

Toward Automating Size-Gradation Analysis of Mineral Aggregate

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One of the most important properties of an aggregate blend is its size gradation, which defines the percentages (by weight or volume) of different particle sizes that are present in the blend. Since aggregate represents more than 90 percent of a hot asphalt mix, aggregate gradation profoundly influences the properties of the hot mix (such as air voids, workability, and asphalt binder required) and the properties of the pavement (such as stiffness, stability, and durability). Aggregate gradation is determined by the well-known and widely used sieve analysis method. One major drawback of this method is the consumption of time and effort. The time factor is a major barrier to implementing sieve analysis as an aggregate gradation control measure in asphalt plants where production rates are high and interruptions to the production process are very undesirable. There has been some progress in the automation of gradation analysis of the coarse portion of an aggregate blend. The gradation of the fine portion, however, has major effects on the properties of an aggregate blend. A simple and low-cost approach to automate the gradation analysis of fine aggregate is presented in this paper. The approach is based on the concept of differential settling of aggregate particles in a fluid medium because of differences in particle sizes. It is essentially a fractionating-column methodology. A prototype system was fabricated to test particles passing the No. 8 sieve (or <2.38 mm in size). The system is described in the paper, along with some example results.

Modern asphalt plants are almost fully automated. Execution of different activities in an asphalt concrete (AC) production process is fast, resulting in high production rates. These activities are associated mainly with aggregate handling and include the following: aggregate cold feeding, heating, proportioning, and mixing with asphalt cement to produce AC (1). The order of these activities may differ depending on whether the plant is one in which there is batch mixing or drum mixing. One additional activity that would be very desirable in an asphalt plant is monitoring of aggregate gradation. The aggregate is the main component of an AC structure, occupying more than 90 percent of the structure mass. Hence, properties of the AC are highly affected by the properties of the aggregate, one of the most important of which is aggregate size gradation. Size gradation can be defined as the distribution of particle sizes expressed as a percent of the total weight (or volume). Aggregate size gradation affects almost all the important properties of an AC, including stiffness, stability, durability, permeability, workability, fatigue resistance, resistance to moisture damage, air voids, and asphalt binder required (2).

The only well-established method of determining the size gradation of an aggregate sample is sieve analysis, which is performed by passing the aggregate through a series of sieves stacked with progressively smaller openings from top to bottom and weighing the material retained on each sieve (ASTM C136). This

method is well known for being time-consuming and difficult. In fact, the use of sieves to separate grains according to size is not less than 3,000 years old (3). The relatively long time required to perform sieve analysis is probably the reason for not using it as a measure for aggregate gradation control in asphalt plants. Moreover, because sieve analysis is the only established method for determining aggregate size gradation, monitoring of such an important property of aggregates simply does not exist in asphalt plants. This deficiency in the current AC production process was recognized during the Strategic Highway Research Program, in which the development of an on-line aggregate gradation monitoring and control system applicable to asphalt plants was suggested (4).

Some research studies have been carried out to automate the analysis of aggregate gradations (5–8). These studies resulted in systems that all use a two-dimensional image analysis approach; that is, an aggregate sample is scanned by a camera that generates an image that is then digitized and analyzed by custom-designed software, and the three-dimensional information (volumes of particles) is extracted. The lower bound of the particle size-discerning capabilities of these systems apparently ranges from 1 to 0.3 mm (material passing the No. 50 sieve), but this range is open to question. It may be that the fine particles are hidden by larger particles, that the camera's resolution is limited, or simply that it is impractical to deal with a very large range of particle sizes (400:1 is a typical particle size ratio for an AC aggregate blend). The fine portion of an aggregate sample has a profound effect on many of the AC mix properties, one of the most important of which is the required asphalt cement content. This is because the fine particles contribute the most to the surface area of an aggregate blend, which needs to be coated with asphalt cement in order to obtain the required adhesion, durability, and so on.

The purpose of this paper is to describe a prototype automated system developed at the University of Waterloo, Canada, to deal with the fine portion of an aggregate blend. In its current configuration, the system analyzes aggregate samples with the size range of 2.38 to 0.074 mm, but a hybrid approach in which the entire aggregate size range can be analyzed is also described.

SIGNIFICANCE OF FINES IN AC MIX

The size-gradation specification envelope for the aggregate blend contained in an AC mix must be satisfied. This holds for fine and coarse portions of an aggregate gradation curve. The portion representing the fine particles, however, is of major importance with respect to total surface area of the blend. The surface area is a major factor in defining the optimum asphalt content in a hot mix, and finer particles have more specific surface area (surface area per unit weight) than coarser particles.

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The surface area (a_s) of a particle, depending on the assumed particle shape, can be calculated by

$$a_s = Cd^2 \quad (1)$$

where $C = 6$ for a cubical particle where d is the cube dimension, and $C = \pi$ for a rounded particle where d is the particle's diameter.

To quantify the effect of particle size on the total surface area, assume that particles are rounded with diameter d . Therefore, the volume of one particle is

$$v = \frac{\pi}{6} d^3 \quad (2)$$

The volume (V) of a given weight (W) of aggregate particles having a certain specific gravity (G_s) can be calculated as

$$V = \frac{W}{G_s \rho_w} \quad (3)$$

where ρ_w is the density of water. The number of aggregate particles (N) is therefore

$$N = \frac{V}{v} = \frac{6}{\pi} \frac{W}{G_s \rho_w d^3} \quad (4)$$

The total surface area of all particles (A_s) can be calculated using

$$A_s = a_s * N = \frac{6W}{G_s \rho_w d} \frac{1}{d^2} \quad (5)$$

which shows that the surface area of a given number of particles is inversely proportional to the particle size. For example, assuming that $G_s = 2.67$ and $\rho_w = 1000 \text{ kg/m}^3$, a 1-kg sample of 74- μm particles has a total surface area of 30 m^2 , whereas a 1-kg sample of 10-mm particles has a total surface area of only 0.2 m^2 .

Aggregate gradations can be used to calculate the total surface area per unit weight of an aggregate blend. For example, to calculate the total surface area of an aggregate blend (in square meters per kilogram), the following table is used by multiplying the factor by the percentage passing for each sieve size and totaling for all sieve sizes (all noted sieves must be used in the analysis) (2) (1 $\text{ft}^2/\text{lb} = 0.205 \text{ m}^2/\text{kg}$):

Sieve Size (mm)	Surface Area Factor
Maximum sieve size	0.41
4.76 (No. 4)	0.41
2.38 (No. 8)	0.82
1.19 (No. 16)	1.64
0.590 (No. 30)	2.87
0.297 (No. 50)	6.15
0.149 (No. 100)	12.30
0.074 (No. 200)	32.80

The foregoing factors show that smaller particles contribute substantially more to the total surface area of an aggregate blend than do coarser ones. Consequently, they have more effect on the asphalt content required for an AC mix.

In a study on binder mixes by Kandhal and Cross (9), direct relationships were established between asphalt content and percentage passing sieves No. 4 (P_4) and 8 (P_8). These relationships

are

$$AC = 2.186 + 0.060P_4 \quad R^2 = 0.64 \quad (6)$$

$$AC = 2.025 + 0.084P_8 \quad R^2 = 0.63 \quad (7)$$

where R^2 is the statistical coefficient of determination for the two regression equations.

Equations 6 and 7 show that material passing the respective sieve size influences the asphalt content of the hot mix.

GENERIC REQUIREMENTS FOR ON-LINE AGGREGATE GRADATION MONITORING SYSTEM

Part of an early stage of the research that led to publication of this paper was the identification of the requirements for an on-line system to monitor the aggregate gradation in the AC production process. In the early stages of the research, video-imaging was assumed to be the best available and applicable technology for solving the problem, and hence the requirements developed may be a little skewed toward video-imaging. However, learning about the developed imaging systems and their limitations led to a search for other approaches to address the fine-particle-size portions of an aggregate blend.

Location in Asphalt Plant

Asphalt plants are generally of two types, batch mixing and drum mixing. They differ in several ways, including gradation control of the aggregate used in the AC mix. In batch-mixing plants, the primary control of aggregate gradation is at the cold feed bins, where proportions of aggregate are controlled before the aggregate is fed into the dryer. The secondary or final gradation control is at the hot bins, where the aggregate is screened according to size and the amounts from different bins are controlled by the gates at the bottom of the hot bins. In drum-mixing plants, gradation control at the cold feed bins is critical because after that point, aggregate is fed into the dryer, where it is dried, heated, and mixed with the asphalt cement (1).

Although ideally it would be desirable to check the aggregate gradation of the final mix, it is apparent that this check is more difficult in a drum-mixing operation than in a batch-mixing operation, simply because in the former, the aggregate is dried, blended, and mixed with the asphalt cement in one phase (in the drying drum), and hence access to the dried aggregate (before the asphalt cement is added) is more challenging than in batch-mixing plants.

In a batch-mixing operation, the monitoring system needs to be near the pugmill, where the final aggregate blend is ready to be mixed with the asphalt cement. Sampling of aggregate in the final blend is the current practice in batch-mixing plants where aggregates in the hot bins are analyzed for gradation, and the results of the analysis are used to proportion the hot bins at the beginning of a plant operation.

System-Specific Requirements

System requirements are summarized in Figure 1 and are based on the current configuration of asphalt plants and the nature of

the material to be analyzed. They are categorized as performance/operating requirements and output requirements. In addition to the accuracy of the output results, the most important requirement is the processing time, which prohibited implementation of sieve analysis as a measure to monitor aggregate gradation in asphalt plants.

In a modern batch-mixing plant, the time needed to produce one batch of AC mix is approximately 10 min; that is, a particle takes 10 min to travel from the cold feed bin to the pugmill and be mixed with asphalt cement. It is apparent that to check every batch of AC produced, the processing time of a monitoring system must be less than 10 min to allow for adjustments at the cold bins or at the hot bins, or both, and to reduce the amount of out-of-specification batches. However, if such processing time was found to be unrealistic, it could be increased to less than 20 min and every other batch would be checked, in which case 50 percent of the batches would be checked. For a continuous operation, 50 percent is a very good representation of the population.

WHAT APPROACH BEST MEETS THE REQUIREMENTS?

A number of potential approaches were considered to meet the requirements identified in the previous section. The first was the image analysis approach because of its apparent applicability and because it has found use in many industrial, scientific, engineer-

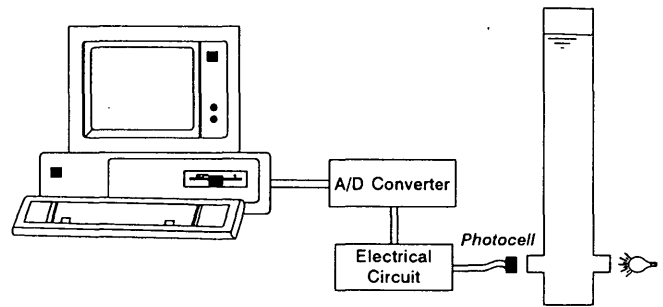


FIGURE 2 Schematic of main system components.

ing, medical, and other areas. Included was careful consideration of the work carried out by other investigators or agencies (5-8).

It appeared, however, that in addition to the limitations with this approach for fine-particle-size gradation analysis, it also did not meet some of the other requirements of Figure 1, such as processing time. Moreover, the cost could be quite prohibitive.

Consequently, other approaches were considered and some were further evaluated in pilot experiments. The one that seemed the most promising, the simplest, and with a low cost was the fractionating water column approach, described in the next section.

FRACTIONATING WATER COLUMN

The fractionating water column approach utilizes the difference in effect of drag force on particles of different sizes when they settle under gravity in a water column. This phenomenon was modeled (in a more general form) by Sir George Stokes and has become known as Stokes' law (10).

This phenomenon was exploited to develop a system to analyze aggregate particles in the fine size range (<2.38 mm). It uses a water column to separate particles according to size. A schematic of the main system components is shown in Figure 2. The system consists mainly of a Plexiglass tube 1.5 m long and 77 mm in (inner) diameter with a "window" near the bottom of the column through which a constant-power light is transmitted, which is received on the other side by a serial array of light-sensitive photocells. The resistance of the photocells changes with changing received light intensity. The electrical circuit consists of a DC power supply that applies a constant voltage across the photocells. When the photocells change their resistance (as a result of a change in light intensity), the current through the circuit changes proportionally and a voltage measured across a constant resistance in the circuit is recorded. The recording of the voltage reading is automated by the use of an analog-to-digital (A/D) converter board, which sends the digitized voltage signals to a computer run by software that reads the signals from the A/D board and stores the results for analysis.

Basic Concept

The basis for the system is Stokes' modeling of the drag force that a solid spherical particle is subjected to when traveling in a fluid medium.

PERFORMANCE/OPERATING REQUIREMENTS

- ☞ High resolution: must be able to distinguish and measure particles as small as 0.074 mm and preferably smaller.
- ☞ Must be capable of discerning particles in the size range of 30 mm to 0.074 mm.
- ☞ Should not require extensive sample pre-processing prior to testing.
- ☞ Should require a minimum of skilled operator intervention.
- ☞ Must be resistant to high temperatures from heated aggregate.
- ☞ Must be compatible with asphalt plant rough environment (e.g., the exposed parts must be wear and dust proof).

OUTPUT REQUIREMENTS

- ☞ Must provide results quickly (processing time < 10 minutes).
- ☞ Results must closely approximate the results attained with standard sieve analysis (tolerances may be based on specification gradation envelopes).
- ☞ Results from the same sample must be repeatable.
- ☞ Output must be compatible with a personal computer (i.e., digitized output).

FIGURE 1 Generic system requirements for on-line aggregate size-gradation analysis.

The aim was to maintain some separation among particles in a fine aggregate blend and to develop a way of measuring the amount (weight or volume) of particles in each size range. To sort particles according to size, a water column is used and a sample of mixed fine aggregate is introduced at the water surface. The particles travel downward at different speeds; according to Stokes (10), the terminal velocity v of a spherical solid particle falling freely in a fluid is given by

$$v = \frac{d^2 g (\rho_s - \rho_f)}{18\eta} \quad (8)$$

where

- d = particle diameter,
- g = gravitational acceleration,
- ρ_s = mass density of solid particle,
- ρ_f = mass density of fluid, and
- η = dynamic viscosity of fluid.

Assuming that the particles in the tested size range (<2.38 mm) reach their terminal velocity in a very short time, their mean velocity h/t (where h is the distance travelled in time t from the water surface to the photocell detection level) could be used in Equation 8, which can be rewritten as

$$t = \frac{18\eta h}{d^2 g (\rho_s - \rho_w)} \quad (9)$$

when water is used as the fluid medium ($\rho_f = \rho_w$). For a given water temperature and assuming the same density for all solid particles, the term $18\eta h/g(\rho_s - \rho_w)$ has a constant value. Therefore, Equation 9 can be rewritten as

$$t = \frac{C}{d^2} \quad (10)$$

where, assuming a room temperature of 24°C and using parameter values given elsewhere (11),

$$\begin{aligned} C &= \frac{18\eta h}{g(\rho_s - \rho_w)} \\ &= \frac{18 (8 \times 10^{-3} \text{ N} \cdot \text{sec/m}^2) (1.5 \text{ m})}{(9.907 \text{ m/sec}^2) (2670 - 996) \text{ kg/m}^3} \\ &= 13.2 \times 10^{-6} \text{ m}^2 \cdot \text{sec} \end{aligned}$$

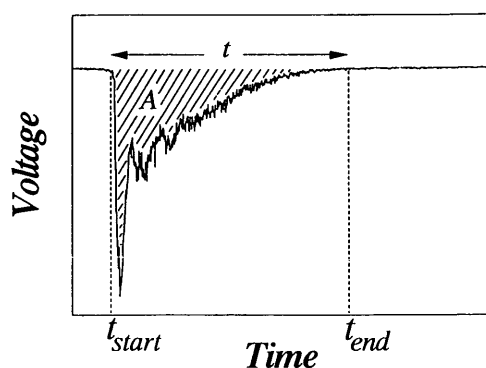


FIGURE 3 Typical voltage-time profile of aggregate sample run through system shown in Figure 2.

Taking the logarithm of both sides of Equation 10 yields

$$\text{Log } t = a - b \text{ Log } d \quad (11)$$

where $a = \text{Log } C - 4.9$ (theoretically), and $b = 2$ (theoretically). It should be noted that the tested sample size (50 g) is very small compared with the body of water contained in the column of Figure 2. Therefore, when heated aggregate is tested, it is not expected to change the water temperature significantly or the viscosity of the water.

To determine the experimental values of a and b in Equation 11, five size ranges of fine aggregate were considered. These size ranges, along with their corresponding sieve numbers, are as follows:

Size Range (mm)	Corresponding Sieve No.
2.38–1.19	8–16
1.19–0.595	16–30
0.595–0.300	30–50
0.300–0.149	50–100
0.149–0.074	100–200

To calibrate the system, washed samples were used to eliminate the effects of the presence of “dust” (material less than 0.074 mm in size or passing the No. 200 sieve). To cover the range of expected weights found in real samples, five to six weights were considered in each size range. From each weight group, 10 samples were analyzed. This resulted in 50 to 60 samples per size range for a total of approximately 280 samples. These samples were run through the system (shown schematically in Figure 2) and a voltage-time profile (similar to that in Figure 3) was produced for each.

Figure 3 shows the two pieces of information extracted from each voltage-time profile: scan time, t (in seconds), required by all particles in the sample to cross the photocell sensing zone, and the area, A (in volt-seconds), bound by the initial voltage level and the voltage profile during time t .

Assuming no interference (the presence of one particle does not affect the settling time of another particle), time t is assumed to be the same for all samples in one size range. Therefore, for each size range, an average time, t_{av} , is calculated by averaging the scan times of all samples in that size range. It should be noted that the column's diameter (77 mm) may cause some boundary drag, which could affect the settling mechanism of particles depending on their position with respect to the column boundaries. The column's diameter, therefore, is one of the system variables that should be tested at a subsequent stage for sensitivity.

After a regression analysis was performed between t_{av} and the mean particle size in each of the size ranges shown earlier, the experimental values of parameters a and b in Equation 11 were determined to be -3.16648 and 1.38584 , respectively.

The deviations (≈ 33 percent between respective absolute values) of the experimental values obtained for constants a and b from the theoretical values (obtained from Stokes' law) are assumed to account for simplifying assumptions, such as lack of particle interference and spherical particles.

Using the experimental values for a and b in Equation 11 and solving for d yields

$$d = \frac{f_1}{10^{f_2 \log t}} \quad (12)$$

where d is in millimeters and t in seconds, and $f_1 = 5.189434$, and $f_2 = 0.721584$. From each group of samples representing a certain weight in a size range, an average area, A_{av} , is calculated by averaging the areas produced by the samples in that group. As expected, A_{av} increases, for a given size range, with increasing weight. This is because more weight means more particles, and hence more light blockage (less registered voltage) in a given instant. A relationship between the weight of a sample (in grams) and the produced area (in volt-seconds) is established for each size range.

The actual area-weight relationships for the five size ranges considered are shown in Figure 4, in which they exhibited linear correlations. Therefore regression analyses were performed and the regression lines were passed through the origin point on the basis of the logic that when no particles were introduced (weight of 0 g), there would be no drop in voltage (area of 0 v · sec). Note also that the slope of the line representing the area-weight relationship increases with decreasing mean size. This proportionality is modeled by the curve shown in Figure 5, which relates the slope of the regression line (area/weight ratio) and mean size of each size range. The equation represented by the curve in Figure 5 is

$$S = 0.124188 + \frac{0.120318}{d^2}$$

(13)

where S is the slope of the regression line (from Figure 4) in volt-seconds per gram, and d is the particle size in millimeters.

The two relationships represented by Equations 12 and 13 are used to determine the size gradation of an aggregate sample using the system shown in Figure 2. After some sensitivity analyses were performed on the results of different mixed samples, it was found that the calculated gradation is closest to the actual one when a value of 0.82 is used for the parameter f_2 in Equation 12. The values of the parameters in Equations 12 and 13 may have to be adjusted for samples retrieved from a different type of aggregate. This could be done by testing samples with known gradations. The calculation procedure is summarized in Figure 6. After a mixed sample is introduced at the surface of the water

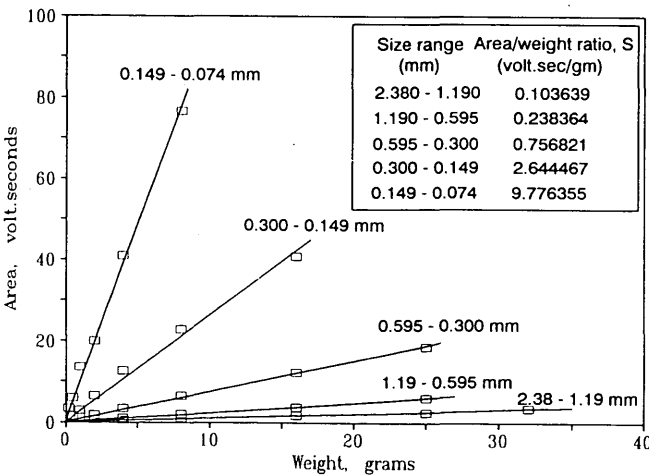


FIGURE 4 Area-weight relationships for five particle size ranges.

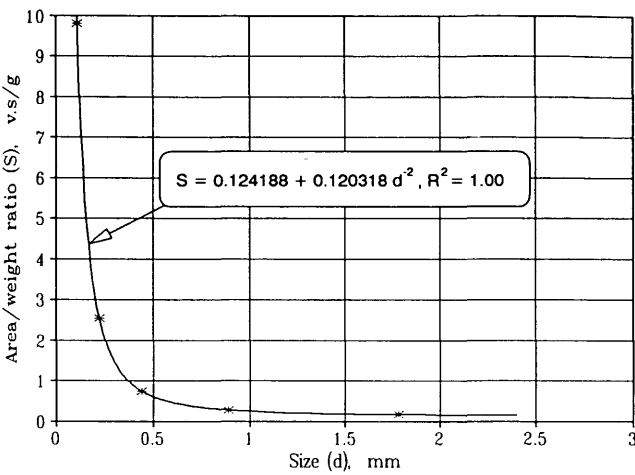


FIGURE 5 Area/weight ratio versus particle size.

column, the particles separate (as they travel downward) according to their sizes and produce a voltage-time profile similar to the one shown in the middle of Figure 6. The area bound by the profile and the initial voltage horizontal line is divided into small slices. Each slice a_i represents a small number of particles crossing the photocell sensing level at time t_i . The size d_i of the particles producing the area a_i is determined by substituting the value of t_i in Equation 12. The weight w_i of these particles is obtained by dividing the area a_i by the ratio S from Equation 13 corresponding to size d_i . The result of performing this process on all the area slices produced by the voltage-time profile is a set of d_i, w_i pairs, which are similar to the results obtained by conventional sieve analysis. These pairs are then used to construct the size gradation curve of the tested mixed sample as shown at the right side of Figure 6. A scan time of about 200 sec is required to run a mixed sample through the system.

DISCUSSION OF EXAMPLE GRADATIONS
CALCULATED BY FRACTIONATING WATER
COLUMN

The fractionating water column prototype was tested with a set of aggregate blends with particle sizes ranging from 0.074 mm (No. 200 sieve size) to 2.38 mm (No. 8 sieve size), the actual gradations of which were predetermined. These blends represent washed material passing the 2.38-mm sieve and retained on the 0.074-mm sieve. The calculated gradations of these blends are shown in Figures 7 and 8 along with their actual gradations for comparison. Figures 7 and 8 show that the calculated gradation curves suggest an underestimation of the coarser portion of the blend and an overestimation of the finer portion. These deviations of the calculated gradation curve from the actual one seem to represent a trend. The amount of deviation, however, varies for different tests.

Showing the gradations of two different samples on the same graph (Figures 7 and 8) adds to the credibility of the approach in that the calculated gradation curves follow their actual counterparts and do not deviate randomly. The tested aggregate blends represent the fine portions of aggregate blends whose gradations

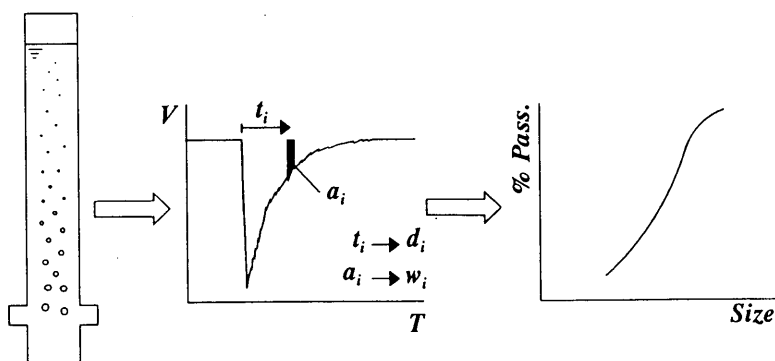


FIGURE 6 Schematic summary of analysis process.

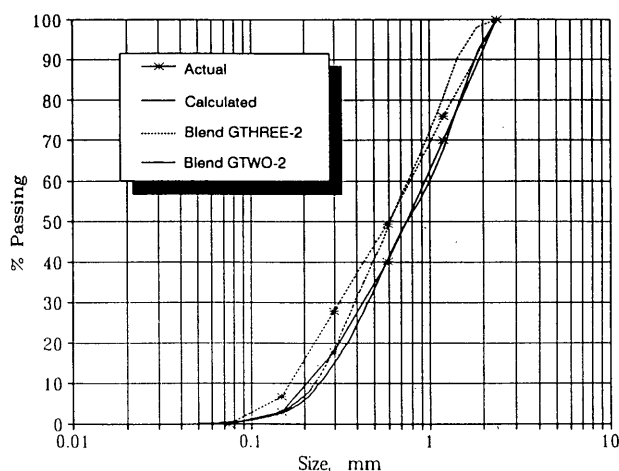


FIGURE 7 Examples of system output: Blends GTHREE-2 and GTWO-2.

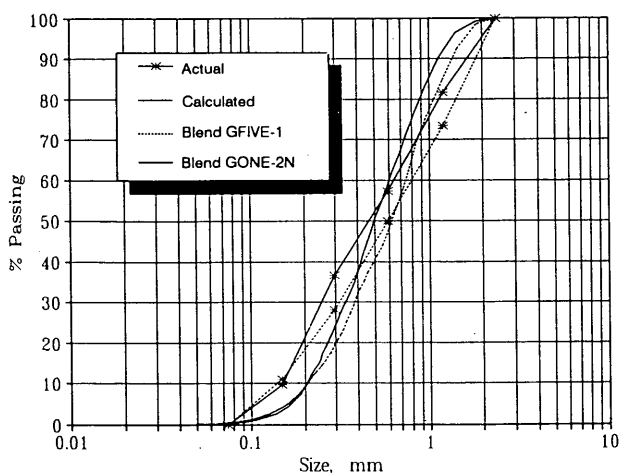


FIGURE 8 Examples of the system output: Blends GFIVE-1 and GONE-2N.

fall in the specification envelope for a densely graded aggregate of an asphalt hot mix that is normally used for leveling or as a binder or surface course (12).

Figure 9 shows the gradation of an aggregate blend containing particles of 26.5 mm maximum size. This blend is typical for a hot-mix asphalt used as a binder (12). The calculated gradation of the fine portion (<2.38 mm) of the blend is superimposed on the respective part of the curve to show how the calculated gradation would look in the context of a total blend gradation. It is clear that the "absolute" deviations would be reduced when the calculated gradation of the fine particles is shown as part of a total gradation curve. The absolute deviation of percent passing at any particle size will be reduced by the value of the percent passing the 2.38-mm sieve in the total aggregate blend.

In the sieving process, the fine particles require longer sieving times than coarser particles. If an aggregate sample was sieved down to the 2.38-mm sieve, the passing material could be analyzed using the developed system. This hybrid approach is illustrated schematically in Figure 10. To further automate the analysis

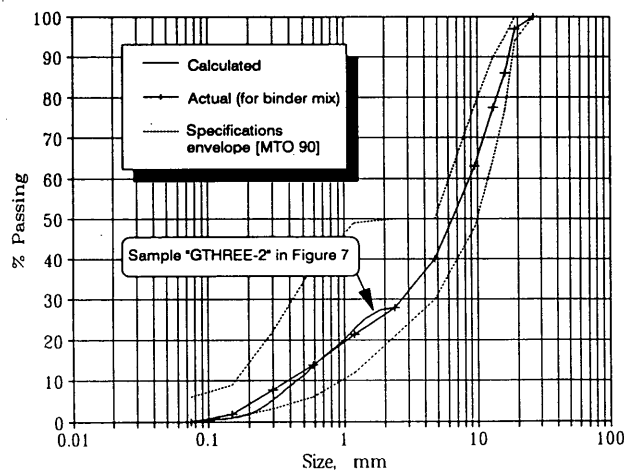


FIGURE 9 Gradation of fine portion (tested by fractionating water column) in context of total gradation curve of aggregate blend.

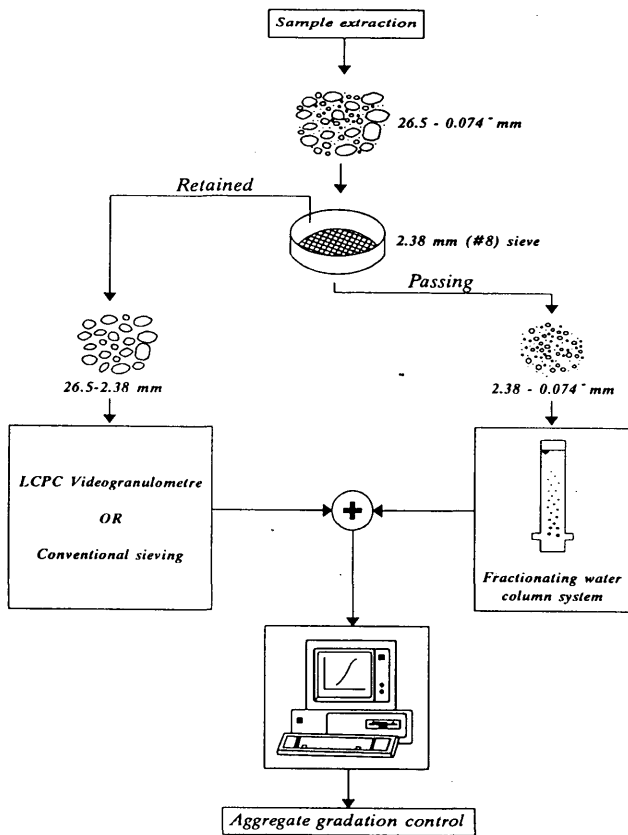


FIGURE 10 Conceptual illustration of hybrid system.

of the coarser portion of an aggregate blend (>2.38 mm), a system such as the French Videogranulometre (8) could be employed, and the full process would then be nearly fully automated. The gradations of the coarse and fine portions of the blend could easily be combined to produce the total gradation curve.

One aspect of the developed system that should be addressed is the capability of handling samples with dust (material finer than 74 μ m or passing the No. 200 sieve). This could be accomplished by adding another photocell near the top of the water column (Figure 2). The dust material is composed of very small particles

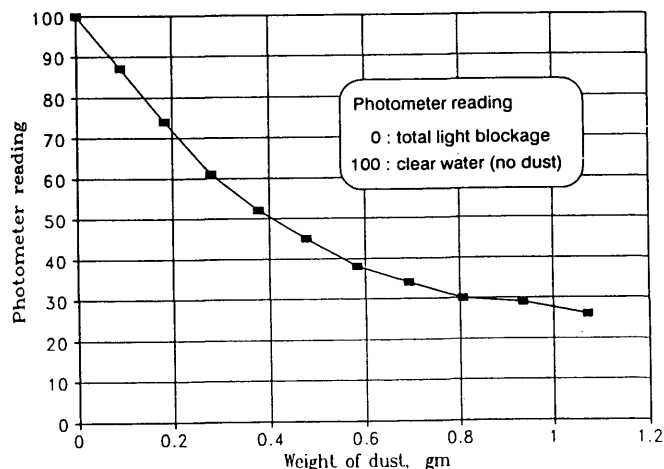


FIGURE 11 Results of pilot study on dust using photometer.

that will not have enough time to settle during the test period (200 sec). A voltage reading (at the end of a test) by the top photocell could be related to the amount of dust present in the tested sample. If necessary, the voltage reading of the bottom photocell could also be used to help in accurately determining the amount of particles finer than 74 μ m remaining in the water column.

Relating the light intensity to the amount of dust was proved to be possible by a simple experiment that was performed during the early stages of the research using a simple photometer and a jar filled with water. The jar was placed between a light source and the photometer's light sensor. Different amounts of dust were added to the water in the jar and the corresponding photometer readings were recorded. The weight of dust versus the photometer reading exhibited the relationship shown in Figure 11. A similar relationship could be established for the fractionating water column system.

CONCLUSION

For a very long time, sieve analysis was (and still is) the only established method for determining the size gradation of an aggregate blend. One major drawback associated with sieving is the relatively long processing time. Some research investigations resulted in working systems for automating the size gradation analysis of the coarse portion (>1 mm) of an aggregate blend. The fractionating water column methodology presented in this paper was developed to automate the analysis of the fine portion (<2.38 mm). The time required to run a sample of fine aggregate through the water column is approximately 200 sec (3.3 min). The voltage-time readings produced are already in digital format, and hence all the calculations (currently performed using electronic spreadsheets) could be performed in a negligible amount of time by a computer program that can be coded to replace the spreadsheets.

Some modifications to the fractionating water column system are required to make it adaptable to a full-scale environment. These modifications include the hardware (and consequently the software) to handle dust in a tested aggregate blend and the tube setup to automate the flushing and replacement of water after a test is performed. If the time needed to set the system for another test was found to be inconveniently long; two (or more) tubes could be used, each with a photocell and a light source. The A/D converter can very easily be instructed to read the voltage from the photocell of the tube that is being used. After these modifications are implemented, the system can be used as part of a hybrid system to automate the analysis of an aggregate blend. The other part of such a hybrid system would be to analyze the coarse portion (>2.38 mm) of the blend.

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