TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

IDEA *Innovations Deserving Exploratory Analysis Project*

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

ON LINE REAL-TIME MEASUREMENT AND CONTROL OF AGGREGATE GRADATION IN ASPHALT PLANTS

Felix Alba
Felix ALBA Consultants Inc.
Murray, Utah

Report of Investigation

INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS
MANAGED BY THE TRANSPORTATION RESEARCH BOARD (TRB)

This NCHRP-IDEA investigation was completed as part of the National Cooperative Highway Research Program (NCHRP). The NCHRP-IDEA program is one of the four IDEA programs managed by the Transportation Research Board (TRB) to foster innovations in highway and intermodal surface transportation systems. The other three IDEA program areas are Transit-IDEA, which focuses on products and results for transit practice, in support of the Transit Cooperative Research Program (TCRP), Safety-IDEA, which focuses on motor carrier safety practice, in support of the Federal Motor Carrier Safety Administration and Federal Railroad Administration, and High Speed Rail-IDEA (HSR), which focuses on products and results for high speed rail practice, in support of the Federal Railroad Administration. The four IDEA program areas are integrated to promote the development and testing of nontraditional and innovative concepts, methods, and technologies for surface transportation systems.

For information on the IDEA Program contact IDEA Program, Transportation Research Board, 500 5th Street, N.W., Washington, D.C. 20001 (phone: 202/334-1461, fax: 202/334-3471, http://www.nationalacademies.org/trb/idea)

ACKNOWLEDGMENTS

We would like to thank the National Cooperative Highway Research–IDEA Program for its contining technical and financial support, all Staker Co. personnel who collaborated with us during installation and testing, and, in particular, the following persons who, in many ways, helped make this project a success: Mike Worischeck, Steve Madrigal, and Randall Clark of Staker Co.; Jim Morton, Dave Clawson, and Jim Murray of Seltec Controls; Robert Morrison of R.L. Helms Construction Co.; John Elkins of Granite Construction Co.; and Jose M. Membrillo of ELSAN S.A., Spain.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The final performance of an asphalt pavement strongly depends on the size distribution (gradation) of the aggregates in the final mixture. In a typical asphalt plant, the target size distribution—also called job mix formula (JMF)—being sent into the mixer is obtained by proportioning aggregates, with different controlled gradations, coming out of four or more bins. These proportioning factors (PFs) are calculated off-line, based on the average values of the gradations in each of the stockpiles from which the different bins are loaded.

Current practice in the asphalt industry is to use sieve analysis to determine the gradation of each stockpile. Samples are taken regularly at the entrance of the mixer and sieved, and adjustments to PFs are made, if necessary. Sieving is the classical standard for industry. It is a time- and effort-consuming technique and is not suitable for on-line real-time measurement and control because, in many cases, by the time the plant manager identifies the source of the problem, the job is complete and out of specifications.

The IDEA product developed during this contract measures, on-line and in real-time every 5 minutes, the size distribution of the aggregates coming out of each belt feeder (*1*). Based on these measurements and the JMF, the optimal PFs for all bins are calculated to dynamically adjust the speed of their belt feeders.

This novel aggregate gradation control technology (AGCT) is based on the principles of machine vision, image processing, stereology, and deconvolution mathematics. Figure 1 shows the measurement and control concept, which starts with a lamp and a high-resolution line-scan video camera at each belt feeder associated with each cold bin.

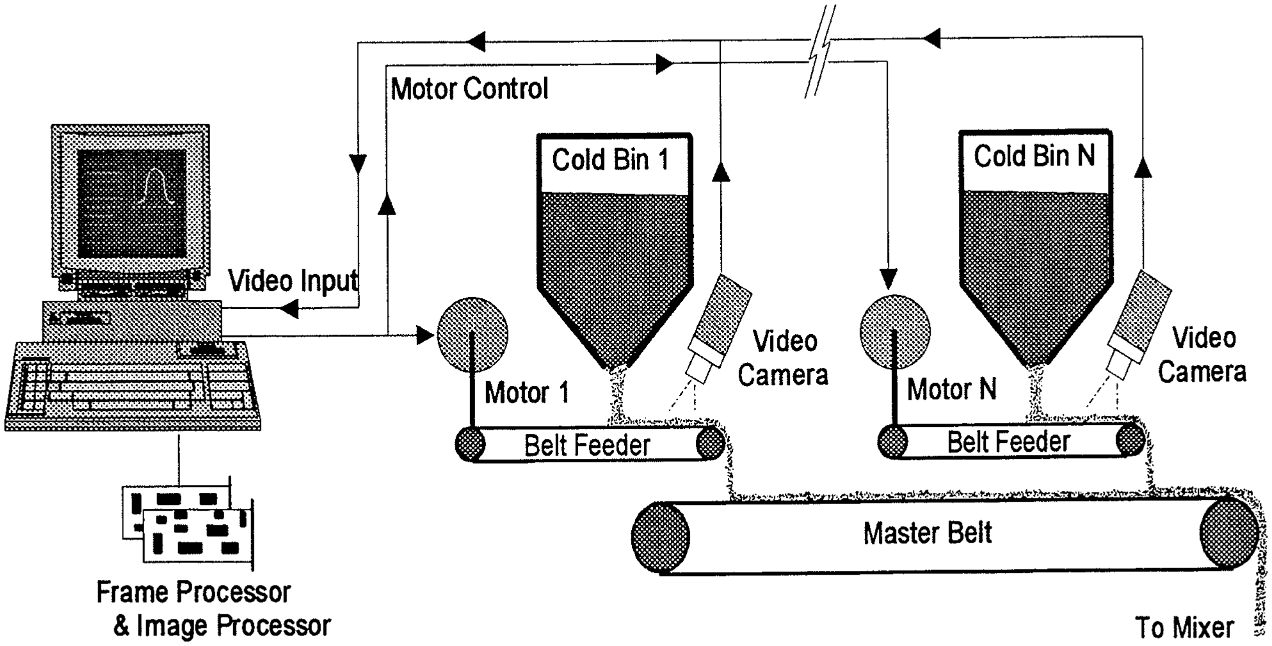

FIGURE 1 Concept for aggregate gradation control technology (L = lamp; C = high-resolution line-scan video camera; BF = belt feeder; CB = cold bin; MB = master belt; FG = frame grabber; IP = image processor; HC = host computer).

The raw images of the aggregates falling to the master belt are gathered by frame grabbers and preprocessed by image processor boards connected to the data bus of a host computer. Additional image processing and particle recognition algorithms executed in the host computer determine the chord-length distribution of the aggregates. The chord-length distribution is transformed into volumetric (sieve) size gradation by numerically inverting a mathematical stereological model that relates monodimensional information to tridimensional information. Finally, to comply with the JMF, the host computer uses optimization algorithms to calculate in real-time the optimal PFs for each bin. Belt feeder speeds are adjusted accordingly.

By applying this novel technology, asphalt plants are expected to (*a*) deliver an asphalt product that complies with the JMF, (*b*) run more uniformly with fewer dead periods, (*c*) require less asphalt and aggregates for the same throughput, and (*d*) produce better pavement with a higher performance-to-cost ratio.

This IDEA project was structured in two phases. Phase 1 consisted of determining the feasibility of the concept in a laboratory prototype setup and a pilot-scale arrangement (*2–5*). During Phase 2, the implementation and testing of a full-scale prototype was conducted at Staker Co. in Salt Lake City, Utah (*6–8*).

Phase 2, Stage 1, included the underground installation of all power and video signals from the bins to the computer room, design and construction of the camera housing, and design and construction of the electronic interface between the line-scan camera and the image frame grabber inside the computer (*7*).

Phase 2, Stage 2, consisted of testing hardware, developing a suitable software structure to conduct all necessary experimental work, and developing software for image processing and particle recognition. This facilitated the solution of practical problems encountered in a full-scale operation, such as variable belt feeder speed and rock humidity. All image preprocessing was programmed in C language, numerical routines in FORTRAN 77, and the operator interface in Visual BASIC for MS-DOS (*8*).

During Phase 2, Stage 3, the necessary software was developed to close the control loop (i.e., progressing from the gradation measurement to the determination of the optimal PFs to the actuation of the belt feeders). To accomplish these tasks, it was necessary to link our computer with the Seltec Controls Co. computer control system installed at Staker Co. The full-scale prototype was evaluated for its reproducibility and accuracy compared with the reproducibility and accuracy of standard sieve analysis and for its effectiveness in recommending proper PFs on a real-time basis.

As a result of this continuous long-term evaluation, AGCT proved to be a reliable and accurate tool for on-line real-time measurement and control of gradation in drum-mix plants. The aggregates (3/4-, 1/2-, and 3/8-in. rock and 1/8-in. sand) were tested by installing the same hardware in corresponding bins.

Agglomeration of humid, very fine aggregates impairs instrument accuracy on the fine tail of the size distribution. Semiempirical techniques—based on empirical knowledge gathered over the years by the asphalt industry—that essentially extrapolate the measured gradation toward the fine tail region of the distribution have been successfully developed to compensate for this intrinsic deficiency in the technology.

Overall reproducibility of the instrument for the bins tested was within 2 percent absolute on each mesh size, and the accuracy relative to standard sieving was within 4 percent absolute on each mesh size. With this performance of the basic measurement of the aggregate gradations, the prototype proved to react rapidly to plant upsets by updating the optimal PFs so that gradation of the total mix could be maintained within specifications.

In addition to this final report, the report *Design and Manufacturing Documentation for the AGCT Technology* has been submitted to the NCHRP-IDEA Program (*1,7*). The next step in this project is to design a commercial prototype, capable of monitoring and controlling all bins simultaneously, so that global automatic control of the plant can be achieved. Several instrumentation companies are interested in pursuing the commercialization of this emerging technology, and preliminary negotiations are taking place.

THEORETICAL FOUNDATION

AGCT is based on the principles of machine vision, image processing, stereology, and deconvolution mathematics. A high-resolution line-scan camera is employed to generate images of the aggregates on the feeder belt. High resolutions of 5,000 or more pixels per line can be achieved because a line-scan camera provides a one-dimensional cut of a bidimensional image transversal to the belt (a line) and the frame grabber generates the second dimension from movement of the belt.

First, the raw image is spatially filtered, which eliminates spot noise and smooths irregular particle features while preserving edge information. Second, the image is enhanced, if necessary, by stretching the image's intensity dynamic range to cover the full 8-bit range (0–255). Third, the histogram of the image is calculated, and two optimal threshold values are determined. Because humidity of the aggregates can substantially change these optimal threshold values, their dynamic calculation is crucial. Fourth, the image is thresholded, converting the gray-level image into a trinary image of particle (white), no particle or shadow (black), and uncertainty (a dead zone between the threshold values, which minimizes the probability of confusing the aggregate texture with very fine particles).

The chord-length distribution is subsequently determined from the ternary image. A chord length is the length of the chord defined by the intersection of a particle border with the line transversal to the belt being scanned by the camera. The chord-length distribution is calculated from a large number of these chords (typically 30,000 to 50,000). Particle boundaries must be identified to calculate this distribution accurately. Imperfect illumination, variable reflectivity of particles, and aggregate overlapping conspire against the successful recognition of particle boundaries. In essence, recognition of particle boundaries calls for the computer to emulate the ability of the human brain to isolate objects from confusing scenes of shadows and overlapped aggregates. The principles behind the particle recognition algorithm (PARTREAL), which was designed and programmed to accomplish this difficult statistical task, have been discussed in an earlier report (*5*).

From stereological and probability considerations (*2,5*), the following integral equation relates the chord-length distribution with the volumetric (sieve) size distribution:

$$f_L(L) = \mu_L . \int_0^\infty \left[\, p(L/d)/\mu_{L/d}(d) \,\right] . f_V(d).dd \qquad (1)$$

where

$f_L(L)$ = density function for chord-length distribution by number,

$f_V(d)$ = density function for volumetric sieve distribution,

$p(L/d)$= conditional probability for chord-length distribution associated with a mono–size distribution of sieve size *d*,

$\mu_L = \int_0^\infty L.f_L(L).dL$ (mean of chord-length distribution), and

$\mu_{L/d} = \int_0^\infty L.p(L/d).dL$ (mean of conditional chord-length distribution).

In equation (1), $f_L(L)$ is measured as the line-scan camera scans the aggregate on the belt; *p*(*L*/*d*) can be determined from first principles for very simple shapes only (spheres, ellipsoids, and the like). Because of the irregular shape of the aggregates, a semiphenomenological model for this function has been developed. This model is based on first principles and empirical information. Empirical information is being introduced into the model through two free parameters associated with the shape of the aggregates, the values of which are determined by calibration experiments. Details regarding this crucial aspect of the AGCT instrument are described by Alba (*5*).

The distributions μ_L and $\mu_{L/d}$ are numerically computed. Equation (1) becomes a Fredholm integral of the first kind inversion problem, which the computer solves in real time, determining the unknown volumetric (sieve) size distribution $f_V(d)$. This inversion problem is not straightforward and has demanded considerable research and development because of an inherent nonuniqueness and instability of the numerical solution (*2–8*).

Finally, with the measured gradation for each bin and the JMF, the instrument determines the optimal PFs by solving the following optimization problem.

Find $P = (P1, P2, \ldots, PNb)^T$ to minimize the following objective function:

$$\mathrm{OBJ} = (F.P - \mathrm{JMF})^T.W.(F.P - \mathrm{JMF}) \tag{2}$$

where

P = vector of PFs with $\Sigma P_J = 1$;
F = matrix whose rows are the sieve distributions for each bin; and
W = weight matrix that conveys information concerning JMF tolerance, practical plant management conditions such as the need to save a particular aggregate, and PFs not lower than 10 percent to avoid discontinuous discharge from a particular bin to the master belt.

This mathematical problem, which the AGCT instrument solves using quadratic programming techniques (*2*), can be expressed as "Look for a distribution of belt feeder speeds for each bin such that the final produced mix deviates from the JMF the least, complying with all practical operating constraints."

HARDWARE DEVELOPMENT

PLANT MODIFICATIONS AND WIRING

To avoid ground-loop problems and electromagnetically induced noise detected early during the first attempts to gather video signals, metal conduits (about 60 m) were installed underground from the computer to all bins in the plant, carrying the video and control signals between the frame grabber inside the computer and the camera interface by the bin. Metal conduits also were run from the interface to the camera housing carrying the DC power, video, and control signals to the camera. In this manner, all signals were double shielded from electromagnetic interference. In addition, a ground wire was installed parallel to the conduits to ensure electrical continuity throughout the whole system. A dedicated ground was built for the instrumentation,which in turn was powered through an isolation transformer. Two quartz halogen lamps of 300 watts each were installed inside the bin gate (*7*).

PROTOTYPE DESCRIPTION

A Pulnix line-scan camera that produces images with 5,000 pixels/line was used with the EPIX 4-MB video frame grabber. An ad hoc interface between the frame grabber and the camera was developed jointly with EPIX, Inc., to improve the overall resolution of the system. For coarse materials (3/4-, 1/2-, 3/8-in.), an inexpensive Pentax A 50 mm F2 lens was attached to the camera, providing a resolution transversal to the belt feeder of about 50 μm/pixel. For the sands, a macrolens Pentax FA 100 mm F2.8 was employed, which provided a transversal resolution of 7 μm/pixel. Longitudinal resolution depends on the integration time of the camera (500 μs) and speed of the belt feeders. It typically oscillates between 30 μm/line and 70 μm/line.

Figure 2 shows the camera housing plus illumination installed on the bin structure. The camera is refrigerated with compressed air. This air provides a slightly higher interior pressure to seal the housing from dust and, on its way out of the chamber, is redirected to blow flush to the lens window to minimize dust deposits on the glass. An electronic air drier and purifier protects the camera from water and oil existing in the air line. The housing is attached to a fine lead-screw adjustment position mechanism that allows precise focusing of the camera to any of the bins and aggregate sizes. Detailed design and manufacturing specifications are described elsewhere (*7, 9*).

Figure 3 displays the computer system, comprising a 486/50 computer, a 330-MB hard disk, 5.25- and 3.5-in. floppy disk drives, a removable Bernoulli 90-MB disk drive for off-line image storage, VGA monitor, printer, and video monitor to visually inspect images. The system is connected through an RS-232 communication link to the Seltec computer in the control room.

SOFTWARE DEVELOPMENT

The following software has been designed and coded for the AGCT prototype to provide the following:

- Image grabbing and preprocessing (C language);
- Measurement of chord-length distribution (Visual BASIC);
- Stereological mathematical modeling (Visual BASIC and FORTRAN);
- Numerical inversion of the stereological integral [equation (1), Visual BASIC, and FORTRAN];
- Real-time calculation of the optimal PFs for each bin [equation (2) and FORTRAN];
- Calibration of the instrument (Visual BASIC and FORTRAN); and
- Operator interfacing (Visual BASIC).

Development of this complex multilanguage software started during the first stages of this project. Detailed accounts of software structure is reported by Alba (*3*, *8*). The source code is described by Alba (*9*).

EXPERIMENTAL RESULTS

RESULTS FOR THE 1/2-in. BIN

A problem initially encountered with the measurement of coarse aggregates was the impossibility for the instrument to accurately measure a low percentage (3 to 5 percent) of material under #200 mesh (74 μm), which existed as a film of dust attached to the particles. This dust did not exist if the aggregate had been washed. This impossibility is inherent in the technology; if the camera is focused on the rocks, it cannot see the dust and vice versa.

Even though neglecting this low percentage of dust does not significantly affect plant control (typically a plant mix contains about 10 percent of material under #200 mesh, which comes mainly from the sand bins), a semiempirical technique to account for this deficiency in the technology was developed. The light reflectivity of the aggregate changes significantly whether it is washed or not, which alters the statistical pattern of the signals. When the instrument detects a dry condition, it adds a constant percentage of about 4 percent to the fraction under the #200 mesh. This simple technique improved the accuracy with which the instrument determined the optimal PFs to minimize deviations from the JMF.

In one of the runs, the instrument monitored the gradation coming out of the 1/2-in. bin, without calculating the PFs in real time. Tables 1 and 2 display typical deviations in our instrument readings from the average gradation used by Staker. Note the detection of fines by the technique described previously. By 1:33 p.m. (Table 3), the percentage passing 3/8 in. increased by almost 14 units along with the percentage passing #4 mesh, which increased about threefold. Operations people who were experiencing a rapid decrease in mixer temperature were contacted immediately.

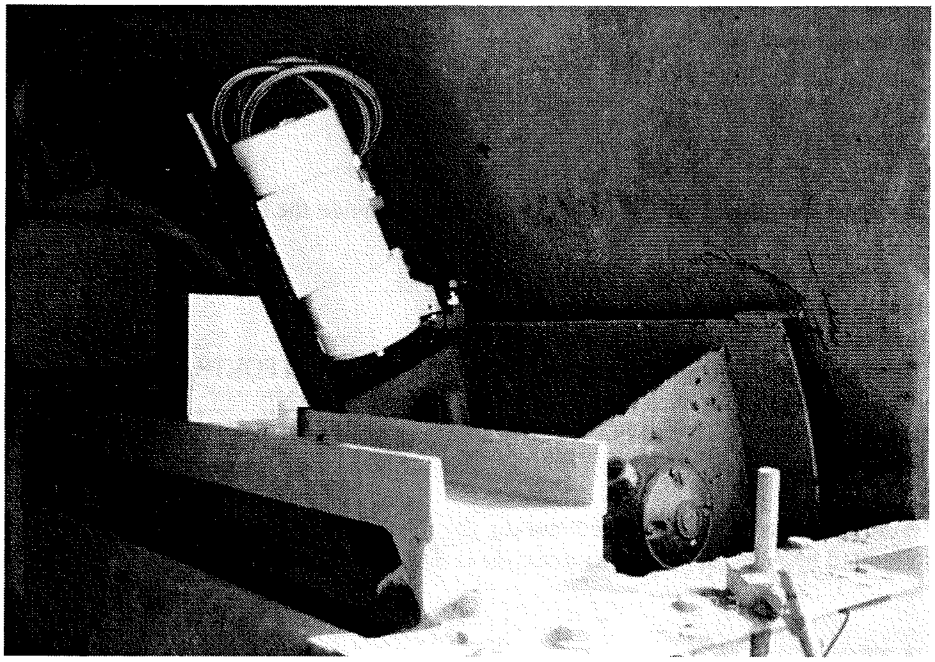

FIGURE 2 Camera housing plus illumination on bin structure.

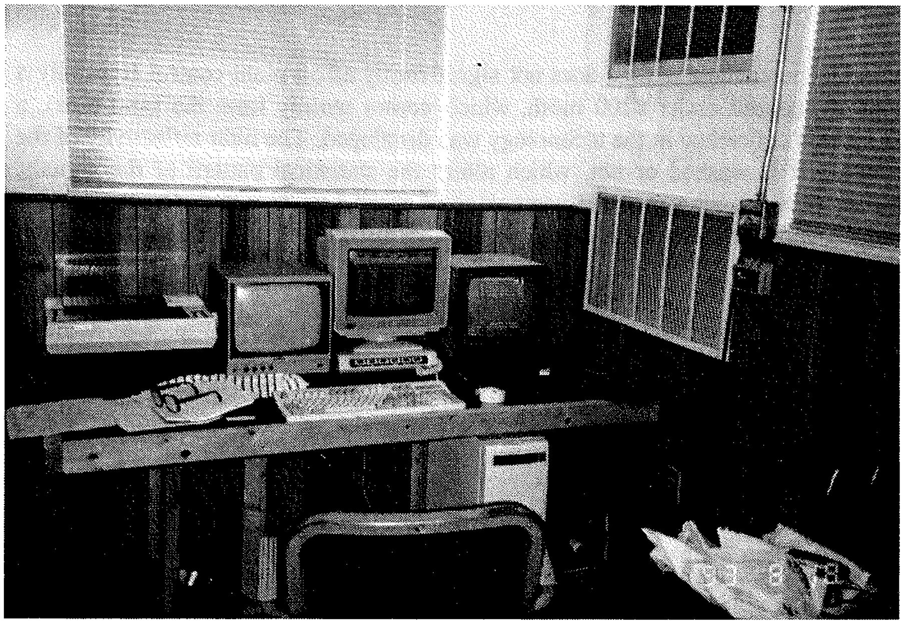

FIGURE 3 Computer system setup.

TABLE 1 Measurement of Sieve Size Distribution During Normal Plant Operation (Cumulative Format)

05-11-1994			13: 27: 24
Mesh	Staker (%)	AGCT (%)	Abs. Dev. (%)
1	100.00	100.00	0.00
3/4	100.00	100.00	0.00
1/2	100.00	99.46	-0.54
3/8	75.00	80.52	5.52
#4	4.20	7.26	3.06
#8	3.20	3.30	0.10
#16	2.80	3.22	0.42
#30	2.70	3.22	0.52
#50	2.70	3.22	0.52
#100	2.50	3.17	0.67
#200	2.30	2.15	-0.15

TABLE 2 Measurement of Sieve Size Distribution During Normal Plant Operation (Cumulative Format)

05-11-1994			13: 29: 24
Mesh	Staker (%)	AGCT (%)	Abs. Dev. (%)
1	100.00	100.00	0.00
3/4	100.00	100.00	0.00
1/2	100.00	99.10	-0.90
3/8	75.00	77.65	2.65
#4	4.20	7.61	3.41
#8	3.20	3.70	0.50
#16	2.80	3.61	0.81
#30	2.70	3.60	0.90
#50	2.70	3.60	0.90
#100	2.50	3.56	1.06
#200	2.30	2.41	0.11

TABLE 3 Measurement of Sieve Size Distribution During Plant Upset (Cumulative Format)

05-11-1994			13: 33: 24
Mesh	Staker (%)	AGCT (%)	Abs. Dev. (%)
1	100.00	100.00	0.00
3/4	100.00	100.00	0.00
1/2	100.00	99.71	-0.29
3/8	75.00	88.72	13.72
#4	4.20	12.79	8.59
#8	3.20	3.84	0.64
#16	2.80	3.45	0.65
#30	2.70	3.44	0.74
#50	2.70	3.44	0.74
#100	2.50	3.39	0.89
#200	2.30	2.30	0.00

TABLE 4 Measurement of Sieve Size Distribution at Return to Normal Plant Operation (Cumulative Format)

05-11-1994 Mesh	Staker (%)	AGCT (%)	13: 52: 55 Abs. Dev. (%)
1	100.00	100.00	0.00
3/4	100.00	100.00	0.00
1/2	100.00	99.96	-0.04
3/8	75.00	82.14	7.14
#4	4.20	4.57	0.37
#8	3.20	3.36	0.16
#16	2.80	3.35	0.55
#30	2.70	3.35	0.65
#50	2.70	3.35	0.65
#100	2.50	3.31	0.81
#200	2.30	2.24	-0.06

After visual inspection of the bins, it was determined that the 1/2- and 3/4-in. aggregates had a considerably higher content of water and fines. The cause was soon identified: a new loader operator was scooping too low from the stockpiles. By 1:52 p.m., the problem had been corrected (Table 4). The prototype had reacted quickly to a transitory plant upset.

Our instrument was storing data on a disk at the time of the plant upset; therefore, we subsequently reproduced the plant transient by retrieving the gradations and instructing the computer to calculate the optimal PFs. In this manner, we were able to evaluate—off-line—what the control reaction of our instrument would have been if it had been connected in the on-line control mode.

Tables 5 and 6 correspond to Table 2: Table 5 for a mix called 1/2State and Table 6 for a mix called 3/4State. The instrument recommended a set of PFs that placed the resulting mix within tolerance with respect to the JMF. Proposed PFs were very close to the ones determined off-line by Staker for the 3/4State mix; however, they differed considerably for the 1/2State mix because Staker was trying to save the 1/8-in. material, and at that time our optimization algorithms did not have the "intelligence" to do this. We subsequently included this capability in our system. The standard deviation from the JMF was lower for the 3/4State mix than for the 1/2State mix. This is simply a consequence of having one more aggregate in the 3/4State mix.

Tables 7 and 8 correspond to Table 3 and demonstrate the control action taken by our instrument upon plant upset. The change in the 1/2-in. material was very important for the 1/2State mix, and our instrument, to minimize deviation from specifications, recommended shutdown of the PM bin, increasing the 1/8-in. aggregate from 30 to 40 percent. This increase and drastic shutdown would not have happened if our instrument had known that Staker was trying to save the 1/8-in. aggregate. The upset was not significant for the 3/4State mix, and the instrument was able to maintain a very good standard deviation with minor adjustments to the PFs. This again was due to the existence of one more aggregate in this mix. Tables 9 and 10 show the plant back to a steady state, with the instrument recommending approximately the same PF with a final mix within specifications.

TABLE 5 Proportioning Factors for 1/2State Mix During Normal Plant Operation (Deviations Based on AGCT Sieve Results)

Mesh	1/8 in.	PM	Point	1/2 in.	Mix	JMF	DEV
1	100.0	100.0	100.0	100.0	99.9	100.0	-0.1
3/4	100.0	100.0	100.0	100.0	99.9	100.0	-0.1
1/2	100.0	100.0	100.0	99.1	99.7	100.0	-0.3
3/8	100.0	99.0	97.0	77.6	94.3	93.6	0.7
#4	98.0	72.0	88.0	7.4	70.7	70.0	0.7
#8	60.0	43.0	82.0	3.4	50.0	51.4	-1.4
#16	30.0	27.0	79.0	3.4	36.3	38.0	-1.7
#30	19.0	21.0	71.0	3.4	29.5	27.0	2.5
#50	8.0	16.0	59.0	3.4	21.9	22.0	-0.1
#100	5.5	13.5	30.0	3.3	13.2	13.0	0.2
#200	3.0	11.0	4.0	2.2	5.0	7.0	-2.0

Proportioning Factors (%) Std. Dev. from JMF

AGCT:	30.2	24.0	25.4	20.3		1.22	
Staker:	16.0	46.0	22.0	16.0	05-30-1994		08: 08: 14

TABLE 6 Proportioning Factors for 3/4State Mix During Normal Plant Operation (Deviations Based on AGCT Sieve Results)

Mesh	1/8 in.	PM	Point	1/2 in.	3/4 in.	Mix	JMF	DEV
1	100.0	100.0	100.0	100.0	100.0	99.9	100.0	-0.1
3/4	100.0	100.0	100.0	100.0	100.0	99.9	100.0	-0.1
1/2	100.0	100.0	100.0	99.1	48.0	92.8	93.4	-0.6
3/8	100.0	99.0	97.0	77.6	12.0	84.4	84.0	0.4
#4	98.0	72.0	88.0	7.4	5.0	62.2	62.0	0.2
#8	60.0	43.0	82.0	3.4	4.5	43.1	43.5	-0.4
#16	30.0	27.0	79.0	3.4	3.5	31.4	32.0	-0.6
#30	19.0	21.0	71.0	3.4	3.0	25.7	25.0	0.7
#50	8.0	16.0	59.0	3.4	2.5	19.7	20.0	-0.3
#100	5.5	13.5	30.0	3.3	2.5	12.7	12.0	0.7
#200	3.0	11.0	4.0	2.2	2.5	6.2	7.0	-0.8

Proportioning Factors (%) Std. Dev. from JMF

AGCT:	15.6	39.3	19.3	12.3	13.4		0.51	
Staker:	14.0	40.0	16.0	18.0	12.0	05-30-1994		0:8 08:32

TABLE 7 Proportioning Factors for 1/2State Mix During Plant Upset (Deviations Based on AGCT Sieve Results)

Mesh	1/8 in.	PM	Point	1/2 in.	Mix	JMF	DEV
1	100.0	100.0	100.0	100.0	99.9	100.0	-0.1
3/4	100.0	100.0	100.0	100.0	99.9	100.0	-0.1
1/2	100.0	100.0	100.0	99.7	99.8	100.0	-0.2
3/8	100.0	99.0	97.0	88.7	95.6	93.6	2.0
#4	98.0	72.0	88.0	12.8	69.5	70.0	-0.5
#8	60.0	43.0	82.0	3.9	49.7	51.4	-1.7
#16	30.0	27.0	79.0	3.5	36.6	38.0	-1.4
#30	19.0	21.0	71.0	3.5	29.8	27.0	2.8
#50	8.0	16.0	59.0	3.5	21.8	22.0	-0.2
#100	5.5	13.5	30.0	3.4	12.1	13.0	-0.9
#200	3.0	11.0	4.0	2.3	3.1	7.0	-3.9

Proportioning Factors (%) Std. Dev. from JMF

AGCT:	40.3	0.0	29.7	29.9		1.74	
Staker:	16.0	46.0	22.0	16.0	5-30-1994		08: 11:29

TABLE 8 Proportioning Factors for 3/4State Mix During Plant Upset (Deviations Based on AGCT Sieve Results)

Mesh	1/8 in.	PM	Point	1/2 in.	3/4 in.	Mix	JMF	DEV
1	100.0	100.0	100.0	100.0	100.0	99.9	100.0	-0.1
3/4	100.0	100.0	100.0	100.0	100.0	99.9	100.0	-0.1
1/2	100.0	100.0	100.0	99.7	48.0	92.3	93.4	-1.1
3/8	100.0	99.0	97.0	88.7	12.0	84.7	84.0	0.7
#4	98.0	72.0	88.0	12.8	5.0	62.3	62.0	0.3
#8	60.0	43.0	82.0	3.9	4.5	43.0	43.5	-0.5
#16	30.0	27.0	79.0	3.5	3.5	31.4	32.0	-0.6
#30	19.0	21.0	71.0	3.5	3.0	25.8	25.0	0.8
#50	8.0	16.0	59.0	3.5	2.5	19.7	20.0	-0.3
#100	5.5	13.5	30.0	3.4	2.5	12.7	12.0	0.7
#200	3.0	11.0	4.0	2.3	2.5	6.1	7.0	-0.9

Proportioning Factors (%) Std. Dev. from JMF

AGCT:	15.6	38.1	19.7	11.9	14.6		0.64	
Staker:	14.0	40.0	16.0	18.0	12.0	05-30-1994		08:12:38

TABLE 9 1/2State Mix at Return to Normal Plant Operation (Deviations Based on AGCT Sieve Results)

Mesh	1/8 in.	PM	Point	1/2 in.	Mix	JMF	DEV
1	100.0	100.0	100.0	100.0	99.9	100.0	-0.1
3/4	100.0	100.0	100.0	100.0	99.9	100.0	-0.1
1/2	100.0	100.0	100.0	99.9	99.9	100.0	-0.1
3/8	100.0	99.0	97.0	78.9	94.4	93.6	0.8
#4	98.0	72.0	88.0	4.7	70.3	70.0	0.3
#8	60.0	43.0	82.0	3.4	50.2	51.4	-1.2
#16	30.0	27.0	79.0	3.4	36.4	38.0	-1.6
#30	19.0	21.0	71.0	3.4	29.5	27.0	2.5
#50	8.0	16.0	59.0	3.4	21.8	22.0	-0.2
#100	5.5	13.5	30.0	3.4	12.9	13.0	-0.1
#200	3.0	11.0	4.0	2.3	4.7	7.0	-2.3

Proportioning Factors (%) Std. Dev. from JMF

AGCT:	33.1	19.7	25.8	21.3		1.22	
Staker:	16.0	46.0	22.0	16.0	05-30-1994		08:37:14

TABLE 10 3/4State Mix at Return to Normal Plant Operation (Deviations Based on AGCT Sieve Results)

Mesh	1/8 in.	PM	Point	1/2 in.	3/4 in.	Mix	JMF	DEV
1	100.0	100.0	100.0	100.0	100.0	99.9	100.0	-0.1
3/4	100.0	100.0	100.0	100.0	100.0	99.9	100.0	-0.1
1/2	100.0	100.0	100.0	99.9	48.0	92.8	93.4	-0.6
3/8	100.0	99.0	97.0	78.9	12.0	84.5	84.0	0.5
#4	98.0	72.0	88.0	4.7	5.0	62.1	62.0	0.1
#8	60.0	43.0	82.0	3.4	4.5	43.3	43.5	-0.2
#16	30.0	27.0	79.0	3.4	3.5	31.5	32.0	-0.5
#30	19.0	21.0	71.0	3.4	3.0	25.7	25.0	0.7
#50	8.0	16.0	59.0	3.4	2.5	19.6	20.0	-0.4
#100	5.5	13.5	30.0	3.4	2.5	12.7	12.0	0.7
#200	3.0	11.0	4.0	2.3	2.5	6.2	7.0	-0.8

Proportioning Factors (%) Std. Dev. from JMF

AGCT:	16.2	39.0	19.2	11.9	13.6		0.50	
Staker:	14.0	40.0	16.0	18.0	12.0	05-30-1994		08:37:37

In conclusion, for the coarse aggregates (3/4-, 1/2-, and 3/8-in.), the prototype demonstrated that it can measure the gradation with a reproducibility better than 2 percent absolute on each mesh and with an accuracy (relative to standard sieving) better than 4 percent absolute on each mesh.

RESULTS FOR THE 1/8-in. BIN

This bin typically has an aggregate size distribution with about 98 percent under #4 mesh, 70 percent under #8, 40 percent under #16, 12 percent under #50, and about 2 percent under #200. Mathematically characterizing the size distribution obtained by sieving indicates that these aggregates possess bimodal gradations: a fine mode with a mean of about 0.4 mm and a coarse mode with a mean of about 2.5 mm, with the latter amounting to about 70 percent by volume of the distribution.

The macrolens with a focal length of 100 mm provides enough resolution (7 µm/pixel) to discriminate the dust (Table 11). The instrument reports about 10 percent by number of measured chord lengths under 60 µm; however, the percentage by length under 60 µm is only 0.33 percent.

By using the stereological model, which predicts the chord-length distribution associated with any volumetric (sieve) size distribution, it can be seen that for the distribution given by laboratory sieving, the expected percentage by length under 60 µm is much larger than 0.33 percent (3 to 5 percent). Even though the technology has the capability of discriminating the dust, the high humidity of this type of aggregate causes particles to agglomerate considerably, which causes our instrument to underreport the fines. This is a clear limitation in the technology —the camera cannot see the totality of the primary particles, which instead are reported in conventional sieving after washing.

Despite this limitation, we devised a technique based on empirical knowledge gathered over the years by the asphalt industry about the functional structure of these distributions. In this technique, the instrument (*a*) uses about 70 percent of the basic measured chord-length distribution, discarding the fines tail that lacks accuracy; (*b*) inverts the stereological model as usual but considers the resulting volume distribution only as the coarse mode of the final result; and (*c*) adds to this coarse mode a fine mode that conforms to the typical contents of aggregate fines and links with the coarse mode smoothly. This technique is equivalent to exatrapolating the missing 30 percent of the distribution from the measured 70 percent, but it has proved to be more consistent and accurate.

TABLE 11 Chord-Length Distribution for 1/8-in. Bin

Chord-Length Distribution

Size (mm)	Cumul. (%)	STD/Mean (%)	Number
0.01	0.05	-	2,744
0.02	0.05	-	88
0.04	0.22	-	2,303
0.06	0.33	-	897
0.11	1.10	10.97	3,620
0.19	2.87	7.93	4,659
0.32	8.10	5.09	8,062
0.56	19.89	3.99	10,529
0.97	42.75	2.16	11,927
1.67	72.54	1.10	9,216
2.89	92.70	0.62	3,740
5.01	99.28	0.40	722
8.67	99.96	0.07	46
15.00	100.00	0.00	1

Parameters and Statistics

Date: 09-21-1994	Time: 13: 54: 52
Aggregate I.D.:	cone8th1
Tonnage (tn/h):	96.5
Black/White (%):	0.0. 0.5
Threshold Band:	2,2
Threshold Values:	116,120
Continuity:	0.56
Edge Tolerance:	0.56
Deactivation:	1.00
Chords/Measurement:	58,553
Particles/Measurement:	7,568
Res. Part./Measurement:	114

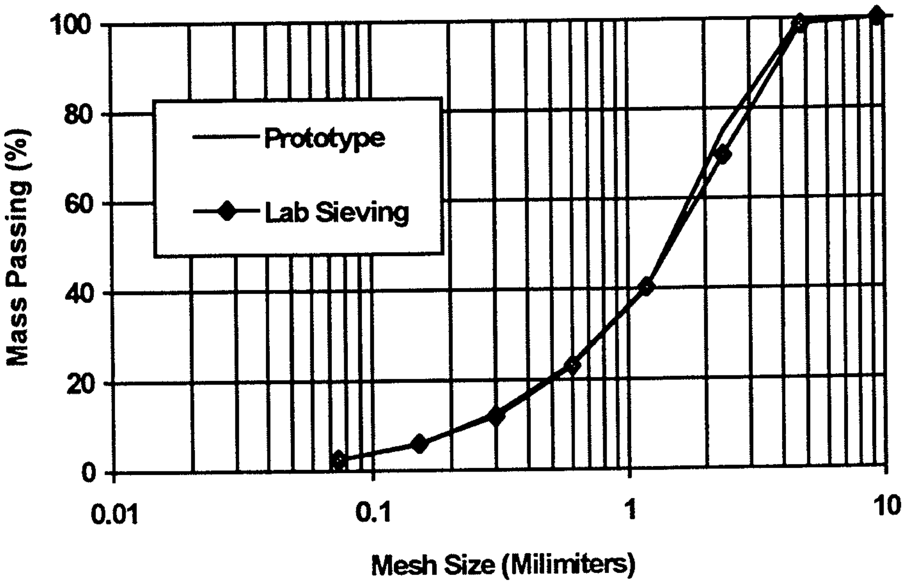

FIGURE 4 Sieve size distribution for 1/8-in. Bin.

TABLE 12 Proportioning Factors for 1/2State Mix (Deviations Based on AGCT Sieve Results)

Mesh	1/8 in.	PM	Geneva	1/2 in.	Mix	JMF	DEV
1	100.0	100.0	100.0	100.0	99.9	100.0	-0.1
3/4	100.0	100.0	100.0	100.0	99.9	100.0	-0.1
1/2	100.0	100.0	100.0	100.0	99.9	100.0	-0.1
3/8	100.0	99.0	99.0	70.0	92.4	92.0	0.4
#4	99.8	78.0	98.0	8.0	68.8	70.0	-1.2
#8	76.7	51.0	94.0	4.0	51.5	50.0	1.5
#16	39.4	34.0	85.0	3.5	36.3	38.0	-1.7
#30	23.1	26.0	60.0	3.3	25.9	25.0	0.9
#50	12.3	18.0	20.0	3.2	14.0	14.0	-0.0
#100	5.7	15.0	12.0	3.0	10.2	10.0	0.2
#200	2.4	12.0	3.5	2.8	6.9	7.0	-0.1

Proportioning Factors (%)   Std. Dev. from JMF

AGCT:	16.4	44.1	16.5	22.9	0.84	
Staker:	22.0	34.0	20.0	24.0	09-23-1994	16:47:24

4 of 5   Taking Images   Continuous

TABLE 13 Proportioning Factors for 3/4State Mix (Deviations Based on AGCT Sieve Results)

Mesh	1/8 in.	PM	Geneva	1/2 in.	3/4 in.	Mix	JMF	DEV
1	100.0	100.0	100.0	100.0	100.0	99.9	100.0	-0.1
3/4	100.0	100.0	100.0	100.0	100.0	99.9	100.0	-0.1
1/2	100.0	100.0	100.0	100.0	45.0	92.1	92.0	0.1
3/8	100.0	99.0	99.0	70.0	8.0	82.1	82.0	0.1
#4	99.8	78.0	98.0	8.0	5.0	64.2	62.0	2.2
#8	77.2	51.0	94.0	4.0	4.0	47.4	45.0	2.4
#16	40.0	34.0	85.0	3.5	3.5	31.9	34.0	-2.1
#30	23.5	26.0	60.0	3.3	3.0	22.6	23.0	-0.4
#50	12.5	18.0	20.0	3.2	2.5	12.8	14.0	-1.2
#100	5.8	15.0	12.0	3.0	2.2	9.3	10.0	-0.7
#200	2.5	12.0	3.5	2.8	2.0	6.5	7.0	-0.5

Proportioning Factors (%) Std. Dev. from JMF

AGCT:	20.0	41.1	10.5	14.0	14.3		1.26	
Staker:	18.0	20.0	24.0	20.0	18.0	09-23-1994		16:51:21

4 of 5 Taking Images Continuous

Figure 4 depicts a typical agreement between the average sieve gradation used by Staker and the AGCT measurement. Again, reproducibility is within 2 percent absolute on each mesh, and accuracy relative to standard sieving is within 4 percent absolute on each mesh.

Table 12 shows one screen of the instrument on a day when it operated continuously from 7 a.m. to 5 p.m. At the time the plant was processing the 1/2State mix. Table 13 corresponds to about 4 min later when the plant switched to 3/4State mix. In both cases, the recommended PFs maintained the deviations from the JMF well within tolerance. The factors determined by our instrument differ considerably in some cases from the averages used by Staker because some practical considerations of the plant manager had not been included in the system's knowledge base (e.g., PFs less than 10 percent provoke discontinuous aggregate discharge on the master belt and should be avoided). This important practical constraint was later included in the prototype knowledge base.

CONCLUSIONS

We have concluded from extensive testing of the prototype that AGCT is a reliable and accurate tool for on-line real-time measurement and control of the gradation in drum-mix plants. Limitations have been identified, and semiempirical solutions have been implemented. Different aggregates have been tested, ranging from 3/4-, 1/2-, and 3/8-in. rock to 1/8-in. sand, by installing the same hardware in corresponding bins. The extensive experimental data for these aggregates indicate that the technology can measure the gradation with a reproducibility better than 2 percent absolute on each mesh, with an accuracy relative to lab screening better than 4 percent absolute on each mesh. Substantial data shown to Staker plant managers on how the prototype would react under plant transient deviations from steady state proved that real-time accurate control of the plant is possible.

The next step for this project is to design a commercial prototype capable of monitoring all bins simultaneously so that global automatic control of the plant can be achieved. Considerable capital investment is needed for this step, and we are currently looking for instrumentation companies interested in the commercialization of this emerging technology.

REFERENCES

1. Contract NCHRP-91-ID023B, September 1992.
2. Alba, F. *Research Proposal for Development of a Prototype for On-Line Real-Time Measurement and Control of Aggregate Gradation in Asphalt Plants, Phase I.* Felix ALBA Consultants, Inc., October 1990.
3. Alba, F. *Development of a Prototype for On-Line Real-Time Measurement and Control of Aggregate Gradation in Asphalt Plants, Phase I, Stage 1.* Progress Report to SHRP-IDEA. Felix ALBA Consultants, Inc., August 1992.
4. Alba, F. *Development of a Prototype for On-Line Real-Time Measurement and Control of Aggregate Gradation in Asphalt Plants, Phase I, Stage 2.* Progress Report to SHRP-IDEA. Felix ALBA Consultants, Inc., February 1992.
5. Alba, F. *Development of a Prototype for On-Line Real-Time Measurement and Control of Aggregate Gradation in Asphalt Plants, Phase I.* Final Report to SHRP- IDEA. Felix ALBA Consultants, Inc., May 1992.
6. Alba, F. *Development of a Full-Scale Prototype for On-Line Real-Time Measurement and Control of Aggregate Gradation in Asphalt Plants, Phase II.* Proposal to SHRP-IDEA. Felix ALBA Consultants, Inc., April 1992.
7. Alba, F. *Development of a Full-Scale Prototype for On-Line Real-Time Measurement and Control of Aggregate Gradation in Asphalt Plants, Phase I.* Report to NCHRP-IDEA. Felix ALBA Consultants, Inc., February 1993.
8. Alba, F. *Development of a Full-Scale Prototype for On-Line Real-Time Measurement and Control of Aggregate Gradation in Asphalt Plants, Phase II, Stage 2.* Report to NCHRP-IDEA. Felix ALBA Consultants, Inc., September 1993.
9. Alba, F. *Design and Manufacturing for the AGCT Technology.* Felix ALBA Consultants, Inc., December 1994.