Micro-Deval Test for Evaluating the Quality of Fine Aggregate for Concrete and Asphalt

C. A. Rogers, M. L. Bailey, and B. Price

The sulfate soundness test has been used for many years for evaluating the physical suitability of fine aggregate. This test suffers from poor within-laboratory and multilaboratory precision; it is a time-consuming and expensive test. The work described here was an evaluation of alternative tests for measuring soundness of fine aggregate. The tests studied were the attrition test and a modified version of the French micro-Deval test usually used for coarse aggregate. The micro-Deval test was found to have a significant correlation with magnesium sulfate soundness loss and water absorption of fine aggregate. Unlike the attrition test, the micro-Deval test is relatively insensitive to the gradation of the sand being tested and has excellent precision. The test is conducted by placing 500 g of water-saturated sand in a ball mill with 1250 g of 9.5-mm steel balls and 750 ml of water. The mill is rotated at 100 rpm for 15 min. The aggregate is washed over a 75-μm sieve and the loss is calculated as a mass percent of the original oven-dry weight. The test may be completed in less than 48 hr. Aggregates that give more than 25 percent loss are judged to be marginal for use in portland cement concrete and asphaltic concrete. The Ontario Ministry of Transportation has adopted the micro-Deval test for measuring the quality of fine aggregate for concrete and asphalt.

In many areas of North America, especially near urban areas, it is recognized that construction aggregates are a depleting resource. The sterilization of resources by restrictive zoning regulations, building development, and "not in my back yard" (NIMBY) groups further contribute to shortages of moderate-cost aggregates. As a result, there is often pressure to use lower-quality or marginal-aggregate sources. At the same time, there is a demand from engineers to use higher-quality aggregates than were used in the past. For instance, where higher truck tire pressures and axle loads are causing rutting of asphalt pavements made with natural sand and gravel aggregates, the solution is to use quarried aggregates, excluding some traditional sources. Higher traffic volumes call for the use of pavement surfacing aggregates of better frictional properties, again excluding some traditional sources. There is, thus, a conflict between development, which tends to reduce aggregate resources, and an increasing demand for high-quality aggregates as a result of this development.

Aggregate testing and evaluation procedures and specifications have not kept pace with the modern technology. Some of the testing procedures used today are not necessarily the best available for the evaluation of the suitability of aggregates. Aggregates are often rejected for certain uses when they fail to meet one or more specifications, yet the actual field performance in concrete or asphalt may be satisfactory.

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The automatic rejection of aggregates that fail to meet existing specification requirements can lead to a reduction in available aggregate resources. The use of tests with an improved correlation with field performance and better precision than some of the current tests would allow the selection of some of the so-called marginal aggregates with greater assurance that they will be suitable.

One of the most commonly used aggregate tests in North America is the magnesium sulfate soundness test. The forerunner of the present magnesium sulfate soundness test was developed in 1828. The purpose was to simulate the forces generated by freezing water in building stone. In the early 19th century, there was no means of freezing water in the laboratory so this test served well. The magnesium sulfate soundness test has been used for many years for testing fine aggregate. On fine aggregate, the sulfate soundness test unfortunately has poor multilaboratory precision. In repeated studies of the multilaboratory variation in five Ministry of Transportation laboratories, it was found (*1*) that the average coefficient of variation was 10.5 percent, and the 95 percent difference limits were 30 percent (over a range in values from 7 to 22 percent loss). In other words, in repeated testing of a sand with an average loss of 16 percent, the range in values reported by various laboratories will be from 13.6 to 18.4 percent, 19 times in 20. ASTM (C 88) does not give precision data for the fine aggregate test, but notes that: "Since the precision of this test method is poor . . . it may not be suitable for outright rejection of aggregates without confirmation from other tests more closely related to the specific service intended."

In the late 1970s, work by the Ontario Ministry of Transportation found a significant correlation ($r = 0.68$) between the wet attrition test of Davis et al. (*2*) and sulfate soundness loss of fine aggregates (*3*). In the late 1980s, it was decided to study this relationship further in the testing program reported in the following sections. It was thought that wet abrasion or attrition tests would be more precise than the sulfate soundness test, be quicker, and measure more or less the same properties as the sulfate soundness test. A number of wet abrasion tests were selected for study.

TESTING PROGRAM

ASTM Attrition Test

This test has been adopted by ASTM (C 1137–90). It consists of placing a washed, graded, 500-g sample of sand in an eightsided container where it is subjected to vigorous abrasive action with a high-speed impeller at 850 rpm in the presence of 175 ml of water. Loss is measured by the decrease in fineness modulus or the increase in the amount of material passing the 75-μm sieve. In this study, the ASTM procedure was used with a WEMCO impeller and tank with the following modifications: test duration was extended from 6 to 10 min because 6 min seemed somewhat arbitrary and causing significant loss in the test was desired. The sands were washed over a 75-μm sieve and dried before testing but were not graded to a standard grading. Change in fineness modulus (FM) was not reported.

MTO Attrition Test

This test is similar to the ASTM attrition test. It has been used by the Ministry of Transportation Ontario (MTO) for 10 years for evaluating the objectionable mud-producing properties of sand spread on icy road surfaces (*3*). The impeller device, more robust than that used in the ASTM procedure, was that specified by Davis et al. (*2*). A 500-g sample was tested in 175 ml of water for 10 min at an impeller speed of 390 rpm. This speed was adopted several years ago because the 850 rpm originally used by Davis et al. (*2*) was found to cause excessive splashing.

Micro-Deval Abrasion Test

This test has been developed in France (*4–6*) for the evaluation of coarse aggregate. It has since been adopted in the province of Québec (*7*). It consists of abrading a sample of 500 g of stone with 5000 g of 9.5-mm-diameter steel balls and 2.5 L of water in a 5-L steel jar, 200 mm in diameter. The jar is rotated at 100 rpm for 2 hr. Loss is measured by measuring the amount of material passing a 1.25-mm sieve. For testing fine aggregate, the test was modified as follows: A 700-g sample of sand was washed on a 75-μm sieve and oven-dried. A representative oven-dry subsample of 500 ± 5 g was prepared and immersed in tap water at room temperature for 24 hr. Excess water was poured off and the sample placed in a steel jar with 1250 g of steel balls and 750 ml of water. The jar was rotated at 100 rpm for 15 min. The sample was washed over a 75-μm sieve and oven-dried to constant mass. Loss was expressed as percent by mass of the original sample mass.

Samples were also tested to determine their gradation, absorption, relative density, and loss in the magnesium sulfate soundness test.

SAMPLE COLLECTION

Ideally, it would have been desirable to test a group of samples that had a field performance history ranging from good to bad. After over 40 years of experience, the Ministry of Transportation has never used a fine aggregate that caused or resulted in premature failure of concrete or asphalt that could be attributed to inadequate physical properties measured by the sulfate soundness test. Asphalt pavements have failed because of unsatisfactory fine aggregate particle shape or unsatisfactory grading. Concrete has failed because of some alkali-silica reactive component in the sand, poor grading, or the presence of objectionable quantities of organic acids. It has not been possible to attribute failure to an unsatisfactory property measured in the sulfate soundness test. Fine aggregates that had a sulfate soundness loss of up to 45 percent have occasionally been used in asphaltic concrete without apparent failure. This experience created a problem in devising a satisfactory sampling system.

A number of natural sands and crusher screenings that are used in Ontario exceed the sulfate soundness requirements for various applications. The Ministry of Transportation has specifications for maximum magnesium sulfate soundness loss for concrete and asphalt fine aggregate. The limit for portland cement concrete and high-quality asphaltic concrete use is a maximum of 16 percent loss, and 20 percent for lower-quality asphaltic concrete use. The specifications allow these limits to be exceeded if satisfactory field performance of concrete or asphalt and results of accelerated freeze-thaw testing of concrete can be shown to be satisfactory. For instance, natural sands found in the vicinity of the Niagara Escarpment typically contain large amounts of cemented particles and porous sandy carbonates that result in sulfate soundness losses of up to 25 percent. These sands perform well in asphalt and concrete and are approved and used for these applications (*8*). In 1989, a portland cement concrete supplier in Eastern Ontario was able to demonstrate that a natural sand performed well in field concrete and in accelerated laboratory tests. Despite sulfate soundness losses of up to 25 percent this material was approved for use in Ontario highway work. There are other examples, particularly with the crusher screenings from carbonate quarries that typically yield high sulfate soundness losses, yet perform well in asphaltic concrete. The reason for their high losses is not exclusively caused by any large amount of weak or otherwise unsound particles but is partly caused by the coarseness of gradation of these screenings, which in the test calculations, can unfairly penalize them. New York State has also recognized this problem with coarse sands giving high sulfate losses, and now calculates loss in this test using a standard grading, irrespective of the grading of the sand tested.

In order to aid in setting specification limits for any new test that was adopted as a substitute for the sulfate soundness test, testing those sands that had a record of satisfactory field performance but exceeded the current specification limits was desired. A suite was selected of about 110 samples of fine aggregate that had a history of satisfactory performance in portland cement concrete or asphaltic concrete, or both. These samples were selected and sampled by highway engineers in the five administrative regions in Ontario. The location and nature of the samples tested are described elsewhere (*9*). The samples consisted of 86 natural sands and 21 quarry screenings. The quarry screenings were nearly all from Paleozoic carbonate quarries in southern Ontario. The natural sands consisted either of 100 percent of siliceous particles of Precambrian age from northern Ontario, or mixtures of Precambrian siliceous particles and Paleozoic sediments (carbonate, siltstone, sandstone, sandy carbonate, and shale) found in southern Ontario.

RESULTS AND DISCUSSION

The first task was an investigation of the influence of sample grading on degradation in the wet attrition and abrasion tests. A good-quality natural sand and crusher screenings from a shaley limestone quarry were prepared to four different gradings. The FM varied from 2.15 to 3.77. Samples of these materials were then tested in the ASTM and MTO attrition tests and the micro-Deval test. Results are shown in Figures 1 and 2. For the case of the attrition tests, the finer graded samples gave significantly lower losses than the coarse samples. In these tests, it is postulated that the larger particles have greater kinetic energy than the smaller particles, which led to greater disintegration on impact with the walls of the container. Alternatively, larger particles may simply be less resistant to damage than smaller particles. This observation indicated that, in future development, samples should be tested at a standard grading to remove the bias introduced by either coarser or finer gradings.

In contrast, the micro-Deval test demonstrated a negligible or reverse response. The finer the grading of the sample, the greater the loss. This influence of grading was relatively small at low losses (<20 percent), but became more obvious with higher-loss materials. This test is conducted at low speed in contrast to the attrition test. The particles have little kinetic energy and the main means of disintegration is a grinding action between the particles and between the particles and the steel balls. In this case, it would be expected that the amount of breakdown would be a direct function of energy

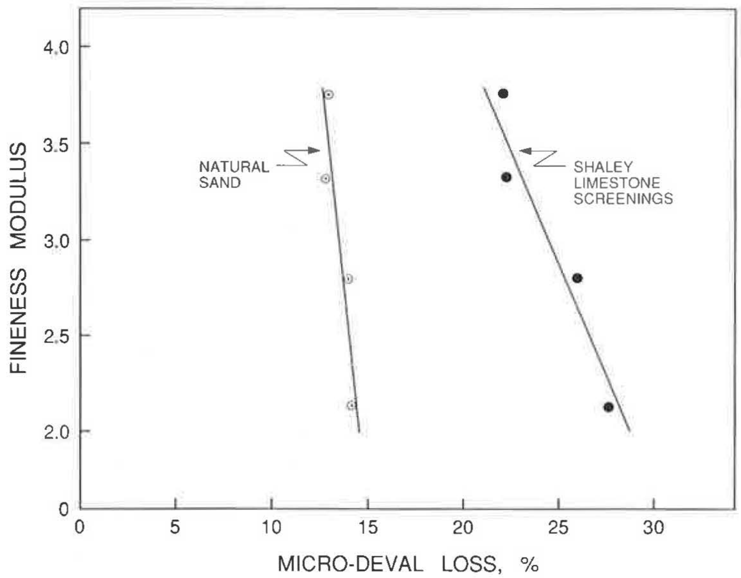

FIGURE 1 Attrition loss versus fineness modulus of sand and screenings.

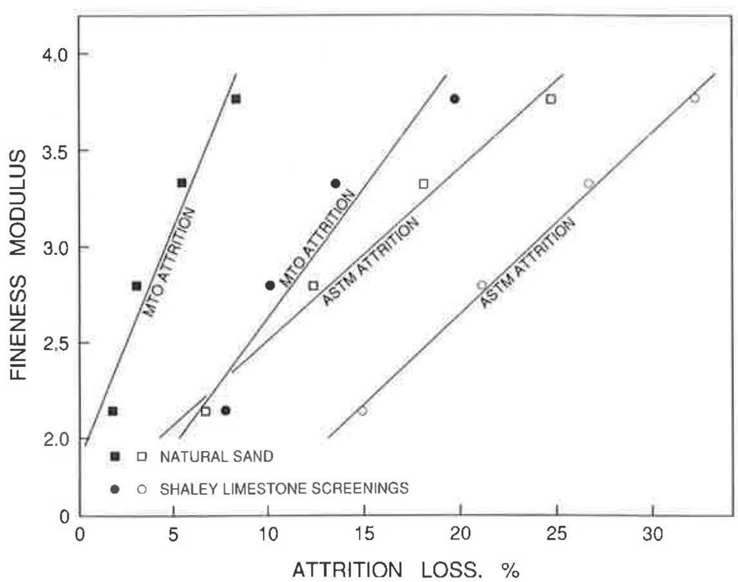

FIGURE 2 Micro-Deval loss versus fineness modulus of sand and screenings.

expended and also the original size of the particles. Less work has to be done on a fine than on a coarse graded sample to cause material to break down to pass the 75-μm sieve. This observation was confirmed by testing a further eight different materials at the four different gradings.

The within-laboratory variability of the three tests was determined by testing 10 replicate samples of natural sand and shaley limestone screenings. The results are presented in Table 1. The ASTM attrition tests gave the highest loss with the shaley limestone, but also had a wide variation. With the low-loss natural sand, the MTO attrition test has the widest variation, but this is mainly because of the low mean loss of 4.1 percent obtained in this test with this material, which distorts variability when using coefficient of variation. The micro-Deval test had the lowest within-laboratory variation of about 1 to 2 percent.

The micro-Deval test was thus found to be relatively insensitive to sample grading and also to have the lowest within-laboratory variation. These two attributes are much desired. The requirement to prepare samples to a standard grading before testing is time consuming and expensive. In the case of very fine or very coarse materials, large amounts of material must be sieved to obtain the desired standard grading. In some cases, such as with fine sands, it is difficult to obtain enough coarse material to make up a sample to a standard grading. In any event, such a sample can hardly be representative.

In order to investigate likely multilaboratory variation in the micro-Deval test, an experiment was devised. Replicate samples of 58 different materials were tested in different equipment at different times by different technicians. The micro-Deval loss of the materials ranged from 5 to 31 percent; the average coefficient of variation was 3.2 percent. In practical terms, this means that testing of replicate samples of a material with a mean loss of 20 percent in different laboratories should give results between 18.2 and 21.8 percent, 95 percent of the time. This variation is wider than that found in the within-laboratory investigations (Table 1) but it is still excellent compared to many other materials tests.

In spite of the marked effect of grading on loss in the attrition tests, they were conducted without using a standard grading. The samples were washed, dried, and prepared to 500 g, but no attempt was made to grade the material to a constant grading. It was desired to see if, despite the effect of grading on loss, any useful relationship existed between these tests. Figure 3 shows the relationship between the ASTM and MTO attrition tests. As should be expected, there is an excellent correlation, but there is a marked difference in performance in the two tests. On average, there is about 3 times more loss in the ASTM attrition test. This is because of the higher speed of the impeller (850 rpm) in this test compared to the MTO test (390 rpm). Over the course of testing the 110 samples, there was considerable wear on the ASTM impeller and this had a marked effect on loss in the test. After every 10 samples were tested, a replicate sample of laboratory sand was tested. There was a consistent and gradual reduction in loss in this test from the start of the program to completion, from 42 to 36 percent loss for shaley limestone screenings and from 16 to 12 percent with natural sand. After 110 samples had been tested, a new impeller was fitted to the ASTM attrition device, and loss of these materials increased to the original values of 42 and 16 percent. In any future development of the ASTM attrition test, this problem will have to be compensated for. Because more robust blades are mounted on the impeller, the MTO attrition test did not show this problem, and results of testing replicate samples remained consistent throughout the program.

Figure 4 shows the relationship between the ASTM attrition test and magnesium sulfate soundness loss. There is a significant correlation both for natural sands and screenings. The attrition loss of the screenings was considerably greater than that for natural sands, probably because of the coarser gradation of screenings compared with natural sands. Had testing been conducted at constant grading, such a marked difference would probably not have been observed. However, there is a relationship that could be used to predict sulfate soundness loss.

The relationship between micro-Deval and magnesium sulfate soundness loss of all samples is shown in Figure 5, that for concrete sands in Figure 6, and that for asphalt sands and screenings in Figure 7. There is excellent correlation for both natural sands and for crusher screenings. In Figures 6 and 7, proposed new requirements are shown for various applications. They will replace the existing magnesium sulfate soundness specifications. In Figure 7, the proposed requirement for hot-laid (HL) 1 and 3 fine aggregates refers to the highest-quality asphaltic concrete used exclusively for surface courses. The requirements for HL 2, 4, and 8 refer to lower-quality asphaltic concrete used in surface courses on secondary highways and in binder courses. In May 1990, on an experimental basis, these requirements were adopted for some Ontario highway contracts. Adoption of these new criteria will result in the acceptance of some materials that had previously not met the soundness requirements. This is intentional. At the time materials were selected for sampling, it was specified

TABLE 1 WITHIN-LABORATORY VARIABILITY OF ATTRITION AND MICRO-DEVAL TESTS

	NATURAL SAND		SHALEY LIMESTONE SCREENINGS	
	Mean loss	C of V.	Mean loss	C of V.
micro-Deval	13.8%	1.9%	23.4%	1.1%
ASTM Attrition	13.3%	11.0%	38.8%	6.8%
MTO Attrition	4.1%	14.1%	20.1%	5.4%

Number of replicates = 10, C of V = coefficient of variation

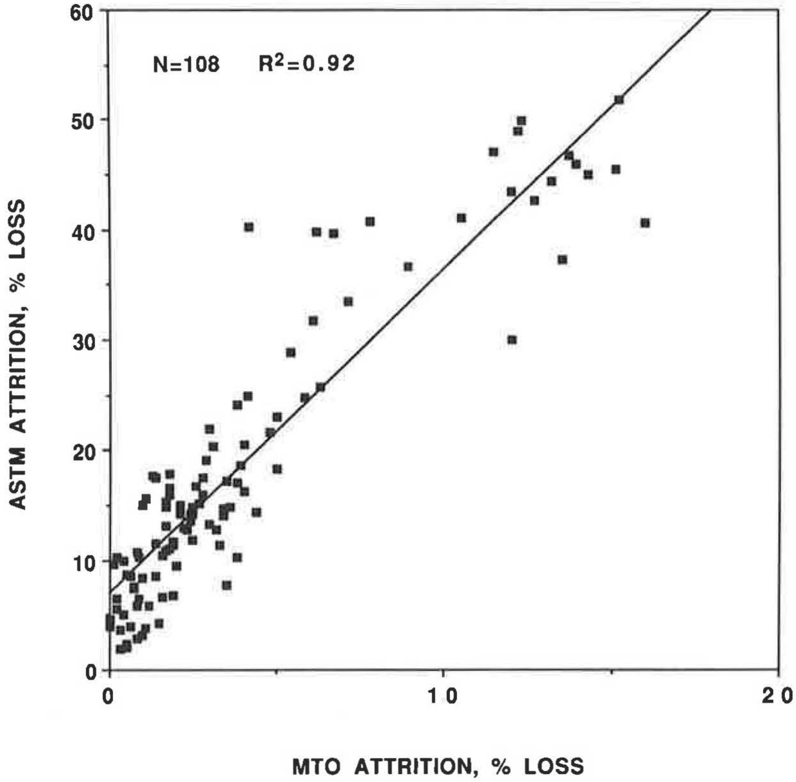

FIGURE 3 ASTM attrition loss versus MTO attrition loss for sands and screenings.

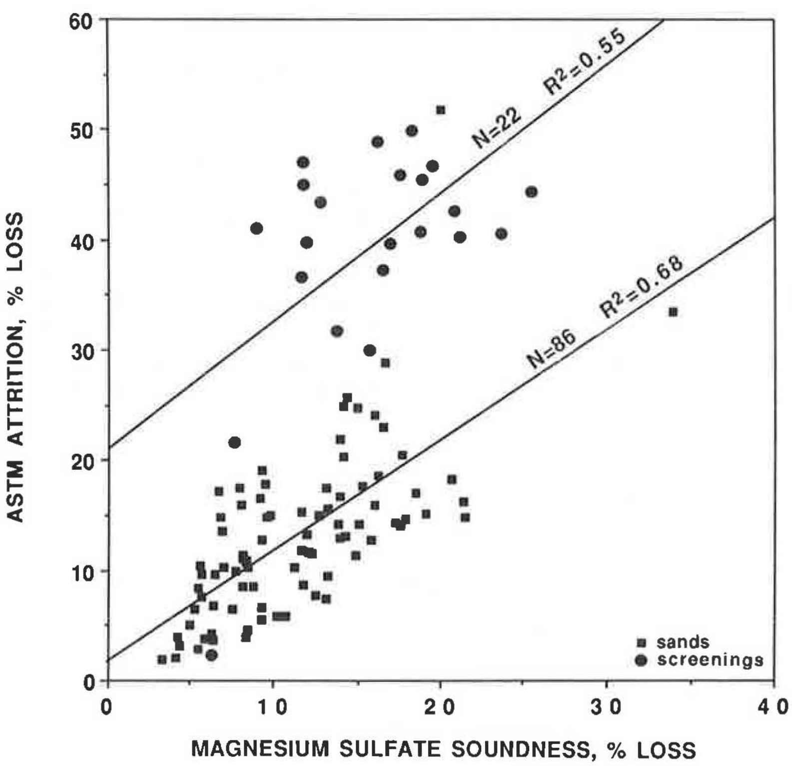

FIGURE 4 ASTM attrition loss versus magnesium sulfate soundness loss.

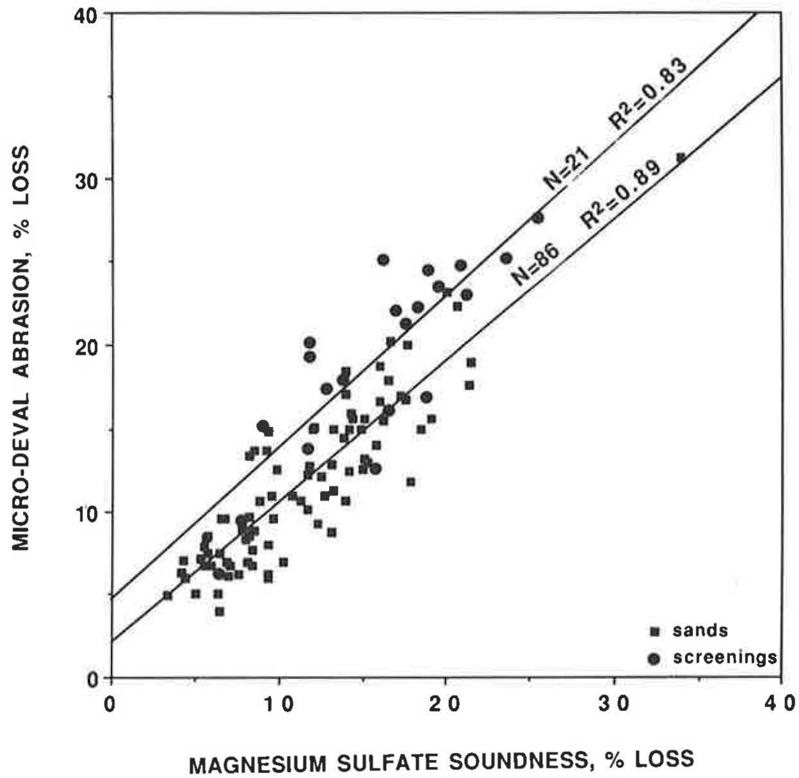

FIGURE 5 Micro-Deval abrasion loss versus magnesium sulfate soundness loss for sands and screenings.

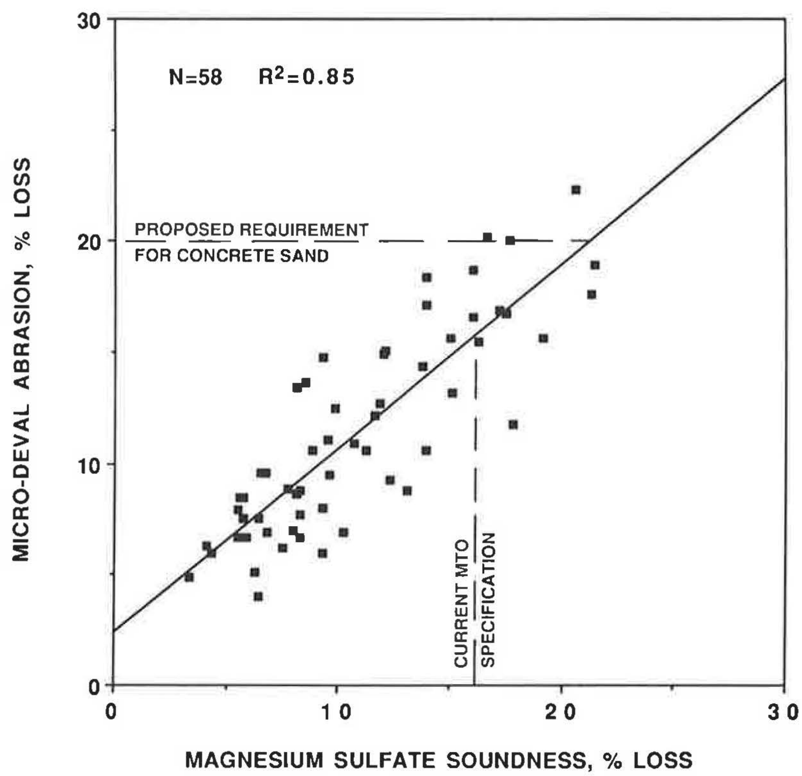

FIGURE 6 Micro-Deval abrasion loss versus magnesium sulfate soundness loss for concrete sands.

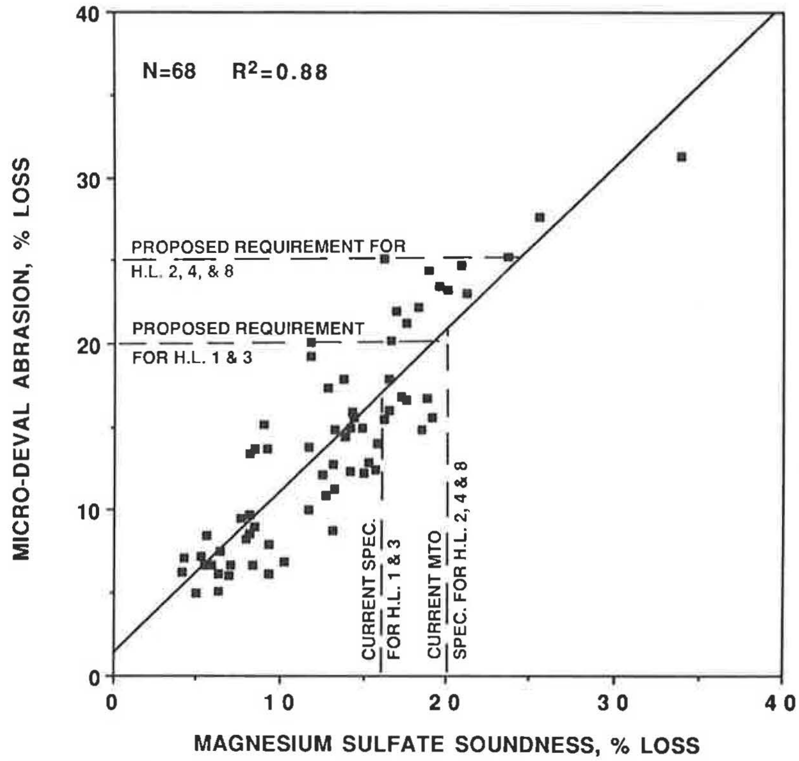

FIGURE 7 Micro-Deval abrasion loss versus magnesium sulfate soundness loss for asphalt sands and screenings.

that the materials should be those currently used on MTO work, even if they exceeded the current soundness specifications. These materials had a record of having been used without any known or obvious deleterious effect, so an adjustment to selection criteria is justified.

In order to see how reliable the micro-Deval test was at measuring the quantity of low-quality material in an otherwise satisfactory sand, a low-strength, slaking shale (Queenston) was oven-dried, crushed, and sieved. This shale was then blended with a high-strength quartz sand (from Ottawa, Illinois) at various levels of substitution. The results, shown in Figure 8, indicated an excellent relationship between amount of shale and loss in the test.

Significant correlation was found between water absorption and performance in the various tests. In the wet attrition/abrasion tests, this is probably partly caused by a slaking effect. Material that is susceptible to slaking has a high microporosity (shales, clays, and shaley limestones). The more po-

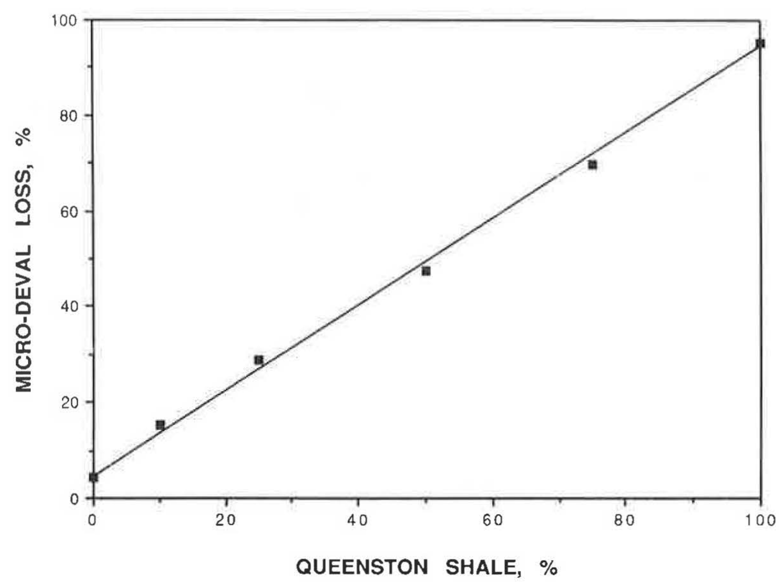

FIGURE 8 Micro-Deval loss versus amount of low-strength Queenston shale in quartz sand.

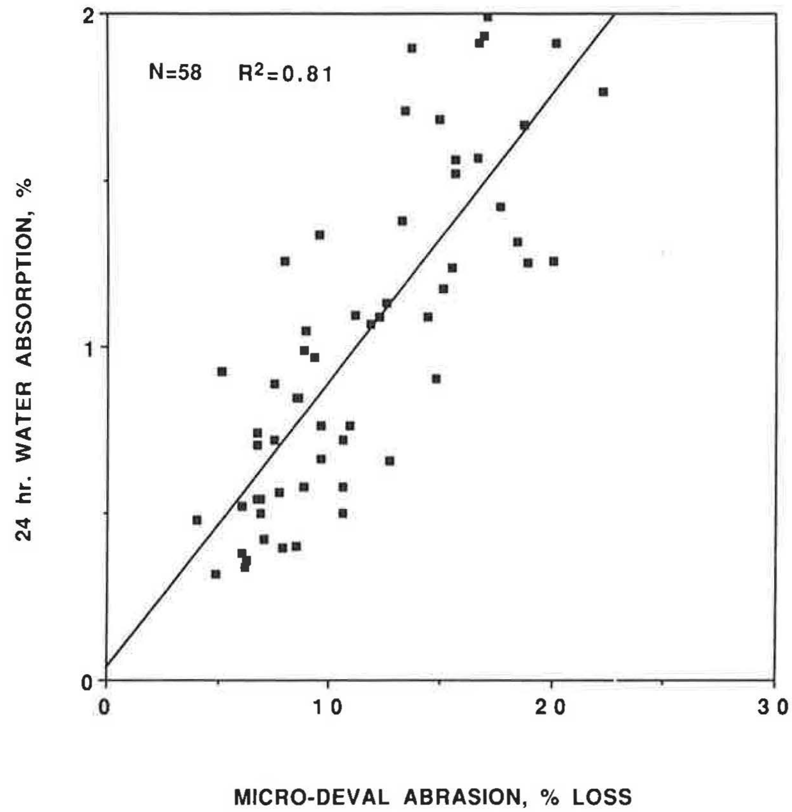

FIGURE 9 Twenty-four-hour water absorption versus micro-Deval abrasion loss for concrete sands.

rous materials will generally be weaker and break down more readily when subjected to abrasion or attrition. The correlation between natural concrete sand and micro-Deval loss shown in Figure 9 is particularly striking. A significant correlation was also found between water absorption and magnesium sulfate soundness loss ($r = 0.64$) and between water absorption and ASTM attrition loss ($r = 0.71$). Adams and Pratt (*10*), Mather (*11*), and Chamberlin (*12*) all found high positive correlations between water absorption of natural sands and loss in magnesium sulfate soundness tests ($r = 0.81, 0.81,$ and 0.82, respectively). This relationship is logical, because the higher the porosity, the more sulfate solution that can enter the particles and exert destructive pressure when crystallized in the drying cycle of the test.

IMPLEMENTATION

A detailed procedure for the micro-Deval test has been written (*9*). A feature of the test is a requirement to periodically test a reference material to observe and control within and between laboratory variation. It is intended that after every 9 samples are tested, a 10th sample, which is the reference aggregate, should be tested and results plotted on a control chart. If a laboratory only rarely conducts the test, then testing of the reference aggregate should be conducted whenever the test is performed. MTO has purchased a 15-tonne stockpile of shaley limestone screenings that is being used as reference material.

CONCLUSIONS

The magnesium sulfate soundness test for fine aggregate has a poor multilaboratory precision and is not always suitable if rigid specification criteria are applied. The test is time consuming, taking 10 days.

The micro-Deval test is a rapid, simple test. Results can be obtained within 2 days. It has good correlation with the sulfate soundness test. The predicted within-laboratory and multilaboratory variability of the micro-Deval test is good, and can be easily controlled using a reference material. The test is suitable for identifying fine aggregates that contain significant amounts of poor or weak rock types.

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