NCAT Report 02-09

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October 2002

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BACKGROUND

Aggregates to be utilized in hot mix asphalt (HMA) must be both tough and durable. Aggregates must withstand the effects of HMA production, transportation, and construction. Additionally, once placed on the roadway, aggregates must also resist the effects of traffic and the environment.

Historically, the toughness of aggregates has been determined using the Los Angeles (L.A.) Abrasion and Impact test (AASHTO T96). This test entails placing an aggregate sample of specified grading into a large steel drum. Six to twelve steel charges are also placed in the drum. Both the aggregate sample and steel charges are rotated in the drum for 500 revolutions. The aggregates and steel charges are tumbled and dropped within the drum and after the specified number of revolutions, the amount of breakdown in the aggregates, in the form of a percent loss, is determined.

Some research has suggested that the L.A. Abrasion and Impact test does not provide a good evaluation of quality for HMA aggregates (1). This concern is primarily due to the size and drop distance of the steel charges. Each steel charge has a mass of about 420 g. Because the inside of the drum has shelves, the aggregates and charges are picked up within the drum and then dropped a distance almost equal to the drum diameter. The large steel charges dropping this distance result in large impact loads being imparted onto the aggregate particles. Because of these large impact loads, high quality, coarse-grained crystalline materials, such as some granites, tend to yield high loss values although they typically perform well in the field (1). Other lower quality, soft materials, like slates, tend to have low loss values because the crystalline structure of these materials can absorb the impact loads (1).

The long-term durability characteristics of aggregates are generally determined using a soundness test. Both the Magnesium and Sodium Sulfate Soundness tests are common methods of evaluating the durability of aggregates. These tests provide a measure of an aggregate's ability to resist weathering forces, particularly freeze-thaw conditions.

Test procedures for both the Magnesium and Sodium Sulfate Soundness tests are similar. A sample of aggregate is immersed into a sulfate solution for a period of time to saturate the aggregate void structure. Next, the aggregates are drained and dried to a constant mass. Both magnesium and sodium freeze at a higher temperature than water. The temperature of the sulfate solution during immersion is such that the salts within the solution crystallize (freeze) in a manner that simulates ice crystallization. This crystallization causes expansive forces within the pore structure of the aggregate and, thus, causes degradation of the aggregate sample. Five immersion/drying cycles are typically utilized to provide a durability indication, as a percent loss, for the aggregate source.

During the National Cooperative Highway Research Program (NCHRP) Project 4-19, "Aggregate Tests Related to Asphalt Concrete Performance in Pavements" (2), the L.A. Abrasion and Impact test and the two soundness tests were evaluated. Additionally, other tests, such as the Micro-Deval test, were assessed to evaluate the toughness/durability of aggregates used in HMA pavements. Based upon this large research study, the Micro-Deval test was recommended as an aggregate test related to raveling, pop-outs, and pot-holing. The Micro-Deval test, in conjunction with the Magnesium Sulfate Soundness test, was recommended in lieu of the L.A. Abrasion and Impact test and other soundness tests.

Micro-Deval Test

The Micro-Deval test was developed in France during the 1960s and was based on the Deval test developed in the early 1900s (3). The Micro-Deval test provides a measure of abrasion resistance and durability of mineral aggregates through the actions of abrasion between aggregate particles and between aggregate particles and steel balls in the presence of water. The test method for the Micro-Deval apparatus has been standardized in AASHTO TP 58-00, "Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus."

The Micro-Deval test entails abrading a graded sample within a small-diameter drum (194 ± 2 mm) with steel charges in the presence of water. The steel charges are smaller (9.5-mm diameter) than those used in the L.A. Abrasion and Impact test (46.8- mm diameter). Micro-Deval samples are soaked in two liters of water for a minimum of one hour prior to testing. Both the aggregate and water are included in the drum during the test. The drum is rotated at a rate of 100 ± 5 rpm for two hours. Unlike the L.A. Abrasion and Impact test, there are no shelves within the drum, so degradation is due to abrasion between the aggregate particles and charges.

Most of the recent literature on the Micro-Deval test has originated from the Ontario Ministry of Transportation. Senior et al (1) recently reported on a study evaluating toughness/durability aggregate test methods for characterizing aggregates within granular bases, Portland cement concrete (PCC), and HMA. For this study, the researchers conducted tests on aggregates of known field performance. Based upon the findings, the authors concluded that the Micro-Deval test and petrographic examinations were the best performance predictors for granular bases. For PCC, the authors recommended the unconfined freeze-thaw test and the Micro-Deval test for differentiating between marginal and poor performing aggregates. The authors concluded that the Micro-Deval test, unconfined freeze-thaw, and polished stone value test were needed to categorize aggregates for HMA surface courses.

Lane et al (4) presented specifications for Micro-Deval test results for HMA aggregates (Table 1) from Ontario. An interesting observation from Table 1 is that the criteria change for wearing surfaces to be placed on high volume roadways depending on the aggregate mineralogical type.

Table 1. Micro-Deval Specification for Coarse Aggregates in HMA (4)

Application		Maximum loss (%)
Asphalt wearing courses	premium[1]	5-15[3]
	secondary[2]	17
Asphalt base courses		21

Notes:
1. AADT > 2500 lane.
2. AADT < 2500 lane.
3. Varies with rock type (5% for igneous and metamorphic gravel; 10% for traprock, diabase and andesite; 15% for dolomitic sandstone, granitic meta-arkose and gneiss).

Because of the success that others have had with the Micro-Deval test method in characterizing coarse aggregates, a study was needed to characterize aggregates common to the Southeast utilizing this new test method. Results of Micro-Deval testing also need to be compared to typically used toughness/durability tests.

OBJECTIVE

The objective of this research was to characterize the toughness/durability of selected aggregates from throughout the Southeastern United States with respect to their Micro-Deval test results. This study involved comparisons between Micro-Deval test results and typically used toughness/durability tests.

SCOPE

The objective of this study was accomplished through the testing of 72 aggregates obtained from eight states. At the onset of the study, each participating state was requested to identify at least five aggregates from their respective state. It was recommended that each state identify at least two aggregate sources that could be categorized as good, two aggregates that were fair, and one aggregate that was poor with respect to performance. In some cases, a state decided to provide only aggregates that had a good performance history or provide aggregates having both good and fair performance histories. Each of the identified aggregates was tested to determine the percent loss during the Micro-Deval test in accordance with AASHTO TP 58-00, "Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus." In order for comparisons to be made between the Micro-Deval and other typical toughness/durability test results, both the L.A. Abrasion and Impact and Sodium Sulfate Soundness values of each aggregate were obtained. In some instances, the participating states supplied the L.A. Abrasion and Impact and Sodium Sulfate Soundness results; however, when the results were not available from a state, NCAT conducted testing to obtain the values.

TEST RESULTS AND ANALYSIS

Within this section, results of testing conducted on 72 aggregates from eight different states and the analyses of the test results are provided. The first part of this section provides test results for each of the eight participating states. An evaluation of test results by state was needed because of the subjective aggregate performance ranking system used in this study. A good aggregate source in one state may not be considered a good aggregate source in another state. Also included in this section will be a comparison of the three test methods. At the conclusion of this section, the Micro-Deval data will be analyzed separately.

Evaluation of Individual State Data

Alabama Sources

The state of Alabama requested that a total of 15 different aggregate sources be tested. Of these 15 aggregate sources, five different mineralogical types were tested: granite, limestone, gravel, sandstone, and slag. Micro-Deval, Los Angeles Abrasion and Impact, and Sodium Sulfate Soundness results for all 15 aggregate sources are presented in Table 2. Thirteen of the 15 aggregate sources were rated as having a good performance history. The remaining two aggregate sources were categorized as having a fair performance history. However, the use of four of the 15 aggregates (AL1, AL2, AL9, and AL12) was restricted in surface courses based upon their polishing characteristics. All four of the aggregates having some form of restricted use were limestones. Micro-Deval test results ranged from a low of 2.0 percent loss to a high of 20.6 percent loss. Los Angeles Abrasion and Impact values ranged from a low of 15 percent loss to a high of 54 percent loss. All of the Sodium Sulfate Soundness results were relatively low, with loss values less than or equal to 4 percent.

Table 2. Results of Testing for Alabama Aggregates

Source ID	Aggregate Type	Micro-Deval, % Loss	LA Abrasion, % Loss[1]	Sodium Sulfate Soundness % Loss[1]	Performance Rating
AL1	Limestone	8.5	22	1.0	Good
AL2	Limestone	9.6	20	0.0	Good
AL3	Granite	14.5	36	0.0	Fair
AL4	Granite	5.8	35	0.0	Good
AL5	Gravel	20.6	37	0.0	Good
AL6	Granite	2.0	15	1.0	Good
AL7	Sandstone	11.9	43	2.0	Good
AL8	Slag	3.6	15	0.0	Good
AL9	Limestone	15.2	26	2.0	Good
AL10	Sandstone	20.2	54	1.0	Fair
AL11	Sandstone	11.2	53	4.0	Good
AL12	Limestone	10.5	24	1.0	Good
AL13	Gravel	2.8	29	1.0	Good
AL14	Gravel	8.6	46	0.0	Good
AL15	Gravel	6.2	39	0.0	Good

[1] Values supplied by ALDOT

Results of testing on the Alabama aggregate sources are illustrated in Figure 1. Within this figure, L.A. Abrasion and Impact and Sodium Sulfate Soundness results are plotted versus Micro-Deval test results. Also within the figure, the symbols show the performance ranking for each test result. Based on the figure, all but two of the aggregates had Micro-Deval percent loss values less than the 18 percent maximum recommended by NCHRP 4-19 (2). Of the two sources not meeting the 18 percent maximum value, one was categorized as a good performer (AL5-gravel) and one was categorized as a fair performer (AL10-sandstone). Statistically, the relationship between L.A. Abrasion and Impact results and Micro-Deval results was significant (p-value=0.046) at a level of significance of 95 percent. However, the relationship was not significant between the Sodium Sulfate Soundness results and Micro-Deval results (p-value=0.639).

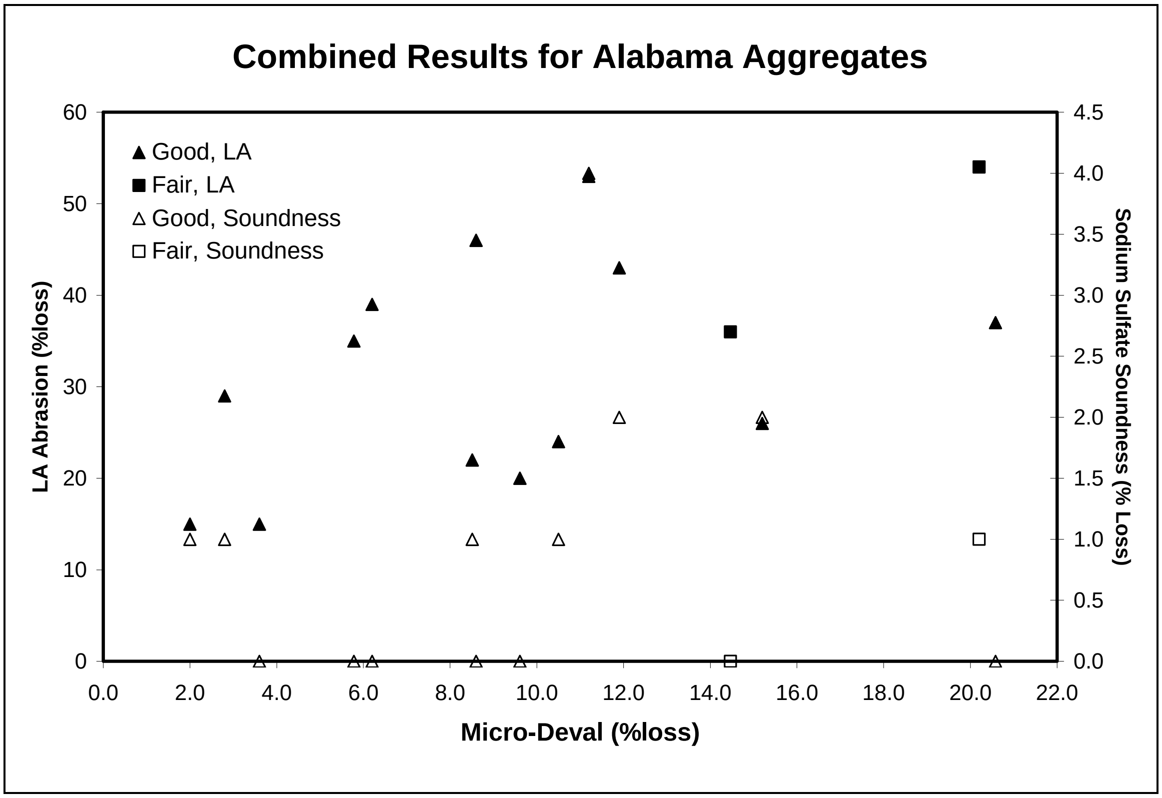

Figure 1. Test Results for Alabama Aggregates by Performance Ranking

Florida Sources

Ten aggregate sources were tested from the state of Florida. Of these ten, seven sources were a limestone, two were granite, and one was a gravel source. Results of testing conducted on these aggregate sources are presented in Table 3. Four sources from Florida are restricted in use: FL1, FL2, FL9, and FL10. Each of these sources is restricted in HMA surface courses because of polishing characteristics. Based on Table 3, five of the aggregate sources were categorized a good performers, two were categorized as fair performers, and three had poor performance histories. Micro-Deval results ranged from a low of 3.3 percent loss to a high of 39.3 percent loss. L.A. Abrasion and Impact values ranged from a low of 18 percent loss to a high of 43 percent loss. Similar to the Alabama aggregate sources, all of the Florida sources had relatively low Sodium Sulfate Soundness results with the highest value being 2.6 percent loss.

Table 3. Results of Testing for Florida Aggregates

Source ID	Aggregate Type	Micro-Deval, % Loss	LA Abrasion, % Loss	Sodium Sulfate Soundness %Loss	Performance Rating
FL1	Limestone	30.1	37	2.6	Poor
FL2	Limestone	20.7	43	0.4	Poor
FL3	Limestone	20.7	30	0.8	Good
FL4	Limestone	39.3	35	1.8	Fair
FL5	Limestone	23.1	31	0.5	Good
FL6	Gravel	5.1	40	0.1	Poor
FL7	Granite	3.3	18	0.2	Good
FL8	Granite	6.7	20	0.3	Good
FL9	Limestone	9.9	24	0.1	Fair
FL10	Limestone	19.8	34	0.1	Good

Test results for the Florida aggregates are illustrated in Figure 2. Again, different symbols are utilized in Figure 2 to show the different performance categories identified by the Florida DOT. The figure illustrates that three different aggregate sources identified as good performers had Micro-Deval percent loss values higher than the 18 percent maximum recommended in NCHRP 4-19 (2). All three of these sources were a limestone (FL3, FL5, and FL10). One of the two aggregate sources that were identified as a fair performer had the highest Micro-Deval value at 39.3 percent loss (FL4-limestone), while

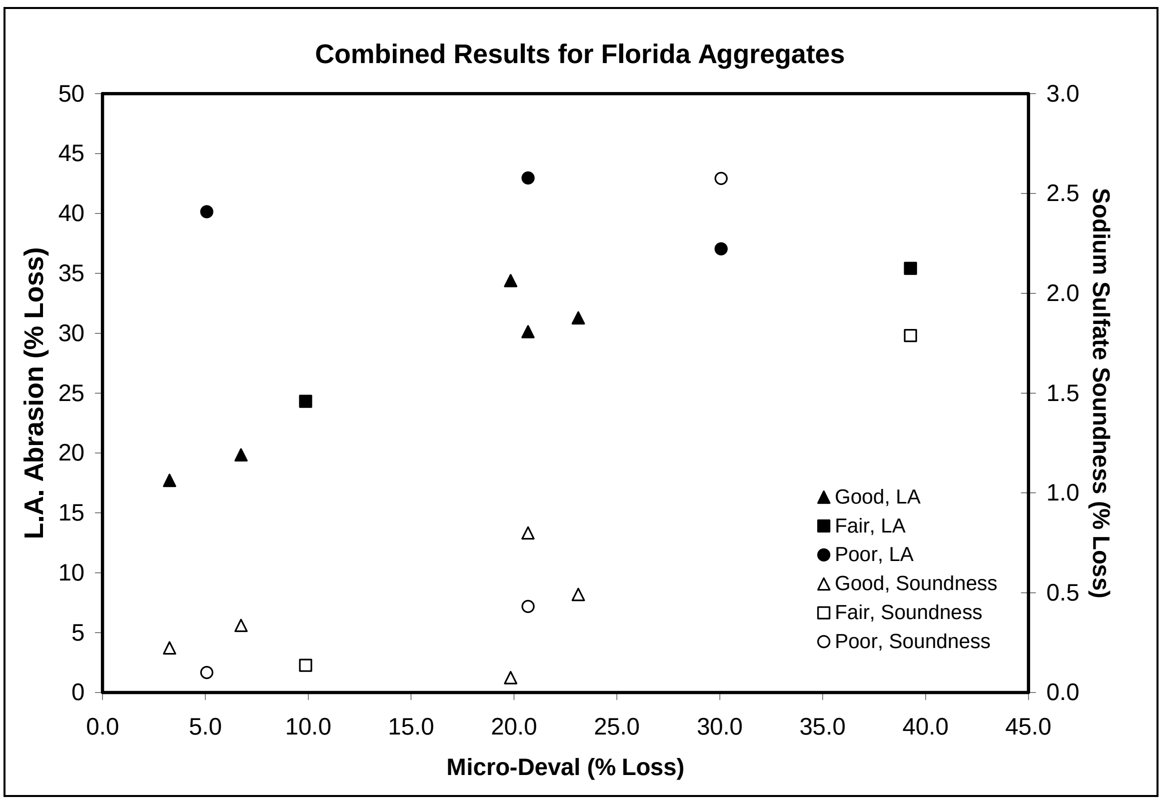

Figure 2. Test Results for Florida Aggregates by Performance Ranking

the other source (FL9-limestone) had a low Micro-Deval percent loss of 9.9. Two of the three sources identified as poor performers had Micro-Deval values in excess of the 18 percent maximum (FL1 and FL2) while the other source had a very low Micro-Deval percent loss of 5.1 percent. The Florida Micro-Deval results do appear to be somewhat related to both L.A. Abrasion and Impact and Sodium Sulfate Soundness results. As both L.A. Abrasion and Impact and Sodium Sulfate Soundness results increase, Micro-Deval results also increase. Statistically, the relationship between L.A. Abrasion and Impact and Micro-Deval was not significant (p-value=0.128), but the relationship was significant between the Sodium Sulfate Soundness and Micro-Deval results (p-value=0.009).

Georgia Sources

The Georgia DOT selected five aggregate sources for testing in this study. All five of the aggregates were granite. Two sources were categorized by the Georgia DOT as good performers, two sources as fair performers, and one source as a poor performer. Results of testing conducted on the Georgia aggregate sources are presented in Table 4. Micro-Deval test results ranged from a low of 4.6 percent loss to a high of 22.9 percent loss. The aggregate source categorized as being a poor performer had the highest Micro-Deval percent loss (GA1). This source would not meet the recommended maximum of 18 percent loss (2). L.A. Abrasion and Impact values ranged from a low of 21 percent loss to a high of 66 percent loss. Four of the five Georgia sources had Sodium Sulfate Soundness values that were less than 2 percent loss. The other source had a very high loss at 24 percent and was categorized as a poor performer.

Table 4. Results of Testing for Georgia Aggregates

Source ID	Aggregate Type	Micro-Deval, % Loss	LA Abrasion, % Loss[1]	Sodium Sulfate Soundness % Loss	Performance Rating
GA1	Granite	22.9	66	24.0	Poor
GA2	Granite	6.4	54	0.4	Fair
GA3	Granite	6.8	50	1.3	Fair
GA4	Granite	4.6	21	1.0	Good
GA5	Granite	4.8	43	1.9	Good

[1] Values supplied by GDOT

Test results for the five Georgia aggregates are illustrated in Figure 3. This figure shows that all of the aggregates that were categorized as good or fair performers had Micro-Deval results less than 7 percent loss. The lone poor performing aggregate source had a much higher Micro-Deval percent loss than the good or fair performing sources. As would be expected from the data in Table 4, there was not a significant relationship between L.A. Abrasion and Impact and Micro-Deval results for the Georgia aggregate sources (p-value=0.174). Micro-Deval results for four of the five sources were very similar and there was a fairly large difference in L.A. Abrasion and Impact values for those four aggregates. There was, however, a significant relationship between Sodium Sulfate Soundness and Micro-Deval results (p-value=0.002).

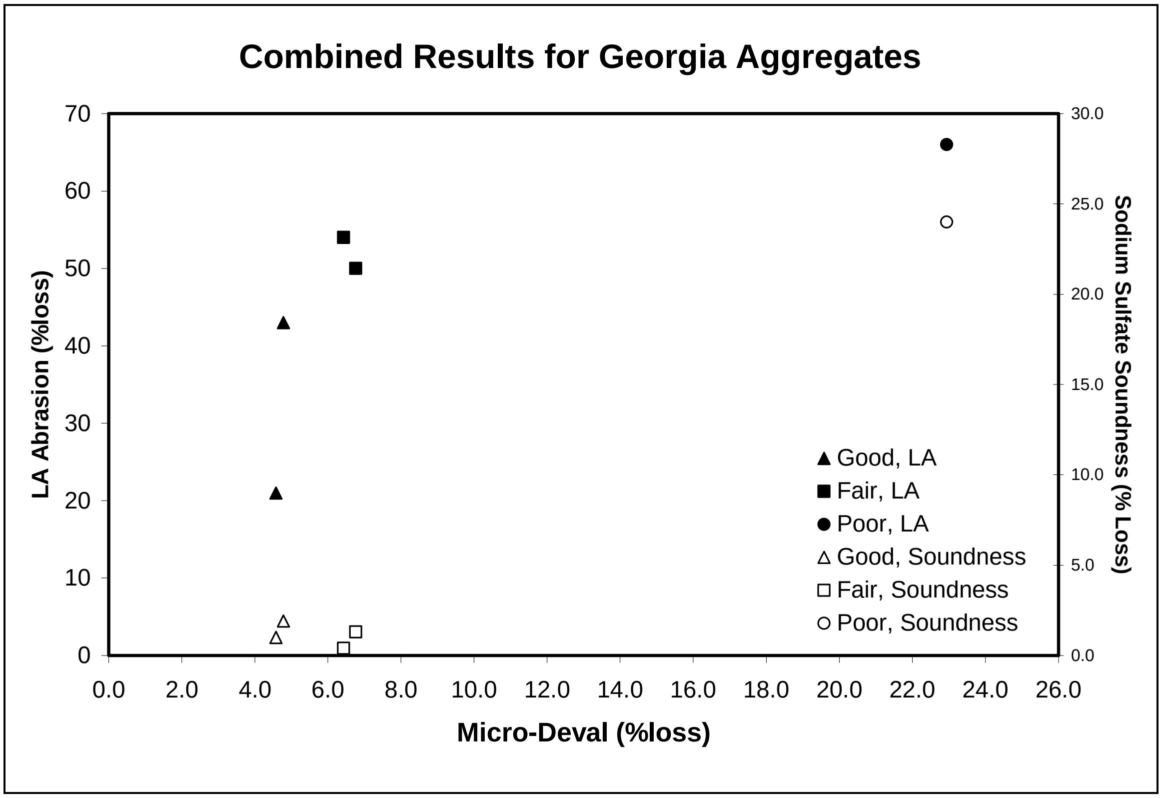

Figure 3. Test Results for Georgia Aggregates by Performance Ranking

Kentucky Sources

The Kentucky Transportation Cabinet (KYTC) selected five aggregate sources for testing. All five were limestone sources, with two sources being categorized as good performing aggregates, two sources as fair performers, and one source categorized as a poor performer. Results of testing conducted on the Kentucky aggregates are presented in Table 5. Two of these sources have restricted use, KY1 and KY4, depending upon the bench layer of limestone being quarried. Micro-Deval results ranged from a low of 7.8 percent loss to a high of 30.7 percent loss. The two aggregates that were categorized as good (KY2 and KY5) had Micro-Deval values less than the maximum of 18 percent loss recommended by NCHRP 4-19 (2). The two aggregate sources categorized as being fair performers (KY1 and KY4) both had Micro-Deval values above 25 percent loss and the lone aggregate source identified as a poor performer (KY3) had a Micro-Deval value of 18.3 percent. Los Angeles Abrasion and Impact results ranged from a low of 16 percent loss to a high of 31 percent loss. Sodium Sulfate Soundness results ranged from a low of 1.8 percent loss to a high of 27.0 percent loss.

Table 5. Results of Testing for Kentucky Aggregates

Source ID	Aggregate Type	Micro-Deval, % Loss	LA Abrasion, % Loss[1]	Sodium Sulfate Soundness % Loss[1]	Performance Rating
KY1	Limestone	30.7	31	11.0	Fair
KY2	Limestone	14.2	16	3.7	Good
KY3	Limestone	18.3	28	27.0	Poor
KY4	Limestone	25.2	21	9.7	Fair
KY5	Limestone	7.8	17	1.8	Good

[1]Values supplied by KYTC

Figure 4 illustrates the Micro-Deval, L.A. Abrasion and Impact, and Sodium Sulfate Soundness test results for the Kentucky aggregate sources. Based on the figure, there does appear to be a reasonable relationship between L.A. Abrasion and Impact and Micro-Deval test results. Statistically, neither relationship is significant.

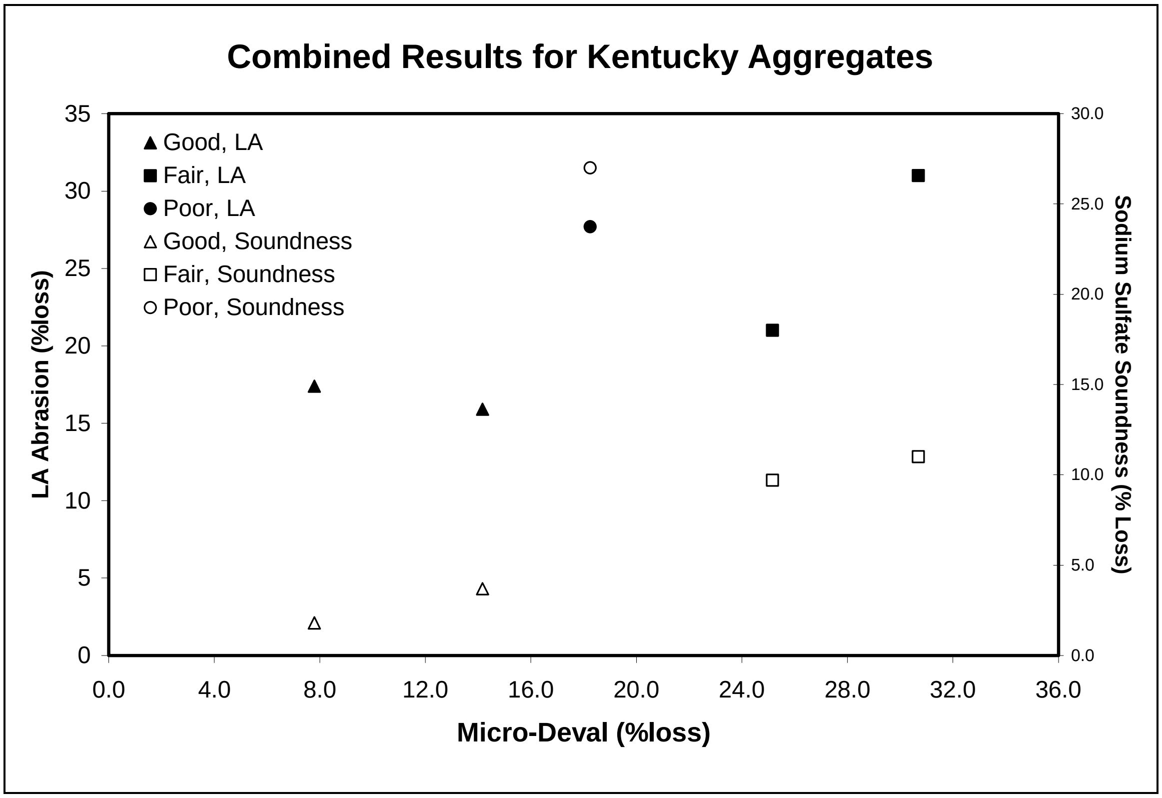

Figure 4. Test Results for Kentucky Aggregates by Performance Ranking

Mississippi Sources

The Mississippi DOT selected five aggregate sources for inclusion within this study. All five of the aggregates were gravels containing a high percentage of chert. All five of the aggregate sources were categorized as being good performers in HMA layers. None of the sources have restrictions on their use. Micro-Deval test results were all less than or equal to 2.0 percent loss. L.A. Abrasion and Impact values were all similar, ranging from 14 to 20 percent loss. Results of Sodium Sulfate Soundness testing were all relatively low and ranged from 0.3 to 5.9 percent loss. Table 6 and Figure 5 illustrate all of the test results for the Mississippi aggregate sources.

Table 6. Results of Testing for Mississippi Aggregates

Source ID	Aggregate Type	Micro-Deval, % Loss	LA Abrasion, % Loss	Sodium Sulfate Soundness %Loss	Performance Rating
MS1	Gravel-Chert	1.4	19	2.1	Good
MS2	Gravel-Chert	2.0	18	0.3	Good
MS3	Gravel-Chert	N/A	18	5.9	Good
MS4	Gravel-Chert	1.5	14	3.5	Good
MS5	Gravel-Chert	1.4	20	1.2	Good

N/A – Sample was not tested.

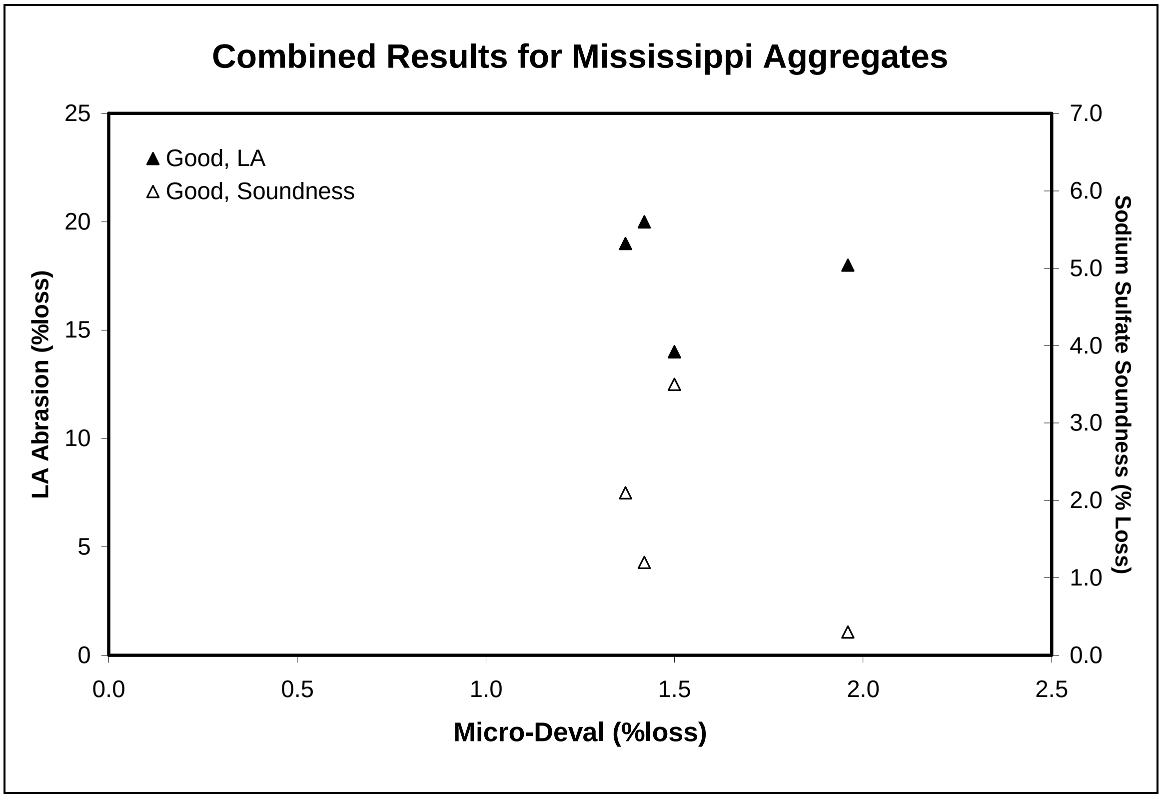

Figure 5. Test Results for Mississippi Aggregates by Performance Ranking

North Carolina Sources

Ten aggregate sources were tested for the North Carolina DOT. Aggregate types included granite, gravel, slate, traprock, and limestone. All ten sources of aggregate were categorized as being good performers. Test results for the ten North Carolina aggregates are presented in Table 7. Micro-Deval test results ranged from a low of 4.3 percent loss to a high of 29.4 percent loss. Only one of the sources had a Micro-Deval value higher than the 18 percent maximum recommended by NCHRP 4-19 (2). L.A. Abrasion and Impact values ranged from a low of 17 percent loss to a high of 45 percent loss. Sodium Sulfate Soundness results ranged from a low of 0.0 percent loss to a high of 5.6 percent loss.

Table 7. Results of Testing for North Carolina Aggregates

Source ID	Aggregate Type	Micro-Deval, % Loss	LA Abrasion, % Loss[1]	Sodium Sulfate Soundness % Loss[1]	Performance Rating
NC1	Granite	4.3	34	0.3	Good
NC2	Granite	9.4	34	0.0	Good
NC3	Gravel	7.9	43	5.6	Good
NC4	Slate	12.6	20	0.1	Good
NC5	Granite	5.8	17	1.1	Good
NC6	Granite	8.4	20	0.1	Good
NC7	Traprock	14.2	45	1.1	Good
NC8	Limestone	29.4	45	2.7	Good
NC9	Granite	14.9	35	0.6	Good
NC10	Granite	10.9	29	0.1	Good

[1]Values supplied by NCDOT

Figure 6 illustrates the results of testing conducted on the North Carolina aggregate sources. Results shown in Figure 6 are somewhat sporadic. Statistically, there was not a significant relationship between the L.A. Abrasion and Impact and Micro-Deval results (p-value=0.148) or the Sodium Sulfate Soundness and Micro-Deval results (p-value=0.601).

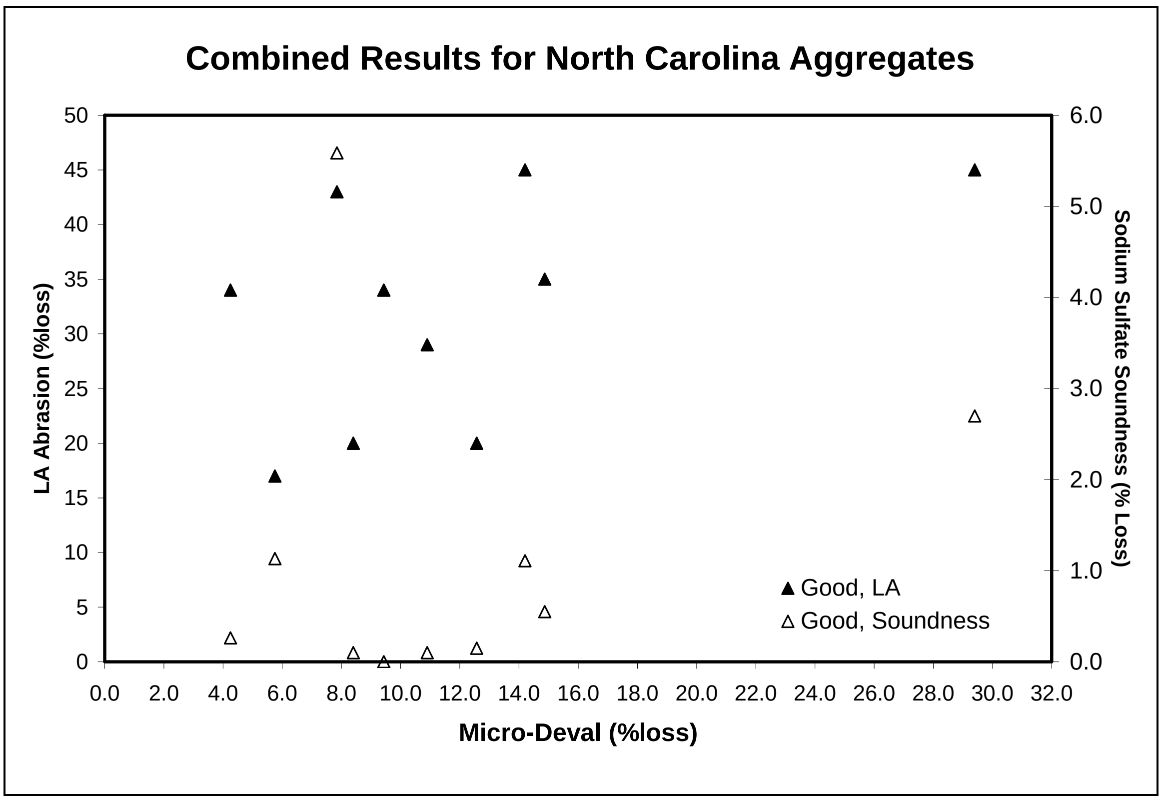

Figure 6. Test Results of Testing on North Carolina Aggregates by Performance Ranking

South Carolina Sources

The South Carolina DOT identified 15 aggregate sources to be tested within this study. Five different aggregate types were included: granite, granite-gneiss, gravel-quartzite, marble-schist, and steel slag. Seven of the aggregate sources were categorized as being good performers and seven sources were identified as fair performers. The remaining aggregate source was categorized as being a poor performer. Table 8 presents the test results on the South Carolina aggregate sources. Source SC12 is restricted from use on high volume roadways because the L.A. Abrasion and Impact value is above 55 percent. Source SC2 is restricted to only low volume roadways due to high L.A. Abrasion and Impact and SC6 is restricted to low volume roads because of high flat-and-elongated values. Micro-Deval test results ranged from a low of 5.6 percent loss to a high of 28.1 percent loss. Only one of the 15 aggregate sources (SC9-marble-schist) had a Micro-Deval result above the 18 percent maximum loss recommended by NCHRP 4-19 (2). Interestingly, the lone aggregate source categorized as poor (SC2-gravel-quartzite) had the second lowest Micro-Deval value at 5.7 percent loss. One of the seven aggregate sources categorized as fair, SC9 (marble-schist) had the highest Micro-Deval value at 28.1 percent loss. L.A. Abrasion and Impact values ranged from a low of 14 percent loss to a high of 61 percent loss. Sodium Sulfate Soundness results were all relatively low, with the highest being 3.4 percent loss.

Table 8. Results of Testing for South Carolina Aggregates

Source ID	Aggregate Type	Micro-Deval, % Loss	LA Abrasion, % Loss[1]	Sodium Sulfate Soundness % Loss[1]	Performance Rating
SC1	Granite	13.1	51	2.2	Fair
SC2	Gravel-Quartzite	5.7	52	0.4	Poor
SC3	Granite	6.3	36	0.7	Fair
SC4	Granite	8.5	45	0.5	Fair
SC5	Granite	7.8	31	0.1	Good
SC6	Granite-Gneiss	10.1	14	0.8	Good
SC7	Granite	5.8	28	0.1	Good
SC8	Granite	7.9	19	3.4	Good
SC9	Marble-Schist	28.1	26	2.9	Fair
SC10	Granite	5.6	40	1.2	Good
SC11	Granite	7.8	45	0.5	Good
SC12	Granite	10.9	56	0.4	Fair
SC13	Granite	7.8	51	0.1	Good
SC14	Granite	10.4	61	1.4	Fair
SC15	Steel Slag	7.9	19	2.1	Fair

[1]Values supplied by SCDOT

Test results for the 15 South Carolina aggregate sources are illustrated in Figure 7. This figure shows that all but one of the aggregate sources have Micro-Deval test results between about 6 and 13 percent loss. Therefore, there was little distribution in test results for the South Carolina sources. The relationship between L.A. Abrasion and Impact and Micro-Deval results was not significant (p-value=0.686); however, the relationship between Sodium Sulfate Soundness and Micro-Deval results was significant (p-value=0.043).

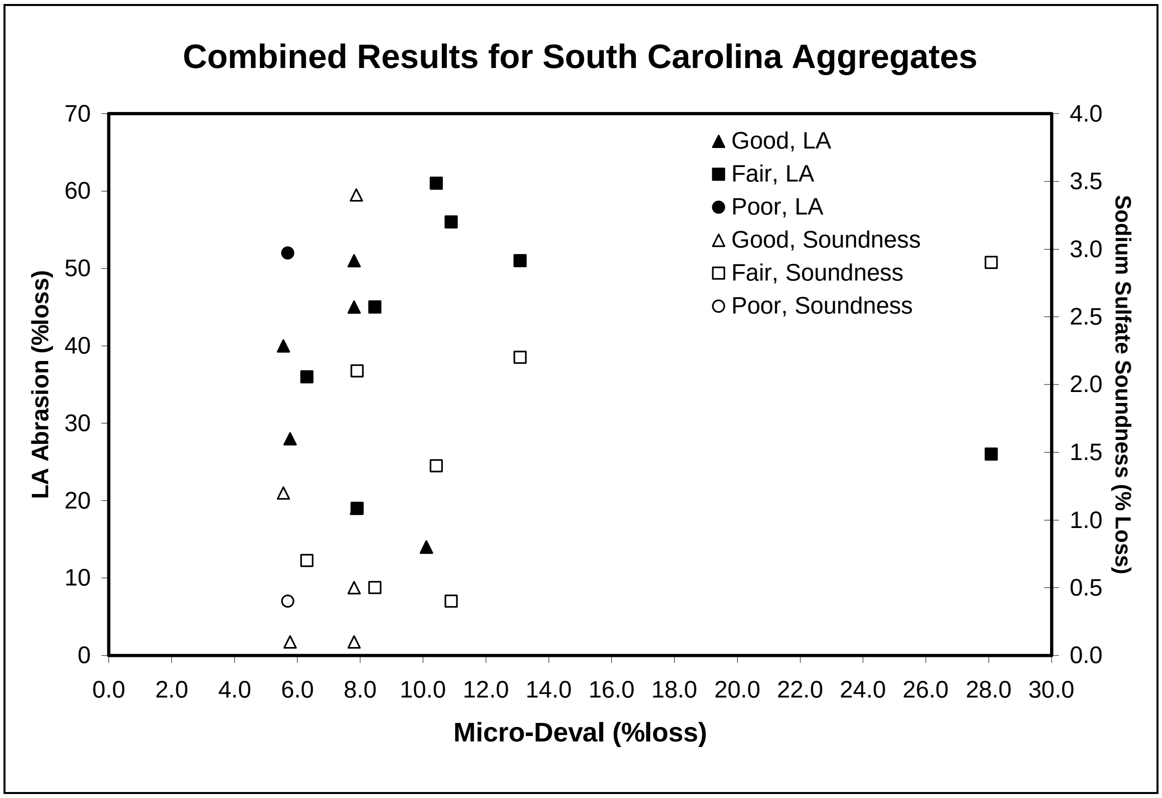

Figure 7. Test Results for South Carolina Aggregates by Performance Ranking

Tennessee Sources

Table 9 presents the results of testing conducted on seven aggregate sources identified by the Tennessee DOT. All seven of these sources were categorized as being good performers. Three different aggregate types (gravel, limestone, and sandstone) were included in the seven sources. Micro-Deval test results ranged from a low of 4.4 percent loss to a high of 21.8 percent loss. Three of the seven sources had Micro-Deval results greater than the 18 percent maximum recommended by the NCHRP 4-19 researchers (2). L.A. Abrasion values ranged from a low of 13 percent less to a high of 38 percent loss. Sodium Sulfate Soundness results were less than or equal to 2.0 percent loss.

Table 9. Results of Testing for Tennessee Aggregates

Source ID	Aggregate Type	Micro-Deval, % Loss	LA Abrasion, % Loss	Sodium Sulfate Soundness %Loss	Performance Rating
TN1	Gravel	19.2	38	0.7	Good
TN2	Limestone	12.4	13	1.0	Good
TN3	Limestone	13.8	23	0.9	Good
TN4	Gravel	4.4	19	1.8	Good
TN5	Sandstone	21.8	24	1.0	Good
TN6	Limestone	14.9	19	1.3	Good
TN7	Limestone	21.6	27	2.0	Good

Results of testing conducted on the Tennessee aggregate sources are illustrated in Figure 8. Neither the L.A. Abrasion and Impact or the Sodium Sulfate Soundness results were significantly related to the Micro-Deval results (p-values of 0.187 and 0.648, respectively).

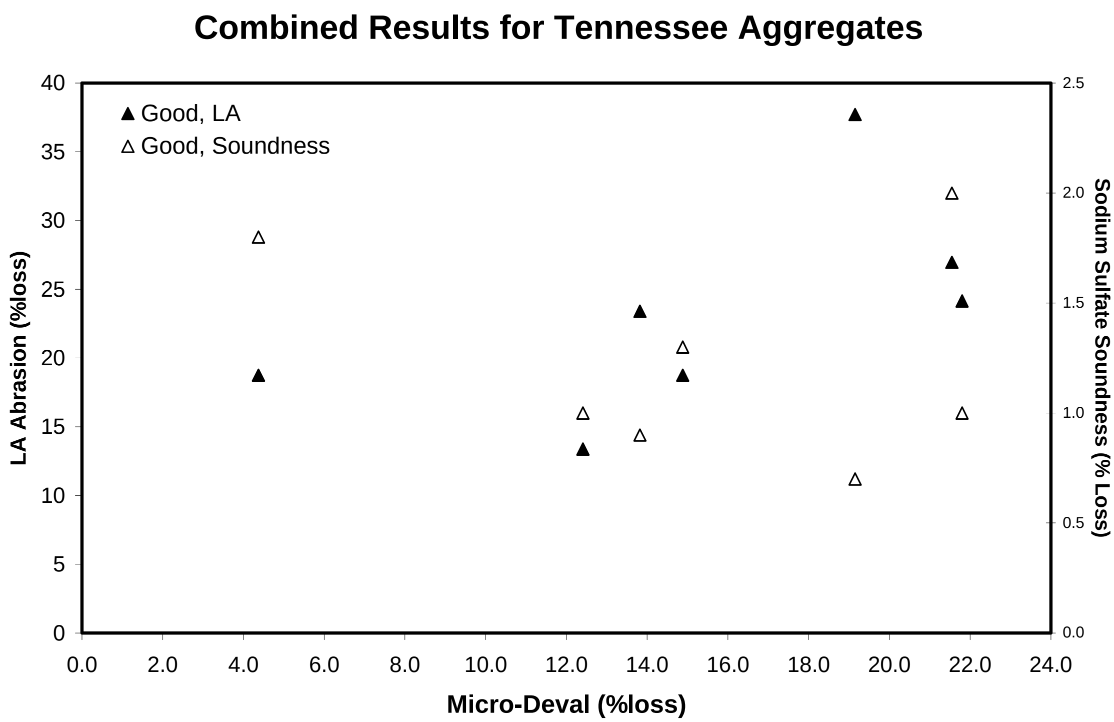

Figure 8. Test Results for Tennessee Aggregates by Performance Ranking

Summary of Individual States Results

The ability of the Micro-Deval test to categorize aggregate quality similar to a state's known performance history showed mixed results. For the five states that identified sources having at least two different performance histories, only twice did the Micro-Deval results match the categories (Alabama and Georgia). For the Alabama aggregate sources, a Micro-Deval value of 14 percent loss appears to be a reasonable dividing line between good and fair performing aggregates (Figure 1). Eleven of the 13 aggregates categorized as good had Micro-Deval values less than 14 percent loss. The two aggregate sources categorized as fair both had Micro-Deval values in excess of 14 percent (14.5 and 20.2 percent loss) and two aggregate sources categorized as good had Micro-Deval values above 14 percent loss (15.2 and 20.6 percent loss). This suggests that the 18 percent loss maximum recommended by NCHRP 4-19 (2) may be appropriate for Alabama aggregate sources.

For the Georgia materials (Figure 3), all of the aggregate sources categorized as good or fair had Micro-Deval values of less than 7 percent loss. The lone source categorized as poor had a Micro-Deval value in excess of 22 percent loss. This suggests that a critical Micro-Deval test value of 18 percent loss, or less, may be appropriate.

For the Kentucky materials (Figure 4), the ability of the Micro-Deval test to categorize aggregate sources similar to performance history had mixed results. First, both of the aggregate sources categorized as good performers had Micro-Deval values of less than 15 percent loss. Aggregate sources categorized as fair performers had Micro-Deval values between 25 and 31 percent loss. However, the lone aggregate source categorized as poor had a Micro-Deval value of 18.3 percent loss. A maximum Micro-Deval value of 18 percent loss would exclude the aggregate source identified as a poor performer, but it would also exclude two aggregate sources that were considered fair performers. Interestingly though, both of these fair performers are only allowed for restricted use. Therefore, the ability of the Micro-Deval to characterize performance showed mixed results.

For both the Florida and South Carolina aggregate sources, the Micro-Deval did a poor job distinguishing between sources having different performance histories. Micro-Deval results for the Florida aggregate sources having good performance histories were as high as 23 percent loss (Figure 2). This suggests that the 18 percent loss maximum recommended by NCHRP 4-19 (2) may be too stringent for Florida materials. Florida sources categorized as fair performers had Micro-Deval values ranging from 10 to 39 percent loss. Again, these values suggest that a maximum criterion of 18 percent loss would be too stringent. Two of the Florida aggregate sources identified as being poor performers did have Micro-Deval values above 18 percent (20.7 and 30.1 percent loss). However, the other source identified as a poor performer had a Micro-Deval value of 5.1 percent loss (gravel source). Therefore, the Micro-Deval test did a poor job distinguishing between Florida aggregate sources having different performance histories.

Aggregate sources from South Carolina having good performance histories had Micro-Deval results ranging from 5.6 to 10.1 percent loss (Figure 7). These values do appear to suggest a maximum value of 18 percent loss is reasonable. Test results for the sources categorized as fair performers had Micro-Deval values ranging from 6.3 to 28.1 percent loss. However, six of the seven sources categorized as fair did have Micro-Deval values less than or equal to 13.1 percent loss. The lone aggregate source identified as a poor performer had a Micro-Deval value of 5.7 percent loss. This result was the second lowest Micro-Deval value encountered for the South Carolina sources. Interestingly, similar to the Florida data, this lone source was a gravel source.

Comparison of Test Methods

Figure 9 presents all of the Micro-Deval test results from this study in the form of a frequency histogram. This figure shows that there was a wide spread in test results. Micro-Deval values ranged from a low of 1.4 to a high of 39.3 percent loss. The average Micro-Deval percent loss for all of the data was 11.9 and the standard deviation was 8.2 percent loss. The figure also shows that over 76 percent of data fell below the 18 percent critical value recommended by NCHRP 4-19 (2).

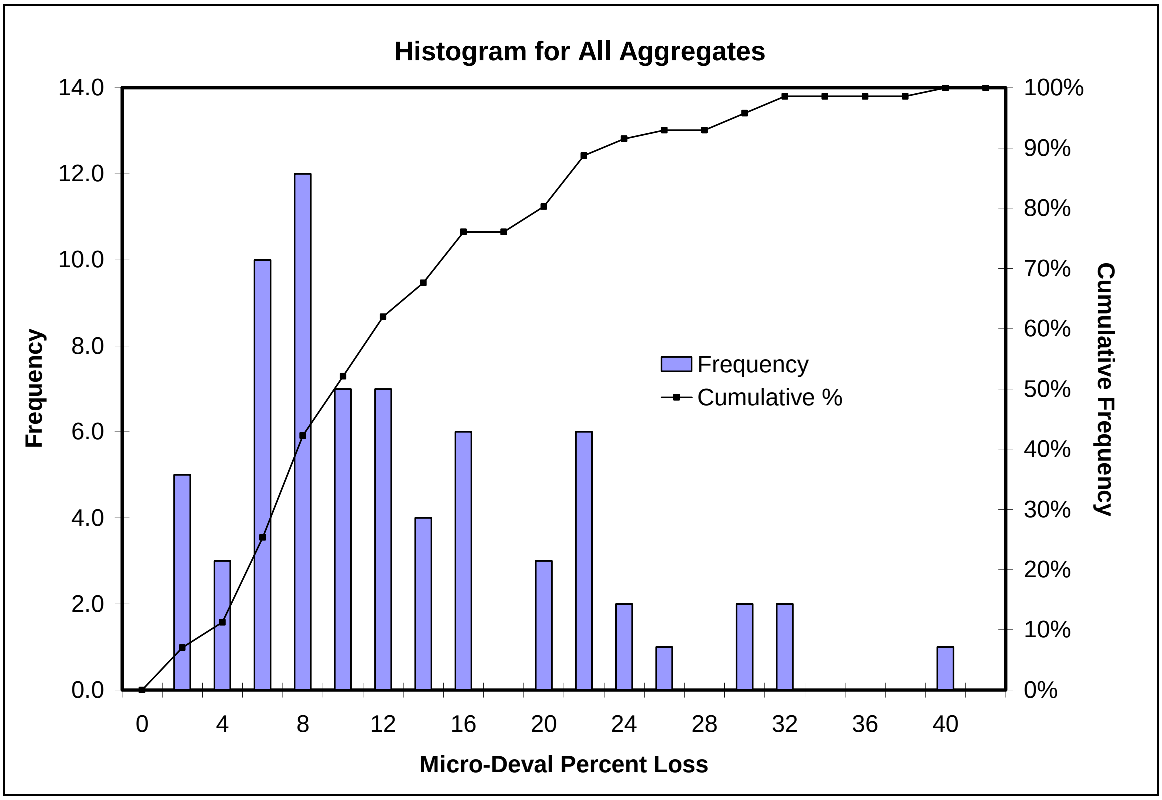

Figure 9. Histogram of All Micro-Deval Test Results

Figure 10 illustrates all of the L.A. Abrasion and Impact test results in the form of a histogram. Approximately half of the aggregate sources tested (48 percent) had percent loss values less than 30 and almost 90 percent had percent loss values less than 50. The average L.A. Abrasion and Impact test result was 31 percent, with a standard deviation of 13 percent loss.

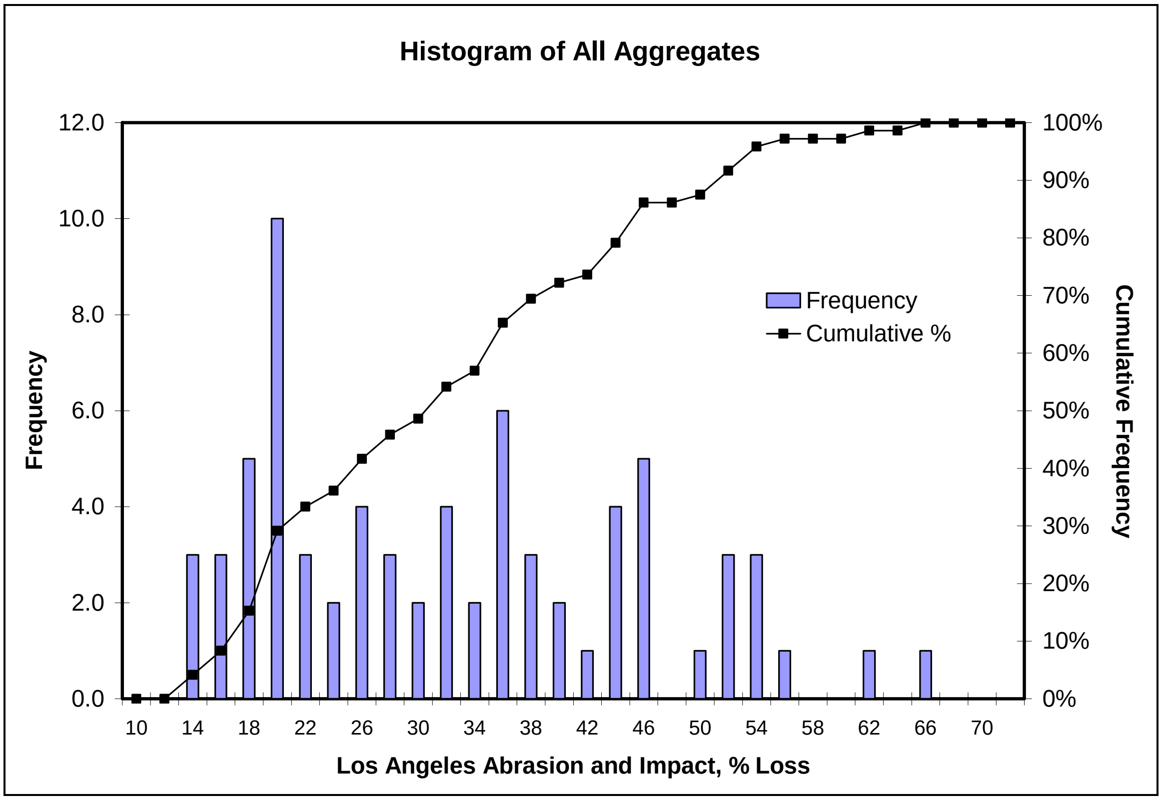

Figure 10. Histogram of All L.A. Abrasion and Impact Test Results

Figure 11 presents a histogram of all Sodium Sulfate Soundness test results. Approximately 92 percent of the test results had percent loss values less than 5 percent loss and 96 percent had test results less than 10 percent loss. The average test result was 1.3 percent loss, with a standard deviation for all results of 4.5 percent loss.

Figure 12 presents a frequency histogram of Micro-Deval test results for all of the aggregates, by performance category. This figure shows that approximately 85 percent of the sources categorized as good performers had test results below the 18 percent loss maximum value (2). The average test result for the good performers was 10.1 percent loss, with a standard deviation of 6.6 percent loss. Values ranged from a low of 1.4 percent loss to a high of 29.4 percent loss.

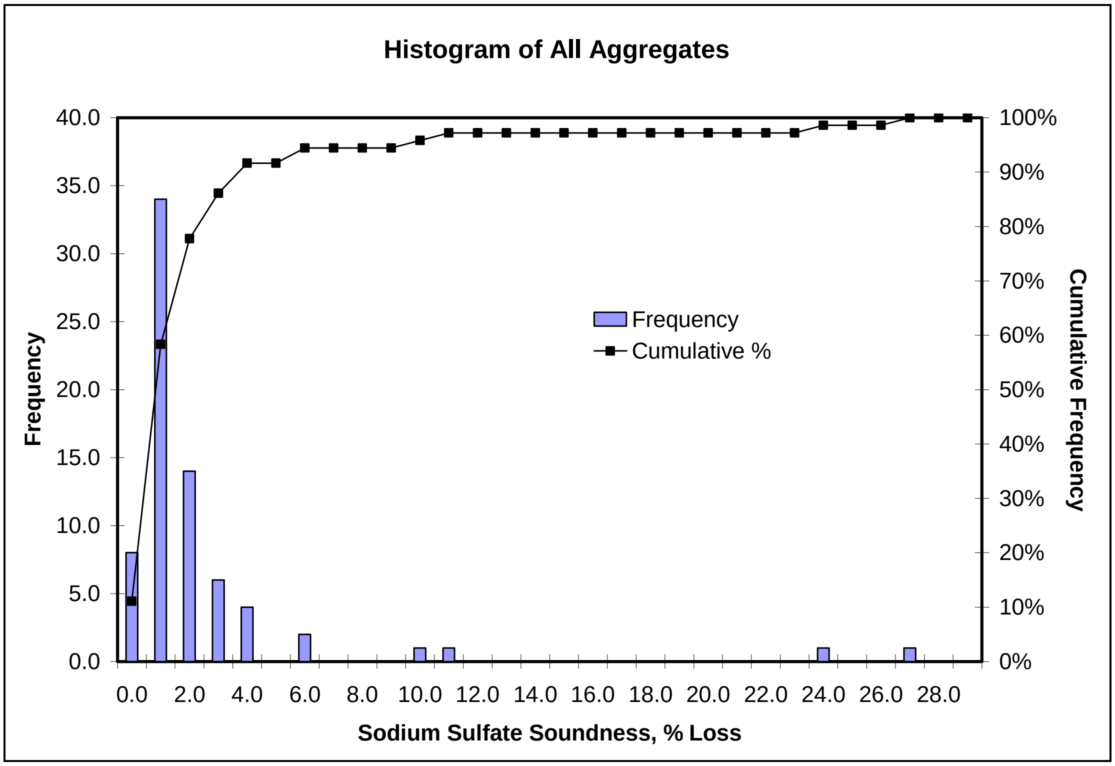

Figure 11. Histogram of All Sodium Sulfate Soundness Test Results

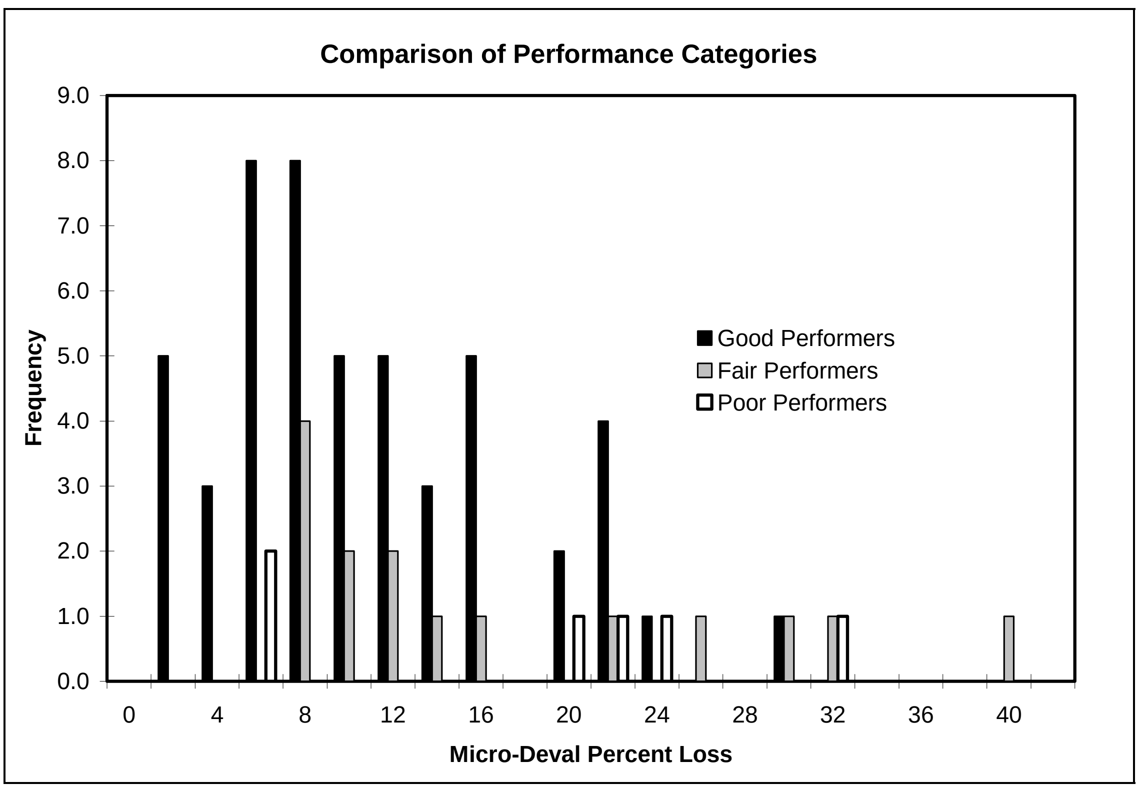

Figure 12. Comparison of Micro-Deval Test Results by Performance Category

Figure 12 also illustrates Micro-Deval test results conducted on sources having a performance category of fair. Approximately 67 percent of these data have Micro-Deval results less than 18 percent loss. The average test result for the fair performers was 15.9 percent loss with a standard deviation of 10.4 percent loss. As with most performance characterizations, the marginal type materials generally are the hardest to categorize. This difficulty may explain why the standard deviation of the fair performers was higher than for the sources categorized as good performers. Micro-Deval results for the fair performers ranged from a low of 6.3 to a high of 39.3 percent loss.

Only six of the 72 aggregates were categorized as being poor performers. Interestingly, two of the six aggregates had Micro-Deval results less than 6 percent loss. Both of these sources were gravel. The average Micro-Deval result for the poor category aggregates was 17.1 percent, which is lower than the 18 percent maximum recommended by NCHRP 4-19 (2); however, if the two gravel sources that had the Micro-Deval results less than 6 percent loss were removed from the data set, the average would be 23.0 percent loss. The standard deviation of Micro-Deval results including the two gravel sources (values less than 6 percent) was 9.9 percent loss. Micro-Deval results for the aggregates categorized as poor ranged from a low of 5.1 percent loss to a high of 30.1 percent loss.

Figure 13 illustrates the results of L.A. Abrasion and Impact testing by performance category. This figure shows that sources categorized as good performers had an average L.A. Abrasion and Impact percent loss of 28, with a standard deviation of 11 percent. Sources categorized as good performers had test results ranging from a low of 13 percent to a high of 53 percent loss. Sources having a performance rating of fair had an average L.A. Abrasion and Impact value of 40 percent loss, with a standard deviation of 14 percent. Values for the sources categorized as fair performers ranged from 19 to 61 percent loss. Sources categorized as poor performers had an average L.A. Abrasion and Impact test result of 44 percent loss, with a standard deviation of 13 percent. The sources categorized as poor had test results ranging from 28 to 66 percent loss. Similar to the Micro-Deval results, there was a wide range of results for both the fair and poor performance categories.

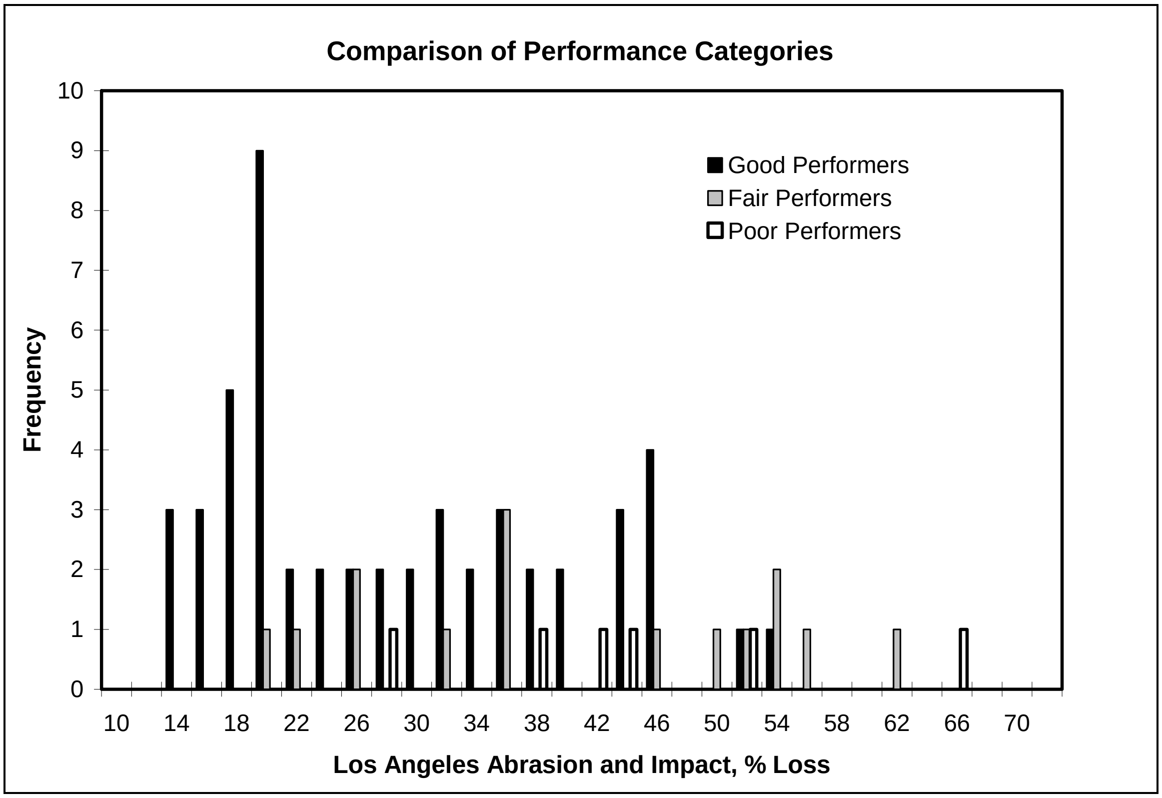

Figure 13. Comparison of L.A. Abrasion and Impact Test Results by Performance Category

Figure 14 illustrates all of the Sodium Sulfate Soundness test results by performance category. This figure shows that all of the good performing aggregate sources had very low soundness test results. The average percent loss of the good performing aggregates was 1.2, with a standard deviation of 1.4 percent loss. Values for the good performance category of aggregate sources ranged from 0.0 to 5.9 percent loss. There was a wide range of Sodium Sulfate Soundness test results for sources categorized as fair performers. The average result was 1.9 percent loss, with a standard deviation of 3.4 percent loss. Values ranged from 0.0 to 11.0 percent loss. Aggregate sources categorized as poor also had a wide range in test results. The average was 9.1 percent loss, with a standard deviation of 12.8 percent loss. Values ranged from 0.1 to 27.0 percent loss.

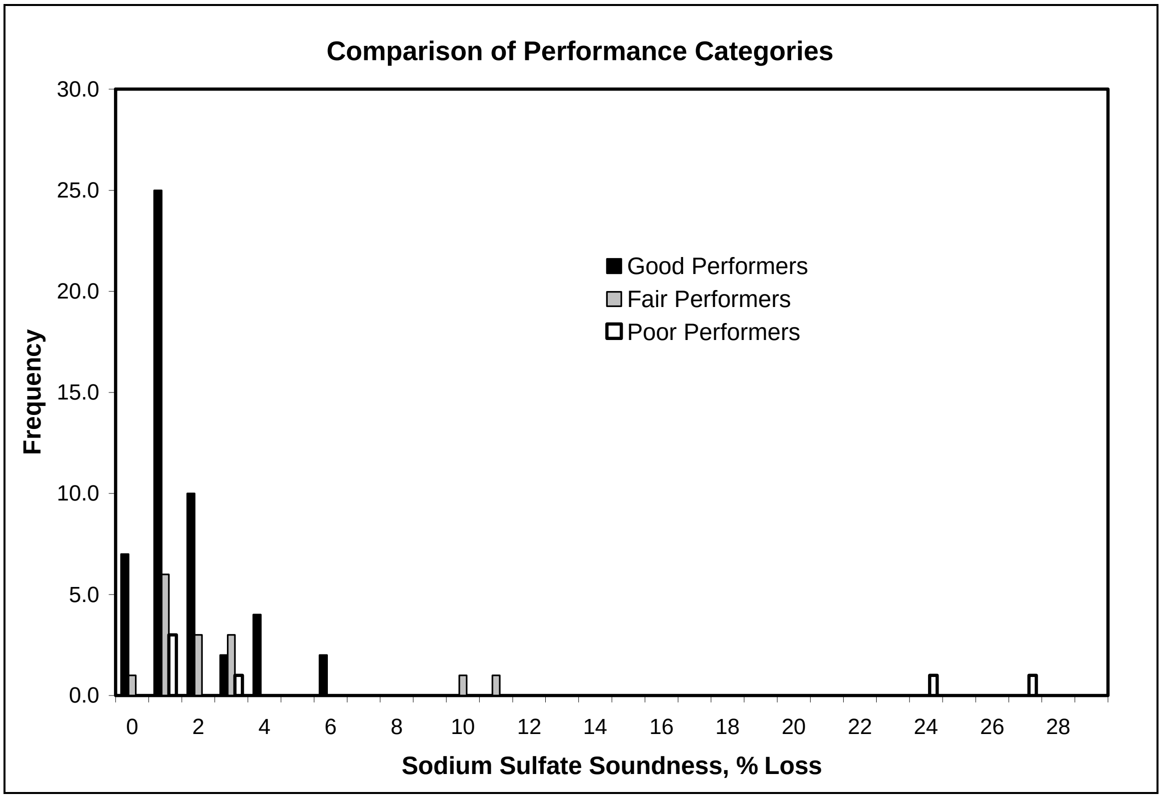

Figure 14: Comparison of Sodium Sulfate Soundness Test Results by Performance Category

Figures 12 through 14 showed a wide range in test results by performance category for all three test methods. A procedure for comparing the variability of each test method within a given performance category would be to evaluate the coefficients of variation (COV) for each category. The COV is defined as the standard deviation for a sample population divided by the mean of the same sample population, expressed as a percentage. Therefore, the COV normalizes the variability based on the mean. Table 10 presents the COV for each performance category by test method. Based on the COV, the Sodium Sulfate Soundness test method had the most variability for each of the performance categories. COV values for the Sodium Sulfate Soundness test ranged from 114.3 to 141.8 percent. The test method with the least variability within each performance category was the L.A. Abrasion and Impact method, which had a range of COVs from 29.8 to 39.3 percent. COVs for the Micro-Deval test were between the Sodium Sulfate Soundness and L.A. Abrasion and Impact test methods and had a range from 57.9 to 65.3 percent. All three test methods had mean test results that followed the performance categories. For each method, sources categorized as good had the lowest mean test result and the sources categorized as poor had the highest mean test result.

Table 10. Coefficients of Variation for Each Test Method, By Performance Category

Test Method	Performance Category	Mean Test Result, % Loss	Standard Deviation	Coeff. Of Variation, %
Micro-Deval	Good	10.1	6.56	64.8
	Fair	15.9	10.37	65.3
	Poor	17.1	9.91	57.9
Los Angeles Abrasion and Impact	Good	28.2	11.07	39.3
	Fair	39.9	13.96	35.0
	Poor	44.3	13.19	29.8
Sodium Sulfate Soundness	Good	1.2	1.39	114.3
	Fair	2.4	3.36	141.8
	Poor	9.1	12.78	140.7

Figure 15 illustrates the relationship between L.A. Abrasion and Impact test results and Micro-Deval results. Symbols on this figure show the performance category for each data point. Also included on this figure is the 18 percent maximum Micro-Deval loss recommended by NCHRP 4-19 (2). Based on the figure, there is a very poor relationship between L.A. Abrasion and Impact and Micro-Deval results. The R^2 value for the relationship was very low at 0.06. This was not totally unexpected because the two tests measure different characteristics of the aggregates. The L.A. Abrasion and Impact test measures an aggregate's resistance to both abrasion and impact, while the Micro-Deval test measures an aggregate’s resistance to abrasion only. The trend line does, however, show increasing L.A. Abrasion and Impact results with increasing Micro-Deval results.

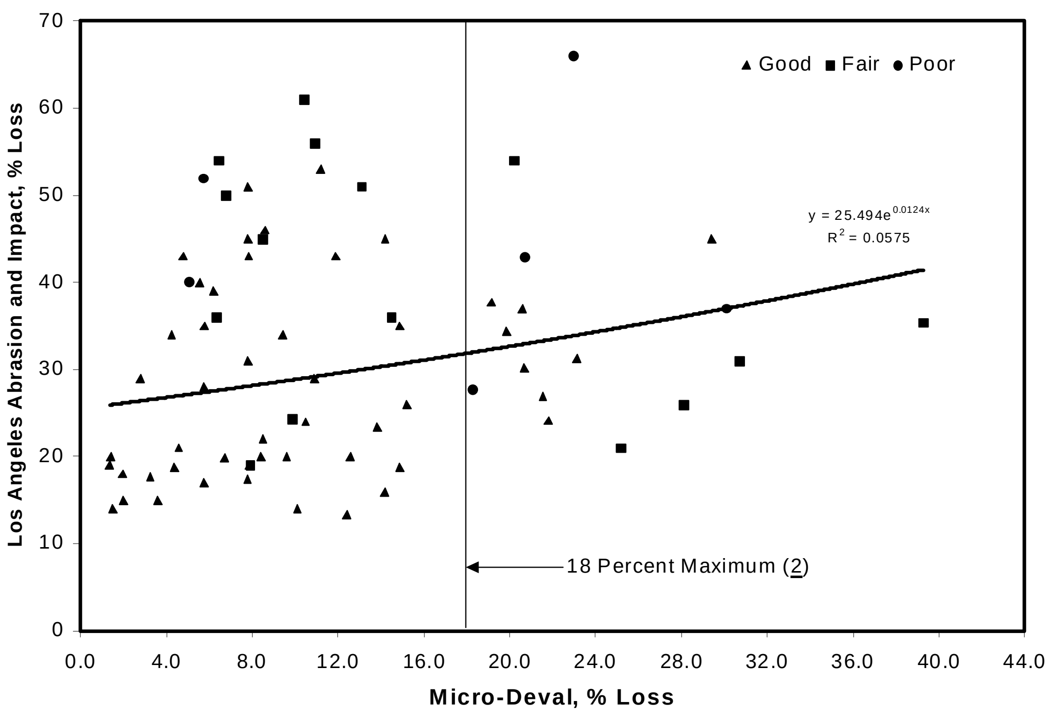

Figure 15. Comparison of L. A. Abrasion and Micro-Deval Test Results

Figure 16 illustrates the relationship between Sodium Sulfate Soundness and Micro-Deval results. Again, there was a poor relationship between the two tests as the R^2 value was 0.10. The trend line does show increasing Sodium Sulfate Soundness test results with increasing Micro-Deval results.

Based on the data presented within this section, there is no relationship between Micro-Deval results and either L.A. Abrasion and Impact or Sodium Sulfate Soundness results. However, this was expected because each test measures a different quality characteristic. Of the three tests, the Los Angeles Abrasion and Impact test showed the least variability by performance category.

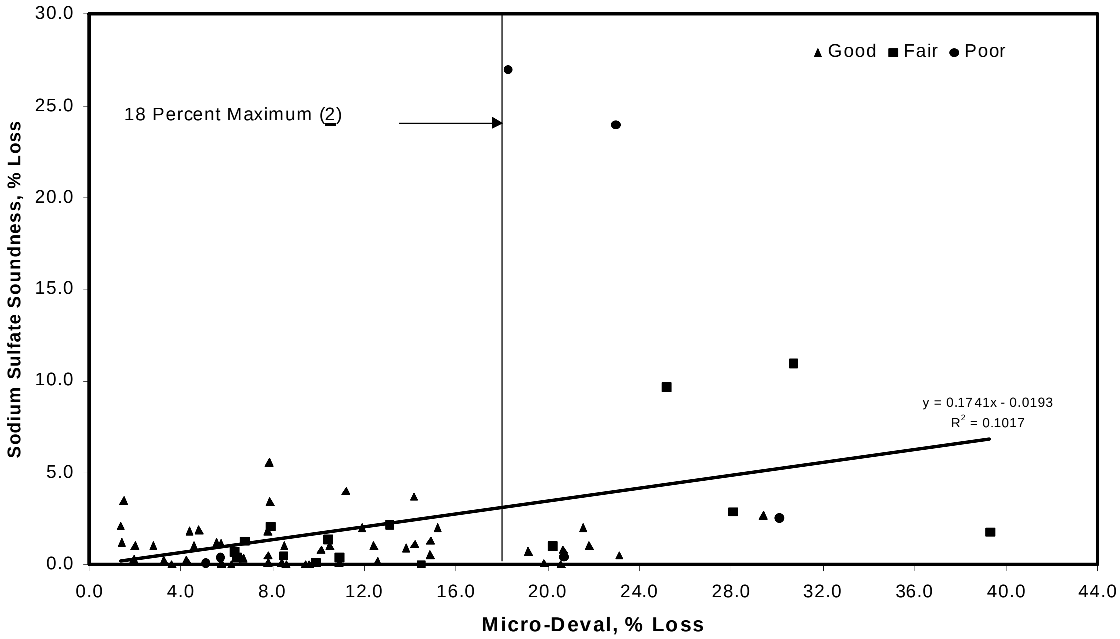

Figure 16. Comparison of Sodium Sulfate Soundness and Micro-Deval Test Results

Analysis of Micro-Deval Test Results

Figure 12 showed a wide range of Micro-Deval results for aggregates within a given performance category. A possible reason for these wide ranges of values is the subjectivity of assigning performance categories from state to state. Another possible reason was identified by Ontario (4). Recall from Table 1, the Ontario Ministry of Transportation has differing Micro-Deval specifications for different aggregate mineralogical types. The wide range of aggregate mineralogical types tested for this study may explain, in portion, the wide range of Micro-Deval results within each performance category. To investigate this possibility, four primary aggregate types were separated from the entire aggregate database: granites, limestones, gravels, and sandstones. These aggregate types were selected because there was at least four test results for each. Figure 17 illustrates Micro-Deval results for the granite aggregates by performance category. This figure shows that the Micro-Deval test did a good job of differentiating between the different performance categories. All of the granites categorized as good had Micro-Deval results less than 15 percent loss. The average for the good performing granites was 7.0 percent loss. The granites categorized as fair had Micro-Deval results ranging from 6.3 to 14.5 percent loss with an average of 9.6. The lone granite aggregate categorized as being a poor performer had a Micro-Deval result of 22.9 percent loss.

The ability of the Micro-Deval test to differentiate between performance categories for limestone aggregates is illustrated in Figure 18. A total of 21 limestone aggregates were tested. Ten of these aggregates are restricted in use by the respective states. Good performing limestone aggregates had an average of 15.8 percent loss (17.5 percent loss excluding the restricted sources). This value is much higher than the good performing granite aggregates. Micro-Deval results for the good performing limestones ranged from 7.8 to 29.4 percent loss, a much wider range than the granite aggregates. The fair performing limestones had an average test result of 26.2 percent loss and a very wide range in values (9.9 to 39.3 percent loss). Only a single source categorized as fair did not have a restriction (Micro-Deval value of 39.3 percent loss). The poor performing limestones all had Micro-Deval results above 18 percent loss and averaged 23.0. Again, only a single source categorized as poor did not have a restriction (Micro-Deval value of 18.3 percent loss).

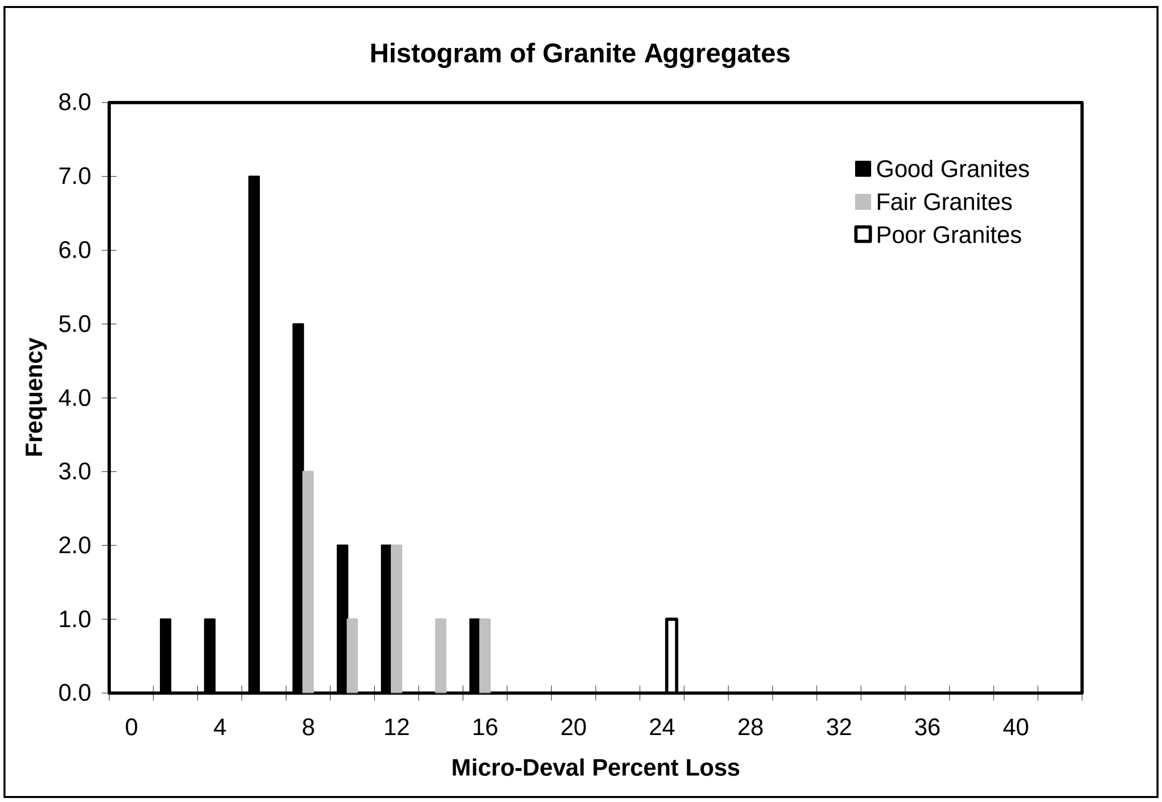

Figure 17. Histogram of Micro-Deval Results for Granite Aggregates By Performance Category

A total of 14 aggregates included in the study were identified as being gravel. Figure 19 illustrates the Micro-Deval results for these 14 aggregates by their performance ranking. Only two performance categories were identified for these gravels: good and poor. Twelve were identified as being good performers, while two were identified as being poor performers. Of those gravel sources identified as good performers, nine of the twelve had Micro-Deval values less than 9 percent loss. The remaining two good performers had Micro-Deval values in excess of 19 percent loss. The average test result for the good performers was 6.9 percent loss. Interestingly, the two gravel sources categorized as poor performers had low Micro-Deval test results (5.1 and 5.7 percent).

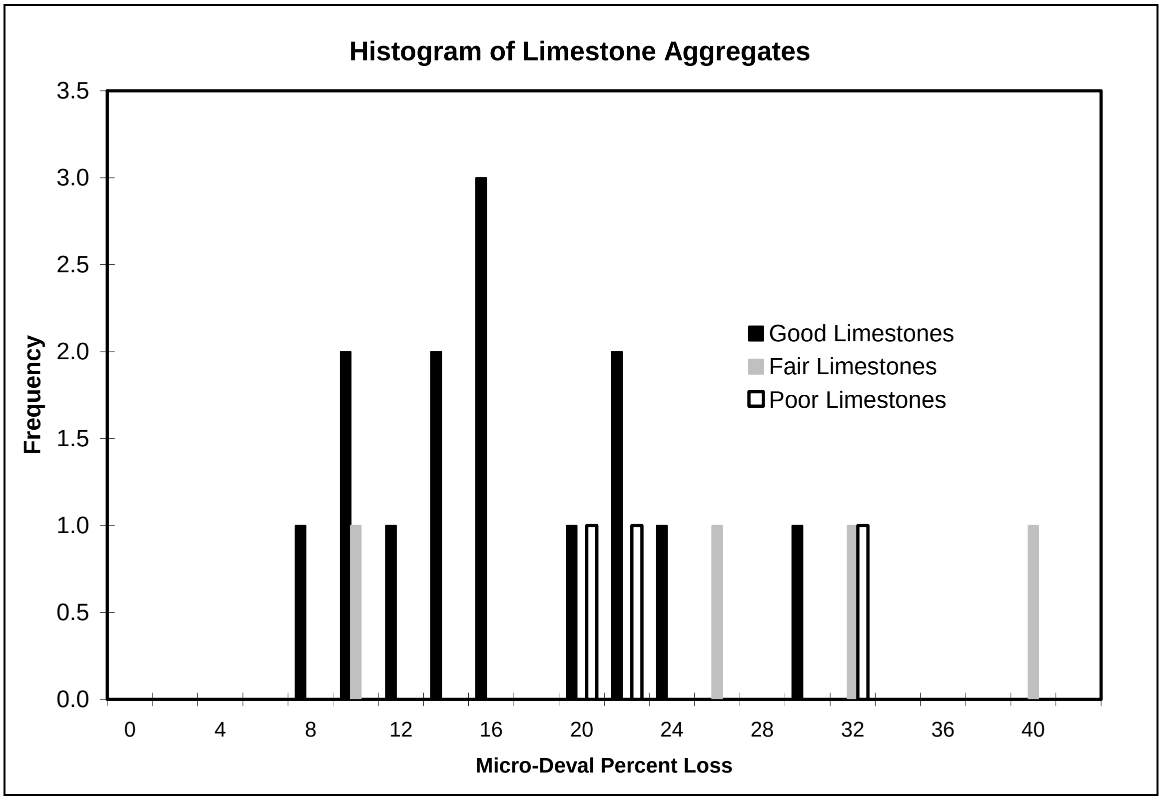

Figure 18. Histogram of Micro-Deval Results for Limestone Aggregates By Performance Category

Only two performance categories were also identified for the sandstone aggregates: good and fair. Micro-Deval results for the sandstone aggregates are illustrated in Figure 20. This figure shows that test results ranged from 11 to 22 percent loss. The average percent loss for the good performing sandstones was 15.0. Only a single sandstone source was identified as a fair performer and it had a Micro-Deval test result of 20.2 percent loss.

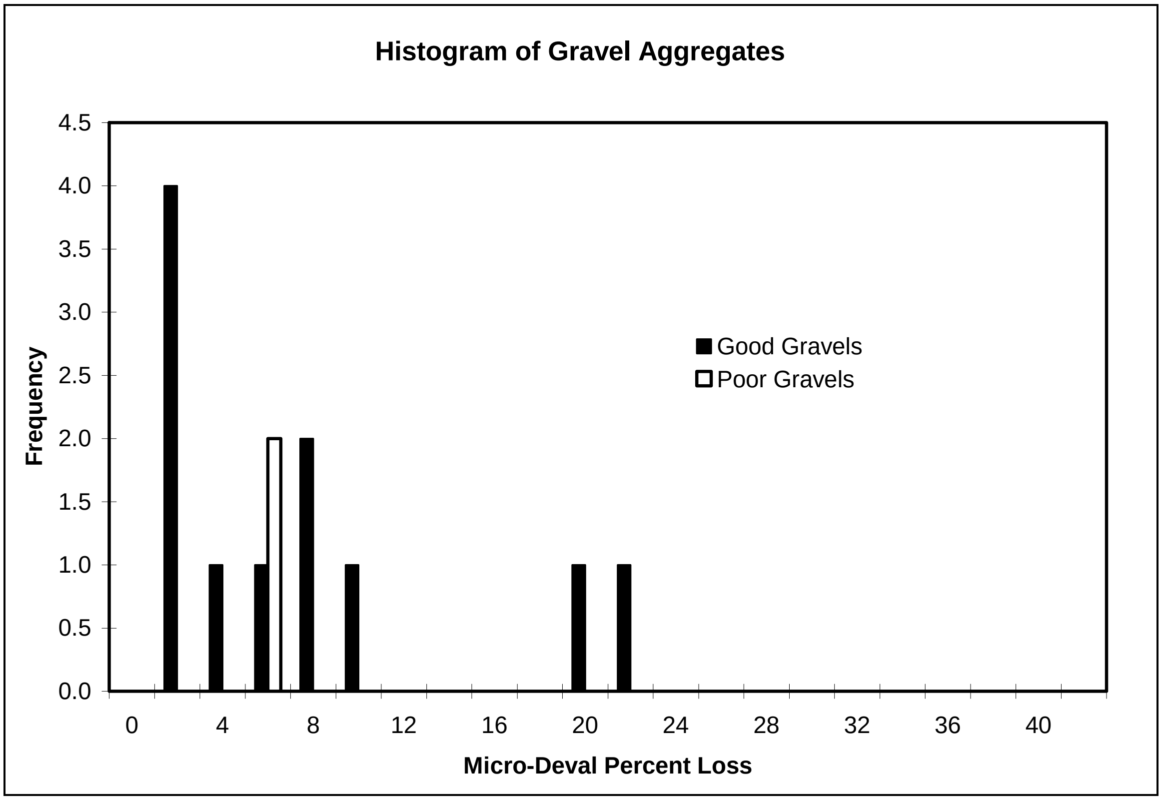

Figure 19. Histogram of Micro-Deval Results for Gravel Aggregates By Performance Category

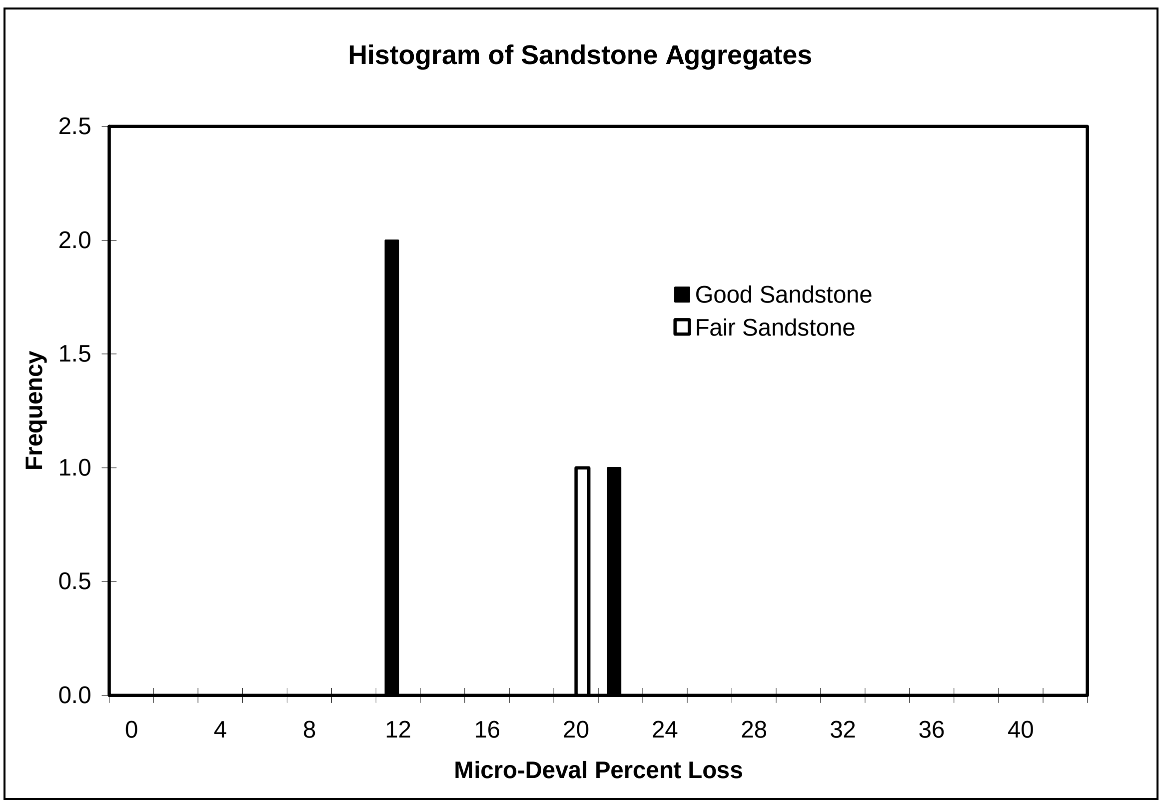

Figure 20. Histogram of Micro-Deval Results for Sandstone Aggregates By Performance Category

Figures 16 through 20 suggest that mineralogical type may affect the range of Micro-Deval results encountered. To investigate this possibility, an analysis of variance (general linear model) was conducted on the four aggregate types and included only sources identified as good performers. For this analysis, aggregate type was the only variable and sources identified as having restricted use were not included. Results of the analysis of variance are shown in Table 11. This table shows that for the aggregates that were categorized as good performers, the effect of aggregate type was significant at a level of significance of 95 percent. This result would indicate that an aggregate's mineralogical type would affect the expected results from the Micro-Deval test method. Further, this significance of mineralogical type may also suggest that specification criteria may change based upon the parent aggregate type similar to the specifications of the Ontario Ministry of Transportation (Table 1).

Table 11. Results of Analysis of Variance for Limestones, Granites, Gravels, and Sandstones Identified as Good Performers

Source	Degrees of Freedom	Mean Squares	F-statistic	P-value
Aggregate Type	3	285.62	10.22	0.000
Error	38	27.96		
Total	41			

Because aggregate type was found to be significant in the analysis of variance, a Duncan's multiple range test (DMRT) was conducted. For this statistical method, a level of significance of 95 percent was utilized. Results of the DMRT are presented in Table 12. For this table, aggregate types with the same letter ranking are not significantly different.

Table 12. Results of Duncan's Multiple Range Test for Limestones, Granites, Gravels, and Sandstones Identified as Good Performers

Aggregate Type	Mean Percent Loss	Duncan's Ranking
Granite	7.0	A
Gravel	6.9	A
Sandstone	17.5	B
Limestone	15.8	B

CONCLUSIONS

The objective of this study was to characterize aggregate sources using the Micro-Deval test. To accomplish this objective, 72 aggregates from eight different states were tested. These 72 aggregates were categorized by performance history by the respective states. Based on the results of this study, the following conclusions are provided:

- The Micro-Deval test had mixed results in categorizing aggregate sources in relation to the performance histories provided by the respective states.
- There was generally no relationship between either the L.A. Abrasion and Impact or Sodium Sulfate Soundness test results and the Micro-Deval test results for an individual state's data.
- There was no relationship between either the L.A. Abrasion and Impact or Sodium Sulfate Soundness test results and the Micro-Deval test results when the data was evaluated as a whole.
- Specifications developed for the Micro-Deval test method may need to be based upon the parent aggregate type. There were significant differences between aggregate types when aggregates categorized as good performers were compared.

ACKNOWLEDGEMENTS

The authors would like to thank the participating members of the Southeastern Superpave Center for contributing to this research. The participants identified aggregate sources and assigned performance categories to each source. Thanks is also expressed to the following members of the Southeast Superpave Center Management Committee for reviewing this report: Cecil Jones, Allen Myers, Milt Fletcher, Merril Zawanka, and Gale Page. Members of the NCAT Application Steering Committee who reviewed the report included: Mr. Chuck VanDeusen, Jay Winford, Dean Wietzel, and Eric Harm.

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