock, NY	5	Gravel, NV	9	Limestone, IA	13	Sandstone, PA
2	Granite, GA	6	Limestone, IA	10	Gravel, PA	14	Limestone, MN
3	Steel Slag, IN	7	Granite, SC	11	Limerock, FL	15	Siltstone, VA
4	Gravel, MN	8	Gravel, MN	12	Limestone, TX	16	Basalt, OR

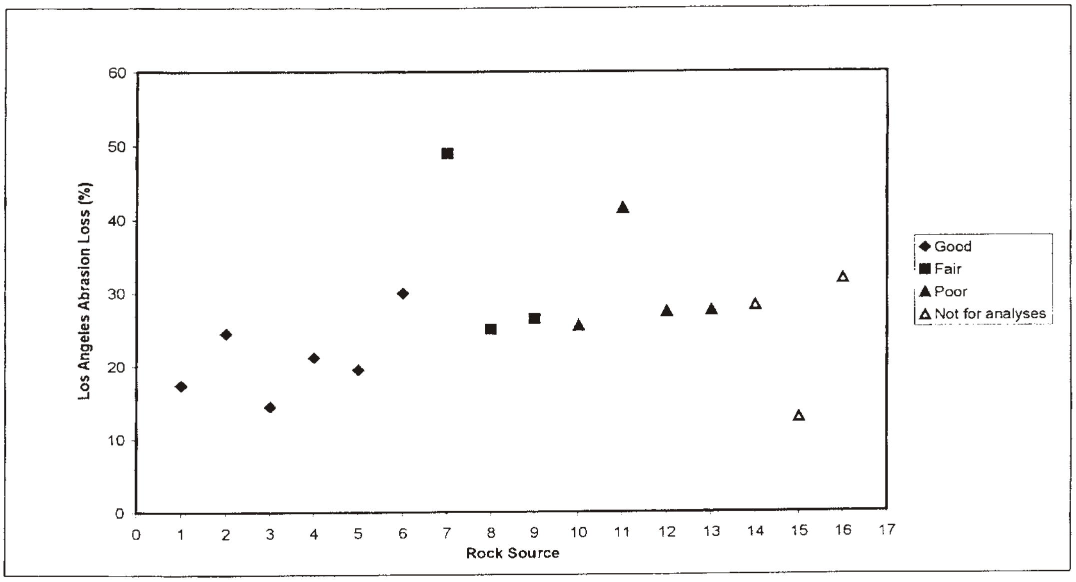

Figure 1. Pavement Performance Ratings and Los Angeles Abrasion (Toughness/Abrasion Resistance)

Rock Source	Description	Rock Source	Description	Rock Source	Description	Rock Source	Description
1	Traprock, NY	5	Gravel, NV	9	Limestone, IA	13	Sandstone, PA
2	Granite, GA	6	Limestone, IA	10	Gravel, PA	14	Limestone, MN
3	Steel Slag, IN	7	Granite, SC	11	Limerock, FL	15	Siltstone, VA
4	Gravel, MN	8	Gravel, MN	12	Limestone, TX	16	Basalt, OR

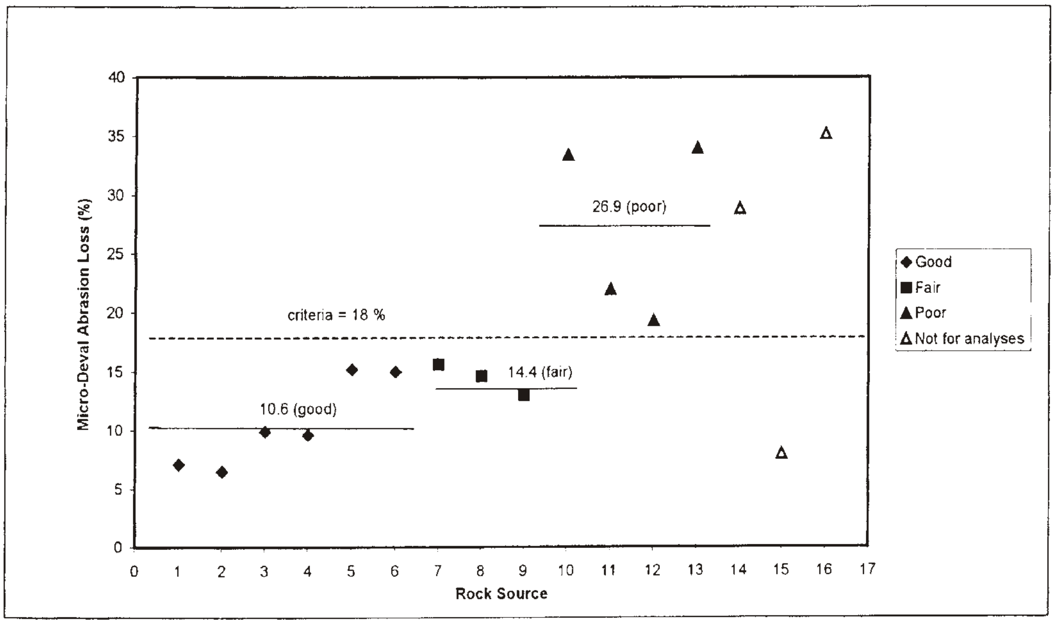

Figure 2. Pavement Performance Ratings and Micro-Deval Abrasion (Toughness/Abrasion Resistance)

Rock Source	Description	Rock Source	Description	Rock Source	Description	Rock Source	Description
1	Traprock, NY	5	Gravel, NV	9	Limestone, IA	13	Sandstone, PA
2	Granite, GA	6	Limestone, IA	10	Gravel, PA	14	Limestone, MN
3	Steel Slag, IN	7	Granite, SC	11	Limerock, FL	15	Siltstone, VA
4	Gravel, MN	8	Gravel, MN	12	Limestone, TX	16	Basalt, OR

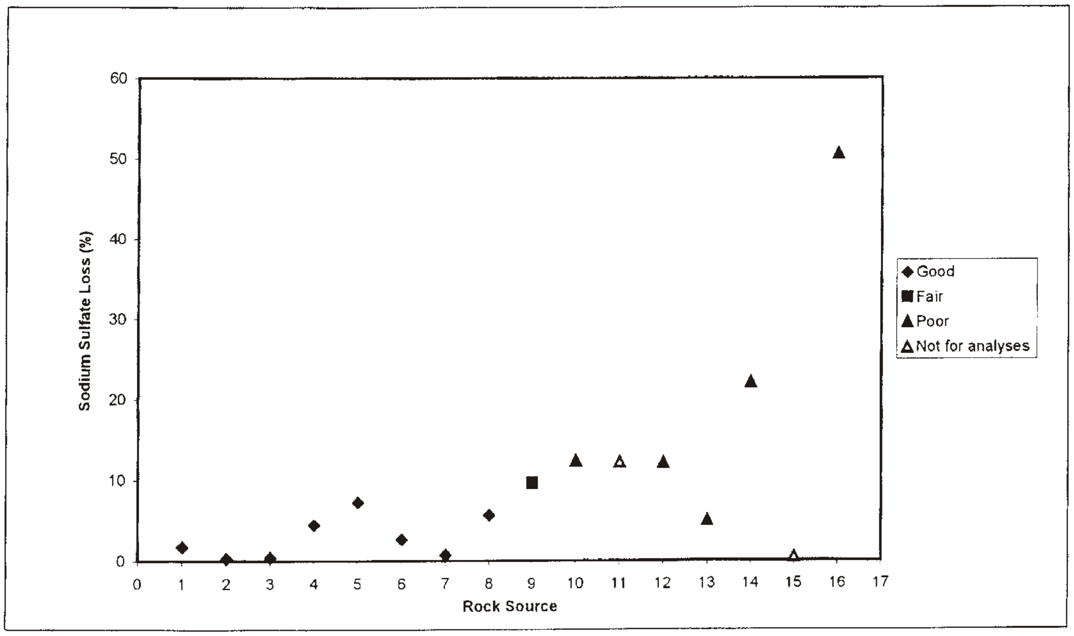

Figure 3. Pavement Performance Ratings and Sodium Sulfate Soundness (Soundness/Durability)

Rock Source	Description	Rock Source	Description	Rock Source	Description	Rock Source	Description
1	Traprock, NY	5	Gravel, NV	9	Limestone, IA	13	Sandstone, PA
2	Granite, GA	6	Limestone, IA	10	Gravel, PA	14	Limestone, MN
3	Steel Slag, IN	7	Granite, SC	11	Limerock, FL	15	Siltstone, VA
4	Gravel, MN	8	Gravel, MN	12	Limestone, TX	16	Basalt, OR

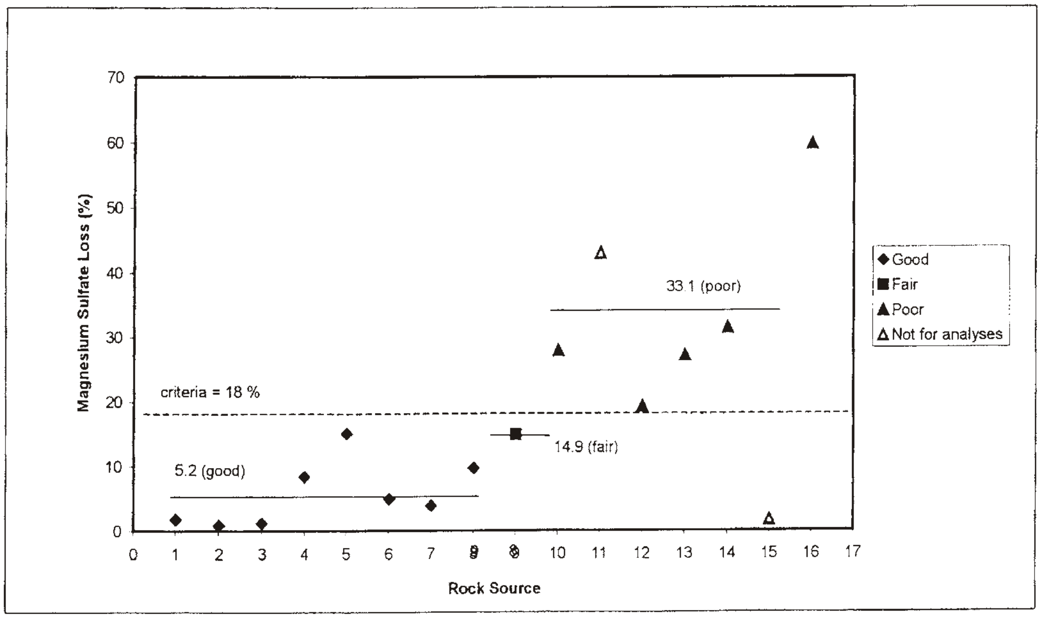

Figure 4. Pavement Performance Ratings and Magnesium Sulfate Soundness (Soundness/Durability)

Rock Source	Description	Rock Source	Description	Rock Source	Description	Rock Source	Description
1	Traprock, NY	5	Gravel, NY	9	Limestone, IA	13	Sandstone, PA
2	Granite, GA	6	Limestone, IA	10	Gravel, PA	14	Limestone, MN
3	Steel Slag, IN	7	Granite, SC	11	Limerock, FL	15	Siltstone, VA
4	Gravel, MN	8	Gravel, MN	12	Limestone, TX	16	Basalt, OR

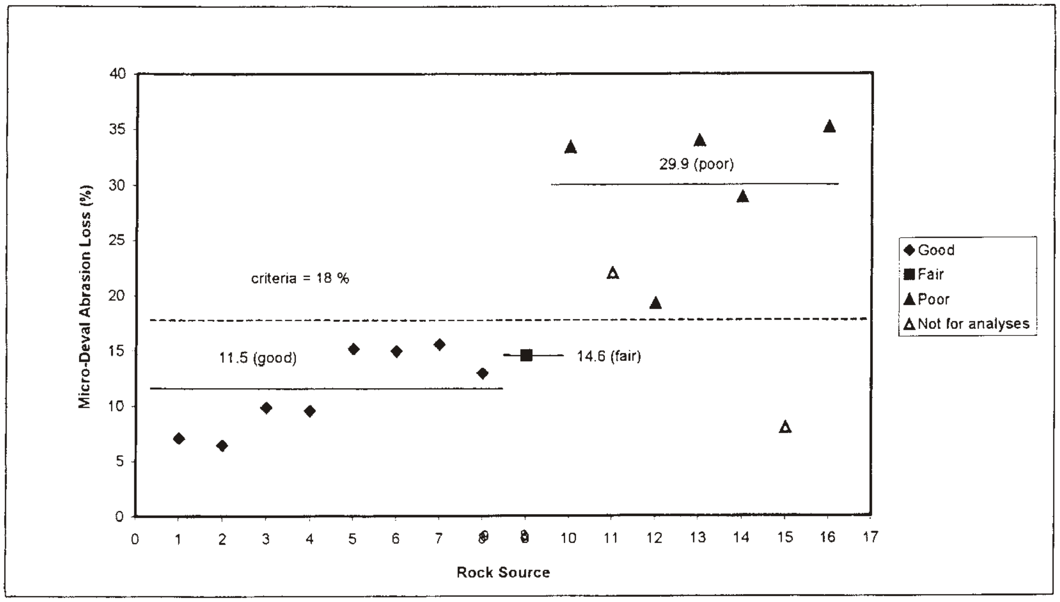

Figure 5. Pavement Performance Ratings and Micro-Deval Abrasion (Soundness/Durability)

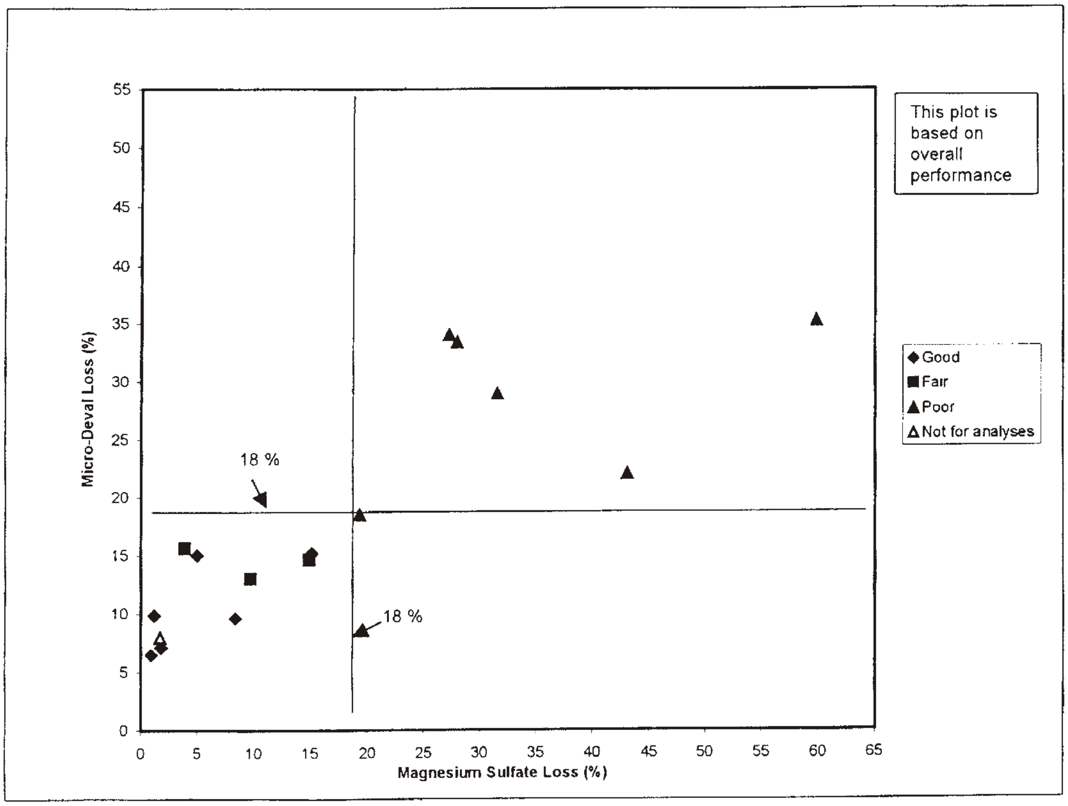

Figure 6. Magnesium Sulfate and Micro-Deval Loss (%) Criteria for Eliminating Poor Performing Aggregate

Regression Analysis

Regression analyses were performed to develop relationships between pavement performance and aggregate properties. The analyses included model selections for toughness/abrasion resistance, durability/soundness and overall performance (the worst rating) as shown in Table 1. For the purpose of this study, pavement performance was the dependent variable and rated performance assigned values of 5, 3 and 1 for good, fair and poor performance respectively. Results of single variable correlations are summarized in Tables 2, 3 and 4 for toughness/abrasion resistance, durability/soundness and overall performance, respectively.

Eight independent variables were examined for toughness/abrasion resistance, nine independent variables (including Micro-Deval abrasion loss) were examined for soundness/durability, and a suite of ten independent variables selected and examined for overall performance.

The results in Table 2 indicate the Micro-Deval has the highest R value (R = -0.81) which far exceeds the R values of the other tests. This correlation is also the only one with significance level greater than 5 % (p # 0.0007).

The results in Table 3 show a number of variables with relatively good correlations that are significant at 5 % level, but the two with highest R and lowest p are Micro-Deval (R = -0.87, p # 0.0001) and magnesium sulfate soundness (R = -0.81, p # 0.0004).

Table 4 reveals several variables with relatively good correlations that are significant at 5 % level but again the two with highest R and lowest p are Micro-Deval (R = -0.85, p # 0.0001) and magnesium sulfate soundness (R = -0.79, p # 0.0004).

Table 2. Summary of Correlations between Performance Rating and Toughness/Abrasion Resistance Tests

Test	Coefficient of Correlation, R	Significance Level for Correlation, p
Superpave Gyratory Compactor, AASHTO 8 + Fine, Mix	-0.16	0.6110
Superpave Gyratory Compactor, AASHTO 8 + Fine, Bare Aggregate	-0.28	0.3466
Aggregate Impact Value	-0.41	0.1679
Aggregate Crushing Value	-0.41	0.1636
Superpave Gyratory Compactor, AASHTO 8, Mix	-0.44	0.1285
Superpave Gyratory Compactor, AASHTO 8, Bare Aggregate	-0.45	0.1266
Los Angeles Abrasion	-0.48	0.0955
Micro-Deval	-0.81	0.0007

Table 3. Summary of Correlations between Performance Rating and Durability/ Soundness Tests

Test	Coefficient of Correlation, R	Significance Level for Correlation, p
AASHTO Freeze-Thaw, Pro. C	-0.58	0.0297
AASHTO Freeze-Thaw, Pro. B	-0.64	0.0145
Sodium Sulfate	-0.64	0.0129
Modified Canadian Freezing-Thawing	-0.67	0.0093
Canadian Freeze-Thaw	-0.68	0.0078
AASHTO Freeze-Thaw, Pro. A	-0.73	0.0033
Aggregate Durability Index	0.74	0.0024
Magnesium Sulfate	-0.81	0.0004
Micro-Deval Abrasion	-0.87	0.0001

Table 4. Summary of Correlations between Overall Performance Rating and Tests

Test	Coefficient of Correlation, R	Significance Level for Correlation, p
Aggregate Impact Value	-0.45	0.0917
Los Angeles Abrasion	-0.48	0.0673
AASHTO Freeze-Thaw, Pro. B	-0.50	0.0566
Canadian Freeze-Thaw	-0.54	0.0380
AASHTO Freeze-Thaw, Pro. C	-0.58	0.0221
Superpave Gyratory Compactor, AASHTO 8, Bare Aggregate	-0.59	0.0214
Aggregate Durability Index	0.63	0.0121
AASHTO Freeze-Thaw, Pro. A	-0.71	0.0032
Magnesium Sulfate	-0.79	0.0004
Micro-Deval	-0.85	0.0001

Forward Selection Multiple Variables Procedure

The forward selection procedure was tried to see if multiple variable correlations could be found with improved correlation and significance. However, only the single variable correlations identified above were found significant at a 5% confidence level. The independent variable selected for all three performances cases was the Micro-Deval loss. This was expected since Micro-Deval loss had the highest correlation coefficients and significance levels in the single variable analyses.

The single variable regression equations are as follows:

- Toughness/Abrasion Resistance
  Performance Rating = 6.053 - 0.167 (Micro-Deval Loss)

R^2 = 0.66, p # 0.0007

- Durability/Soundness
  Performance Rating = 6.473 - 0.166 (Micro-Deval Loss)
  R^2 = 0.76, p # 0.0001

- Overall
  Performance Rating = 5.940 - 0.158 (Micro-Deval Loss)
  R^2 = 0.72, p # 0.0001

Application of the above equations to source 4 (gravel, good performance), source 8 (gravel, fair performance), and source 13 (sandstone, poor performance) yields the following predictions:

		Predicted Performance		
Source	Micro-Deval Loss, %	T/A	D/S	Overall
4	9.6	4.4	4.9	4.4
8	14.6	3.6	4.0	3.6
13	34.0	0.4	0.8	0.6

The equations provide reasonable and similar predictions of performance for all three sources with the equation based on durability and soundness always picking somewhat higher performance ratings.

CONCLUSIONS AND RECOMMENDATIONS

The qualitative visual examinations of plots of aggregate properties and pavement performance ratings, based on toughness/abrasion resistance and durability/soundness, suggest Micro-Deval and magnesium sulfate loss are the two best indicators of potential pavement performance. Losses of 18% for both tests appear to separate good and fair from poor performers.

Single variable correlations between aggregate properties and performance ratings indicate the Micro-Deval test has the strongest and the magnesium sulfate test the second strongest correlations with performance. The forward selection process provided only single variable (Micro-Deval loss) equations with 5% significance level for all three performance cases. No multiple variable equations were found.

Based on the total analysis, the Micro-Deval is an obvious choice for a test to control aggregate quality. The magnesium sulfate soundness test is a strong second choice because of its history of use, its lack of required special equipment, its identification as an important individual variable for performance based on durability/soundness and overall performance.

It is recommended that state transportation agencies begin to run the Micro-Deval and magnesium sulfate soundness tests on available aggregate sources. This database will permit a more in-depth evaluation of the test methods and selection of limiting criteria based on state specific environmental conditions and traffic.

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