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INTRODUCTION AND BACKGROUND

The determination of the grading of an aggregate blend or stockpile is one of the oldest test procedures used in the hot mix asphalt (HMA) and aggregate industries. The control of aggregate grading by the HMA industry begins during aggregate production and ends when the grading of the finished HMA is determined. Sieve analyses are used in many different applications, some of which are the determination of aggregate grading for use in HMA mix design procedures (Marshall, Hveem, and Superpave), the process control of produced material, and the particle size control and monitoring of quarried materials. In the HMA industry, sieve analyses are often performed on plant produced samples to determine the proximity of the produced aggregate blend to the job mix formula aggregate grading. The number of grading tests performed for a given project depends on many factors such as the number of stockpiles, type of HMA plant, tonnage of HMA produced, process control methods used, and acceptance procedures outlined by the owner. Further, the grading of the aggregate blend in HMA can be considered one of the most important mix parameters since it affects, in varying degrees, the stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance, moisture susceptibility, and volumetrics of the produced mixture (*1*). Therefore, it is very critical that the grading analysis of the produced material be done in a timely and accurate manner, so as to yield the true result, and to allow for the adjustment of the aggregate grading, if necessary, to ensure a quality product. Although aggregate grading analysis is one of the oldest test procedures, it remains a very time consuming and labor intensive task.

There is a need today within the HMA industry for a rapid, automated method to determine aggregate grading. This automated method should reduce the time required to perform a grading test as well as reduce the amount of technician time required. The need to reduce the test time arises from the fact that grading testing of aggregate samples is used for process control during the production of HMA and requires a significant amount of time for an HMA project. A typical project may require from 5-10 grading tests per day depending on the specification requirements, number of aggregates, and plant production rate. If the test time for grading testing can be reduced by 50 percent (approximately 15 minutes), several hours of total test time per day can be saved.

Today, the most widely accepted and accurate method for aggregate grading determination is through a washed or wet sieve analysis, as outlined in ASTM C117 (*2*) and ASTM C136 (*3*). The main reason for performing a wet sieve analysis is to obtain a more accurate indication of the true grading, primarily on the material passing the 0.075 mm sieve. As one might expect, when the amount of material passing the 0.075 mm sieve is low, the washed and the dry sieving procedures often yield very comparable results; however, when the percent passing is high the results can vary considerably.

A method of determining the grading of an aggregate blend in a more efficient manner is greatly needed in the HMA and aggregate industries. By increasing the efficiency of the grading analysis, there is a potential for greater control to be obtained over the produced product by the increased ability to perform more grading analysis throughout production.

Besides aggregate stockpile gradings, the grading of the finished HMA mixture must also be determined for control and acceptance purposes. To obtain the aggregate grading either the aggregate must be recovered from the HMA or a belt sample taken and analyzed. The technician time involved is approximately one-half to one hour for each test. Add this to the time required to determine stockpile gradings and several hours of technician time can easily be expended on a relatively small amount of process control. The need to automate the testing procedure is evident.

If grading testing can be automated, the resulting reduction in time requirements would allow the producer to choose one of two options. With the increase in available technician time, more testing could be performed to allow for better process control. Or if desired, fewer technicians would be needed to perform the same level of process control.

OBJECTIVES

The main objective of this study was to research, select, and evaluate method(s) that might be used to automate the determination of aggregate grading in order to shorten the testing time involved, and to decrease the amount of technician time required. Any method developed to meet this goal should also be affordable and be able to provide an accurate grading; especially important is an accurate measure of the percent passing the 0.075 mm sieve.

To accomplish the objectives a significant amount of background research was done on the various methods of automatic grading analysis. A device was then selected for further research and evaluation. This evaluation consisted of determining the accuracy and precision of the device when compared to conventional accepted grading analysis procedures.

SCOPE

To accomplish the stated objective three main tasks were completed. These tasks included 1) a review of current technology available within other industries that deal with measurement of particle sizes (grading), 2) selection of the best current technology, and 3) establishment of acceptable operational parameters and test procedures for the automated grading device.

CURRENT TECHNOLOGY REVIEW

In reviewing current technologies for possible application to aggregate grading testing, many possibilities were investigated. Several industries make use of grading tests for manufacturing and/or quality control of products. For example, both the food and drug industries make wide use of grading testing to assist them during production. In addition, the in-line measurement of particle size is used by heavy industries such as power generation and steel manufacturing to help control plant emissions.

The HMA and aggregate production industries have continued to pursue new technology aimed at increasing the accuracy of grading testing while decreasing the time required. Air separation techniques are now being used at aggregate production facilities to “air wash” aggregates. Washing of the coarse aggregate in this manner creates less waste and reduces environmental concerns.

In the preparation of this report, all of these technologies were carefully reviewed. Each of these was judged against the four criteria of reduced test time, reduced technician time, affordability, and the ability to obtain an accurate grading. The methods reviewed are discussed individually in the following paragraphs.

Gradex 2000

The Gradex 2000 Particle Size Analyzer, manufactured by Rotex, Inc., located in Cincinnati, Ohio, has been used for a number of years in many industries, such as the pharmaceutical, ceramic, food products, etc. (*4*). However, its application in the hot mix asphalt and aggregate industries as a means of determining the grading of an aggregate blend has only recently been evaluated.

The automatic grading device, shown in Figure 1, accomplishes grading analysis by automating the conventional sieve analysis procedure which has been used for many years with good results. The grading device consists of a set of standard 203 mm diameter round U.S. sieves, an automatic feeding/loading assembly (optional), a collection pan, and a 0.1 gram resolution electronic balance. The device, as first built, was capable of holding six full-height sieves or nine half-height sieves, or any combination thereof.

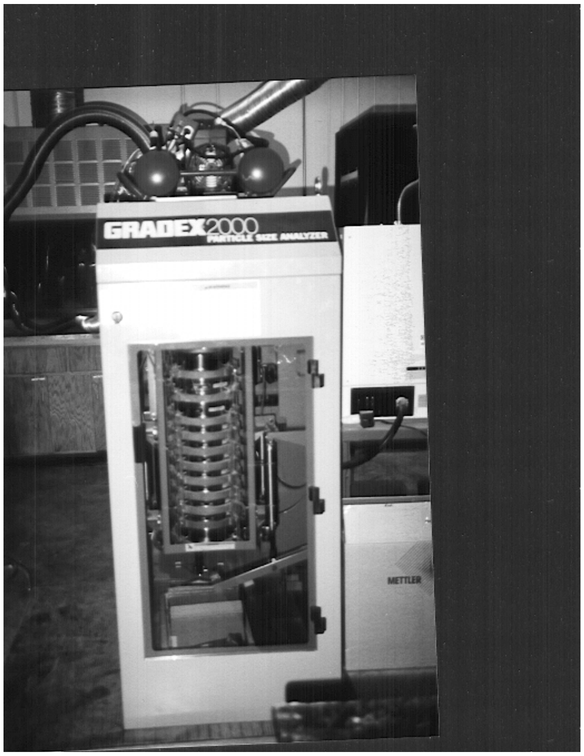

Figure 1. Gradex 2000 Particle Size Analyzer

A computer system, complete with operational software for the grading device, is interfaced with the device to allow for operator control and retrieval of grading analysis data. Operation of the device is very simple and requires a minimum amount of labor. First the operator completes all of the sample information using the provided computer software. This information includes items such as the operator's name, test specimen identification, sieving time, etc. Next, a sample is loaded into the top of the device, either manually through the feed chute, or by the automatic feeding/loading assembly, which is sold as an attachment. Once the sample is loaded, the operator initiates the grading analysis by the touch of a key. The device then sieves the material for the specified sieving time (approximately 10 minutes) in a rotary or tapping motion, which is currently used by many mechanical sifters or shakers in operation today. After sieving is complete, the sieves are emptied, as shown in Figure 2, into the collection pan, which rests upon the electronic balance. This process begins with the pan and proceeds through the sieves from fine to coarse, until the last sieve is emptied. After each individual sieve is emptied into the collection pan, a brush, shown in Figure 3, operated through air pressure, cleans the inside of the sieve to remove any particles which may have become lodged during the sieving process. After the individual sieve has been cleaned, it is returned to its appropriate location in the sieve stack. Following the completion of the sieving, weighing, and cleaning procedures, the results of the

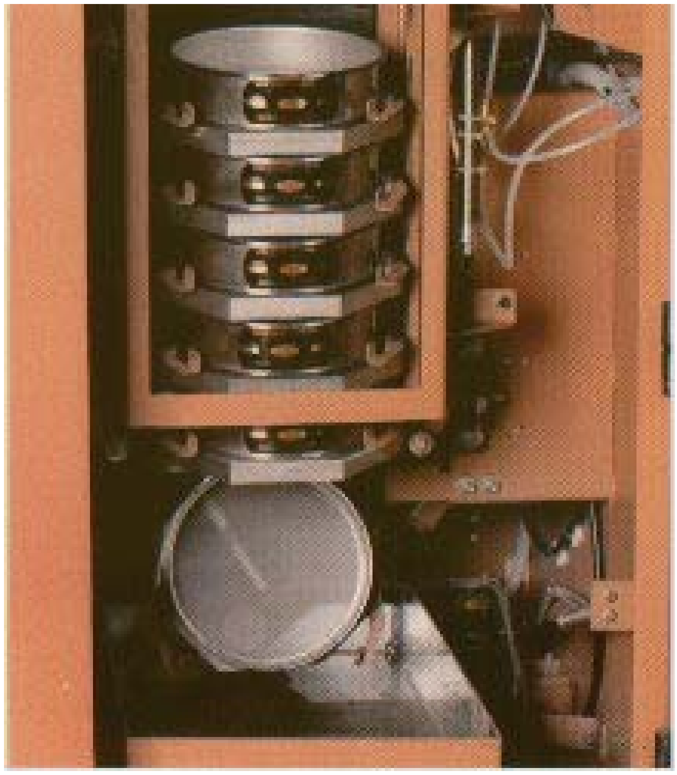

Figure 2. Gradex 2000 Sieve Configuration (*4*)

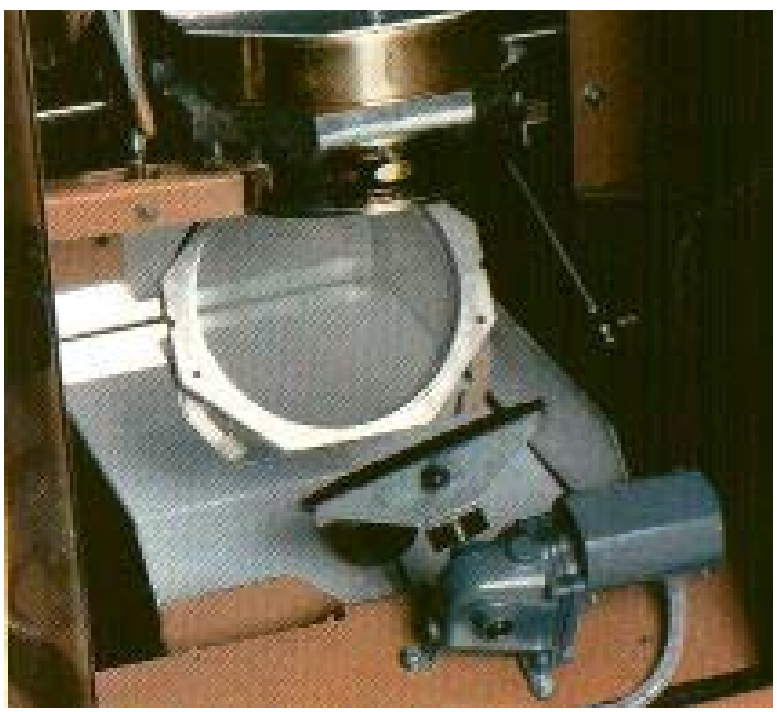

Figure 3. Gradex 2000 Brush Cleaning Attachment (*4*)

grading analysis can be viewed on the computer screen or saved to a data file. A sample of the product file information is shown in Figure 4. As is shown, information such as sample identification, sieves used for analysis, and tabular results showing the percent retained and percent passing are provided for the user.

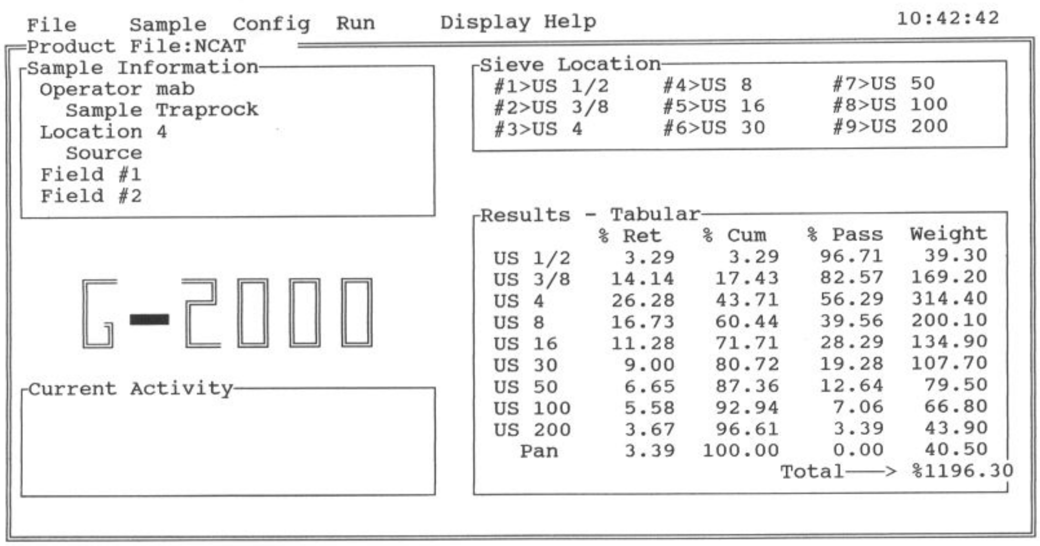

Figure 4. Product File Information from Gradex 2000

In order to determine accuracy of the Gradex 2000 to determine the grading of aggregate samples, two blended aggregate mixes were prepared and tested in the device. The results of this preliminary testing with the Gradex 2000 are shown in Table 1. None of the results shown in Table 1 include sample washing prior to the grading determination. The results indicate that the Gradex 2000 is accurate at determining the percent passing for most sieves, but it has a tendency to underestimate the percent passing the 0.075 mm sieve. However, some of the under-estimating on the 0.075 mm sieve is believed to have been caused by sieve blinding, a problem that can be remedied. Note also that the Gradex 2000 is limited in the number of sieves that it can hold. The sieve stack can consist of either six full height sieves or nine half height sieves. Mixture 1 was tested using a stack of six full height sieves. Mixture 2 was tested using a stack of nine half height sieves. The ninth sieve in this stack was a “placeholder” (a sieve frame with no wire). Placeholder sieves can be used to make the Gradex 2000 even more flexible. For example, in testing Mixture 2, the desire was to use only eight sieves. Since the machine can only hold six full height, or nine half height sieves, it was necessary to use half height sieves for Mixture 2 testing. A placeholder sieve was therefore inserted into the stack as the ninth sieve. The placeholder does not measure an aggregate fraction size, but simply allows the Gradex 2000 to hold the stack properly.

A shorter testing time is possible if the sample is not washed prior to testing. If an accurate measure of the percent finer than the 0.075 mm sieve is required, the sample can be washed prior to using the Gradex 2000. However, in certain instances, an apparent reduction in both test time and required technician time can be realized while obtaining an accurate measure of the percent passing the 0.075 mm sieve. This arises from the ability to automatically test several samples in sequential order. Therefore, if a technician has several aggregate gradings to perform, all of the preliminary work such as washing the sample (or extracting the asphalt cement) could be performed during the working day and the resulting aggregate samples could be set to sequentially test during the night. When the technician returned the next day, the computer

Table 1. Grading Results Comparing Standard Dry Sieve Analysis With the Gradex 2000

Sieve Size (mm)	Percent Passing			
	Mixture 1		Mixture 2	
	Standard Test	Gradex 2000	Standard Test	Gradex 2000
25.0	100.0	100.0	100.0	100.0
19.0	100.0	99.8	100.0	99.7
12.5	78.8	78.9	89.2	89.9
9.5	24.7	24.1	49.0	49.1
4.75	1.1	0.5	25.6	25.3
2.36	1.0	-	20.3	20.2
1.18	1.0	-	17.3	-
0.600	0.9	0.4	14.5	14.1
0.300	0.9	-	13.5	-
0.150	0.8	-	10.8	-
0.075	0.5	0.1	5.0	1.2

would have all of the grading testing completed. In this scenario an accurate measure of the percent passing the 0.075 mm sieve is achieved, the technician time involved is reduced (he/she doesn't have to empty and weigh the contents of each sieve), and the grading testing time is removed from the normal work day. At the time of this study the cost for the Gradex 2000 varies, depending upon equipment configuration, from $17,000 to $25,000.

VDG-40 Video Grader

The VDG-40 Video Grader was developed by the Laboratoire Central des Ponts et Chaussèes (the French Public Works Laboratory) and is currently marketed in North America by a Canadian Company. It has recently become the standard French test method for the determination of aggregate grading as well as percent flat and elongated particles. The equipment consists of a chute through which the aggregate is fed, a vibrator and rotating drum for separating particles, a light source, and a bank of photosensitive cells (5). A schematic of the machine is shown in Figure 5. A personal computer is used to collect and analyze the data. The VDG-40 can be used to continuously monitor the grading of an aggregate stream. Cost for the standard VDG-40 Video Grader is approximately $50,000.

Prior to sample testing, the VDG-40 must be calibrated. This is done by preparing two blended aggregate samples, one corresponding to the minimum grading specification and the second to the maximum grading specification. These samples are tested in the machine individually to allow it to establish the grading envelope. Once the grading envelope has been determined for the given aggregate blend, testing of samples can begin (*6*).

To test a sample in the VDG-40, all particles smaller than 1.0 mm must first be removed from the sample. This is due to the limits of the machine. It is capable of testing aggregate sizes ranging from 1.0 to 50.0 mm although it can be adapted to handle particles up to 63.0 mm. The separation of particles smaller than 1.0 mm involves washing and "scalping" the sample with a 1-mm sieve. The total weight of the sample, the weight of the sample portion finer than the 1-mm sieve, and the weight of the sample portion coarser than the 1-mm sieve must all be entered

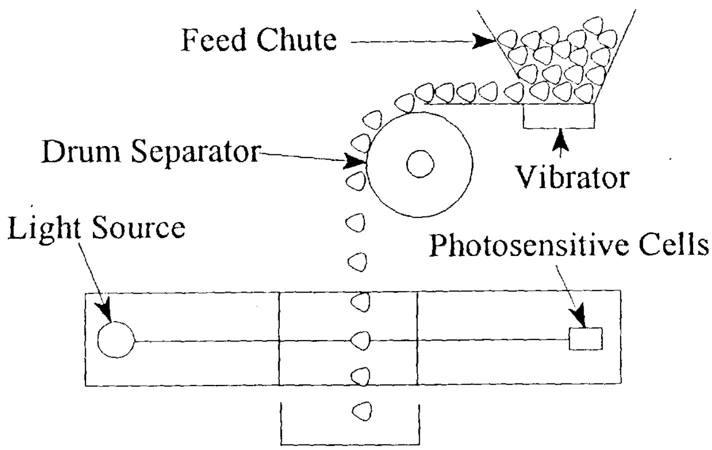

Figure 5. Schematic of the VDG-40 Video Grader (5)

into the computer by the operator. The fraction of the sample larger than the 1-mm sieve can then be introduced into the machine. The particles are fed through the chute and onto the vibrator which helps to separate the particles. The particles then pass over the drum and fall through the light curtain established by the light source and light-sensitive cells. The resolution of the light-sensitive cells is 0.2 mm horizontally and 0.4 mm vertically. When the aggregate particles pass through the light, the computer determines a two-dimensional shape for the particles. The computer software can then determine a three-dimensional shape for the aggregate particles using the principle of an ellipsoid of revolution. In addition, the computer also determines flat and elongated characteristics. A sample takes approximately eight minutes to be tested once it has been introduced into the VDG-40 (5).

The VDG-40 is automated, but suffers from lack of ability to test particles smaller than 1.0 mm. In addition, the washing and scalping needed prior to testing increases the overall test and technician time involved, thus increasing the cost for testing.

Full-Scale Particle Size Analyzer

In 1972, a report was completed at the University of Texas-Austin describing a full-scale particle size analyzer (7). The analyzer, based on sedimentation theory, consisted of an inner and outer ring. The outer ring was 6.1 m tall and 90 cm in diameter. The basic purpose for the outer ring was to hold the water and to provide structural support for the inner ring. The inner ring was 5.2 m tall and had an outside diameter of 76 cm. Two gates, one at the top and one at the bottom were used to hold the sample until introduction into the column and to collect it once it had settled in the column. The inner ring was suspended in the water by a scale linkage connecting it to the outer ring. This scale linkage served as a means of transferring the force applied to either the upper or lower gate to load a cell. This mechanism allowed for the sample mass to be determined on the upper gate prior to its introduction. It also allowed for the mass of the sample to be recorded as a function of time as it settled onto the bottom gate. No cost estimate was included in the report, but any such estimate would certainly be outdated. Indeed the ideas used for this full-scale particle size analyzer could benefit from technology developed since 1972.

Operation of the full-scale analyzer involved taring the mass of the inner column and water, introducing the sample onto the top gate and recording its mass, opening the top gate to introduce the aggregate sample into the water column, and recording the mass of the sample particles as a function of time as they settled onto the bottom gate. The report concluded that a particle size ranging from 0.43-37.5 mm could be separated and analyzed (*7*).

Comparison of this method against the criteria outlined earlier is difficult. It appears that a version of this equipment making use of current technology would be automated and reduce both test time and technician time requirements. The cost for the system is unknown, but would most certainly be relatively expensive. It also has limits on particle sizes that can be analyzed and it will not produce an accurate measure of the percent passing the 0.075 mm sieve. Although the aggregate is washed in the water column, the 0.075 mm particles cannot be detected by the system because of their small size.

Fractionating Water Column

This method was evaluated at the University of Waterloo (*8*) and is a smaller, modified version of the full-scale particle size analyzer previously discussed. It consists of a 1.5 m long by 77 mm inner diameter plexiglass tube that is filled with water. Near the bottom of the tube a constant intensity light shines through the water column and impinges on a bank of light-sensitive photocells. The photocells are connected to a computer via electrical circuitry and an analog to digital (A/D) converter board. When the intensity of the light shining on the photocells changes, the photocells respond by changing their voltage output. This changing voltage is registered and converted by the A/D board and then recorded by the computer. Estimated cost for the equipment including the computer is $5,000-$10,000.

To determine the grading of an aggregate sample, the sample is put into the column at the top. The particles descend in the water according to their sizes as modeled by Stoke’s law. As the particles pass through the light curtain established by the light source and photocells, the light intensity is altered and the varying voltages are recorded by the computer. By recording the voltage as a function of time, the computer can calculate the grading of the aggregate sample. This method has been shown to produce fairly good results when compared with standard sieve analysis. The method does have a tendency to slightly underestimate the coarse fraction and overestimate the fine fraction.

This method is automated and takes approximately three minutes to test a sample. It therefore meets the criteria for reduced test time and technician involvement. The method is also simple and the equipment relatively inexpensive. The disadvantage of this system is that it is currently limited in the particle sizes that can be accommodated. The system is designed to determine the grading of particles ranging from 2.38 mm to 0.075 mm. This limitation means that the grading of the coarse aggregate fraction is not determined, nor is an accurate measure of the percent finer than the 0.075 mm obtained. The researchers do offer alternatives for solving these problems. The retained 2.38 mm fraction could first be separated out and its grading determined by some other method (conventional sieve analysis for example) while the minus 2.38-mm, retained 0.075 mm fraction grading could be determined by the Fractionating Water Column. This would lengthen the test time. Aljassar and Haas (*8*) also suggest that the minus 0.075 mm fraction could possibly be handled by the water column with some modifications to the current technology. The size limitations of this method make it unattractive at present, but research on this method is ongoing and should be monitored for significant progress towards solving the problem.

Laboratory Particle Size Analyzers

Another method that can be used to determine particle size uses laser diffraction/Mie scattering theory. Machines based on this method consist of an optical bench which contains the lasers, mirrors, and other optical equipment, a sample chamber, and a computer for control, data acquisition, and displaying results. The cost varies according to machine capability and manufacturer, but is approximately $40,000.

To use a particle size analyzer the sample is first put into suspension in a fluid, normally water and then placed in the sample chamber. The analysis is done by shining laser light through the suspended sample and measuring the intensity of the scattered light as a function of the scattering angle. The resulting light intensity function is then analyzed by the software to determine what distribution of particle sizes would scatter the light in a similar pattern (*9*). The operator only needs to aid the computer in properly calibrating the system, and supply the proper information to the computer for sample identification. When the analysis is complete, the computer displays the results in any one of various formats selected by the user.

Particle size analyzers are automated and can typically analyze a sample in under 10 minutes with a minimal amount of technician time required. The test does provide an accurate measure of the percent passing the 0.075 mm sieve. However, the equipment is expensive and limited to the measurement of only small particle sizes. Typical equipment can measure particles ranging in size from 0.1 to 2000 µm. This inability to handle larger particles makes these systems unsuitable for determining the grading of complete aggregate samples. However, this type of system could accurately determine the grading of the finer portion of an aggregate grading.

Imaging Analysis

Imaging analysis to determine aggregate grading is now in the early stages of development and holds promise for the future. Several different projects are under way to develop the equipment and methods.

The imaging analysis process involves using a camera to “look” at the aggregate and determine its grading. This process can be broken into five separate components: Image generation and capture, and image coding, image reconstruction, image enhancement, and image analysis. Image generation and capture is the process of creating the image with the camera. This can sometimes be difficult because some information may be lost in the process due to shadows, particle overlap, and other uncontrollable conditions. Image coding refers to the techniques for storing the image. For example, most systems store the image such that each screen element (pixel) is associated with an x-y coordinate system and brightness. Image reconstruction is used to correct problems in the image such as distortion. Image enhancement is used to make the digitized image clearer. For example, enhancement of the image is used to separate particles that overlap. Image analysis is when the computer actually determines the parameters sought. In this step, the two-dimensional shape of the particles is determined (*10*).

In a practical sense, grading analysis by imaging techniques uses a photographic image in a digitized form. The computer software uses the digitized photograph and chooses the boundary lines for each aggregate particle according to the given algorithms. Having identified the boundaries of each of the particles, the computer then determines the two-dimensional shape of each particle from which it estimates the three-dimensional shape. This projection of two dimensions into three is again dependent of software algorithms. Once the number of particles and their sizes have been determined, the computer calculates the grading of the sample in question.

Laboratory work in imaging analysis has been performed at Purdue University where the techniques were used to differentiate siliceous and calcareous sands (*10*). Work has also been performed at the University of Arkansas-Little Rock (UALR) on techniques to identify aggregate shape and grading using imaging analysis. This work could hold promise for future laboratory aggregate testing methods. The cost of a system similar to this is highly variable with estimates ranging from $15,000 to $50,000.

One full-scale imaging analysis study worth note is being field tested by Felix Alba, Associates of Murray, Utah (*11*,*12*). The study involves the real-time determination of aggregate grading.

Each of the cold feed bins is instrumented so that the grading from each is constantly monitored using imaging analysis techniques. When the information is sent to the control computer, it checks to make sure that the current blend of aggregates being used by the plant will meet the job-mix-formula. If not, the computer can alter the feeding rate of any of the cold feed bins in order to alter the total aggregate blend. In this fashion, the aggregate blend being fed to the plant can be kept in constant control. The system has shown remarkable promise and is expected to cost between $70,000 and $100,000. This process offers obvious advantages. However, it is unable to determine the amount of dust present in the aggregate.

Image analysis is a fully automated system that holds potential for determining aggregate grading in a short period of time or on a continuous basis and all but eliminates the need for a technician. However, the current cost is high and no accurate measure of the percent passing the 0.075 mm sieve is possible. A considerable amount of work remains to be done before this method can be used in practice.

SUMMARY OF CURRENT TECHNOLOGIES

Table 2 shows a summary of the methods reviewed along with approximate costs and availability. Each of the methods has advantages and disadvantages when compared to the others. None of them can be employed immediately to accurately determine a complete grading from the coarsest sieves through the 0.075 mm sieve.

Table 2. Summary of Current Technology

Technology	Estimates Availability (Years)	Estimates Cost
Gradex 2000	Immediate	$17,000-25,000
VDG-40 Video Grader	Immediate	$50,000
Full-Scale Particle Size Analyzer	Unknown	Unknown
Fractionating Water Column	1-2	$5,000-10,000
Laboratory Particle Size Analyzer	Immediate	$40,000
Laboratory Image Analysis	5-10	$15,000-50,000
Full Scale Imaging Analysis	1-5	$70,000-100,000

In reviewing the current technologies available for adaptability to grading testing, it is obvious that no one technology currently exists to fulfill the criteria of reducing test time, reducing technician involvement, providing an accurate measure of the grading, including the percent passing the 0.075 mm sieve, and being affordable. Table 3 lists each of the methods reviewed and how well they meet the first three criteria. While several of the systems are automated and reduce both the testing time and required technician time, they suffer from the inability to measure the range of particle sizes used in HMA mixes. Some technologies can measure larger particles while others measure the smaller sizes. None of the systems currently offers adequate means for accurately determining the amount of material passing the 0.075 mm sieve present in an aggregate sample.

Table 3. Capability Summary of the Technologies Reviewed

Technology	Reduced Test Time	Reduced Technician Time	Accurate Measure of % Passing 0.075 mm Sieve
Gradex 2000	Maybe	Yes	No
VDG-40 Video Grader	No	No	No
Full-Scale Particle Size Analyzer	Yes	Yes	No
Fractionating Water Column	Yes	Yes	No
Laboratory Particle Size Analyzer	Yes	Yes	No
Laboratory Imaging Analysis	Yes	Yes	No
Full-Scale Imaging Analysis	Yes	Yes	No

Gradex 2000

The main problem with developing an automated grading analysis system seems to be in determining how to get an accurate measure of the percent passing the 0.075 mm sieve within the time allotted. If this requirement is waived, then the Gradex 2000 can quickly be adapted for use. Contractors and laboratories could use the same sieves they currently employ and the only added expense would be the Gradex 2000 and computer. If an accurate measure of the percent passing the 0.075 mm sieve is required, the Gradex 2000 still presents the best alternative. Although the actual testing time involved would not be reduced, the automation makes it possible to reduce the technician time required.

VDG-40 Video Grader

The VDG-40 Video Grader is one of only two technologies reviewed that offers the potential ability to obtain an accurate measure of the percent passing the 0.075 mm sieve. However, if the percent passing the 0.075 mm sieve is coating the coarser aggregate particles, the ability of accurately determining the percent passing the 0.075 mm sieve material is reduced. Additionally, this method does not reduce test time or technician time requirements and is expensive.

Full-Scale Particle Size Analyzer

This method does have the potential to reduce test time and technician involvement, but its cost is estimated to be high and it does not offer an accurate measure of the percent passing the 0.075 mm sieve. In addition, it is limited in the particle size that can be evaluated.

Fractionating Water Column

At the present time, the method lacks the ability to produce an accurate measure of the percent passing the 0.075 mm sieve. In addition, it is limited in the particle size that can be evaluated.

Laboratory Particle Size Analyzer

At present the equipment is relatively expensive. This method is also limited in the particle size that can be evaluated. Additionally, the equipment does not physically measure the grading, but rather statistically estimates the grading. This equipment is also somewhat sensitive and requires a clean, stable environment that may not be available in some HMA production laboratories.

Imaging Analysis

Both laboratory and full-scale imaging analysis are in their infant states for grading applications. The equipment is expensive and cannot offer an accurate measure of the percent passing the 0.075 mm sieve. Research efforts are ongoing and should be closely monitored for improvements.

SELECTION OF AN AUTOMATED GRADING DEVICE FOR FUTURE STUDY

Based on the initial portion of this study, it appeared that the Gradex 2000 is the only method that could be adopted immediately to improve the way that aggregate grading is determined. In order to bring the Gradex 2000 technology to the HMA industry as quickly as possible, a complete laboratory study of its capabilities has been performed. The study was focused in order to provide answers to the following questions.

1. Ruggedness: Is the equipment rugged enough to withstand daily use?
2. Comparable: Does the Gradex 2000 produce results comparable to the standard grading test method?
3. Repeatability: Does the Gradex 2000 produce repeatable results?
4. Test Time: Does it reduce the test time?
5. Technician Time: Does it reduce the technician time requirements?
6. Accurate Measure of the Grading: Can a method be developed to accurately determine the grading of aggregates? In particular, can the amount of material passing the 0.075 mm sieve be determined while reducing test time?

The following sections of the report provide a discussion of the laboratory testing conducted to provide answers to the questions provided above.

TESTING AND EVALUATION OF THE GRADEX 2000 PARTICLE SIZE ANALYZER

As mentioned previously, the automatic grading device, as originally built, has the capability of holding either six full-height or nine half-height (203 mm diameter) sieves. Therefore, it was recognized that if the device was to be used for the testing of aggregate blends for the HMA and aggregate industries, the sieve holding capacity would have to be increased. To accomplish this, the manufacturer modified the device to accommodate up to ten sieves and a pan, with the top three sieves (coarse) being full-height and the remaining seven being half-height sieves. The sieve diameter remained at 203 mm. For economic reasons, the sieve diameter was not changed to 305 mm. It was thought that if the device proved itself as a viable option for grading analysis, it could be later modified to accommodate 305 mm diameter sieves.

Optimization of the Required Sieving Time and Sample Test Size

Once it was determined that the automatic grading device offered the most realistic and economical approach to an automated grading analysis and the sieve modification work completed, laboratory work was done to determine the optimum sieving time and sample size.

The testing consisted of using three aggregate types (limestone, granite, and gravel), two sample sizes (1200 and 1500 grams), and four different shaking times (5, 10, 15, and 20 minutes). The grading used for the work consisted of a typical Stone Matrix Asphalt (SMA) grading. Using a grading of this type was thought to provide two worst case scenarios 1) a heavy concentration of material on one sieve (4.75 mm) and 2) a large amount of material passing the 0.075 mm sieve, both of which could produce sieve blinding. In addition to performing grading analysis with the automatic grading device, testing was also conducted using a conventional mechanical shaker, which is commonly used by laboratories for grading analysis.

The grading results for the 4.75 mm, 0.150 mm, and the 0.075 mm sieves are found in Tables 4, 5, and 6. The results indicate that the automated grading device can accurately and precisely determine the grading of material on the 4.75 mm sieve, but as expected since the automated grading device performs only a dry sieve analysis, there is some small amount of error on the percent passing the 0.150 mm and a greater amount of error on the 0.075 mm sieve. This could be solved by using an adjustment factor on one or both of these sieves.

For the SMA grading evaluated, it was determined that there was no practical difference in the resulting grading analysis for sample sizes of 1200 and 1500 grams. Any larger sample may lead to blinding of the sieves, especially on the 4.75 mm sieve. A larger sample could possibly be used for well-graded mixture; however, the most logical approach would be to use one conservative sample size (1500 grams) for all mixes evaluated.

The method of determining the appropriate amount of sieving time was to determine the sieving time where the increase in the amount of material passing the 0.075 mm sieve gained by additional sieving time was not significant (i.e., the time where the increased amount of material passing the 0.075 mm sieve did not justify the increased sieving time). From an observation of the data, in Tables 4, 5, and 6, it appears that approximately 10 minutes is sufficient sieving time for the gradings evaluated.

Table 4. Results of the Sample Size and Shake Time Testing for the Limestone Aggregate

GRANITE AGGREGATE		Gradex 2000								CONVENTIONAL SHAKER	
		1200 Grams				1500 Grams				1200 Grams	1500 Grams
Sieve Size (mm)	SMA Percent Passing Target Value	Sieve Time (Min)				Sieve Time (Min)				Sieve Time (Min)	Sieve Time (Min)
		5	10	15	20	5	10	15	20	10	10
4.75	24.0	24.6* 0.249	24.8 0.047	24.9 0.236	24.9 0.094	24.7 0.170	24.8 0.125	24.90 0.330	25.0 0.141	24.8 0.082	24.6 0.141
0.15	11.5	10.0 0.216	9.8 0.262	10.0 0.141	10.1 0.047	9.7 0.082	9.9 0.125	9.9 0.094	10.0 0.047	11.7 0.000	11.6 0.000
0.075	10.0	6.46 0.193	6.74 0.205	6.93 0.281	6.83 0.012	5.95 0.069	6.83 0.205	6.83 0.000	6.84 0.037	6.87 0.386	6.72 0.094

*Note: The top number indicates the average from three replicates while the bottom is the associated standard deviation.

Table 5. Results of the Sample Size and Shake Time Testing for the Granite Aggregate

GRANITE AGGREGATE		Gradex 2000								CONVENTIONAL SHAKER	
		1200 Grams				1500 Grams				1200 Grams	1500 Grams
Sieve Size (mm)	SMA Percent Passing Target Value	Sieve Time (Min)				Sieve Time (Min)				Sieve Time (Min)	Sieve Time (Min)
		5	10	15	20	5	10	15	20	10	10
4.75	24.0	24.4* 0.047	24.6 0.125	24.8 0.327	24.7 0.116	24.3 0.155	24.7 0.196	24.6 0.163	24.8 0.046	24.6 0.245	24.3 0.125
0.15	11.5	9.5 0.045	9.8 0.163	10.0 0.043	10.1 0.078	9.5 0.057	9.9 0.091	10.0 0.212	10.1 0.054	11.7 0.000	11.7 0.000
0.075	10.0	6.33 0.042	6.67 0.126	7.06 0.219	6.85 0.029	5.81 0.142	6.67 0.054	6.85 0.287	6.92 0.053	6.96 0.082	6.84 0.082

*Note: The top number indicates the average from three replicates while the bottom is the associated standard deviation

Table 6. Results of the Sample Size and Shake Time Testing for the Gravel Aggregate

GRAVEL AGGREGATE		Gradex 2000								CONVENTIONAL SHAKER	
		1200 Grams				1500 Grams				1200 Grams	1500 Grams
Sieve Size (mm)	SMA Percent Passing Target Value	Sieve Time (Min)				Sieve Time (Min)				Sieve Time (Min)	Sieve Time (Min)
		5	10	15	20	5	10	15	20	10	10
4.75	24.0	25.2* 0.176	25.6 0.233	25.7 0.167	25.4 0.076	25.0 0.062	25.2 0.016	25.1 0.270	25.5 0.182	24.7 0.189	24.8 0.245
0.15	11.5	10.4 0.235	10.6 0.174	10.5 0.101	10.9 0.053	9.8 0.128	10.1 0.045	10.1 0.093	10.6 0.108	11.1 0.163	11.2 0.125
0.075	10.0	6.88 0.225	7.28 0.174	7.06 0.068	7.40 0.067	6.09 0.152	6.70 0.054	6.67 0.057	7.32 0.205	6.89 0.249	6.82 0.141

*Note: The top number indicates the average from three replicates while the bottom is the associated standard deviation

Evaluation of a Correction Faction for Grading Adjustment

Once the optimum sieving time and sample size were determined, the next step in the evaluation process was to determine if the amount of minus 0.075 mm sieve material obtained through the automated grading device's dry grading procedure could be adjusted, through the use of an adjustment factor, to match a corresponding washed sieve result.

From the coarse sieve sizes down to about the 0.150 mm sieve, the automated grading device provides results which are comparable with the testing variability of conventional washed grading test results. However, because the automated grading device uses a dry grading process, there is some amount of error on the 0.150 mm and the 0.075 mm sieves, with the error increasing as the sieve size becomes smaller. Therefore, a method of correcting the sieve analysis results for those sieves would be beneficial to increasing the accuracy of the automated grading device results.

Laboratory work was undertaken to determine if an adjustment factor could be used for dry sieve analysis correction with the automated grading device. This adjustment factor, as mentioned above, would adjust the dry sieve analysis results for the percent passing the 0.150 and the 0.075 mm sieves of the automated grading device based upon washed grading results. To accomplish this goal the test plan shown in Table 7 was established and completed.

Table 7. Test Plan for Adjustment Factor Evaluation

AGGREGATE TYPE	AGGREGATE PREPARATION TYPE							
	Stockpile (Lab Batched, No AC)				Ignition Furnace 5.5% PG 64-22			
	SMA Grading		Dense Grading		SMA Grading		Dense Grading	
	Gradex	Washed	Gradex	Washed	Gradex	Washed	Gradex	Washed
Granite	X[1]	X	X	X	X	X	X	X
Limestone	X	X	X	X	X	X	X	X
Gravel	X	X	X	X	X	X	X	X

Notes: (1) Each cell represents three replicates.

The testing plan consisted of using three aggregates (granite, limestone, and gravel), two grading types (SMA and conventional dense or well graded), and two aggregate preparation types (stockpile and ignition furnace). The stockpile samples for both the SMA and the dense gradings were batched from individual aggregate stockpile sizes, which were shaken out in the lab. Sieve analysis were then performed on these samples by two methods:

1. Automated Grading Device (Dry Sieve Analysis)
2. Conventional Washed Sieve Analysis

The ignition furnace samples were laboratory batched samples with 5.5 percent asphalt cement added and then burned in the ignition furnace at the standard 538°C test temperature. This was done to determine the accuracy of the automated grading device (dry) and washed grading results. Once aggregate samples were recovered from the furnace, testing was conducted in the same manner as that for the stockpile samples.

The results shown in Tables 8, 9, and 10 indicate that, as expected, the amount of error between the automatic grading device and the washed sieve analysis increased as the sieve size decreased. Therefore, adjustment factors were calculated simply by subtracting the dry percent passing obtained with the automatic grading device from the washed percent passing an individual sieve

By observing the adjustment factors for the 0.075 mm sieve, shown in Table 11, it is evident that for all the mixes evaluated the SMA samples showed a higher adjustment factor (average of 4.15 percent) than the dense samples (average of 3.75 percent). This is most likely a result of the high percent passing of the SMA grading. It also appears that the average adjustment factor for all stockpile samples tested (3.67 percent) was slightly less than the average adjustment factor for all the ignition furnace samples (4.23 percent). This would indicate that the ignition furnace possibly reduces the amount of percent passing the 0.075 mm sieve material which can be removed from a sample during a dry sieve analysis.

Table 8. Test Results for the Granite Aggregate

Sieve Size (mm)	Target Grading		Average Percent Passing							
			Laboratory Batched				Samples after Ignition Furnace			
	SMA	Dense	SMA		Dense		SMA		Dense	
			Gradex	Washed	Gradex	Washed	Gradex	Washed	Gradex	Washed
19.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5	90.5	95.0	90.4	90.9	95.0	96.1	90.6	91.1	95.5	96.0
9.5	54.5	86.0	56.8	56.2	86.5	86.6	55.3	56.8	85.6	86.7
4.75	24.0	65.0	24.2	25.3	65.1	65.6	24.3	26.3	65.0	65.8
2.36	20.5	50.0	21.0	21.2	50.0	50.8	20.2	22.3	50.4	51.4
1.18	18.0	38.0	18.5	18.8	38.2	39.2	17.9	20.0	38.8	40.4
0.6	14.5	27.0	15.1	15.8	27.1	28.7	15.1	17.0	27.8	29.9
0.3	13.5	18.0	13.9	14.8	17.2	19.8	13.0	15.2	18.1	20.8
0.150	11.5	9.0	10.5	13.0	7.7	11.3	9.7	13.0	9.1	12.0
0.075	10.0	6.0	7.3	10.6	4.2	7.6	6.2	10.4	4.7	8.1

Table 9. Test Results for the Limestone Aggregate

Sieve Size (mm)	Target Grading		Average Percent Passing							
			Laboratory Batched				Samples after Ignition Furnace			
	SMA	Dense	SMA		Dense		SMA		Dense	
			Gradex	Washed	Gradex	Washed	Gradex	Washed	Gradex	Washed
19.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5	90.5	95.0	89.6	90.1	94.6	94.7	90.0	88.4	94.5	95.0
9.5	54.5	86.0	55.2	55.7	85.5	85.2	54.6	55.2	85.6	86.0
4.75	24.0	65.0	24.7	25.7	65.2	65.5	23.9	24.6	65.2	65.2
2.36	20.5	50.0	20.6	21.1	49.9	50.3	19.8	20.5	50.0	49.4
1.18	18.0	38.0	18.0	18.7	37.7	38.4	17.4	18.2	37.8	38.2
0.6	14.5	27.0	14.6	15.4	26.4	27.6	14.2	15.6	26.6	27.6
0.3	13.5	18.0	13.4	14.6	16.8	19.3	12.6	14.9	17.2	20.2
0.150	11.5	9.0	9.9	13.0	7.2	11.3	9.5	13.6	8.6	12.4
0.075	10.0	6.0	6.6	10.8	4.1	8.1	6.3	11.2	4.6	8.8

Table 10. Test Results for the Gravel Aggregate

Sieve Size (mm)	Target Grading		Average Percent Passing							
			Laboratory Batched				Samples after Ignition Furnace			
	SMA	Dense	SMA		Dense		SMA		Dense	
			Gradex	Washed	Gradex	Washed	Gradex	Washed	Gradex	Washed
19.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5	90.5	95.0	89.7	90.4	95.0	95.6	90.5	90.6	95.4	95.8
9.5	54.5	86.0	55.7	55.5	86.1	85.5	55.2	56.0	85.7	86.5
4.75	24.0	65.0	24.6	25.5	65.3	65.7	24.2	25.5	65.4	65.6
2.36	20.5	50.0	20.9	21.3	49.8	50.7	20.0	21.1	50.4	50.7
1.18	18.0	38.0	18.1	18.8	38.1	39.9	17.8	19.1	38.7	39.3
0.6	14.5	27.0	14.9	15.6	26.9	27.7	14.9	15.5	27.5	28.3
0.3	13.5	18.0	13.8	14.6	16.9	19.7	12.9	14.6	17.9	20.7
0.150	11.5	9.0	10.0	13.1	7.6	11.4	9.7	13.5	8.9	12.3
0.075	10.0	6.0	7.1	10.8	4.3	7.7	6.3	10.9	4.7	8.8

Table 11. Adjustment Factor Results

Sieve Size (mm)	Laboratory Batched Samples (Stockpile)						Ignition Furnace Samples					
	Granite		Limestone		Gravel		Granite		Limestone		Gravel	
	SMA	Dense	SMA	Dense	SMA	Dense	SMA	Dense	SMA	Dense	SMA	Dense
0.300	0.9	2.6	1.2	2.5	1.2	2.8	2.7	2.7	2.3	3.0	1.7	2.8
0.150	2.5	3.6	3.1	4.1	3.1	3.8	3.3	2.9	4.1	3.8	3.8	3.4
0.075	3.3	3.4	4.2	4.0	3.7	3.4	4.2	3.4	4.9	4.2	4.6	4.1
Average (0.075)	3.67						4.23					
SMA Overall Average (0.075)	4.15											
Dense Overall Average (0.075)	3.75											

Based upon these results, it appears that an adjustment factor could be used with reasonable accuracy for the gradings and aggregates used in the study. Since these gradings are somewhat the extremes (i.e., gap-graded and dense-graded), it would be expected that an intermediate grading would have adjustment factors lying somewhere between those determined in this study, provided the sample size was held constant.

POTENTIAL USE

The main benefit to using the automatic grading device is the amount of technician and testing time which would be saved in the laboratory. This is time which the technician could be devoting to other test procedures or other matters which require attention. An illustration of the potential time savings which could result from using the automatic grading device, with an adjustment factor for the dust fraction (passing the 0.075 mm sieve) of the sample, is offered in the example below:

EXAMPLE:

Consider that a conventional washed sieve analysis takes the following amount of time:

Washing to remove minus 0.075 mm material:	10 minutes
Drying remaining material to constant mass:	3 hours
Sieving the dried material:	10 minutes
Weighing the material:	5 minutes
Calculating the grading:	5 minutes
TOTAL:	**3.5 hours (210 minutes)**

Now consider the amount of time taken by the automatic grading device to perform a grading analysis.

Sieving the dried material:	10 minutes
Weighing the material:	5 minutes
Calculating the grading:	Calculation takes place at the same time as weighing.
TOTAL:	**15 minutes**

The example shows that a potential time savings of over three hours could result from the use of the automatic grading device. As can be seen, the main difference in the two testing times is the time for washing and drying the aggregate sample. However, if one washed sieve analysis was performed for every ten tests, then grading accuracy and time savings could be acquired simultaneously. A possible approach would be to use a running average of the last four washed sieve analysis to determine the adjustment factors for the automatic grading device testing results. Table 12 provides an illustration of the approach for the 0.075 mm sieve. From an observation of Table 12, it is evident that this approach would save a large amount of laboratory testing and technician time and money. By the increased time savings, the user is also offered the ability to perform more grading analyses throughout production. This potential for increased time savings, which could result in more testing, could be of great benefit, especially in a production situation, where a change in mixture grading could be very costly to the HMA contractor and to the quality of the produced product.

Table 12. Illustration of the Possible Use of an Adjustment Factor.

Test Number	Percent Passing "Washed"	Percent Passing "Gradex"	Adjustment Factor	Running Adjustment Factor	Adjusted Gradex Result
1	6.5	4.5	2.0		
2	6.3	4.7	1.6		
3	6.8	4.8	2.0		
4	6.6	4.6	2.0	1.9 = (Average of Tests 1,2,3,4)	4.6 + 1.9 = 6.5
5		4.6		1.9	6.5
6		4.7		1.9	6.6
7		5.0		1.9	6.9
8		4.5		1.9	6.4
9		4.7		1.9	6.6
10		4.8		1.9	6.7
11		4.5		1.9	6.4
12		4.8		1.9	6.7
13		5.1		1.9	7.0
14	7.0	4.7	2.3	2.0 = (Average of Tests 2,3,4,14)	4.7 + 2.0 = 6.7
15		4.8		2.0	6.8
16		5.2		2.0	7.2
17		5.3		2.0	7.3
18		5.1		2.0	7.1
19		4.7		2.0	6.7
20		4.8		2.0	6.8
21		5.2		2.0	7.2
22		5.1		2.0	7.1
23		5.3		2.0	7.3
24	7.3	4.9	2.4	2.2 = Average of Tests (3,4,14,24)	4.9 + 2.2 = 7.1

The final step in the evaluation of the Gradex was to determine the degree to which an adjustment factor could be applied to the percent passing the 0.075 mm sieve obtained from the Gradex to accurately estimate the true percent passing the 0.075 mm sieve, as determined through a washed sieve analysis. This is essentially a test of the proposed example found in Table 12.

To accomplish the evaluation, two aggregates (limestone and granite) were blended to have the same grading for the plus 0.075 mm sizes with varying dust contents. The objective was to determine whether the adjustment factor or adjustment determined for each of the dust contents was consistent. If so, it would indicate that the percent passing the 0.075 mm sieve for the Gradex is the same percentage of the total dust content regardless of the dust content present in the blend. The importance of this lies in the potential ability of the Gradex with a dry process and an adjustment factor or adjustment to estimate the true dust content of the blend. At the very least it would allow for trends of changing blend grading to be determined so that corrective action could be taken.

The results of the evaluation are provided in Table 13 and in Figures 6 and 7 and indicate the difference between the Gradex and the washed sieve analysis percent passing the 0.075 mm sieve for both the limestone (4.4 to 5.5 percent) and the granite aggregate (2.9 to 3.0 percent) blends remain relatively constant over the range of dust contents evaluated. The difference between the magnitude of the difference for the limestone and the granite blends is most likely a result of the higher dust contents of the limestone blends, compared to the granite blends.

For the limestone aggregate, where the dust contents were higher than the granite aggregate, the difference was more variable. The average difference between the Gradex and the washed sieve analysis was then added to each Gradex result and yielded an average “corrected” difference between the Gradex and the washed sieve analysis of 0.4 and 0.02 percent for the limestone and the granite aggregate, respectively. This indicates applying the dust adjustment factor approach to the Gradex test results can successfully be used over a relatively wide range of expected dust contents to predict the dust content of the aggregate blend.

Table 13. Lab Evaluation of the Varying Percent Passing the 0.075 mm Sieve

LIMESTONE AGGREGATE	Percent Passing the 0.075 mm Sieve			
	Sample 1	Sample 2	Sample 3	Sample 4
Gradex	2.7	4.2	5.6	6.7
Washed	8.2	8.8	10.0	11.7
Difference (Washed - Gradex)	5.5	4.6	4.4	5.0
Average Difference	4.88			
Gradex + Average Difference	7.6	9.1	10.5	11.6
Corrected Average Difference (Gradex Adjusted - Washed)	0.4			
Granite Aggregate	Percent Passing the 0.075 mm Sieve			
	Sample 1	Sample 2	Sample 3	Sample 4
Gradex	1.8	3.4	4.8	5.6
Washed	4.8	6.4	7.8	8.5
Difference (Washed - Gradex)	3.0	3.0	3.0	2.9
Average Difference	2.98			
Gradex + Average Difference	4.8	6.4	7.8	8.6
Corrected Average Difference (Gradex Adjusted - Washed)	0.02			

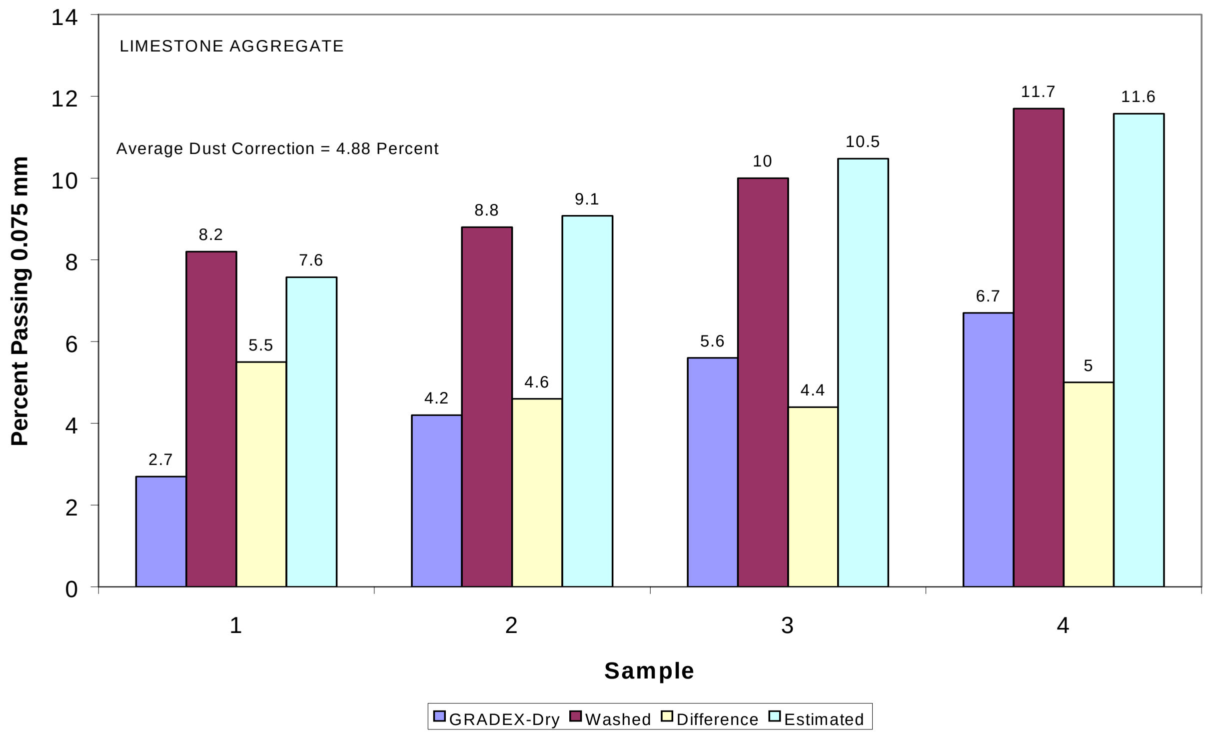

Figure 6. Percent Passing the 0.075 mm Sieve Results for the Limestone Aggregate

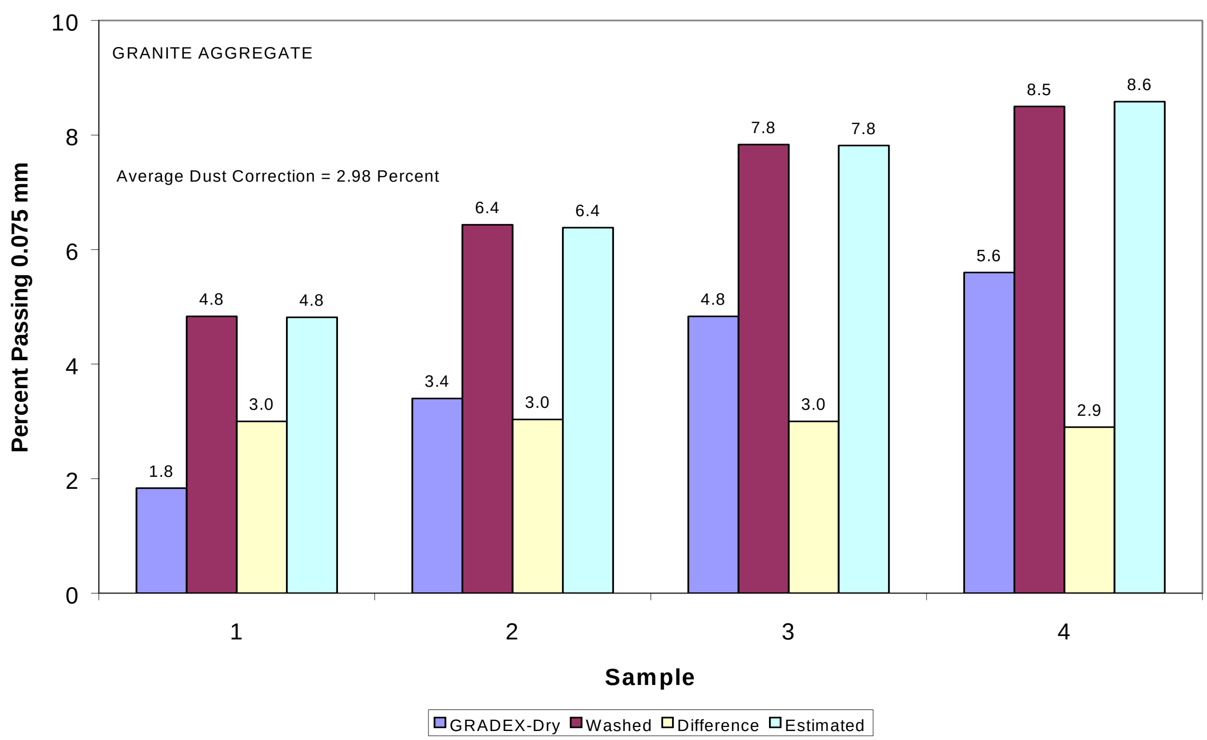

Figure 7. Percent Passing the 0.075 mm Sieve Results for the Granite Aggregate

CONCLUSIONS

The grading of an aggregate sample, whether in the HMA or the aggregate industry, will always be one important element of design, production, or process control. While being crucial and vital to operations, the method of conducting grading analysis has remained relatively constant for many years. However, the method of automatic grading analysis presented herein, the automatic grading device, has proven in the laboratory to provide accurate and precise grading results when compared to conventional grading analysis procedures.

The automatic grading device offers the ability for technician and test time to be reduced, which may allow for a greater control of a produced product, through an increased frequency of testing. At the present time, the only drawback to the automatic grading device evaluated in this study is the inability of the device to wash and dry the aggregate sample prior to the grading analysis. However, a method of using an adjustment factor to adjust the amount of dust or percent passing the 0.075 mm sieve material obtained with using the Gradex was presented and shown to provide acceptable results for a limited laboratory evaluation. The use of the Gradex particle size analyzer for automatic aggregate grading determination could prove to be useful to any laboratory responsible for conducting a large number of aggregate grading tests and also in the field quality control of produced aggregate or asphalt mixes.

RECOMMENDATIONS FOR FUTURE USE

Ultimately, the final application of the Gradex should be as part of a closed loop quality control system in which the sampling, testing, and adjustment of aggregate components are conducted to ensure the gradation is very closely maintained to project specifications. Today, this is being done with a highly modified version of the Gradex, shown in Figure 8, utilized at asphalt plant and quarry operations. The modified Gradex consists of five screens, each of which are able to be shaken at an independent frequency to achieve the optimum screening efficiency. At the present time, the device is able to screen material without drying down to approximately the No. 8 sieve. Technology is currently being developed to allow for a possible washing and drying mechanism, along with more screens, which should allow for more extensive screening of the finer materials.

Figure 8. Modified Gradex for Field Use

The benefits from using the modified Gradex in a closed loop quality control system are easy to see and understand. With the automated procedure, many tests can be performed in a relatively short time and the appropriate adjustments made to the gradation. This should and will directly benefit both the producer, owner, and/or consumer of the produced mix or aggregate blend.

Additionally, the technician time and associated expense are substantially reduced. This should result in a cost savings or the availability of the technician to perform other tasks.

REFERENCES

1. Roberts, F. L., P. S. Kandhal, E. R. Brown, D.Y. Lee, and T. W. Kennedy. Hot Mix Asphalt Materials, Mixture Design, and Construction. NAPA Educational Foundation, Lanham, MD., 1991.
2. American Society of Testing and Materials (ASTM) *C 117: Standard Test Method for Materials Finer than 75 :m (No. 200) Sieve in Mineral Aggregates by Washing*. Philadelphia, PA. 1997.
3. American Society of Testing and Materials (ASTM) *C 136: Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*. Philadelphia, PA., 1997.
4. Gradex 2000 Particle Size Analyzer Catalog 229, ROTEX, INC., Cincinnati, OH, (No Date)
5. Sales Literature on the VDG-40, Obtained from EMACO, Ltd., Montreal, Canada, No Date.
6. Standard for Granulometric Analysis of Aggregate and Determination of Flatness and Elongation of Particles by Video Granulometer, Laboratoire Central des Ponts et Chaussées (the French Public Works Laboratory), May 1993.
7. Harlow, R. L., "Design of a Particle Size Analyzer for Gravel Sized Aggregate." Masters Thesis, University of Texas at Austin, May 1972.
8. Aljassar, A., and Haas, R., "Toward Automating Size-Grading Analysis of Mineral Aggregate." Transportation Research Record 1437, Transportation Research Board, Washington, D.C., January 1994, pp. 35 - 42.
9. Surgrue, S., and Row, G., "True Resolution in Laser Diffraction Particle Sizing: Who Needs it and Where Does it Come From?" Technical Monograph, Coulter Corporation, No Date.
10. Thomas, T. W. White, T. D., and Kuczek, T., "Siliceous Content Determination of Sands Using Automatic Image Analysis." Transportation Research Record 1437, Transportation Research Board, Washington, D.C., 1994, pp. 51 - 58.
11. Alba, Felix, "Phase I Final Report for Developments of a Prototype for On-Line Real-Time Measurement and Control of Aggregate Gradation in Asphalt Plants." Report presented to the SHRP-IDEA Program Manager, May 1992.
12. Alba, Felix, "Phase II (Stage 2) Report for Developments of a Prototype for On-Line Real-Time Measurement and Control of Aggregate Gradation in Asphalt Plants." Report presented to the SHRP-IDEA Program Manager, September 1993.