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Foreword

The papers in this RECORD are of special interest to construction engineers. They cover a wide field from the state of the art of automatic controls to the best utilization of construction equipment, as well as technology of flexible pavement from raw material, mixing, and laydown. They also discuss control of rigid pavement roughness.

The first paper covers the use of electronic devices for automatic control of construction equipment. The survey of the various state highway department requirements as to tolerances is of special value. It is pointed out that personnel properly trained in automatic controls must be available on the job. As to the future, more contractors will be using available automatic devices, and the use of laser beams is still some time off.

The second paper covers a 2-year study in New York State of cause-effect relationships involved in roughness of concrete pavement. There are listed 5 factors common and outstandingly significant in relation to roughness and all pertaining to paving methods, as well as 4 factors purely job-related. The findings are well documented.

The third paper covers the present developments in earthmoving equipment and discusses the proper selection of equipment to avoid mismatch. It is a broad outline of the problem with some worthwhile cost studies.

The fourth paper covers a study of one quality assurance program in New York State for asphaltic concrete, utilizing computer simulation procedures. The model consists of a set of random data generators simulating hot-bin and final-mix gradations. The program has been successfully applied to standard top course. The references will be of value for a further study in depth.

The fifth paper covers the screenless asphalt plant operation as used in Kansas. The test result from 3 projects is tabulated and shows that the control of proportioning at the cold feed offers advantages from the sampling standpoint. With Special Provision to the Standard Specification, the contractor is required to furnish processed aggregate having a gradation so the combined gradation will automatically meet the specified finished gradation requirement. The procedure simplifies the mix control and the assurance program.

The sixth paper supports the thinking that cessation requirements for constructing hot-mix asphalt pavements should be based on a reasonable time to apply breakdown rolling, rather than based on air and base temperature. A mathematical study supports this. Actual measurements found good agreement with the mathematical model.

The seventh paper presents the thesis that "roller requirements should be based on paver speed rather than tonnage rates." Computations are presented covering the theoretical relationship between paver speed and available rolling time. Like the previous paper, it states that thick lifts are easier to compact than thin lifts, also that breakdown rolling produces most of the density.

The eighth paper covers the result of a study of compaction data on asphalt pavements of 15 test sites in Texas over a 3-year period. The proper compaction of the pavement is of the greatest importance. It was found that the pavement on the projects did not stabilize at a density equal to that obtained in the laboratory. It was found that after 2 years of service 80 percent of the test site pavements reached 95 percent or more relative compaction; only 20 percent reached the 100 percent mark. The test result is well documented.

An abridgment reports an investigation of the use of time-lapse photography in work simplification studies of concrete bridge deck construction.

Contents

Automatic Controls on Construction Equipment: State of the Art

LAURENCE C. BOWER and BURRELL B. GERHARDT,
Colorado Department of Highways

The use of electronic devices for automatic control of construction equipment has increased steadily since the inception in 1958. Seventy percent of the state highway departments in the United States have required automatic control at some time or another, and 65 percent regularly specify automatically controlled equipment. Highway departments in Canada have been leaders in the use of this automatic equipment, and United States and European plant manufacturers are experiencing an increasing demand for electronic guidance systems on road construction machinery. A description of typical electronic control devices now on the market is included in this evaluation. Examples are given of the smoothness that may be expected with electronically controlled pavers when conditions are favored by good workmanship and good equipment. Although automatic controls reduce the dependence on operating personnel, there is injected the added problem of setting and maintaining the controls. Personnel properly trained in automatic controls must be available on the job.

•AUTOMATIC CONTROL of construction equipment has been a fairly recent development in spite of its similarity to the type of control used for 20 or 30 years on aircraft, ocean liners, and factory fabricating devices. It was not until 1958 that Honeywell, Barber-Greene, Cedarapids, and Pioneer developed screed control systems using Honeywell components based on a device patented by R. P. Shea (1).

The relatively late advent of automation may have been due in some degree to a failure of engineers to foresee the benefits in quality control and savings in man-hours that can result from electronic devices. Road-building with crushed aggregates and asphalt or cement mixes is really not a very old operation itself. Only recently has road-building fallen into the routine category that makes automation and mass production profitable.

POPULARITY OF AUTOMATIC EQUIPMENT

The decision by Canadian highway departments and some United States agencies to specify automatically controlled pavers may be more responsible for the recent trend toward the use of electronic controls than anything else. Since 1965, practically all bituminous paving contracts in Ontario have specified automatically controlled screeds (2).

The results of an inquiry to state highway departments for this evaluation indicated that 70 percent of the states have required automatically controlled devices at some time or another, and 65 percent regularly specify automatically controlled equipment. Most of the states agree that automatically controlled equipment has not affected the bid price of construction work. Some states expressed the opinion that automatically controlled equipment has reduced bid prices.

Paper sponsored by Committee on Highway Equipment and presented at the 49th Annual Meeting.

Sixteen percent of the states require automatic wire control for fine grading of the base, and 74 percent of the state highway departments leave this matter optional with the contractor.

All states reported that some of their projects had been constructed with automatic equipment, regardless of whether or not it was specified. Two-thirds of the states reported at least 50 percent of their projects constructed with automatically controlled equipment, and one-third of the states reported at least 90 percent of their asphalt-mix pavements being placed with electronic controlled machines. The tolerance and related data reported by the states answering the questionnaire are given in the Appendix. Manufacturers of paving equipment in the United States estimate that 3 automatically controlled machines are being manufactured for every one machine that can be only manually controlled. British firms making asphalt finishers are now fitting guidance systems to between 25 and 50 percent of their new machines, and the same is true on the European continent (3).

SCOPE OF THIS REPORT

Electronic controls of one type or another are used in highway construction today on everything from pile drivers to sidewalk finishers. Probably the greatest application of electronic controls for overall guidance and grade control has been on machines that place or finish grade courses of material on a roadway. This report is limited to an evaluation of the electronic controls on pavers and motor graders available on the market in the spring of 1969.

GENERAL TREND IN DESIGN

Many equipment manufacturers who were contacted to secure information for this report expressed their intention to place automatically controlled equipment on the market at some later date. Because of the rapid advancement in diode and transistor manufacture, automatic equipment that comes on the market a year or so from now is likely to be somewhat different from equipment on the market today. The silicone-controlled rectifier may simplify and reduce the cost of equipment that formerly depended on expensive amplifiers. However, the relay-solenoid-hydraulic cylinder type of control has proved to be very dependable for heavy duty control, and in all probability it will be in use for years to come.

EVALUATION PROCEDURE

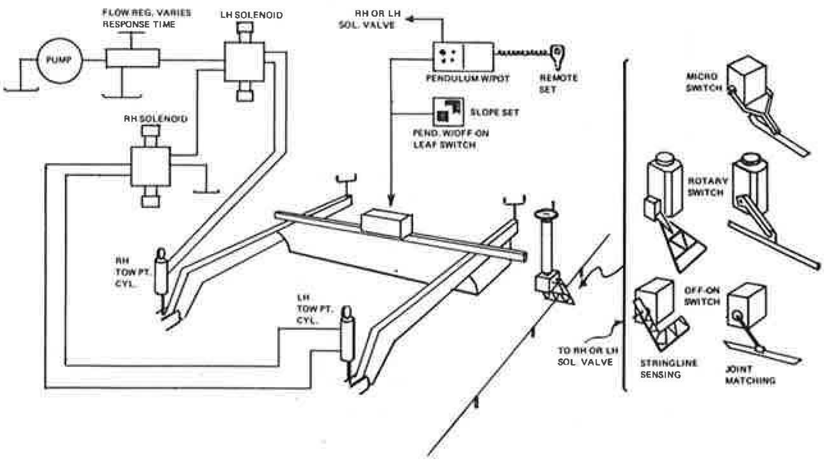
Systems of control employed by the various manufacturers of pavers and graders have been investigated for this report. In general, manufacturers of pavers have used either hydraulic cylinders activated by solenoids and valves or servomotors to vary either the elevation of the paver frame, the elevation of the screed, or the angle of the screed arm with reference to the roadway surface.

Figures 1 through 8 show typical methods of automatic controls and contain remarks about the general field performance of each system. Table 1 gives a comparison of the different types of control.

AUTOMATIC CONTROL OF GRADERS

Although electronic controls on paving equipment have proved to be efficient and reliable, there has been difficulty in applying similar controlling devices to motor graders and dozers. The difficulty is undoubtedly due to the difference in operation of the 2 types of equipment. Whereas the pavers operate steadily on a wide uniform grade, motor graders and dozers are generally purchased to do "pioneering" work on rough terrain as the need arises.

In 1958, a Texas firm adapted automatic controls to a motor grader. The "Educated Blade," as the contractors called it, generally controlled grade elevations within 0.03 ft. Even on a parabolic crown, the motor grader was reported to have operated well by resident engineers and contractors (4). However, the controls did require special



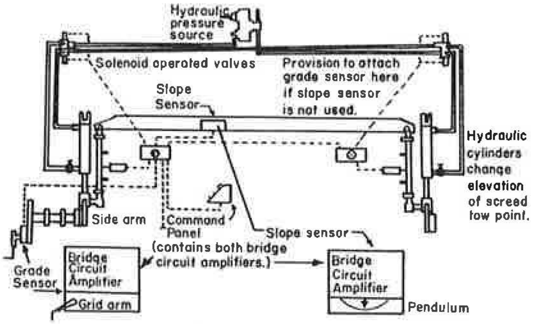
12V system operates solenoid valves to control direction of movement of tow point cylinders. Flow regulator varies system volume controlling response time (speed) of tow point cylinders, giving adjustment for varying job conditions. Sensing components can control either side of the machine and can be interchanged or mixed. Paver wiring and hydraulics common for all available control systems.

Micro Guide – Joint matching sensor requiring higher actuating force utilizes microswitches to operate solenoid valves. No transverse slope control, but dual micro guides can be used for controlling both sides.

Honeywell Grademaster – Stringline mobile or rigid reference may be used for grade control by use of low force off-on switching to operate solenoid valve. Slope control uses pendulum with variable resistance in balanced bridge circuitry to proivde output to operate solenoid valve. This unit provides a remote slope set point device.

Long Grad-Line – Stringline—Same as above.
By use of low force rotary off-on switch energizes relays to operate solenoid valves. Slope control uses pendulum-leaf switch energizing relays to operate solenoid valves. Unit has integral slope setting.

Figure 1. Barber-Greene—automatic screed control systems.



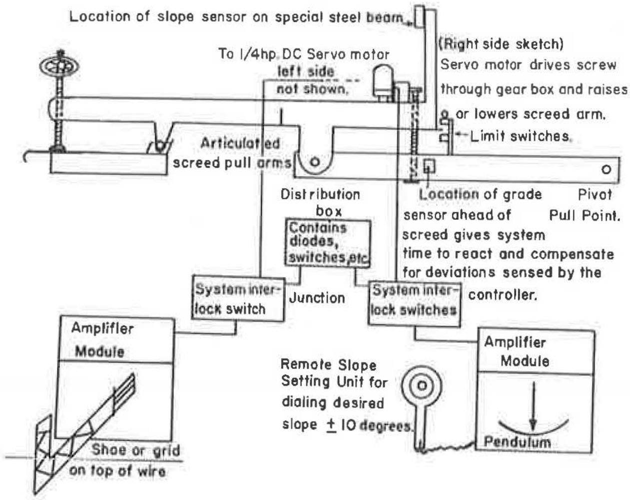
When the elevation of the side arm changes with respect to the reference surface, the grid is rotated, thus varying the resistance of the sensor. This variance is recorded in a bridge circuit and produces a current flow across the bridge circuit. This current is amplified and actuates a solenoid operated hydraulic valve. The valve in turn actuates a hydraulic cylinder that is attached to the tractor frame and forward end of the side arm. The side arm is then raised or lowered until the tow point is again at the present elevation with respect to the reference surface.

With both sides on automatic, if the grade sensor is not connected, the slope sensor will try to control both sides of the screed, which it cannot do. One or both sides will go to their limit of travel and stop the operation.

A pendulum type sensor, which senses level with respect to gravity, is mounted on a beam supported by the side arms. A change in slope of the beam varies the resistance reading of the sensor. This variance, like the variance in the grade sensor, is fed into a bridge circuit. The resulting signal or current flow is amplified and used to control a solenoid operated valve and ram on the side opposite the grade controller. The control panel has a dial on it whereby any slope from 0 to 10% can be dialed in, and the pendulum sensor will automatically adjust the position of the tow points accordingly. When paving around a curve, the slope of the curve can be dialed in by the operator.

Correlation between the beam and the screed is dependent on the setting of the screed adjustment screws. For this reason, caution must be exercised in using the dial for determining the absolute slope of the finished mat.

Figure 2. Blaw-Knox—Blaw-Kontrol for asphalt paver showing the system used to change elevation of the screed tow point for automatic control during paving operations.



Spring loaded ON-OFF Grade Controller

Sensor may be connected to either or both sides of the machine, but two grade controllers are not used if the slope controller is used.

An over deflection mechanism allows the grid to rotate an additional 50 angular degrees either side of the active selector. This enables the grid to override the grade stakes or other means of supporting the grade reference string.

Skis are available in lengths of 9, 29, 30, and 40 feet.

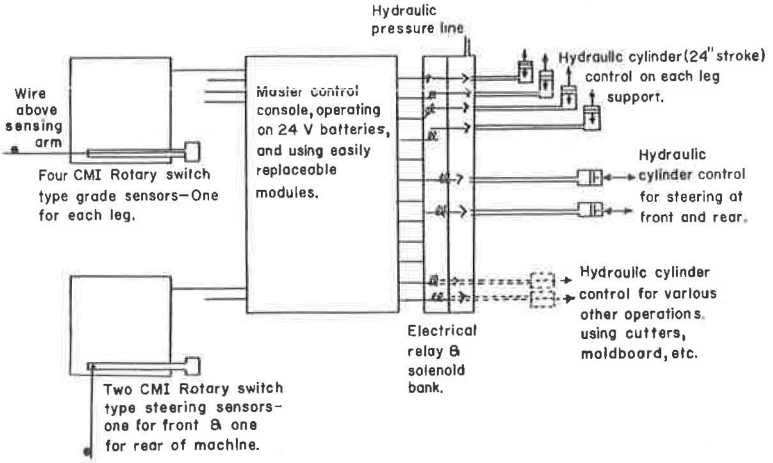
Slope Controller

The slope controller furnishes true horizontal reference. It is a slave of the grade sensor, and maintains the same slope regardless of grade sensor position.

The pendulum microsyn, along with the slope control potentiometer in the command station, forms a bridge circuit. For a specific setting of the slope control knob, there is a corresponding angular position of the Slope Controller housing at which the bridge is balanced. A balanced bridge condition indicates that the predetermined slope is being maintained.

Changes are necessary with the slope knob when paving runs into a super-elevated turn. If a change is not made, the machine will try to take all super-elevation out of the new mat.

Figure 3. Cedarapids—all-electric screed control system.

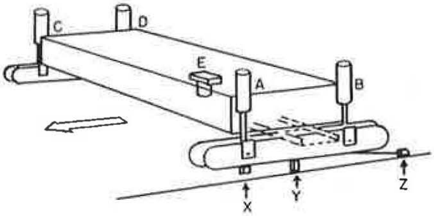


Sensors use a counterbalanced rod touching the side (for steering) or underside (for grade control) of a string line for good stable control. The machine has been observed to operate accurately in 40 mph winds if string line is tight and well supported. The sensors will also follow a form line or skid.

Available also is the Autolevel Control System using a single wire reference and "cross slope control" which can be operated on either side of the machine at the discretion of the operator.

The 24 inch stroke vertical hydraulic cylinder action in each leg is so great that it makes it possible for the machine to crawl up or down over bridges and structures while maintaining a uniform-grade roadway.

Figure 4. CMI Corporation—automatic profile and steering control.



Steering Sensor X

A sensor located at the front and left side of the machine detects deviation from wire line and automatically adjusts crawler to follow the wire.

Elevation Sensor Y

A sensor located at front of machine on the left side controls the front height of the machine for longitudinal travel parallel to guide wire. It is intended to maintain the surface smoothness without affecting the pavement depth. Cylinder (A) raises or lowers to follow the wire.

Elevation Sensor Z

The elevation sensor on the left side at the rear sets the pavement height. Cylinder (B) raises or lowers to maintain required height.

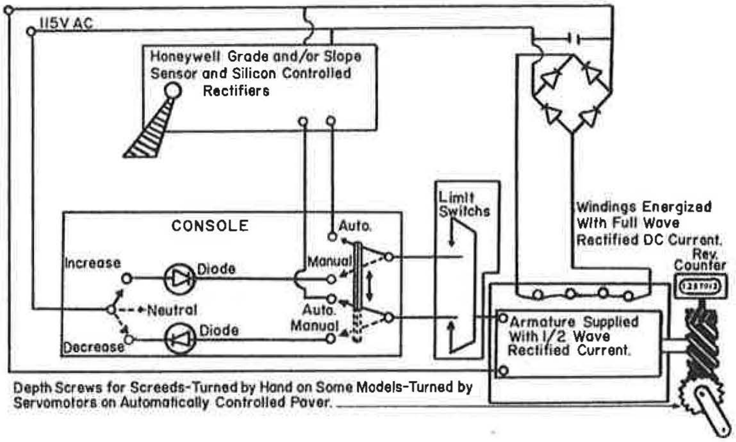
Cross leveling of the machine is set with an oil dampened pendulum (E).

Cylinder (D) raises or lowers to maintain balanced "zero" reading. The cross slope can be set by means of a micrometer adjustment.

Four point suspension is completed with Cylinder (C). Actuated by a torsion bar, the cylinder raises or lowers to correct any machine twisting action. Each point of the 4-point suspension system is thus established in a common plane. Paving from grade reference may be also established.

Note: Sketch and write-up taken from Koehring-Johnson brochure; actual machine not evaluated for this report.

Figure 5. Koehring-Johnson—slipform paver with automatic control.



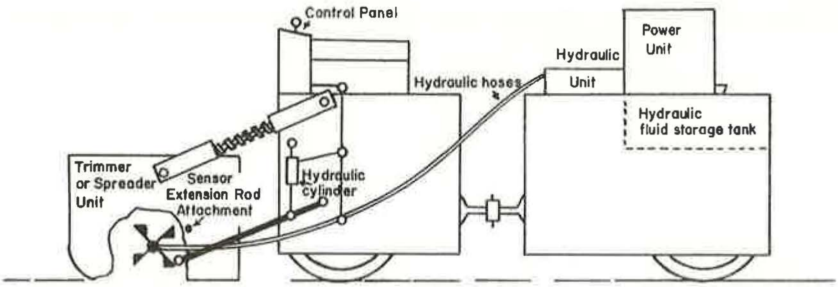
Grade sensor uses a lightweight grid follower along a string line set on the ground or on a traveling string line in the center of a framework towed along the side of the paver.

A slope controller or pendulum may be combined with the grade sensor to control the opposite side from that controlled by the grade sensor for maintaining a predetermined slope. The slope can be manually adjusted or changed by use of the "Remote Slope Control Set". The remote slope control set knob allows changes to be dialed in with the paver in operation, but it must be done gradually. "Manual Automatic" selector switch is provided on each side to change from the automatic grade or slope control to a manual control.

Because mat thickness changes are made by raising or lowering the metering element, or oscillating screed, it becomes feasible to eliminate the manual hand wheels and motorize the depth screws directly. Applying the automation in this manner, eliminates zeroing or adjusting the automatic stroke at the tow-point, and allows a thickness from zero to maximum during the course of a job.

Each side of the paving section is electrically independent, allowing any combination of manual or automatic control. The revolution counters on the depth screws aid in setting the "angle of attack." If records are kept of the counter readings for various thicknesses, the angle of attack can be accurately reset to again lay this thickness.

Figure 6. Pioneer—grade master slope and grade controller.



Automatic steering involves an electric pickup located at either end of the cutting head to sense from single string line or curb. A signal is transmitted to solenoid valves that control the steering system itself.

Grade control is achieved by either a one-line control or a two-line (one on each side of the machine) control. Two line control is recommended for highway construction where an accurate system is necessary and speeds of 50-100 feet per minute are expected.

Grade control may be maintained from a single line if operating speed remains at under 25 feet per minute. In this case a special mercury cross level control patented by RAHCO is brought into play.

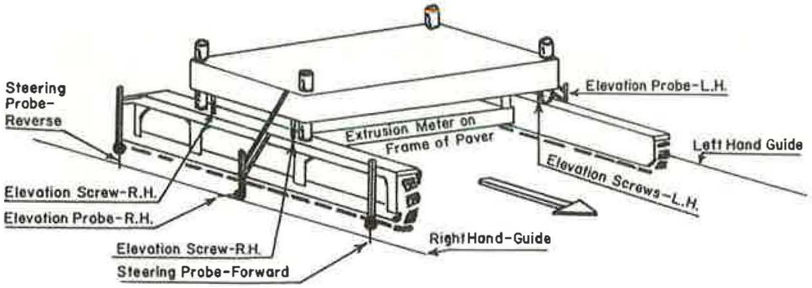
Normally the same reference line that is used to control steering is used to control grade. The mercury control transmits electric impulses to solenoid valves, and they in turn activate control cylinders which in turn raise or lower the cutting head.

For most accurate control, the sensor should be located on a direct line with the cutting or paving head. The closer such control is located to the active head, the better the grade, and the more responsive it appears.

Figure 7. RAHCO—automatic grade and steering control.

calibration and attention that many contractors felt to be excessive. This automatic control equipment was never mass produced.

In 1962, the Gurries Manufacturing Company of San Jose, California, introduced an automatically controlled motor grader. It provided both slope and grade control, but features of its construction and operation were not investigated for this study because of its hydraulic principle. There were no electronics in the system (5).



Pointers of probes are attached to rotating armatures which center themselves between excited coils. Displacement of the probes by the wire guides unbalances the circuits and signals a solenoid to open or close a valve to a hydraulically operated screw jack to raise or lower the frame.

Any deviation in the machine movement immediately displaces the armature, the induced coil voltage is sensed, and, through a control system, a command is then sent to correct for this deviation.

The allowable deviation that can take place before a correction command is initiated, is controlled by a special sensitivity adjustment. This sensitivity control is provided to meet the requirements for all existing job variations — i.e., soil conditions, vehicle speed, etc. If the sensitivity setting is too high, it may cause the machine to hunt or oscillate about the required set point; however, if the setting is too low, this will not provide the desirable results.

Note: Sketch and write-up taken from Rex Chainbelt, Inc., brochure; actual machine not evaluated for this report.

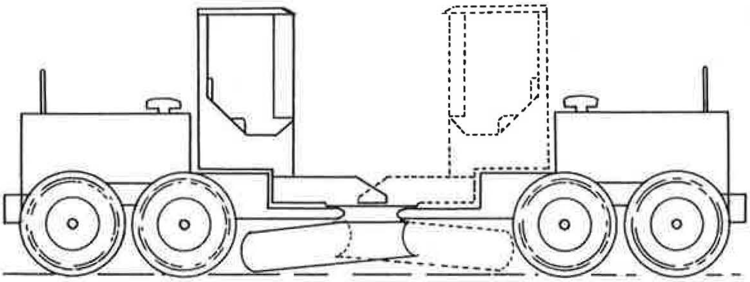
Figure 8. REX Chainbelt, Inc.—automatic guidance controls.

TABLE 1

SYSTEMS USED FOR AUTOMATIC CONTROL OF PAVERS

Manufacturer	Adjusted Point on Frame	Activating Unit	Sensor Control	Sensor Type
Barber-Greene (Fig. 1)	Elevation of tow point	Solenoid valves and hydraulic cylinder	Grade and slope	Microswitch, rotary switch, pendulum (Honeywell)
Blaw-Knox (Fig. 2)	Elevation of tow point	Solenoid valves and hydraulic cylinder	Grade and slope	Variable resistance, pendulum
Cedarapids (Fig. 3)	Pull arm angle	Servomotor	Grade and slope	Rotary switch, pendulum (Honeywell)
CMI (Fig. 4)	Leg height	Solenoid valves and hydraulic cylinder	Grade, slope, and steering	Rotary switch, pendulum
Koehring-Johnson (Fig. 5)	Leg height	Solenoid valves and hydraulic cylinder	Grade, slope, and steering	Microswitch (grade), inductive transducer for slope
Pioneer (Fig. 6)	Depth screws	Servomotor	Grade and slope	Rotary switch, pendulum (Honeywell)
RAHCO (Fig. 7)	Elevation of cutting head	Solenoid valves and hydraulic cylinder	Grade, slope, and steering	Rotary switch and mercury switch
REX Chainbelt, Inc. (Fig. 8)	Hydraulically operated screws at frame corners	Servomotor	Grade, slope, and steering	Rotary induction sensor

Recently, Construction Machinery, Inc., of Oklahoma City and Caterpillar of Peoria have placed electronic controlled motor graders on the market. Both machines will operate from a single line or from a ski or wheeled sensor. They provide both grade and slope control. They depend on an operator for steering. Details of their operation are shown in Figures 9 and 10.

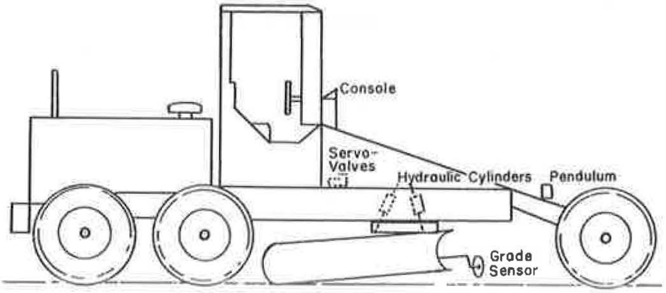


The Autoblade can be guided in both alignment and grade from a single stringline reference, or it can trace a profile from an existing pavement.

Sensors are the CMI Rotary Switch type using counterbalanced rods touching the side or bottom of the string.

The grade controller can make use of skiis as well as a string line. It has cross slope control for automated depth cutting and blading.

Figure 9. CMI Corporation—Autograde Autoblade.



Caterpillar Automatic Blade Control is offered on a factory installed basis for the No. 16, No. 14E and No. 12F Motor Graders. Field installation is not recommended on new or used machines due to the complexity of installation and high cost involved.

Electronic devices for the Automatic Blade Control include:

1. Automatic slope and grade control with integral hydraulic system and blade lift cylinders.
2. Two moldboard attachments for reference grade pick-up purposes, one is a wire follower and the other a wheel follower.

The Control console mounts directly above and forward of the steering wheel. By actuating one or more of the switches the operator has the following choice of control functions: automatic slope and grade control simultaneously, automatic slope control only, automatic grade control only, or manual controls for conventional blading work. The control console is made up of solid state circuitry with replaceable modules.

The desired slope is maintained by use of a powered pendulum, two electric servo-valves, and two hydraulic blade lift cylinders. The operator rotates the slope control dial to the desired percent of slope. The powered pendulum senses this desired change in slope and sends current to one of the two electric servo-valves. The valves allow hydraulic pressure to raise or lower the left cylinders.

Figure 10. Caterpillar—automatic motor grader control.

PROVISIONS FOR SHUTDOWN

Several experimental pavers (not described in this report) have been used in highway construction in the past 10 years with discouraging results because of the failure of the manufacturer to provide immediate "shutoff" in case of sensor malfunction. The sensors on standard automatic equipment in good working order now are provided with auxiliary contacts that are used as paver-stopping circuits in the event that the grid or ski becomes disconnected. Limit switches are provided as protection to the machine and for safety to the operators.

Where there is a chance of conflicting signals being sent to the machine, such as when the grade sensor calls for an upward movement and the slope sensor calls for a downward movement, the signals are routed through a junction box of some type to stop the operation or sound an alarm. On some pavers, it is impossible to connect the slope control if both grade controllers are connected.

The entire sensor unit on the Caterpillar motor grader is designed to come off if struck by a rock or unyielding object. This provision not only prevents the blade from malpositioning, but it also protects the sensor unit from serious damage. On almost all machines, indicating lights are mounted in a conspicuous place on the sensor or on a console in front of the operator.

RESULTS TO BE EXPECTED BY THE USE OF AUTOMATIC CONTROL

When completing the questionnaire for this evaluation, construction engineers from several states mentioned that not all of the results from the use of automatic control were good. During the field evaluation of the different electronically controlled machines, it was noted that automatic control does not ensure a project against imperfections. However, the difficulties were general in nature and could not be associated with the type of electronic control. They were more often associated with the ski or shoe that activated the sensor.

Some of the reported difficulties associated with the performance of automatically controlled machines are as follows:

1. Ski or shoe guided sensors may at times operate under very wobbly conditions. A shoe traveling across a base course or the first asphaltic-mix lift will provide grade control, but control for a leveling up operation is questionable. A 30-ft ski may in some cases be inadequate to bridge humps that should be taken into consideration. Many so-called "rigid trusses" now provided by the manufacturers of pavers are equipped with wheels on each end. Reports indicate a grid following a line on this wheeled frame (even with the most rigid frame) is subject to some bouncing so that the $\frac{1}{8}$-in. control indicated by some manufacturers may not always be achieved. It would appear that a well-established string line attached to ground supports might be a more reliable means of activating a sensor for positive control of a predetermined grade. The apparent advantages of the stationary string-line method of guidance was illustrated by the research performed in Canada in 1965 (6).
2. Unless a ground-supported string line is used, there is a very definite need for the operator or an assigned individual to follow along the side of the machine to clear the pebbles and debris left by the trucks and transfer operations ahead of the paver. This is particularly true when the paver travels over a surface that has been tacked with liquid asphalt. Every particle on the roadway appears to stick to the surface directly in the path of the sensors.
3. There is a tendency for contractors to purchase automatically controlled equipment and place it in the hands of inexperienced operators, or attempt to provide experience for the operators during actual construction. When the finished product is something less than perfect, the casual observer becomes critical of the automatic control system. Manufacturers have attempted to build into their machines systems as foolproof as possible, but operators who make no attempt to study the operations of their machines before using them are very definitely hampering the progress of automatic operation.

Good consistent results with automatic controlled equipment depend on the desire of the contractor's personnel to produce the best surface possible, the condition of the equipment as a whole (not just the automatic controls), and rapid evaluation of results being obtained so that necessary corrective measures can be taken during the progress of the work.

A study made in Texas in 1967 illustrates the results of automatic operation (7). The test site had a flexible base placed with a CMI machine using electronically controlled grade apparatus and was quite smooth and true to cross section. Two asphaltic concrete mats were placed using bituminous pavers with electronically controlled screeds. The roughness was determined with the Reinhart profilograph and consisted of obtaining a profile over areas in which the paver has stop-and-go operation and areas over which different paver speeds were used. Considerable roughness was found in the areas where the paver paused for a change of trucks, and increased roughness was experienced as the paver speed increased.

In 1969, roughness tests were made on a multilift paving project at 50 mph using the Colorado accelerometer attached to the rear axle of a pickup truck. The emulsified asphalt mix base was placed with an electronically controlled CMI machine. Succeeding lifts of asphalt mix were placed with a Blaw-Knox paver using a 30-ft reinforced, aluminum, I-beam ski with spring-loaded feet. Average roughness values after laydown for each layer are given in Table 2.

Slope variance values as low as four have been measured with the CHLOE profilometer on pavements laid with one pass of the CMI paver using the stationary string-line method and good construction procedures.

Figures 11 and 12 show graphs taken from a Reinhart profilograph to illustrate the smoothness that may be expected from both good and bad operation of an automatically controlled paver placing a $1\frac{1}{2}$-in. overlay on a curled concrete pavement. On an asphalt overlay, the roller operation may be as responsible for a rough surface as the control of the paver. On a concrete pavement, the surface smoothness is primarily a result of paver control.

TABLE 2

AVERAGE ROUGHNESS VALUES

Item	Thickness (in.)	Slope Variance or Calif. in./mi	Equivalent BPR Roughness	Present Serviceability Index PSI = 5.03 - 1.91 log (1 + $\overline{SV}$)
Base course	4	20	150	2.6
First lift	2	8	115	3.2
Second lift	1½	5	90	3.6
Final lift	1½	3	45	3.9

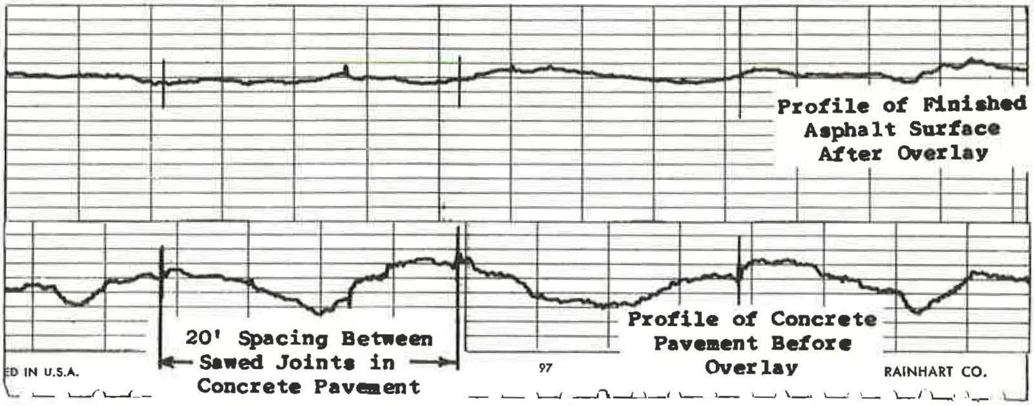


Figure 11. Surface smoothness on an asphalt overlay where the paver was well controlled.

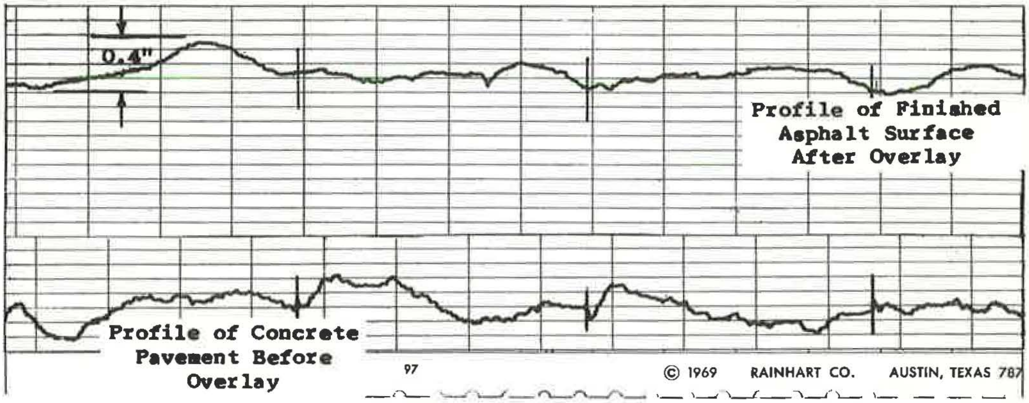


Figure 12. Surface smoothness on an asphalt overlay where the automatically controlled paver underwent a stop-start operation and the steel wheel roller could not remove the resulting depression and hump.

BASIS FOR SPECIFYING AUTOMATICALLY CONTROLLED PAVERS

Engineers from several of the 50 states contacted for this evaluation submitted copies of specifications used to require automatically controlled pavers. The method of wording varied from the simple statement, "Pavers shall be equipped with the necessary attachments, designed to operate electronically, for controlling the grade of the finished surface," to detailed requirements spelled out for each part of the operation.

A more detailed specification is as follows:

> The paving machine shall be equipped with an automatic control system which shall control the elevation of the finished pavement surface, and which is automatically actuated by a system of sensor-operated devices which sense and follow reference lines or surfaces on one or both sides of the machine as required.
>
> Failure of the automatic control system to function properly will be cause for suspension of the paving operations until such time as the automatic control system has been made operative and is functioning properly.
>
> The automatic control system shall be capable of working with the following items, and when required, they shall be furnished with the machine:
>
> Ski-type device at least 40 feet in length.
> 5,000 feet of control line and stakes.
>
> The control line, when required, shall be installed by the contractor and shall be maintained taut and to the grade and alignment established.

The contracting agency should be careful to specify a control system that it feels will provide the best results obtainable, within economic limits. Careful consideration should be given to single-layered pavement projects. On projects constructed with a multilayered pavement structure, this careful consideration may not be as important. Indications are that the short ski or wheeled truss may not provide desired results in some cases, and some laydown results have indicated that even a long rigid ski with or without spring-loaded feet might require several passes to provide a really smooth surface. It is also pointed out that, in addition to the particular type of laydown equipment or controls used, many other factors enter into the final pavement results.

The Ontario Department of Highways studied each hot-mix paving project to determine whether the use of automatically controlled pavers would be advantageous (2). A decision not to specify automatic pavers is usually made when the project is of a small stopgap nature or if the construction is to be of only one lift. Its experience, and the experience of many other agencies, has been that at least one leveling course is required below the surface course to allow the electronic controls to correct irregularities in the grade.

COST OF AUTOMATIC CONTROL

The cost of automatic control for construction equipment does not appear to have retarded its development. Manufacturers provide automatic control for approximately 7 percent more than the cost of the manually operated models. Automatic controls may be installed on most pavers, but Caterpillar does not recommend field installation of electronic controls on the motor grader because of complexity of installation and the high cost involved.

FUTURE USE

Much has been written about the possibilities for remote control of construction equipment by radio and light (laser beam) rays. At this time, there is little if any standard equipment such as this on the market. When an electronic device making use of radio or light beams is assembled and tried on some project, the write-ups make headlines that give hope to everyone awaiting the push-button age. Actually, development appears to be more along the line of reliability and more in line with economics.

By 1970 it appears that the trend will be toward more contractors using available automatic devices rather than some contractors using more sophisticated types of automatic control. The construction engineers from all states contacted for this study expressed the opinion that the use of automatically controlled construction equipment was increasing.

ACKNOWLEDGMENT

All references pertaining to manufactured equipment have been cleared with the manufacturers.

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Appendix

A summary of the information obtained from the 50 states on automatic control and tolerances are given in the following tabulations.

SUMMARY OF INFORMATION ON AUTOMATIC CONTROL AND TOLERANCES FROM 50 STATES

N = No
Y = Yes
? = Unknown

While all possible care has been taken to insure the accuracy of this summary, no responsibility can be taken by compilers for omissions or errors.

State	Do Specs Require Automatic Controls?	Do Specifications Specify a Thickness Tolerance and Final Surface Smoothness Tolerance for: Sub-grade		Subbase				Base Course				Pavement Asphalt / Concrete				Tolerance Changed Since Automatic Control?	Does Availability of Auto Control Affect Bid Prices?	% of Pavement Placed With Automatic Control	Do Contractors Use Auto Controls on Motor Graders?	USAGE		Remarks
		Smoothness	Tolerance	Smoothness	Tolerance	Thickness	Tolerance	Smoothness	Tolerance	Thickness	Tolerance	Smoothness	Tolerance	Thickness	Tolerance	Yes-No		Asph / PCC		Increasing	Decreasing	
Ala	Y	Y	½"	Y	½"	Y	8%	Y	¼"	Y	8%	Y Y	¼" 1/8"	N Y	- ¼"	N	N	85 65	Y	Y		Automatic control encouraged on all projects and required by specs on some.
Alaska	N	N	-	N	-	N	-	Y	3/8"	Y	3/8"	Y Y	3/16" 1/8"	Y Y	3/16" 0.2"	N	N	20 -	N	?	?	
Ariz	Y	N	-	-	-	-	-	Y	3/8"	N	-	Y Y	3/16" 7"/Mi	N Y	- .2"	Y	Y	100 100	Y	Y		Auto control brought on the 3/16" and 7"/Mi tolerance
Ark	Y	N	-	N	-	Y	±1"	N	-	Y	±1"	Y Y	1/8" 1/8"	- Y	- .5"	N	N	75 75	Slope Con-trol	Y		Specs require auto control on Asph paving only
Calif	Y	Y	±.1'	Y	±.08'	N	-	Y	±.05'	N	-	Y Y	.01' .02'&7"	N Y	- .01'	Y	Y	30 90	Y	Y		Specs require auto control on special projects only
Colo	Y	Y	±¼"	Y	¼"	Y	¼"	Y	¼"	Y	¼"	Y Y	3/16" 1/8"	N Y	- .2"	N	N	90 90	Y	Y		Subgrade smoothness tolerance can be nil
Conn	N	Y	2"	N	-	Y	-1"+ 3/4"	N	-	Y	-3/4" + ½"	Y Y	¼" 1/8"	Y Y	½" .25"	N	?	1 1	Y	Y		1 PCC & 2 subgrade in last 2 years with auto control
Del	Y	Y	1/8"	N	-	N	-	Y	¼" Asph 1/8" PCC	N	-	Y Y	¼" 1/8"	- Y	- 0.2"	N	N	80 80	Y	Y		Auto control required for Asph paving only
Fla	Y	Y	½"	-	-	-	-	Y	¼"	Y	½"	Y Y	3/16" 1/8"	Y Y	.5" .5"	N	N	90 90	N	Y		Tolerances on Base & Pavement are for pavement only
Ga	Y	Y	¼"	Y	¼"	Y	½"	Y	⅛"	Y	½"	Y Y	1/8" 1/8"	Y Y	.25" .5"	N	Y	50+ 50+	N	Y		Specs require auto control on subbase & bases under high type pave
Hawaii	Y	N	-	N	-	N	-	N	-	N	-	Y -	3/16" -	Y -	.02' -	N	N	15 -	N	?		Auto control required on special projects only
Idaho	Y	N	-	N	-	N	-	Y	¼"	Y	½"	Y Y	¼" 1/8"	N Y	- 0.2"	N	N	100 100	N	Y		Specs require auto control for asphaltic concrete only
Ill	N	Y	1/8"	Y	3/8"	Y	90%+	Y	¼"	Y	1/8"	Y Y	1/8" 1/8"	- Y	- 10% Plan	N	N	? ?	N	Y		Auto control increasing only for fine grading. Penalty if pave thickness < 1/8"

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State	Do Specs Require Automatic Controls?	Do Specifications Specify a Thickness Tolerance and Final Surface Smoothness Tolerance for: Sub-grade		Subbase				Base Course				Pavement Asphalt / Concrete				Tolerance Changed Since Automatic Control?	Does Availability of Auto Control Affect Bid Prices?	% of Pavement Placed With Automatic Control	Do Contractors Use Auto Controls on Motor Graders?	USAGE		Remarks
		Smoothness	Tolerance	Smoothness	Tolerance	Thickness	Tolerance	Smoothness	Tolerance	Thickness	Tolerance	Smoothness	Tolerance	Thickness	Tolerance	Yes-No		Asph / PCC		Increasing	Decreasing	
Ind	Y	Y	½"	Y	½"	N	-	Y	½"	N	-	Y Y	1/8" 1/8"	N Y	.5" .5"	N	Y	100 35	Y	Y		Auto control not required for concrete pave. No tolerance for subbase under PCC
Iowa	Y	Y	.05'	Y	.05'	N	-	Y	.05'	N	-	Y Y	1/8" 1/8"	N Y	- .15"	N	N	60 60	Y	Y		Auto control required on base & on surface courses more than 1" thick
Kan	Y	N	-	N	-	N	-	Y	¼"	N	-	Y Y	3/16" 1/8"	N Y	- .2"	N	Y	100 1	CMI	?		Specs require auto control on asph paving only. Min. Sub Th =4".
Ky	N	Y	½"	Y	½"	Y	½"	Y	¼"	Y	¼"	Y Y	1/8" 1/8"	Y Y	1/8" .2"	N	N	50 50	Y	Y		
La	N	N	-	N	-	N	-	N	-	Y	3/4"	Y Y	1/8" 1/8"	Y Y	¼" .2"	N	N	Low	Y	Y		
Me	Y	Y	1"	Y	½"	N	-	Y	3/8"	N	-	Y Y	3/16" 1/8"	N Y	- .2"	N	?	20 0	N	Y		Specs require auto control on Interstate paving only
Md	Y	Y	-	Y	½"	Y	½"	Y	¼"	Y	½"	Y Y	1/8" 1/8"	N Y	- .20"	N	N	90 0	N	Y		Auto control mandatory for grade control only
Mass	N	Y	1"	Y	3/8"	N	-	Y	3/8"	N	-	Y Y	¼" 1/8"	Y Y	¼" .25"	Being Con-sidered	?	1 1	Y	Y		Auto control specified as alternate for sub-base & base const.
Mich	Y	Y	.1'	Y	3/4"	Y	3/4"	Y	¼"	Y	½"	Y Y	¼" 1/8"	Y Y	¼" .2"	N	N	5 0	Y	Y		Supplemental specs often require auto control
Minn	N	Y	.1'	Y	.05'	Y	.05'	Y	.05'	Y	.05'	Y Y	¼" 1/8"	Y Y	.5" .1"	N	Y	60 90	Y	Y		Auto control has helped to hold down costs
Miss	Y	Y	1"	Y	1"	Y	1"	Y	½"	Y	1"	Y Y	1/8" 1/8"	N Y	- .2"	N	N	100 0	Y	Y		Auto control specified for asph paving only
Mo	Y	Y	½"	Y	½"	-	-	Y	¼"	N	-	Y Y	1/8" 1/8"	N Y	- .2"	N	N	80 0	Y	Y		Auto control specified for asph paving only
Mont	Y	Y	1/10'	Y	.08' for [illegible] Mtl	N	-	Y	.06' to .04'	N	-	Y Y	3/16" 1/8"	N Y	- 1/8"	Y+1/16"	N	70 70	N	Y		Auto control specified for asph paving only

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State	Do Specs Require Automatic Control?	Do Specifications Specify a Thickness Tolerance and Final Surface Smoothness Tolerance for:														Tolerance Changed Since Automatic Control?	Does Availability of Auto Control Affect Bid Prices?	% of Pavement Placed With Automatic Control	Do Contractors Use Auto Controls on Motor Graders	USAGE		Remarks
		Sub-grade		Subbase				Base Course				Pavement Asphalt Concrete										
		Smoothness	Tolerance	Smoothness	Tolerance	Thickness	Tolerance	Smoothness	Tolerance	Thickness	Tolerance	Smoothness	Tolerance	Thickness	Tolerance	Yes-No		Asph PCC		Increasing	Decreasing	
Neb	Y	N	-	N	Reasonable close conformity							Y Y	1/8" 1/8"	Y Y	¼" .25"	Y	Y	85 85	N	?		A thickness tolerance of ½" has been set on CTB since auto control
Nev	Y	Y	.05'	Y	.05'	N	-	Y	¼"	N	-	Y Y	¼" 7"/Mi	N Y	- .01'	N	N	20 20	Y	Y		
N.H.	N	N	1"*	N	½"*	N	-	N	½"*	N	-	Y Y	3/16" 1/8"	N N	- -	N	Y	5 5	Y	Y		Tolerances shown for subgrade, subbase and base are unwritten*
N.J.	N	N	-	N	-	N	-	N	-	N	-	N Y	- 1/8"	Y Y	8% -	N	N	5 5	N	Y		Thickness tolerances are as directed by the engineer
N.M.	Y	Y	.05'	N	-	Y	½"	Y	3/8"	Y	½"	Y Y	3/16" ¼"	N Y	- .2"	Yes-AC ¼ to 3/16	N	100 0	Y	Y		Specs require auto control on asphaltic concrete only
N.Y.	Y	N	-	Y	½"	N	-	Y	¼"	N	-	Y Y	¼" 1/8"	Y Y	¼" .5"	Yes-PCC 12"/Mi	?	10 10	Y	Y		Auto control used selectively by special specs only
N.C.	Y	Y	.05'	N	-	Y	1"	N	-	Y	1"	Y Y	1/8" 1/8"	N Y	- .25"	N	N	55 55	Y	Y		Auto control required on asphaltic paving & PCC when using slipform
N.D.	Y	N	-	N	-	N	-	Y	¼"	N	-	Y Y	¼" 1/8"	N Y	- .2"	N	N	90 90	Y	Y		Auto control specified on selected projects
Ohio	Y	Y	½"	Y	½"	N	-	Y	3/8"	N	-	Y Y	¼" 1/8"	Y Y	5% Yield .1"	N	N	75 0	Y	Y		Auto control specified on selected projects
Okla	N	Y	½"	Y	½"	Y	½"	Y	½"	Y	½"	Y Y	3/16" 1/8"	Y Y	RC* .2"	N	Y	60 60	N	?		*RC = Reasonable conformity
Ore	Y	* RC	-	Y	.04'	Y	0.10'	Y	.04'	Y	0.1' **	Y Y	.015' .01'	N N	- -	Y	Y	95 95	Y	Y		*Reasonable Conformity **C.T.B. 0.04'
Pa	Y	Y	½"	Y	½"	Y	½"	Y	½"	Y	½"	Y Y	3/16" 1/8"	Y Y	¼" .25"	N	Y	0 42	N	Y		Auto control specified on slip-form pavers only
R.I.	N	N	-	N	-	N	-	Y	3/8"	Y	3/8"	Y Y	3/8" ¼"	Y Y	¼" 3/8"	N	N	30 0	Y	Y		

SUMMARY OF INFORMATION ON AUTOMATIC CONTROL AND TOLERANCES FROM 50 STATES

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State	Do Specs Require Automatic Control?	Do Specifications Specify a Thickness Tolerance and Final Surface Smoothness Tolerance for:														Tolerance Changed Since Automatic Control?	Does Availability of Auto Control Affect Bid Prices?	% of Pavement Placed With Automatic Control	Do Contractors Use Auto Controls on Motor Graders	USAGE		Remarks
		Sub-grade		Subbase				Base Course				Pavement Asphalt Concrete										
		Smoothness	Tolerance	Smoothness	Tolerance	Thickness	Tolerance	Smoothness	Tolerance	Thickness	Tolerance	Smoothness	Tolerance	Thickness	Tolerance	Yes-No		Asph PCC		Increasing	Decreasing	
S.C.	Y	N	-	N	-	Y	½"	Y	¼"	Y	½"	Y Y	1/8" 1/8"	N Y	- 0.2"	N	?	70 ?	Y	Y		Auto control specified for grade control occasionally
S.D.	Y	N	-	N	-	N	-	N	-	N	-	Y Y	¼" 1/8"	N Y	- .2"	N	N	90 90	N	?		
Tenn	Y	Y	Close	Y	Close	N	-	Y	3/8"	N	-	Y Y	¼" 1/8"	N Y	- .25"	Y	N	100 100	Y	Y		"Close" means reasonable close conformity to line and grade
Tex	Y	Y	½"	Y	½"	Y	½"	Y	¼"	Y	½"	Y Y	1/8" 1/8"	N Y	- .25"	N	Y	90 90	N	Y		Specs requite auto control on ACP primarily
Utah	N	Y	.1'	-	-	-	-	Y	.5"	Y	.5"	Y Y	1/8" 1/8"	Y Y	¼" .25"	Y	N	75 90	N	Y		
Vt	Y	Y	½"	Y	¼"	Y	1"	Y	¼"	Y	¼"	Y Y	¼" 1/8"	Y Y	¼" .25"	N	Y	20 20	Y	Y		Auto control specified on all major paving projects
Va	N	Y	Elev. .5"	Y	*	Y	.5"	Y	*	Y	.5"	Y Y	3/16" 1/8"	Y Y	.5" .2"	N	N	1 1	N	Y		* Abrupt changes in grade prohibited
Wash	Y*	Y	.1'	Y	±.05'	Y	+.025' to-4%	Y	.02'	Y	+.025' to-4%	Y Y	1/8" 7"/Mi	Y Y	.01'-.025' +.00'	Y	N	? 100	Y	Y		* On 70 MPH design or above
W.Va	N	Y	½"	Y	1"	Y	1"	Y	½"	Y	½"	Y Y	¼" 1/8"	Y Y	¼" 1/8"	Y	N	100 100	Y	Y		
Wis	Y on Asph	N	-	N	-	N	-	Y	1/8" Asph	Y	.2"	Y Y	1/8" 1/8"	N Y	- .20"	Y	Y	75 75	N	Y		Contractors must request permission to use auto control on final course
Wyo	Y	N	*	N	*	Tons/ft		N	*	Tons/ft		Y Y	3/16" 1/8"	N Y	- .2"	Y	N	98 90	Y	Y		* Tolerance depends upon rideability
Wash D.C.	N	N	-	N	-	N	-	N	-	N	-	Y Y	1/8" 1/8"	N Y	- 1/8"	N	?	? 0	N	?		

Construction Control of Rigid Pavement Roughness

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Results of a 2-year study of cause-effect relationships involved in roughness of concrete pavements are reported. Data were derived both from analog traces obtained in each wheelpath within hours after concrete placement on randomly selected pavements, and from qualitative observations of paving methods. Sampled construction consisted of 184 sections of 1- and 2-lane pavement built under 62 different contracts with 8 different form-type finishing machines and 3 different slipform pavers. Statistical analysis was held to a minimum by uncontrolled interactions, but 5 factors were found to be common and outstandingly significant in relation to roughness throughout the contracts studied: (a) backing up of the last finishing machine, (b) absence of a float, (c) use of less than 3 screeds, (d) use of a crown section as compared to a uniformly sloping section, and (e) lane-at-a-time paving. Nine other construction phenomena producing roughness, common to many projects but found less frequently than these five, are also covered in some detail.

•THE NEED TO MINIMIZE the roughness of concrete pavement during its placement derives from the established relationship of initial roughness to subsequent service life. Housel (1) demonstrated that most concrete pavements in Michigan increase in roughness at the same, fixed annual rate. The AASHO Road Test (2) produced procedures for computing the increase in roughness resulting from traffic and environment for many different pavement designs. Tallamy (3) applied Road Test concepts to the New York State Thruway, using an average of roughness measurements on unopened sections as an initial point, to predict the sequence of future pavement reconstruction. From these reports, it follows that the smoother that pavements are built, the longer they will serve traffic.

Over the years, construction control of concrete pavement roughness has been the subject of several studies. The development of the profilograph used in this investigation was reported by California (4). In 1968, Virginia (5) reported on bridge deck roughness measured with a 10-ft straightedge that had been correlated to the BPR roughometer. Virginia's results were particularly important, in that this was the first time that deviations measured with a straightedge were related to roughness measured with a device correlated to human response. The relationship of a profilograph (similar to the one used in this study) to the CHLOE profilometer used at the AASHO Road Test was explored by Texas (6). Together, these studies related initial roughness, as measured by various devices, to the roughness limit at which pavements should be rehabilitated.

Use of a 10-ft straightedge has been specified by New York since 1923 (7). It provided adequate control when paving production was measured in feet per hour of one 9- or 10-ft wide lane, because the inspector could take sufficient samples. However,

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as production increased to feet per minute, while the number of samples per day remained constant, undetected roughness occurred. This problem became aggravated both by further increases in production with the advent of central-mix concrete and by simultaneous placement of multilane pavement. Thus, the proportion of pavement that could be inspected dropped drastically.

Recognizing the increase in roughness resulting from this condition, New York tried a specification based on the BPR-type roughometer. However, this unit could not be operated until the pavement was 7 days old, and even then it could not pinpoint the location of roughness. Thus, it was found impractical as a quality control device. At this point (in 1967), the Engineering Research and Development Bureau was requested to investigate means of rapidly determining pavement roughness as soon as possible after concrete placement.

Because of the urgent need for an early solution to this problem, attention focused on existing equipment for evaluating roughness. The California profilograph (hereafter called the profilograph) was selected because it can be operated on the pavement within 4 to 6 hours after placing, is simple to operate, and provides a permanent record of roughness at a scale sufficient to permit identification of areas requiring remedial action. California's method for reducing the analog record to digital data, given in Appendix A, was also adopted without change. However, no information was available on profilograph reproducibility, operator influence, analog-to-digital conversion errors, machine dependability, or the ability of the manufacturer to produce identical machines with interchangeable parts. It was therefore necessary to evaluate the profilograph sufficiently to determine machine or operator variances. Once this was done, the magnitude and causes of roughness were evaluated.

Statewide paving schedules were obtained for the 1967 and 1968 construction seasons and an itinerary laid out for a 2-man crew to visit an average of 3 paving projects per week. No attempt was made to visit any specific project at a given time. The only 2 controls over contract selection were that paving be in progress on 2 or more projects within about 30 miles of one another, and that a general statewide distribution of sites be maintained. The analog traces for each sample, comprising 1 day's paving on a project, were digitized and the results entered on punched cards, together with observations on equipment and paving procedures.

The first field work began late in the 1967 construction season and thus produced only 71 samples, an inadequate number for detailed analysis in keeping with this study's experimental design. By the end of the second season, a total of 184 samples were available from 62 contracts. Again, full evaluation of the results was impossible because of the many interactions, widely different sample sizes, and the critical independent variables present in individual samples. However, the data were sufficient to permit testing of means and variances using standard statistical tests, when the assumption that each set contained equal percentages of all other independent variables could be verified. Various other analytical methods would have required a prejudgment of expected critical variables. Such prejudgments could not be made legitimately because of the scarcity of published information on cause-effect relationships. In this respect, the results of the present analysis are of immediate use in reducing roughness and in providing the knowledge required to make prejudgments in future work.

DATA COLLECTION AND ANALYSIS

The Profilograph

The profilograph (Fig. 1) is produced by Cox and Sons, Sacramento, California. Snap-lock clamps permit one man to assemble the 3 main frame sections and supporting components in about 10 minutes. The sections and components were found to be interchangeable with those of 2 other profilograph units produced in 2 other years. In 327 miles of operation with this Bureau's profilograph, less than $50 was spent at local hardware stores for minor replacement parts.

The permanent record consists of a continuous trace of roughness along the tested path. The amplitude scale is one-to-one and the distance scale is 25 ft to the inch. Point roughness can be easily located to the nearest foot by scaling. A manually operated

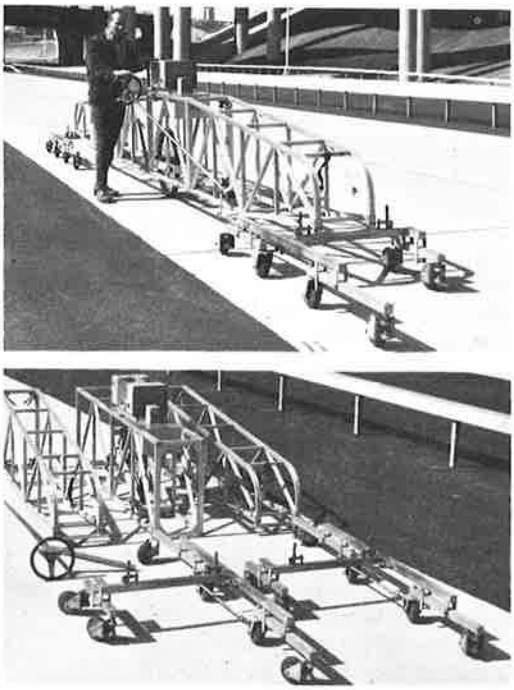

Figure 1. Profilograph assembled and disassembled.

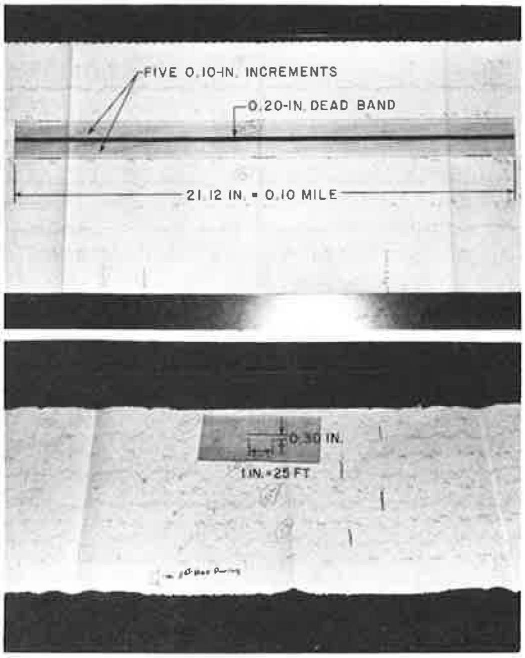

Figure 2. Profilograph traces and transparent templates used in data reduction.

event pen is available to denote stations, joints, or other references to facilitate relocation of points of interest. The analog trace is rapidly reduced to a digital value using a long plastic template, and a square template is used to detect isolated point roughness; both are shown in Figure 2. Digital data are expressed in inches per mile as detailed in the procedure given in Appendix A.

Site Selection and Field Procedures

Pavement sections were selected in a manner that attempted to minimize bias in estimating the variance contributed by specific equipment trains, contractors, projects, or other features that might prove to be significant influences on pavement roughness. The department's 10 regions readily furnished tentative paving dates for all projects. From this information, a map was prepared and projects selected to provide maximum statewide coverage.

The ideal experimental situation was selection of 5 projects within a 30-mile radius for inspection in a given week. The 2-man profilograph crew would then spend one afternoon watching and recording paving operations at one site. The following morning, they would measure roughness in every wheelpath, generating a permanent profilograph trace. The project site sample usually constituted about 0.2 mile of pavement, either 1 or 2 lanes wide. The operators would then continue to the nearest of the remaining 4 jobs. For the next 2 weeks, they would visit new areas with the intention of returning to each area and each job on an average of once every 3 weeks. No advance itinerary of the profilograph team was released. After each season ended, a few samples were taken from pavement placed between the dates when operations were recorded to be sure that no bias arose because of the profilograph's presence.

The original intention of obtaining from 5 to 10 samples from many projects was achieved. Many more projects, however, yielded only 1 to 4 samples. A few projects were also tested for their entire lengths to furnish specific information not available in smaller samples. Two of these were tested throughout their lengths with a 10-ft straightedge, and the results were compared with similar data scaled from the profilograph tapes.

Paving Operations and Equipment Encountered

Five slipform projects were evaluated a total of 20 times, and 57 conventionally formed projects 164 times. Slipform pavers included those manufactured by Guntert-Zimmerman, CMI, and REX. Form pavers were Heltzel, Koehring, REX, Blaw-Knox, Jaeger, Lewis, Flexible Road Joint Machine, and Maxon. The last 4 machines were encountered on only 1 to 4 jobs. The Guntert-Zimmerman was observed placing concrete on processed gravel, soil-cement, and asphalt-stabilized bases; the REX slipform was observed only on asphalt-stabilized base; and all other data are from pavements on gravel base. Paving trains were evaluated that had both 1 and 2 finishing machines, with 2 to 5 screeds, and with and without a pan float. The CMI slipform was the only train to place single-course pavement with vibrated-in-place mesh; all others were 2-course. The most frequently used spreader was the Maxon. The Guntert-Zimmerman, however, dumped bottom course concrete directly on the grade from dump trucks. Central-mix concrete was most frequently used, transported in dump trucks without baffles in Maxon side dumps and in transit mix trucks operated as agitators. Ten contracts used paving mixers.

All slipformed pavement was placed full width, but formed pavement was placed lane-at-a-time, two-at-a-time, and two-plus-one. Both constant cross-slope and crowned tangents were observed. Geometric factors evaluated, in addition to the normal crowned section, were constant cross-slope tangents and curves, cross-slope transitions, and variable-width pavements. On specific projects, roughness-contributing factors evaluated included drainage structure inlets cast into the pavement and frequent interruptions introduced by bridges (but not bridge deck roughness). Contracts ranged from secondary highways on new locations to highly complex urban Interstate reconstruction.

Data Reliability and Limitations

General Data Characteristics and Limitations—The data were not suitable for rigorous analysis because of the numerous interacting variables and widely different sample sizes. However, it was possible to use some statistical tests on the various independent variables (taken one at a time). Thus, frequency distributions were prepared for the presence and absence of each independent variable, and the average, variance, and standard deviation were computed. When the variances were statistically similar, the means were tested at the 1 percent level of significance.

The data are presented as pairs of histograms (Fig. 5) and as both histograms and percentage probability plots (Fig. 7). The percentage probability plots eliminate the effect of different sample sizes, which obscure the trends depicted by the histograms.

An assumption that must be made and tested when analyzing paired data is that the difference being tested is truly due to the defined variable and not the effect of other interdependent variables distributed among the 2 groups being tested. This assumption was applied in screening and selecting samples for analysis. Sample sets of less than 30 generally failed to meet this constraint and are not included in the analysis, even though intuitively a difference should exist.

Trace Reproducibility—The profilograph was tested for trace reproducibility by making 25 forward and 25 reverse runs over the same 0.2-mile section of concrete (2 template lengths). Manual data reduction errors, discussed later, precluded the use of this method of reproducibility testing. Because no optical reduction instruments were available to provide exact trace conversion to digital form, the traces were overlaid in sequential sets of five on a light table, and no measurable differences were found in either the forward or reverse directions. No reproducibility errors could be introduced by changing operators or by interchanging major components, such as the recorder or truss sections from 2 other profilographs built in 2 different years. It was concluded, therefore, that the profilograph was a reproducible measuring device.

Testing the Data Reduction Process—Data analysis centered on 2 forms of testing: (a) determining the reproducibility of data reduction, and (b) determining the relationship of the data to the specified roughness limit of 1/8 in. per 10 lin ft.

Manual conversion of the analog trace to a digital value of inches per mile proved to be the source of greatest error, as shown in Appendix B. From Tables 2, 3, and 4 in Appendix B, it would seem that the standard deviation of the data reduction process can be expected to stay within about 0.5 in. per mile on very smooth pavements (5 in. per mile or less), and to less than 2 in. per mile on all others, with matching ranges of 1 and 5 in. per mile respectively. Thus, the present method of data reduction is judged adequate for the intended purpose.

Comparison of the Profilograph and Straightedge

Another test of the data reduction process involved comparison of profilograph records with those obtained by the department's specified 10-ft straightedge method of measuring deviations exceeding the 1/8-in. limit. The data for this test consisted of straightedge records and matching profilograph traces for both (a) the centerline plus each wheelpath of a 1-lane, 0.22-mile long ramp, and (b) the wheelpaths of 1 lane in each direction on 3.24 miles of divided, 4-lane pavement. The ramp straightedge data given in Table 1 indicated about 25 percent more vertical displacements than did the traces. However, on the longer, main-line pavement, over 50 percent more points were found by the profilograph than the straightedge presumably because of the fatiguing effort of checking about 13 miles of pavement. The time required for the straightedge measurements is not available; it took 2 days for 2 men to profilograph both pavements and 5 days to reduce and check the tapes.

For 2 reasons, the 25-ft profilograph and 10-ft straightedge should seldom agree. First, the straightedge cannot readily detect bumps, but the profilograph produces a trace clearly delineating both depressions and bumps. Second, the response of both devices to roughness is a function of their lengths and of the length of the waveform generated by the paving process. Thus, Figure 3 shows that both devices indicate twice the actual roughness for all pavement wavelengths equal to odd fractions of their lengths (25 and 10 ft), and zero roughness for all even fractions. Further, their response to wavelengths exceeding their own length decreases by one-half for each additional multiple of their length. Similar plots for the BPR roughometer and the General

TABLE 1

ROUGHNESS AT TWO SITES USING DIFFERENT MEASURING DEVICES

Trace		Vertical Displacement, in.											
		1/8	3/16	1/4	5/16	3/8	7/16	1/2	9/16	5/8	11/16	Other	Total
Ramp Pavement													
1	Profilograph	33	26	13	4	5	1	—	—	—	—	—	82
	Straightedge	17	26	35	3	11	—	5	1	3	—	3	104
2	Profilograph	24	22	14	17	3	—	—	—	—	—	—	80
	Straightedge	31	29	24	—	11	1	2	—	—	—	1	99
3	Profilograph	26	21	12	9	4	—	1	—	1	—	—	74
	Straightedge	15	25	36	4	11	—	5	1	3	—	4	104
Main-Line Pavement													
1	Profilograph	486	236	80	32	7	3	—	—	—	—	—	844
	Straightedge	443	53	18	7	2	—	—	—	—	—	—	523
2	Profilograph	453	201	98	20	14	4	2	—	—	—	—	792
	Straightedge	495	116	60	—	2	—	—	—	—	—	—	672
3	Profilograph	511	257	100	44	11	3	1	2	—	1	—	930
	Straightedge	330	56	21	8	2	—	—	—	—	—	—	417
4	Profilograph	521	219	65	17	3	2	1	—	—	—	—	828
	Straightedge	343	68	24	6	—	—	—	—	—	—	—	441

Motors profilometer (10) show that the latter unit is the only device with true response. These last 2 devices obtain their better frequency response from a reference generated by complex electronic circuits, rather than a fixed, finite-length structure.

The profilograph was also compared with a BPR-type roughometer. Both devices made test runs of identical length in the same wheelpaths on the same project. The profilograph traces were run the day after paving, and the roughometer runs as soon thereafter as possible, with the results shown in Figure 4. The indicated lack of correlation is contrary to implications in the literature. It can only be explained by noting the differences in response shown in Figure 3. Neither device has been correlated with driver acceptance of concrete pavement in this state. However, both devices have been so correlated independently elsewhere. Thus, both are assumed to produce an output related to driver response and therefore to each other.

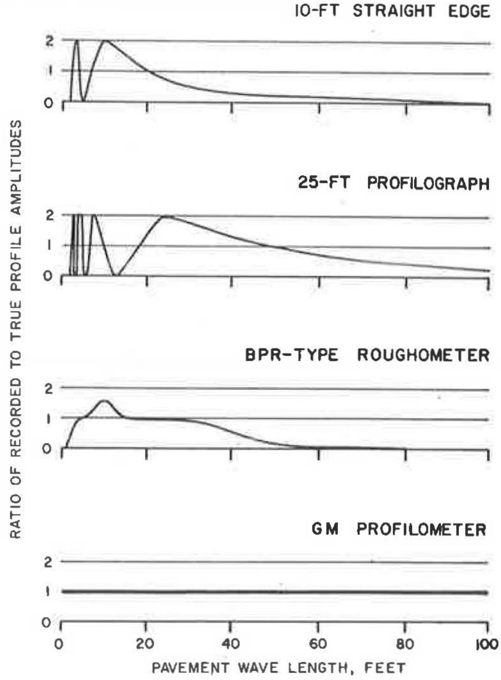

Figure 3. Theoretical differences between 4 roughness measuring devices.

Summary

In conclusion, it was found that the profilograph is suitable as a construction control device for monitoring concrete pavement roughness within hours after placement. The permanently recorded output is exactly reproducible and can be reduced from analog to digital form by trained personnel with an acceptable error. The absence of correlation between the profilograph and roughometer is accepted as predictable from their respective frequency response curves.

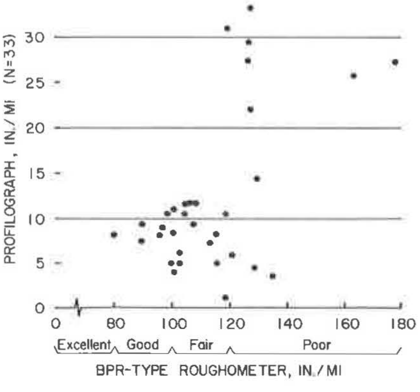

Figure 4. Relationship of profilograph and roughometer roughness (excellent, good, and fair are Bureau of Public Roads qualitative ratings).

DISCUSSIONS OF RESULTS

Sample and Contract Roughness: 1967-1968

A sampling of roughness built into newly constructed concrete pavements in New York State in 1967 and 1968 is shown in Figure 5. Two pairs of histograms are shown, the first averaging all daily test runs in each of the 2 survey years without reference to contract or project, and the second averaging by contract regardless of number of test runs per contract. Of particular interest in the case of average test roughness are the highly significant 25 percent reduction from 1967 to 1968 (from 23.8 to 17.9 in. per mile) and 33 percent reduction in standard deviation (from 13.7 to 9.2). These reductions were not accompanied by a similar change in overall average contract roughness (also shown in Figure 5), although the 34 percent reduction in standard deviation (from 12.8 to 8.5) is significant. The im-

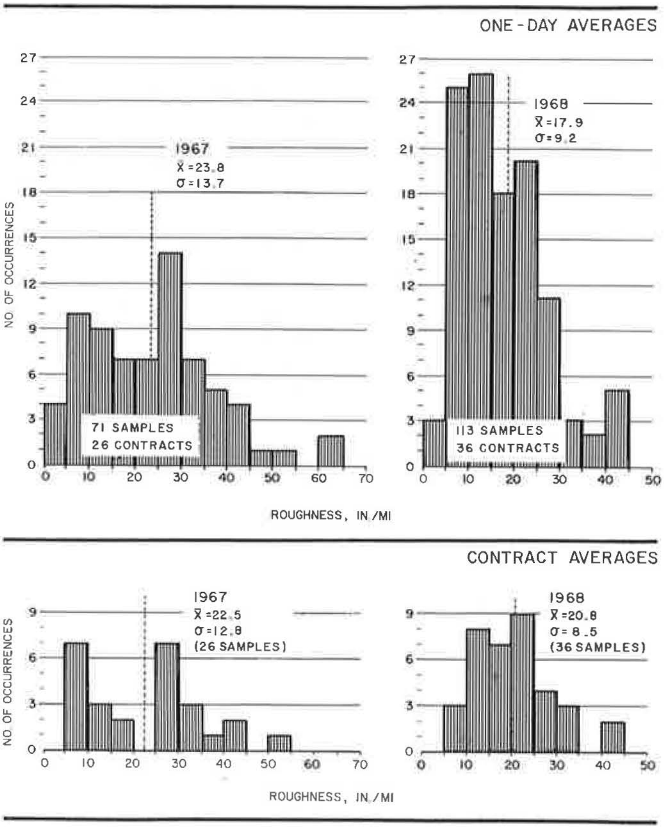

Figure 5. Two-year summary of roughness of newly constructed pavements by test days and by contracts.

plication is that individual projects decreased in number of rough pavement sections placed, but for various reasons (to be discussed later) no significant shift occurred in overall job performance. However, it should be noted that the causes of roughness were not yet defined in 1968, so no corrective action could yet be taken.

The influence of the contractor is shown in Figure 6, where annual averages are plotted for the contractors visited most frequently in this study's 2 seasons. Contractors F, G, H, and I demonstrated that smooth pavements can be placed consistently even in the absence of a roughness specification. Contractor D used a new paving train during 1968. Extensive equipment repairs and modifications are believed responsible for the reduced roughness found for contractor B in 1968. No reason is known for the increased roughness produced by E, the continued poor performance by C, or the extreme roughness produced by A using a late model slipform on an asphalt-stabilized base.

Factors Influencing Roughness Throughout the State

Five factors influencing roughness were readily identified when the combined 1967-1968 data were analyzed as discussed previously: (a) finishing machine backup, (b) presence or absence of float, (c) number of screeds, (d) crown versus constant cross slope, and (e) paving width.

Finishing Machine Backup—Backing up the finishing machine in conventional paving to produce the required multiple passes of the screeds has been standard practice.

However, as Figure 7A shows, obtaining a smooth pavement (one with little detectable roughness) is very difficult. The probability plot accompanying the histogram, showing the same data as percentages, quite vividly demonstrates the effect of backing up if any given set of roughness criteria are to be met. For example, if it is assumed that pavement must be ground smooth when the roughness exceeds 12 in. per mile and removed when it exceeds, 30, continued backing up would result in removal of 20 percent of the pavement and grinding of 73 percent more. Corresponding values for not backing up would be 0 and 64 percent.

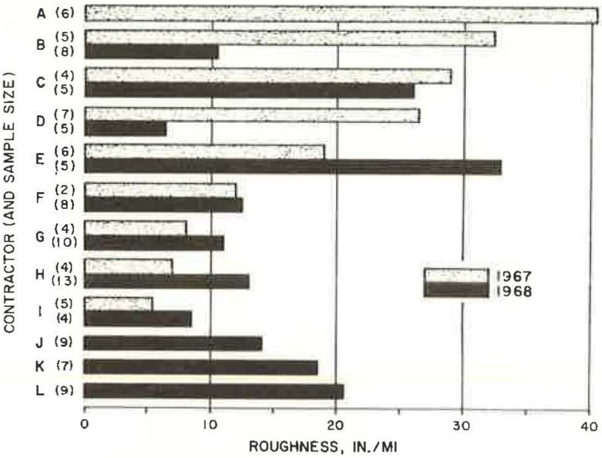

Figure 6. Annual average performance by contractors (numbers in parentheses are total samples measured).

Presence or Absence of Float—A simple pan float hung behind the finishing machine produced the reduction shown in Figure 7B. Using the same limits just mentioned, 20 percent of the pavement would be removed and an additional 76 percent would require grinding, if the

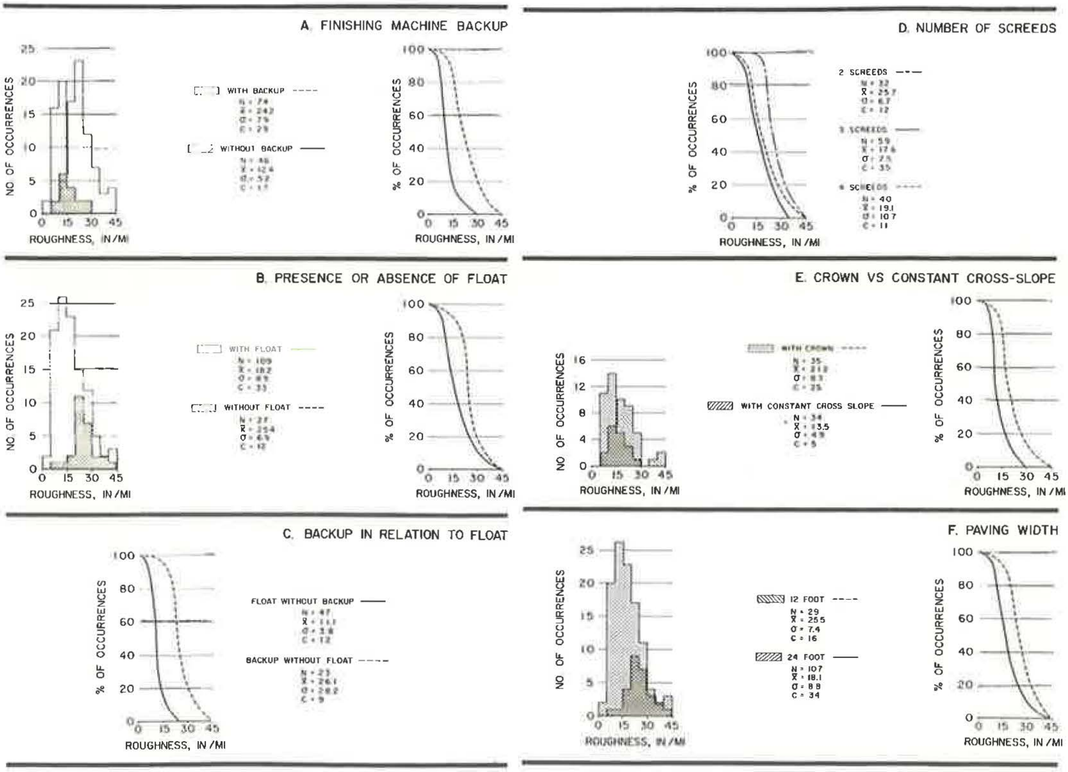

Figure 7. Roughness factors found statewide in 2 test years.

float is not used. Conversely, using the float would result in removing only 10 percent and grinding 70 percent. However, by separating data samples into the smoothest and roughest combinations (Fig. 7C), the former would result in no pavement removal and grinding less than 40 percent. On the other hand, the latter would require removal of 20 percent of the pavement and grinding the balance. Unfortunately, data are insufficient to continue this type of cumulative-effect analysis for the next 3 statewide phenomena discussed.

Number of Screeds—For many years, New York State paving specifications have required the use of 1 finishing machine with a minimum of 2 screeds. However, some regions have required a minimum of 3 screeds and others a minimum of 2 finishing machines with 2 screeds each. Further, some contractors have paving trains including as many as 6 screeds. It was therefore essential to determine the optimum combination. As Figure 7D shows, 3 screeds appear to be adequate, and 4 to produce rougher pavement; however, the difference is so small that it could well represent the previously discussed analog-to-digital conversion error and thus should be ignored. Insufficient data were collected on the other combinations, which thus are not included. One interesting fact that came up during review of multiple-finishing machine trains is that neither ability of the operator, mechanical condition, nor method of operation of the first machine had any significant effect on roughness. For example, one train observed several times producing smooth pavement had a very poorly maintained, badly worn-out old finishing machine, run by an inexperienced operator, followed by a new machine run by an experienced one. The first machine frequently had to back up and always moved at an erratic pace with frequent stops, while the second never backed up and always maintained a uniform pace. The first machine was subsequently rebuilt and assigned an experienced operator, without significant effect on pavement roughness.

Constant Cross Slope—Since the advent of multiple-lane paving, the contribution of the crowned cross section to roughness has been frequently discussed. Figure 7E shows the difference between the normal crown and a constant cross slope on tangent alignment. Here again, this one change would result in removing no pavement and grinding less than 40 percent to meet the previously discussed limits. Another significant point is that the roughest traces were obtained on projects where the contractor tried hardest to obtain a peaked crown. Transitions had an average roughness of 22.4 in. per mile—not significantly different from crowned tangents—but the variance was significantly higher. However, transitions were 66 percent rougher than tangents with constant cross slope and 25 percent rougher than superelevated curves. The implication, therefore, is that the methods used to adjust a finishing machine from 1 section to another require considerable improvement.

Paving Width—The earliest cause-effect relationship detected during this study was the cumulative roughness resulting from lane-at-a-time paving. Figure 7F shows the highly significant 41 percent average increase in roughness for the second lane of a 2-lane roadway, using single-lane rather than full-width placement. Similar increases are encountered for all successive lanes. Thus, the third lane of a pavement placed lane-at-a-time will be about 80 percent rougher than the first.

In summary, 5 factors were found responsible for pavement roughness throughout the state: backing the finishing machine, absence of a float, too few screeds, using a crowned cross section, and lane-at-a-time paving. Unfortunately, the data were insufficient for analysis of the total combined effects of these variables. However, avoidance of the first 2 factors showed that extremely smooth pavement could be produced even with the other three present. Thus, it is hypothesized that avoiding all 5 factors would ensure pavement of minimum roughness.

Factors Affecting Roughness on Single Contracts

Random occurrences of roughness should be expected on individual projects. The causes are legion. Some of the more significant encountered during this study are discussed next and were given special attention in the 1969 construction season.

Base Course—The type and roughness of the base material over which concrete pavement is placed have long been thought to influence final roughness of the riding surface. In this regard, some question has remained as to the effect on roughness of the 12-in. beneficiated gravel base generally used in New York. Unfortunately, the absence of statewide use of treated bases precludes full-scale comparison. However, 2 contracts having such material were encountered and illustrate that presence of such material does not necessarily guarantee smoother pavement because other factors may exert more influence.

The first contract had several replicate sections of 8 in. of gravel, covered with (a) 4 in. of beneficiated gravel, (b) 4 in. of soil-cement, or (c) 3 in. of asphalt-stabilized base. The 8 gravel, 4 soil-cement, and 18 asphalt-stabilized sections had averages of 5.22, 6.88, and 2.59 in. per mile respectively and standard deviations of 3.74, 3.62, and 2.59. Although the asphalt-stabilized sections were numerically smoothest, the differences were not statistically significant. Further, the tendency of asphalt base to be associated with smoother pavement was not verified.

The second contract had 4 in. of bituminous-stabilized base over 8 in. of gravel throughout. Based on measurements made on pavement placed on 6 different days, average roughness was 40.22 in. per mile, with a range of 11.8 to 92.2 making it the roughest placed in the state during the study's 2 years.

Apparently, such extremes in roughness can be attributed to no one condition. Rather, the differences are believed to represent combinations of all parameters operating at their respective limits. However, from the first project, it does appear that special base courses might warrant further testing.

Supervision—Figure 8 shows one project on which the only change in operations was replacement of the paving train foreman between August 1 and 7. All other personnel and all equipment remained constant. The paving was 24-ft wide Interstate on new location. By July 3, the foreman was quite interested in reducing roughness. The following 4 tests show he was able to do so consistently. Unfortunately, his successor never was able to achieve the same control, although he did manage to equal the initial tests. An important point here is that, if the previously discussed roughness limits had been in effect, all pavement placed after August 1 would have required grinding.

Concrete Mix—The combined effects of a harsh mix and backing up the finishing machines are shown in Figure 9. This was formed, 2-lane pavement placed with 2 finishing machines. From data collected for this train on other contracts, a roughness

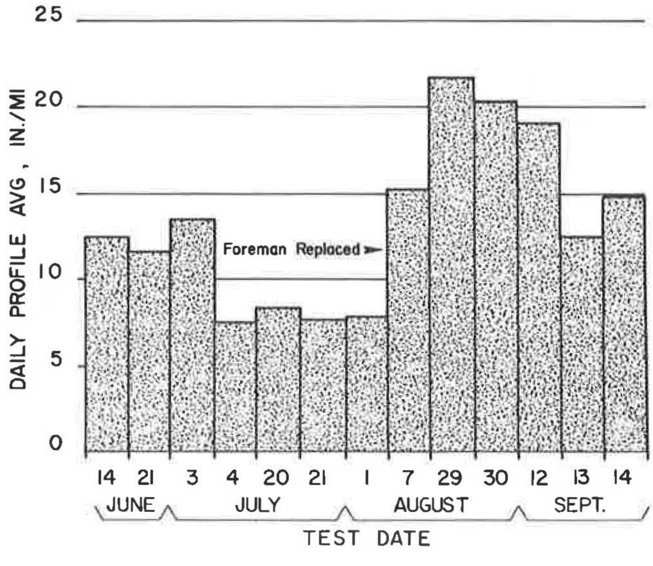

Figure 8. Effect of change of supervision.

average of about 11 in. per mile could be expected. However, the operator of the last finishing machine was backing up on October 22 at his own discretion. When the effect of backing up was pointed out, it was stopped. Then it became obvious that the finishing machines were having trouble because of the harshness of the mix. A 5 percent reduction in the quantity of 2- and 2½-in. stone brought roughness down to a respectable level.

Transverse Joints—The contractor has the option of either forming or sawing transverse contraction joints at the specified 60 ft 10 in. spacing. Figure 10A shows results of poor hand finishing; in this case, every joint is contributing 0.1 to 0.3 in. of roughness. Fortunately, not all joints were as bad as the three shown or average roughness per mile would have been increased 17.4 in. because of joint construction.

Forms—The care required in setting forms and the need for high-strength forms to produce smooth pavement have long been recognized.

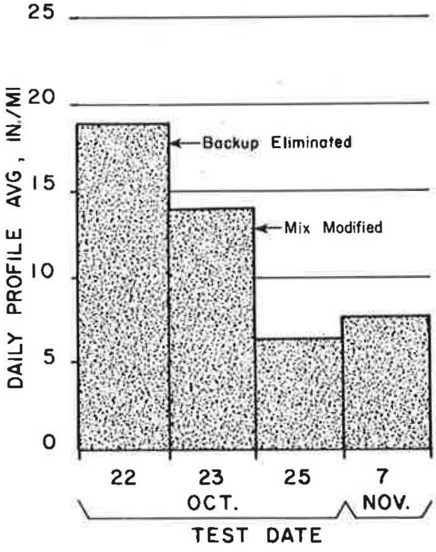

Figure 9. Effects of eliminating backup and modifying mix.

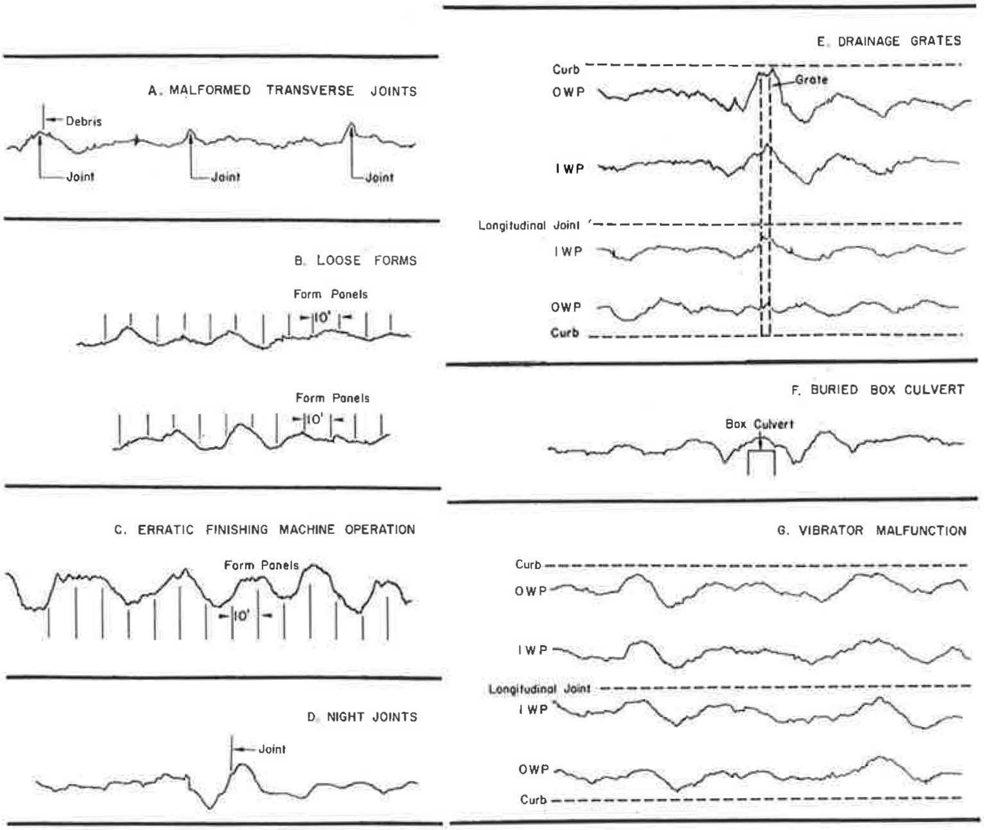

Figure 10. Typical profilograph traces showing roughness-generating conditions.

However, frequently overlooked is the treatment forms received during concrete placement. Figure 10B shows 2 cases of forms loosened by the operator of a Maxon spreader who frequently rammed his hopper against the stops as hard as possible. Loose or poorly set forms will produce even more pronounced roughness patterns. However, the pattern may be obscured by erratic finishing machine operation (shown in Fig. 10C). Here forms with as much as ¼-in. sags between stake pockets and with damaged end plates were poorly set, pushed out of alignment by the grader operator doing fine grading, and further loosened by both the spreader and 2 or more passes of the finishing machine. In this case, it is almost impossible to delineate the forms although one possible relationship is indicated.

Night Joints—Joints formed at the end or the beginning of the construction day are probably the most consistent source of roughness. Figure 10D shows a typical night joint in a very smooth slipform pavement. This joint would require grinding the full width of the pavement. This trace also delineates the multiple response of any finite-length, roughness-measuring device to large surface deviations. The swale to the right of the night joint results from the front support wheels of the profilograph climbing up to the night joint, allowing the sensor wheel to drop with respect to the frame. The high point of the night joint is emphasized by the sensor wheel resting on it while the front and rear support wheels are down. Additional distortion is probably caused by profilograph response to various wavelengths. For example, if the night joint had a wavelength of exactly 25.00, 8.33, or 5.00 ft, the trace would indicate twice the true amplitude. Fortunately, as discussed earlier, these wavelengths are usually canceled by those occurring at 12.50, 6.25, and 3.125 ft, which produce zero response. The trace to the left of the joint would then be a mirror image of the right.

Drainage Structures—Two types of drainage structures were found significantly to influence pavement roughness. The first is the standard flush-mounted inlet frame and grate cast into the pavement. This common parkway design will result in roughness patterns as shown in Figure 10E. The carryover from the edge of the grate through the third wheelpath, at least 16 ft in this case, is quite obvious. At the normally used spacing of 200 to 300 ft between inlets, these structures can constitute a significant source of roughness.

The second type of roughness-producing drainage structure is the buried unit. Figure 10F shows the effect of a large box culvert designed with the top of its roof very near the top of subgrade. In this case, the structure had been carefully backfilled several months prior to paving. The embankment also had served as a haul road for some time. However, the weight of the slipform paver supported by the extrusion plate presumably exceeded the capacity of the backfill material, because the tape implies depressions on either side of the structure.

Vibration—On most formed jobs, the primary means of vibration was a series of pan surface vibrators suspended across the rear of the top course spreader. These were occasionally found to be completely inoperative and were frequently suspected of faulty operation. Because no means of determining their absolute frequency and amplitude was available, only their presence and appearance were noted. Figure 10G shows a set of traces for a 2-lane pavement where the vibrators in the top lane were obviously not working and those in the bottom lane were. The roughness ranged from 18 in. per mile on top to 9 in. per mile on the lower trace. Similar cross-pavement variations were also encountered where surplus mortar was permitted to accumulate on the form rail or tracks of a slipform on the side of the paving operation checked infrequently by the foreman or the inspector.

Finishing Machines—The influence of various components of finishing machines (such as screeds, vibrators, and pan floats) on pavement roughness has been described. To prove that the differences were not due to equipment source, condition, or operation, most of these data were developed on projects where only one parameter was varied. However, data were collected on all equipment trains, and, although limited in regard to slipforms, no large disparities existed.

Eight different types of finishing machines were encountered on conventionally formed pavements. Three produced 95 percent of the data. Their average roughnesses were 19.58, 19.10, and 19.85 in. per mile with corresponding standard deviations of 9.25, 9.10, and 8.00. The other 5 machines were not analyzed in detail because of their small sample sizes. All 8 manufacturers' machines varied in age and condition to the extent that any direct comparison with the new slipform machine would be misleading.

Three manufacturers' slipform pavers were evaluated. One wire-controlled machine paved 3 projects with averages of 6.2, 5.8, and 8.0 in. per mile, with corresponding standard deviations of 4.0, 1.7, and 3.5 in. per mile. A second wire-controlled machine paved one project with an average of 40.2 in. per mile and standard deviation of 13.0. The third machine was a grade-sensing unit, which paved one project with an average of 6.9 in. per mile and standard deviation of 3.4. The first machine was operated by the same personnel on all projects. The other two were run under factory supervision by local crews unfamiliar with this new paving method.

The outstanding feature of these data is the absence of any association between roughness and any one manufacturer or paving method. It is true that conventional equipment produced pavements with average roughnesses generally higher than slipform. However, many projects were equal in roughness to the best slipform contracts. Therefore, it is concluded that the higher averages are attributable to equipment age and condition, use of less than an optimum train, or poor operating methods.

CONCLUSIONS

This study's conclusions fall into 3 categories: suitability of the measuring method, roughness factors found most critical throughout the state, and influence of purely job-related occurrences on roughness:

1. The profilograph is suitable for rapidly obtaining a permanent, reproducible record of pavement roughness within hours after placement.
2. The factors most important in controlling roughness, in order of suggested ease of implementation, are as follows: (a) elimination of paving machine backup, (b) use of a pan float, (c) use of at least 3 screeds, (d) use of constant cross slope, and (e) use of full-width paving, or at least the elimination of lane-at-a-time paving.
3. Many purely job-related factors can override the best specifications. Those appearing most frequently were the following (not necessarily in order of importance): (a) changes in supervision, (b) mix design, (c) faulty equipment, and (d) design details in associated work such as drainage structures.

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Appendix A

EVALUATION OF PROFILES

Test Method No. Calif. 526-D, California Department of Public Works

EVALUATION OF PROFILES

Scope

This method describes the procedure used for determining the Profile Index from profilograms of pavements made with the California type Profilograph and also describes the procedure used to locate individual high areas when their reduction is required by the contract special provisions.

The profilogram is recorded on a scale of one-inch equal to 25 feet longitudinally and one-inch equal to one-inch, or full scale, vertically. The determination of the Profile Index involves measuring "scallops" that appear outside a "blanking" band. The determination of individual high areas involves the use of a special template.

PART I. DETERMINATION OF THE PROFILE INDEX

Procedure

A. Equipment

The only special equipment needed to determine the Profile Index is a plastic scale 1.70 inches wide and 21.12 inches long representing a pavement length of 528 feet or one-tenth of a mile at a scale of 1″ = 25′. A plastic scale for the profilograph may be obtained by the Districts from the Service and Supply Department. Near the center of the scale is an opaque band 0.2 inch wide extending the entire length of 21.12 inches. On either side of this band are scribed lines 0.1 inch apart, parallel to the opaque band. These lines serve as a convenient scale to measure deviations or excursions of the graph above or below the blanking band. These are called "scallops".

B. Method of Counting

Place the plastic scale over the profile in such a way as to "blank out" as much of the profile as possible. When this is done, scallops above and below the blanking band usually will be approximately balanced. See Figure I.

The profile trace will move from a generally horizontal position when going around superelevated curves making it impossible to blank out the central portion of the trace without shifting the scale. When such conditions occur the profile should be broken into short sections and the blanking band repositioned on each section while counting as shown in the upper part of Figure II.

Starting at the right end of the scale, measure and total the height of all the scallops appearing both above and below the blanking band, measuring each scallop to the nearest 0.05 inch (half a tenth). Write this total on the profile sheet near the left end of the scale together with a small mark to align the scale when moving to the next section. Short portions of the profile line may be visible outside the blanking band but unless they project 0.03 inch or more and extend longitudinally for two feet (0.08″ on the profilogram) or more, they are not included in the count. (See Figure I for illustration of these special conditions).

When scallops occurring in the first 0.1 mile are totaled, slide the scale to the left, aligning the right end of the scale with the small mark previously made, and proceed with the counting in the same manner. The last section counted may or may not be an even 0.1 mile. If not, its length should be scaled to determine its length in miles. An example follows:

Section length, miles	*Counts, tenth of an inch*
0.10	5.0
0.10	4.0
0.10	3.5
400′ = 0.076	2.0
Total 0.376	14.5

The Profile Index is determined as "inches per mile in excess of the 0.2-inch blanking band" but is simply called the Profile Index. The procedure for converting counts of Profile Index is as follows:

Using the figures from the above example:

Length = 0.376 miles, total count = 14.5 tenths of an inch

$$\text{Profile Index} = \frac{1 \text{ mile}}{\text{length of profiles in miles}} \times \text{total count in inches}$$

$$\text{PrI} = \frac{1}{0.376} \times 1.45 \doteq 3.9$$

(Note that the formula uses the count in inches rather than tenths of an inch and is obtained by dividing the count by ten.)

The Profile Index is thus determined for the profile of any line called for in the specifications. Profile Indexes may be averaged for two or more profiles of the same section of road if the profiles are the same length.

Example:

	Section length, miles	*Counts, tenths of an inch*	
		Left wheel track	*Right wheel track*
	0.10	5.0	4.5
	0.10	4.0	5.0
	0.10	3.5	3.0
400′ =	0.076	2.0	1.5
Total	0.376	14.5	14.0
PrI (by formula)		3.9	3.7

$$\text{Average} = \frac{3.9 + 3.7}{2} = 3.8$$

The specifications state which profiles to use when computing the average Profile Index for control of construction operations.

C. Limitations of Count in 0.1 Mile Sections

When the specifications limit the amount of roughness in "any one-tenth mile section," the scale is moved along the profile and counts made at various locations to find those sections if any, that do not conform to specifications. The limits are then noted on the profile and can be later located on the pavement preparatory to grinding.

D. Limits of Counts—Joints

When counting profiles, a day's paving is considered to include the last portion of the previous day's work, which includes the daily joint. The last 15 to 30 feet of a day's paving cannot usually be obtained until the following day. In general, the paving contractor is responsible for the smoothness of joints if he places the concrete pavement on both sides of the joint. On the other hand, the contractor is responsible only for the pavement placed by him if the work abuts a bridge or a pavement placed under another contract. Profilograph readings when approaching such joints should be taken in conformance with current specifications.

E. Average Profile Index for the Whole Job

When averaging Profile Indexes to obtain an average for the job, the average for each day must be "weighted" according to its length. This is most easily done by totaling the counts for the 0.1 mile sections of a given line or lines and using the total length of the line in the computation for determining the Profile Index.

PART II. DETERMINATION OF HIGH POINTS IN EXCESS OF 0.3 INCH

Procedure

A. Equipment

The only special equipment needed is a plastic template having a line one-inch long scribed on one face with a small hole or scribed mark at either end, and a slot 0.3 inch from and parallel to the scribed line. See Figure II. (The one-inch line corresponds to a horizontal distance of 25 feet on the horizontal scale of the profilogram.) The plastic template may be obtained from Service and Supply Department.

B. Locating High Points in Excess of 0.3 Inch

At each prominent peak or high point on the profile trace, place the template so that the small holes or scribe marks at each end of the scribed line intersect the profile trace to form a chord across the base of the peak or indicated bump. The line on the template need not be horizontal. With a sharp pencil draw a line using the narrow slot in the template as a guide. Any portion of the trace extending above this line will indicate the approximate length and height of the deviation in excess of 0.3 inch.

There may be instances where the distance between easily recognizable low points is less than one-inch (25 feet). In such cases a shorter chord length shall be used in making the scribed line on the template tangent to the trace at the low points. It is the intent however, of this requirement that the baseline for measuring the height of bumps will be as nearly 25 feet (1-inch) as possible, but in no case to exceed this value. When the distance between prominent low points is greater than 25 feet (1-inch) make the ends of the scribed line intersect the profile trace when the template is in a nearly horizontal position. A few examples of the procedure are shown in the lower portion of Figure II.

REFERENCE
A California Method

End of Text on Calif. 526-D

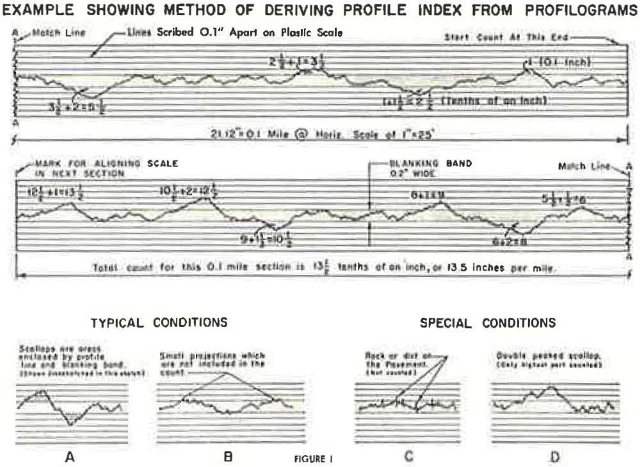

FIGURE I

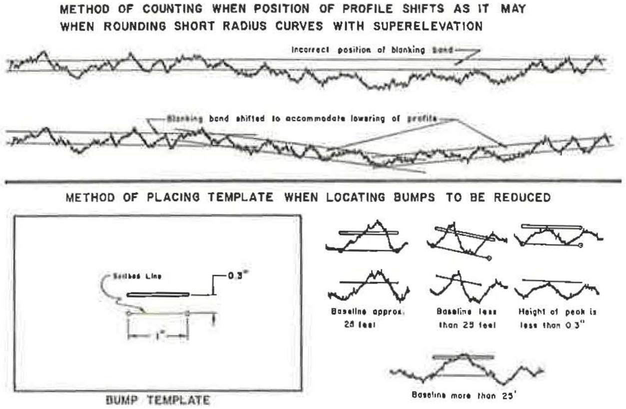

FIGURE II

Appendix B

DATA REDUCTION TESTING

To evaluate the error resulting from manual conversion of the analog trace to a digital value of inches per mile, concrete pavements representing the full range of measured roughness were selected for detailed analysis. Pavements selected had average roughness of 109.84, 14.32, and 3.70 in. per mile, and standard deviations of 7.34, 0.71, and 0.43 in. per mile respectively. Eleven persons, comprising 4 graduate engineers and 7 technicians without previous profilograph experience, reduced each set of 3 traces an average of 5 times in 1 continuous work period. The 2 regular operators had reduced the same traces, 1 set at a time, over a 2-year period. All tapes represented exactly 0.1 mile of pavement and were 21.12 in. long (25 ft per in.). Each person could select the portion of the trace to be covered by the 0.2-in. wide dead band on the template (Fig. 2). The magnitude of projections extending outside of the dead band was determined by counting the number of 0.1-in. increments inscribed on the template to the nearest quarter of an increment.

TABLE 2

REDUCTION OF DATA BY UNTRAINED PERSONNEL

Trace	5-Run Avg.	Standard Deviation	Range	Coefficient of Variation, percent[a]
1	17.10	1.09	15.50-20.00	6.4
2	10.82	1.25	7.75-12.25	11.5
3	10.22	1.15	7.50-12.25	11.2
4	19.11	1.72	16.00-23.75	9.0

[a] $(S/\bar{X})100$ = coefficient of variation.

TABLE 3

REDUCTION OF IDENTICAL DATA BY TRAINED AND UNTRAINED PERSONNEL

Trace	5-Run Avg.	Standard Deviation	Range	Coefficient of Variation, percent[a]
		Trained		
1	5.19	0.28	4.75-5.75	5.5
2	1.81	0.30	1.25-2.25	17.0
3	5.38	0.45	4.75-6.00	8.4
4	2.38	0.42	1.75-3.25	17.6
		Untrained		
1	5.46	0.30	5.25-6.00	5.5
2	1.96	0.34	1.50-2.50	17.3
3	6.04	1.04	4.75-7.50	17.2
4	2.82	0.34	2.25-3.25	12.1

TABLE 4

EFFECT OF TRAINING ON DATA REDUCERS

Operator	Trial[a]	Mean[b]	Standard Deviation	Range	Coefficient of Variation, percent[c]
1	Initial	121.44	2.25	119.50-124.25	1.85
	Replicate[d]	121.13	1.05	119.75-122.25	0.87
2	Initial	114.81	2.27	112.00-117.00	1.98
	Replicate	113.10	1.16	111.50-114.25	1.03
3	Initial	106.50	3.44	104.00-111.50	3.23
	Replicate	109.75	1.19	108.50-111.00	1.08
4	Initial	108.75	4.11	104.50-114.25	3.78
	Replicate	108.50	1.74	107.00-111.00	1.61
5	Initial	108.75	7.62	100.00-115.50	7.00
	Replicate	108.19	1.38	107.00-110.00	1.27
6	Initial	102.25	3.28	99.50-106.00	3.23
	Replicate	95.00	3.68	0.00- 98.75	3.87

[a] A "trial" is examination of the same tape 4 times.

[b] Mean of the 4 examinations.

[c] Coefficient of variation = $(S/\bar{X})100$.

[d] Set of tapes examined after training period.

TABLE 5

SUMMARY

Mean and Standard Deviation	Initial	Replicate
Mean		
Operators 1-5	112.05	112.13
Operator 6	102.25	95.00
Difference	-9.80	-17.13
Standard Deviation		
Operators 1-5	3.94	1.30
Operator 6	3.28	3.68
Difference	-0.66	+2.38

These 2 steps—covering the dead band and counting the increments—were determined to be the sources of error. Five untrained men produced the results given in Table 2 by replicating their reduction of 4 sets of traces 5 times each. The 2 regular operators with 2 years of experience were unable to produce better results for relatively smooth pavement than 2 untrained persons (Table 3). However, as roughness increased, experience provided the most reliable estimates. Tables 4 and 5 give the wide variability both within and between the work of reducers using the same set of traces throughout. Six persons were asked to evaluate the roughness of this set of traces over a 6-month period. The sixth man is one of the very few who did not reduce his standard deviation with time. His efforts are included here to show that such things occur. However, excluding him, these data indicate that a reduction in conversion variance can be achieved, while maintaining a constant mean.

Some Recent Developments in Equipment Applied to Public Works Projects

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The use of recent developments in efficient and more productive earth-moving equipment on public works projects is restricted because of project design, specifications, and other regulatory measures. Removal or modification of these restrictions would result in lower unit price bidding on public works projects, thus passing substantial savings on to the public. Large off-highway trucks, unless matched with appropriate size shovels, do not in themselves create significant savings. Large front-end loaders now make it possible to fully utilize some of the high-capacity trucks with economies that approach the costs of industrial mining operations. These economies are in the range of 20 to 30 percent less cost than those presently being experienced on some public works projects. The application of more productive compacting equipment, in some cases, is ruled out by restrictions of the specifications. End result specifications only would encourage contractors to bind competitively on a performance basis for compaction work. More economical large-diameter blast-hole drilling and blasting equipment appears to have broader application in road-building if a more liberal "subject to the approval of the engineer" policy can be obtained. Public agencies concerned with the cost of projects they design and recommend for construction have the responsibility to recognize the economic advantages of more efficient machinery and make accommodation for them.

•IN THE LAST FEW YEARS there have been many interesting developments in the field of earth-moving equipment. Many of these developments have found ready application by contractors working in public works projects. Others, for several reasons, have not been used. All have the same common denominator—to perform the work more efficiently and at lower costs.

Competitive bidding among responsible contractors within the construction industry should reflect the economies that can accompany these developments. The public, therefore, must ultimately benefit from the joint efforts of contractors to improve their competitive positions in the performance of public works projects.

The purpose of this paper is to illustrate typical examples of the economies that may be gained through the use of some of the more recent developments and to direct attention to those conditions of project design, specifications, local statute, and other regulatory measures that may restrict the application of more efficient machines to public works projects.

TRUCKS AND LOADING EQUIPMENT

Industrial open-pit mining operations have been the principal stimulus in the development of large trucks and shovels. Their operations do not require the mobility essential to the highway construction industry in moving equipment between projects.

Paper sponsored by Committee on Highway Equipment and presented at the 49th Annual Meeting.

TABLE 1

TYPICAL SHOVEL PRODUCTION, ESTIMATED

Item	Model		
	71-B	88-B	280-B
Rating, cu yd	$3\frac{1}{2}$	5	13
Hoist speed, ft/min	93	85	210
Swing speed, rpm	3.3	3.1	3.0
Bench height, ft	30	29	46
Average hoist, ft	20	20	30
Swing arc, deg	60	60	60
Cycle time, min			
Hoist	0.21	0.23	0.14
Swing	0.05	0.05	0.06
Spot	0.03	0.03	0.03
Dump	0.04	0.04	0.04
Swing	0.05	0.05	0.06
Steady	0.01	0.01	0.01
Swing cycle	0.39	0.41	0.34
Move allowance	0.10	0.10	0.10
Total cycle	0.49	0.51	0.44
Bucket rating, cu yd	$3\frac{1}{2}$	5	13
Fill factor, percent	80	80	80
Loose capacity, cu yd	2.8	4.0	10.4
Bank capacity, cu yd	1.9	2.7	7.0
Production per min, cu yd	3.88	5.29	15.91
Production per 50 min hr, cu yd	194	265	796

TABLE 2

TYPICAL LOADER PRODUCTION, ESTIMATED

Item	Model KW-Dart 600
Rating, tons	22.5
Hoist speed, ft/min	137
First gear, mph	3.6
Second gear, mph	7.0
Bench height, ft	24
Average hoist, ft	16
Cycle time, min	
Hoist	0.12
Reverse 45 ft at 3.0 mph	0.17
Forward 45 ft at 3.0 mph	0.17
Dump	0.05
Tilt	0.04
Reverse 45 ft at 5.0 mph	0.10
Forward 45 ft at 5.0 mph	0.10
Total cycle	0.75
Bucket rating, cu yd	13.5
Fill factor, percent	75
Loose capacity, cu yd	10.1
Bank capacity, cu yd	6.8
Production per min, cu yd	9.07
Production per 50 min hr, cu yd	454

Mining also, except for safety, is not hampered by regulatory statutes, and the continuous nature of the work ensures a write-off of the large investments involved with larger equipment. Thus, to reduce costs in mining, the size of the machinery and its cost is virtually unlimited. Industrial operations benefit from a reduction in unit costs in somewhat direct proportion to the size of each succeeding generation of equipment.

In highway work, the need to reduce costs, without sacrificing quality of workmanship, is very important to the public if road-building dollars are to do the same work tomorrow as they do today. The kinds of costs that the mining-type "super" truck and shovel produce and could bring to highway construction would go a long way toward combating the rising costs of road-building.

TABLE 3

TYPICAL FLEET REQUIREMENT (10 MIN HAUL, DUMP AND RETURN CYCLE), ESTIMATED

Item	R-35	R-50	R-100
Rating, tons	35	50	100
Heaped capacity, cu yd	27	38	74
Loose material, lb/cu yd	2,680	2,680	2,680
Bank material, lb/cu yd	4,000	4,000	4,000
Loose measure load, cu yd	26.1	37.3	74.6
Bank measure load, cu yd	17.5	25.0	50.0
$3\frac{1}{2}$-cu yd shovel			
1.9 cu yd/swing, swings	10		
0.39 min/swing, min	3.9		
No. trucks	(3.6)4		
5-cu yd shovel			
2.7 cu yd/swing, swings	7	10	19
0.41 min/swing, min	2.9	4.1	7.8
No. trucks	(4.4)5	(3.4)4	(2.3)3
13-cu yd shovel			
7.0 cu yd/swing, swings		4	8
0.34 min/swing, min		1.4	2.7
No. trucks		(8.1)9	(4.7)5
$13\frac{1}{2}$-cu yd loader			
6.8 cu yd/swing, swings		4	8
0.75 min/swing, min		3.0	6.0
No. trucks		(4.3)5	(2.7)3

TABLE 4

TOTAL FLEET REQUIREMENTS TO PRODUCE 800± CUBIC YARDS PER HOUR, ESTIMATED

Item	Loading Units	R-35 Trucks	Loading Units	R-50 Trucks	Loading Units	R-100 Trucks	Production (cu yd/hr)
3½-cu yd shovels	4						
Trucks		16					776
5-cu yd shovels	3		3				
Trucks		15		12			795
13-cu yd shovels			1		1		
Trucks				9		5	796
13½-cu yd loaders			2		2		
Trucks				10		6	908

TABLE 5

EQUIPMENT DATA AND ESTIMATED HOURLY OWNERSHIP AND OPERATING COSTS

Item	Trucks			Shovels			Loader	Dozer	
Model	R-35	R-50	R-100	71-B	88-B	280-B	600	834	D-8
Gross hp	380	600	1,000	260	325	1,314	700	430	308
Weight, tons	28.0	39.5	68.5	100.3	131.5	392.5	71.5	30.8	29.6
Factory cost, dollars	64,425	93,500	202,600	140,160	165,085	686,660	185,590	78,335	59,200
Freight at $60/ton	1,680	2,370	4,110	6,018	7,890	23,550	4,290	1,848	1,776
Investment	66,105	95,870	206,710	146,178	172,975	710,210	189,880	80,183	60,976
Useful life, hours	15,000	15,000	15,000	20,000	20,000	20,000	10,000	10,000	10,000
(1) Useful life, years	6	6	6	8	8	8	4	4	4
(2) Depreciation	4.41	6.39	13.78	7.31	8.65	35.51	18.99	8.02	6.10
(3) Interest, taxes, and insurance	2.31	3.35	7.23	4.93	5.83	23.95	7.12	3.01	2.29
Hourly ownership	6.72	9.74	21.01	12.24	14.48	59.46	26.11	11.03	8.39
Tires	2.61	4.14	6.02	–	–	–	6.87	3.36	–
(4) Repair labor	2.29	2.80	3.65	6.37	7.53	15.31	6.99	4.51	5.21
(7) Repair parts	1.86	2.27	2.96	4.98	5.88	11.69	6.94	4.20	5.20
(6) Fuel	1.60	2.52	4.20	1.20	1.50	3.68(5)	3.23	1.99	1.42
Lubrication	0.56	0.88	1.47	0.48	0.60	0.42	0.97	0.60	0.50
Hourly operating cost	8.92	12.61	18.30	13.03	15.51	31.30	25.00	14.66	12.33
Total hourly cost	15.64	22.35	39.31	25.27	29.99	90.76	51.11	25.69	20.72

Notes: (1) At 2,500 hours/year
(2) Straight-line depreciation
(3) Interest at 8 percent
Taxes at 3 percent
Insurance at 3 percent
Storage at 1 percent
Total 15 percent of average yearly investment/2,500 hours/year
(4) At 8.22/hour
(5) Electrical energy at 1.5 cents/kwh and duty factor of 25 percent
(6) Diesel fuel at 14 cents/U. S. gal
(7) BLS 1947-1949 parts index = 2.11

TABLE 6

HOURLY LABOR RATES (1968), ESTIMATED

Item	Percent	Item	Percent
Insurance	8.43	Single 8-hr shift	
Compensation	6.88	Foreman	8.23
Liability	1.55	Shovel operator	7.81
		Oiler	7.33
Payroll tax	8.80	Truck driver	7.13
F. I. C. A.	4.40	Tractor operator	7.69
S. U. I.	3.70	Loader operator	7.81
F. U. T. A.	0.70	Heavy duty mechanic	8.22[a]

[a] Average rate for 6-day work week.

TABLE 7

DETAIL OF ESTIMATED DIRECT COST

Labor Costs						Equipment Costs						
								Operation		Depreciation		Total
No.	Type	Qty.	Unit	Rate	Amount	No.	Type	Rate	Amount	Rate	Amount	
							3½-Cu Yd Shovels and 35-Ton Trucks					
2	Foremen			8.23	16.46	2	Pickups	1.00	2.00	0.50	1.00	
4	Shovel operators			7.81	31.24	4	3½-cu yd shovels	13.03	52.12	12.24	48.96	
4	Oilers			7.33	29.32							
16	Truck drivers			7.13	114.08	16	35-ton trucks	8.92	142.72	6.72	107.52	
2	Dozer operators			7.69	15.38	2	Dozers	14.66	29.32	11.03	22.06	
28	Employees					28	Small tools	0.10	2.80			
	Total				206.48				228.96		179.54	614.98
		776	Cu yd/hr									(0.792)
							5-Cu Yd Shovels and 35-Ton Trucks					
2	Foremen			8.23	16.46	2	Pickups	1.00	2.00	0.50	1.00	
3	Shovel operators			7.81	23.43	3	5-cu yd shovels	15.51	46.53	14.48	43.44	
3	Oilers			7.33	21.99							
15	Truck drivers			7.13	106.95	15	35-ton trucks	8.92	133.80	6.72	100.80	
2	Dozer operators			7.69	15.38	2	Dozers	14.66	29.32	11.03	22.06	
25	Employees					25	Small tools	0.10	2.50			
	Total				184.21				214.15		167.30	565.66
		795	Cu yd/hr									(0.712)
							5-Cu Yd Shovels and 50-Ton Trucks					
2	Foremen			8.23	16.46	2	Pickups	1.00	2.00	0.50	1.00	
3	Shovel operators			7.81	23.43	3	5-cu yd shovels	15.51	46.53	14.48	43.44	
3	Oilers			7.33	21.99							
12	Truck drivers			7.13	85.56	12	50-ton trucks	12.61	151.32	9.74	116.88	
2	Dozer operators			7.69	15.38	2	Dozers	14.66	29.32	11.03	22.06	
22	Employees					22	Small tools	0.10	2.20			
	Total				162.82				231.37		183.38	577.57
		795	Cu yd/hr									(0.727)
							5-Cu Yd Shovels and 100-Ton Trucks					
2	Foremen			8.23	16.46	2	Pickups	1.00	2.00	0.50	1.00	
3	Shovel operators			7.81	23.43	3	5-cu yd shovels	15.51	46.53	14.48	43.44	
3	Oilers			7.33	21.99							
9	Truck drivers			7.13	64.17	9	100-ton trucks	18.30	164.70	21.01	189.09	
2	Dozer operators			7.69	15.38	2	Dozers	14.66	29.32	11.03	22.06	
19	Employees					19	Small tools	0.10	1.90			
	Total				141.43				244.45		255.59	641.47
		795	Cu yd/hr									(0.807)
							13-Cu Yd Shovel and 50-Ton Trucks					
1	Foreman			8.23	8.23	1	Pickup	1.00	1.00	0.50	0.50	
1	Shovel operator			7.81	7.81	1	13-cu yd shovel	31.30	31.30	59.46	59.46	
1	Oiler			7.33	7.33							
9	Truck drivers			7.13	64.17	9	50-ton trucks	12.61	113.49	9.74	87.66	
1	Dozer operator			7.69	7.69	1	Dozer	14.66	14.66	11.03	11.03	
13	Employees					13	Small tools	0.10	1.30			
	Total				95.23				161.75		158.65	415.63
		796	Cu yd/hr									(0.522)
							13-Cu Yd Shovel and 100-Ton Trucks					
1	Foreman			8.23	8.23	1	Pickup	1.00	1.00	0.50	0.50	
1	Shovel operator			7.81	7.81	1	13-cu yd shovel	31.30	31.30	59.46	59.46	
1	Oiler			7.33	7.33							
5	Truck drivers			7.13	35.65	5	100-ton trucks	18.30	91.50	21.01	105.05	
1	Dozer operator			7.69	7.69	1	Dozer	14.66	14.66	11.03	11.03	
9	Employees					9	Small tools	0.10	0.90			
	Total				66.71				139.36		176.04	382.11
		796	Cu yd/hr									(0.480)
							13½-Cu Yd Loaders and 50-Ton Trucks					
1	Foreman			8.23	8.23	1	Pickup	1.00	1.00	0.50	0.50	
2	Loader operators			7.81	15.62	2	13½-cu yd loaders	25.00	50.00	26.11	52.22	
10	Truck drivers			7.13	71.30	10	50-ton trucks	12.61	126.10	9.74	97.40	
2	Dozer operators			7.69	15.38	2	Dozers	12.33	24.66	8.39	16.78	
15	Employees					15	Small tools	0.10	1.50			
	Total				110.53				203.26		166.90	480.69
		908	Cu yd/hr									(0.529)
							13½-Cu Yd Loaders and 100-Ton Trucks					
1	Foreman			8.23	8.23	1	Pickup	1.00	1.00	0.50	0.50	
2	Loader operators			7.81	15.62	2	13½-cu yd loaders	25.00	50.00	26.11	52.22	
6	Truck drivers			7.13	42.78	6	100-ton trucks	18.30	109.80	21.01	126.06	
2	Dozer operators			7.69	15.38	2	Dozers	12.33	24.66	8.39	16.78	
11	Employees					11	Small tools	0.10	1.10			
	Total				82.01				186.56		195.56	464.13
		908	Cu yd/hr									(0.511)

ESTIMATED COST DETAILS OF MOBILIZATION

Description	Each	Weight (tons)		Labor				Eqpt. Oper.		Depreciation		Sub-total	Total With 35 Percent Demob.
		Unit	Total	Man-Hours/ Unit	Total Man-Hours	Rate	Amount	Rate	Amount	Rate	Amount		
3½-cu yd shovel	4	100.3	401	2.0	802	7.50	6,015	1.15	922	0.67	537		
R-35 truck	16	28.0	448	1.5	672	7.50	5,040	1.15	773	0.67	450		
Dozer	2	30.8	62	2.5	155	7.50	1,163	1.15	178	0.67	104		
Total			911				12,218		1,873		1,091	15,182	20,496
5-cu yd shovel	3	131.5	395	2.0	790	7.50	5,925	1.15	908	0.67	529		
R-35 truck	15	28.0	420	1.5	630	7.50	4,725	1.15	724	0.67	422		
Dozer	2	30.8	62	2.5	155	7.50	1,163	1.15	178	0.67	104		
Total			877				11,813		1,810		1,055	14,678	19,815
5-cu yd shovel	3	131.5	395	2.0	790	7.50	5,925	1.15	908	0.67	529		
R-50 truck	12	39.5	474	1.5	711	7.50	5,333	1.15	818	0.67	476		
Dozer	2	30.8	62	2.5	155	7.50	1,163	1.15	178	0.67	104		
Total			931				12,421		1,904		1,109	15,434	20,836
5-cu yd shovel	3	131.5	395	2.0	790	7.50	5,925	1.15	908	0.67	529		
R-100 truck	9	68.5	617	1.5	926	7.50	6,945	1.15	1,065	0.67	620		
Dozer	2	30.8	62	2.5	155	7.50	1,163	1.15	178	0.67	104		
Total			1,074				14,033		2,151		1,253	17,437	23,540
13-cu yd shovel	1	292.5	393	2.0	786	7.50	5,895	1.15	904	0.67	527		
R-50 truck	9	39.5	356	1.5	534	7.50	4,005	1.15	614	0.67	358		
Dozer	1	30.8	31	2.5	78	7.50	585	1.15	90	0.67	52		
Total			780				10,485		1,608		937	13,030	17,591
13-cu yd shovel	1	392.5	393	2.0	786	7.50	5,895	1.15	904	0.67	527		
R-100 truck	5	68.5	343	1.5	515	7.50	3,863	1.15	592	0.67	345		
Dozer	1	30.8	31	2.5	78	7.50	585	1.15	90	0.67	52		
Total			767				10,343		1,586		924	12,853	17,352
13½-cu yd loader	2	71.5	143	2.5	388	7.50	2,685	1.15	412	0.67	240		
R-50 truck	10	39.5	395	1.5	593	7.50	4,448	1.15	682	0.67	397		
Dozer	2	29.6	59	2.5	148	7.50	1,110	1.15	170	0.67	99		
Total			597				8,243		1,264		736	10,243	13,828
13½-cu yd loader	2	71.5	143	2.5	358	7.50	2,685	1.15	412	0.67	240		
R-100 truck	6	68.5	411	1.5	617	7.50	4,628	1.15	710	0.67	413		
Dozer	2	29.6	59	2.5	148	7.50	1,110	1.15	170	0.67	99		
Total			613				8,423		1,292		752	10,467	14,130

TABLE 9

CAPITAL INVESTMENT AND MOBILIZATION, ESTIMATED

No.	Item	Amount, $	Total, $
	3½-Cu Yd Shovels and R-35 Trucks		
2	Pickups	2,500	5,000
4	3½-cu yd shovels	146,178	584,712
16	R-35 trucks	66,105	1,057,680
2	Dozers	80,183	160,366
	Mobilization		20,496
	Total		1,828,254
	5-Cu Yd Shovels and R-35 Trucks		
2	Pickups	2,500	5,000
3	5-cu yd shovels	172,975	518,925
15	R-35 trucks	66,105	991,575
2	Dozers	80,183	160,366
	Mobilization		19,815
	Total		1,695,681
	5-Cu Yd Shovels and R-50 Trucks		
2	Pickups	2,500	5,000
3	5-cu yd shovels	172,975	518,925
12	R-50 trucks	95,870	1,150,440
2	Dozers	80,183	160,366
	Mobilization		20,836
	Total		1,855,567
	5-Cu Yd Shovels and R-100 Trucks		
2	Pickups	2,500	5,000
3	5-cu yd shovels	172,975	518,925
9	R-100 trucks	206,710	1,860,390
2	Dozers	80,183	160,366
	Mobilization		23,540
	Total		2,568,221

No.	Item	Amount, $	Total, $
	13-Cu Yd Shovel and R-50 Trucks		
1	Pickup	2,500	2,500
1	13-cu yd shovel	710,210	710,210
9	R-50 trucks	95,870	862,830
1	Dozer	80,183	80,183
	Mobilization		17,591
	Total		1,673,314
	13-Cu Yd Shovel and R-100 Trucks		
1	Pickup	2,500	2,500
1	13-cu yd shovel	710,210	710,210
5	R-100 trucks	206,710	1,033,550
1	Dozer	80,183	80,183
	Mobilization		17,352
	Total		1,843,795
	13½-Cu Yd Loaders and R-50 Trucks		
1	Pickup	2,500	2,500
2	Loaders	189,880	379,760
10	R-50 trucks	95,870	958,700
2	Dozers	60,976	121,952
	Mobilization		13,828
	Total		1,476,740
	13½-Cu Yd Loaders and R-100 Trucks		
1	Pickup	2,500	2,500
2	Loaders	189,880	379,760
6	R-100 trucks	206,710	1,240,260
2	Dozers	60,976	121,952
	Mobilization		14,130
	Total		1,758,602

Note: Foremen—maximum of 2 loading operations supervised by 1 foreman.

Dozers—maximum of 2 shovel loading operations maintained by 1 rubber-tired clean-up dozer, and 1 trapping dozer provided for each front-end loader operation.

TABLE 10

ESTIMATED COST SUMMARY

Fleet Combination	Investment and Mobilization, $	Unit Cost of Equipment Per Cu Yd, $			
		Labor	Operation	Depreciation	Total
1. 3½-cu yd shovels and 35-ton trucks	1,828,254	0.266	0.295	0.231	0.792
2. 5-cu yd shovels and 35-ton trucks	1,695,681	0.232	0.270	0.210	0.712
3. 5-cu yd shovels and 50-ton trucks	1,855,567	0.205	0.291	0.231	0.727
4. 5-cu yd shovels and 100-ton trucks	2,568,221	0.178	0.307	0.322	0.807
5. 13-cu yd shovel and 50-ton trucks	1,673,314	0.120	0.203	0.199	0.522
6. 13-cu yd shovel and 100-ton trucks	1,843,795	0.084	0.175	0.221	0.480
7. 13½-cu yd loaders and 50-ton trucks	1,476,740	0.121	0.224	0.184	0.529
8. 13½-cu yd loaders and 100-ton trucks	1,758,602	0.090	0.206	0.215	0.511

Although some contractors have tried super trucks in highway construction, their use with an appropriate size shovel has not been considered practical. The size of highway projects in terms of quantity of material to be moved and the relatively short time allowed for the job simply could not support the expense of equipping the project with a loading shovel similar to that used in mining, whose size was commensurate with large truck capacity. A further complication was the necessity of electrical energy being available to power the shovel in all locations, some of which were quite remote from regular service. Therefore, except for a few cases, the use of large trucks on highway work has been in the size class of 50 tons or less matched with shovels of 5-cu yd bucket capacity or less.

To illustrate the economy of various combinations of trucks and loading equipment, an estimate (Tables 1 through 10) has been developed. It considers 3 shovel sizes, 1 front end loader size, 3 truck sizes, and the necessary support equipment normally employed with each fleet combination. Each combination has been applied to the same job condition: to excavate and load well shot rock at the rate of approximately 800 cu yd/hr. For purposes of this comparison, truck cycle time away from the shovel is considered to be the same. The functions of hauling, dumping, returning, and spotting are assumed to be 10 min per truck, regardless of truck size. This is a reasonable assumption because the performance of off-highway rear dumps in terms of gross and net weight per effective horsepower is about the same for each vehicle.

TRUCK-SHOVEL MISMATCH

The use of large trucks in conjunction with shovels of smaller than optimum size results in a mismatch of equipment. Data given in Table 10 illustrate this point. When the largest shovel used on highway projects is matched with trucks varying in size from 35- to 100-ton capacity (lines 2, 3, and 4 of Table 10), the mismatch in using the larger trucks increases the estimated costs by as much as 15 percent. The apparent optimum size of vehicle for the 5-cu yd shovel under the conditions of the comparison estimate is the 35-ton truck. Therefore, the use of the larger trucks on highway jobs, unless matched with an appropriate size of shovel, do not necessarily, in themselves, contribute to lower costs.

If large shovels in the 13-yd class were used in highway work, data given in lines 5 and 6 of Table 10 again illustrate the importance of properly matching truck size with shovel size. In this case, however, the mismatch of undersized trucks increases the estimated cost by about 9 percent. The apparent optimum size of vehicle for the 13-cu yd shovel under the conditions of the comparison estimate is the 100-ton truck.

LOADING EQUIPMENT

The controlling item in considering the economies that large shovel and truck combinations can bring to highway construction is the practicality of equipping the job with high-capacity loading equipment. As mentioned previously, numerous factors have made it impractical to utilize the large 13-yd shovels in highway construction, thus the economics inherent with the use of larger trucks have not been realized in highway construction work.

Referring to Table 10, it is obvious that in general the larger the shovel is, the lower the cost. This is very nearly true even when considering a very serious mismatch condition with the 5-yd shovel and 100-ton truck. The use of the 13-yd shovel with its most appropriate truck size, the 100-ton vehicle, produces significant reductions in direct cost; 33 percent lower than the best cost combination for the 5-yd shovel and 40 percent lower than the combination shown for the $3\frac{1}{2}$-cu yd shovel.

The advent of the large front-end loader has made it possible to bring to highway projects the same economies that would accompany the use of large $13\frac{1}{2}$-cu yd class shovels and 100-ton trucks. Data given in Table 10, line 8, indicate one example of lower costs for the loader-truck combination than with the shovel-truck fleet.

The $13\frac{1}{2}$-cu yd front-end loader and 100-ton truck move material at 28 percent lower cost than the best combination for the 5-yd shovel and at 36 percent lower cost than the $3\frac{1}{2}$-yd shovel combination. These figures are based only on direct costs. If direct costs are conservatively assumed to represent two-thirds of total job costs, then the loader and truck combination would move material at 18 percent less cost than the best combination for the 5-yd shovel.

Admittedly, the estimates used here cannot represent average conditions; however, they are an indication that substantial economies may be realized through the use of large front-end loaders and large trucks on highway projects.

RESTRICTIONS

Load, width, and length restrictions on existing roads are one of the principal deterrents to the ready application of large loaders and trucks to highway construction. In some cases, the contractor must expend considerable money and time in dismantling these machines so they may be shipped over highways and, in some cases, by rail. These costs tend to mitigate the advantage of larger equipment, but are expenses reflected in the contractor's bid for the work.

If the respective agencies of county and state road and highway departments were to give full consideration to the one-time loading nature of moving machinery of this type, perhaps all or at least most of the excessive costs connected with dismantling and hauling could be eliminated. This consideration should also apply to the one-time loading on temporary shoring required for some smaller structures.

Specifications written to include realistic mobilization advances would attract bidders who have the technical know-how to utilize large machinery but are reluctant to undertake the high cost of its mobilization and financing on their own.

Because of the high gross weights involved, some road agencies have prohibited haul-road crossings by present size construction machinery. This has occurred in some instances where the contractor has agreed to warrant the complete maintenance and replacement of the road section concerned. With such warranty, a realistic appraisal of the benefits should allow grade crossings, regardless of the vehicle size. Ideally, this matter should be solved prior to the issuance of bid documents so that it can be spelled out in the specifications under the appropriate section.

The noise hazard of construction machinery is receiving increased attention not only from the point of view of potential hearing impairment due to noise among the construction personnel, but also from noise as a public nuisance, particularly during night hours. Both areas of interest are important, the latter one, however, may become the more frequent and more difficult problem to control. Higher unit investment costs in the somewhat specialized large machinery encourage contractors to work long hours or around-the-clock to earn depreciation or write-off at a faster rate.

The owner-agency has the responsibility to define standard rules for noise control for each condition described above. Contractors will then be able to work within the established guidelines without interference.

COMPACTORS

A discussion of recent developments in compaction equipment leads into a study of compaction itself, a subject so complex that no single development can be expected to produce the desired results under all of the great variety of conditions that can be encountered. The numerous disputes and misunderstandings that surround the problems of compaction suggest that designers of public projects do not really know what they want.

Some specifications not only spell out minimum density requirements but also define what equipment shall be used to achieve it. Thus, all bidders are placed in the same category: in effect, pricing compaction as an equipment rental item. The public, as a result, cannot benefit from true competitive bidding for compaction in which contractors exercise their full inventive resources to use and to further develop more efficient and more economical compaction equipment. The governing principle that clearly defines the desired results, leaving the means and the methods of achievement to the discretion of the contractor, should be the only requirement of a specification.

DRILLING AND BLASTING

The continuing effort to improve grade and alignment in highway design is reflected in ever-increasing excavation quantities for any given section of road. The resulting cuts are often large and, where they occur in rock material, should provide more opportunities to use open-pit mining type of drilling and blasting equipment and methods.

As illustrated previously, in considering mining type of shovel and truck equipment for roadwork, substantial savings of approximately the same magnitude can be realized in this phase of construction costs. Again, this is an economy that ultimately is passed on to the public.

Specifications generally require contractors to follow blasting procedures "subject to the approval of the engineer." The wholesale application of large blast hole drilling equipment and its companion mechanized hole loading machinery is obviously out of the question. Back-slope stability, benching, and other detailed excavations cannot be achieved by this type of equipment. However, a combination of the present small diameter equipment and large blast hole machines should be given full consideration by the reviewing engineer.

CONCLUSION

The contracting industry encourages the development and use of more efficient and productive construction machinery. Public agencies have the responsibility to recognize the economic advantages that these developments can bring to public works projects and, consistent with the desired end results, make accommodation for them.

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Discussion

JAMES DOUGLAS, Stanford University—Mr. Lee deserves our applause and gratitude for focusing our attention on the economic advantages provided by the new equipment shaped by modern technology. It is my purpose to augment the information he has already provided by commenting on new analytical processes available to the construction manager to enhance his ability to solve equipment problems.

At Stanford University we have spent a good many years researching new techniques related to equipment operations and equipment economics. Technical reports published by the Stanford Construction Institute in this area are listed at the end of this discussion. Among them will be found the solution of production problems by queueing theory and computer simulation, and economic analysis of equipment life by the computer. These methods can be used to supply quicker and better answers than the conventional method of average cycle times used by Mr. Lee. Nor is it necessary to guess that the economic life of a shovel is 8 years. It can be figured more accurately by the method described in Technical Report 61 (4).

Let me illustrate this point by describing a method of adjusting the conventional production estimate to the simulation estimate, the latter being a better estimate of the true production. Several years ago we studied the output of a shovel-truck system in real life and compared the results to our predictions by computer simulation (5). The results were amazingly close! It was decided that correlation was good enough that difference curves could supply the information required to correct for the discrepancies in the solution by conventional methods. Here is how they were derived.

In order to reconcile the conventional estimate with the simulation estimate, which is more nearly the correct one, it will be helpful first to examine a typical set of production curves where hourly production is plotted against the number of trucks. Figure 1 shows a curve plotted from data generated in 6 computer simulation runs. In this figure, symbols have the following meaning:

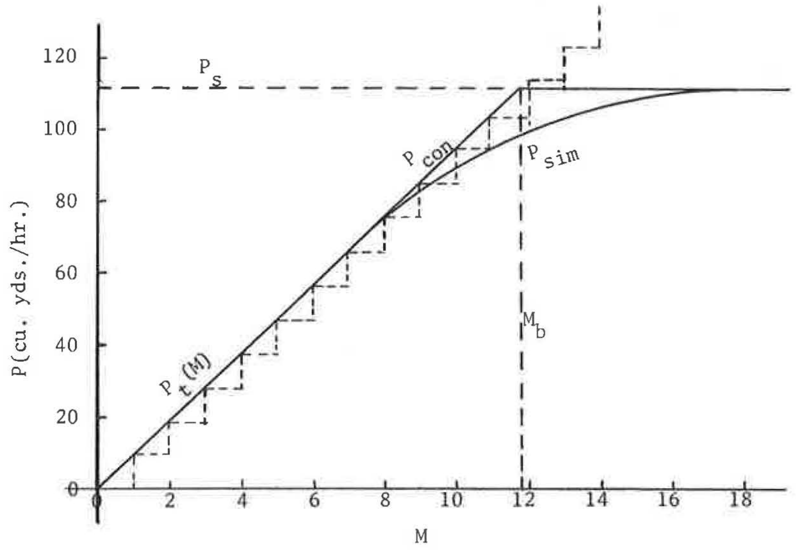

Figure 1.

P = system production in cu yd/hr,

P_{con} = system production computed by the conventional method,

P_{sim} = system production computed by simulation,

P_s = production of the shovel (= 111.4 cu yd/hr),
P_t = production of 1 truck (= 9.4 cu yd/hr),
$P_t(M)$ = production of M trucks in cu yd/hr,
M = number of trucks in the system, and
M_b = number of trucks to balance (= P_s/P_t = 11.8).

Results of these runs are given in Table 11; these were plotted in Figure 1 and the simulation curve smoothed. Smoothing was necessary because the simulation results are random and are accepted with 95 percent confidence as being within 5 percent of the true mean.

It will be observed that when the number of trucks is less than the number required to balance, the truck output appears to limit the system output. When the number of trucks is greater than the balance number, the shovel output is the apparent limit.

A great many systems were both simulated and estimated by the conventional method. Some 130 runs are tabulated in Technical Reports 29 (3) and 37 (5). The systems were normalized by dividing system production by shovel production (which is the limiting output) and plotting against the index, I. This index is obtained by dividing shovel production by truck production (and thus eliminating M as a factor). Figure 2 shows typical system production curves obtained by the conventional method of estimating and by simulation. In Figure 2, symbols are the same as in Figure 1 with the following additions:

P' = normalized production of the system,
d = difference between P_{con} and P_{sim}, and
I = index [= P_s/P_t (M)].

Several interesting facts are revealed by inspection of this figure. First, and most important, the production estimated by the conventional method is an upper bound to the estimate by the simulation model. Second, P_{con} increases from zero as the number of trucks increases (I = ∞ when M = 0). When the balance point (M_b) has been reached, then I = 1.0. Because cost minimization is

TABLE 11

CONVENTIONAL VERSUS SIMULATION ESTIMATES

M	P_{con}	P_{sim}	M	P_{con}	P_{sim}
10	94.4	90.0	13	111.4	101.5
11	103.9	93.7	14	111.4	100.7
12	111.4	103.3	15	111.4	107.5

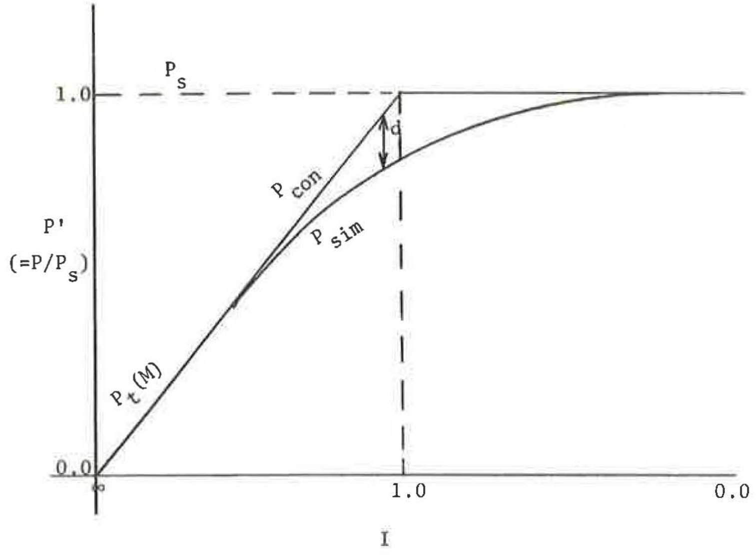

Figure 2.

usually achieved somewhere near the balance point, this will be the region of the curves of most interest. Upon reaching the balance point, there is a definite break in P_{con}, for now the shovel limits the production of the system. When I gets much beyond this point, adding one more truck to the system merely adds one more to the waiting line at the shovel. Third, and last, the curves meet at the 2 ends and have a maximum difference, d, at the balance point.

Whether minimum costs are obtained above or below the balance point appears to be a matter of relative costs (shovel versus truck) and what costs are included (how much overhead is involved?). Very often the estimator figures that one should have more trucks than necessary so the shovel will never have to wait (trucks are cheaper than shovels). Simulation runs have demonstrated the fallacy of this thinking because the cost of an additional truck is greater than its marginal production as the balance point is approached and passed. This statement is emphasized by the results of many simulation runs. Examination of these results reveals that, in the range of interest, the marginal unit cost of production will always increase with the addition of trucks. The final result can only be determined when all costs are related to the best estimate of production.

In studying the results of these 2 methods of estimating production, it is important to quantify the differences between them in order to move from one to the other. The manner of handling delays is the cause of major differences. It has been necessary and sufficient to classify delays in the simulation models as follows:

1. Weather—a matter of weather and climatology to be treated separately;
2. External—those delays caused by factors external to the equipment operation, such as repairs, breakdowns, moving equipment, and dressing the excavation area with the shovel; and
3. Balancing—those delays caused by the interaction of the equipment, such as trucks waiting in line at the shovel and shovel waiting for a truck.

Weather delays should be treated separately from the production estimate because they are highly variable and depend on the local climate at the time of the work. External delays are accounted for in the conventional estimate by use of an efficiency factor; in simulation they are handled by delay probabilities and average external delay times. The real secret to the difference between the conventional and simulation estimates lies in the balancing delays.

Balancing delays can be divided into two kinds: (a) those due to the inherent imbalance in the production capabilities of the 2 links of the system, and (b) those due to the interaction of the equipment. Both methods account for delays due to inherent imbalance. In the conventional method, system production is limited by the capability of the trucks below the balance point and by the shovel above the balance point. The simulation method also accounts for this imbalance in simulating the actual operation. Balancing delays due to cycle variability are not accounted for in the conventional estimate because average cycle times are used in the computation. In the simulation model, delays due to the interaction of the equipment are introduced and consequently decrease the production estimate below the conventional estimate. This explains the difference in the results of the methods, shown in d in Figure 2.

It will be noted that interaction is absent only where the lines converge at the ends. At the balance point, d is a maximum. If shovel and trucks operated independently, output of the 2 links in the system would be equal. However, the inherent variability in cycle times causes waiting lines, bunching on the haul road, and other interactions. Data plotted thus far are convincing that the difference curve drawn by normalizing production and plotting it as an ordinate against the index, I, is sufficiently accurate for estimating production in the shovel-truck system.

The D-factor can be used to convert the conventional estimate of production to the simulation estimate. Dimensionally, the factor is the difference in the 2 values expressed in terms of the system production. Let D = difference factor.

$$d = P_{con} - P_{sim} = D \times P$$

$$P_{sim} = P_{con} - (D \times P)$$

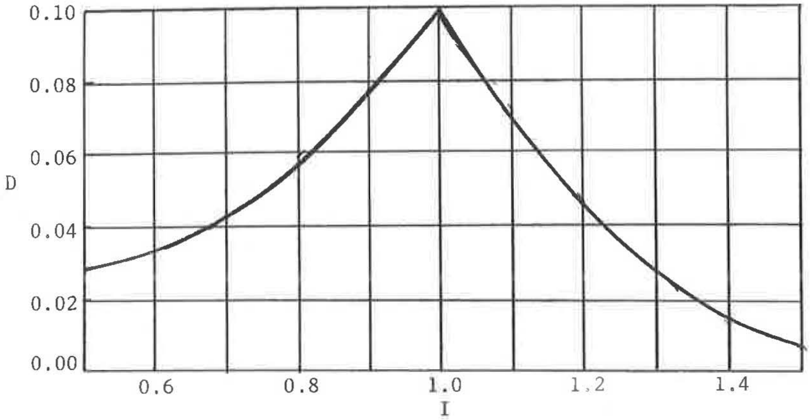

Figure 3.

Figure 3 shows the D-factor plotted against I $[= P_s/P_t(M)]$. The stability of this factor is dependent on the characteristics of the shovel-truck combination and may not hold for other material-handling systems. It appears safe to use with normal shovel-truck operations but must be used with caution when applied to other types of problems.

The results of the 130 computer runs previously mentioned were plotted with many different combinations of system variables. The resulting values fell within 5 percent limits, and the predominant pattern of all plots was similar to Figure 3. In no case was unusual behavior noted. The maximum difference occurs at the balance point where I = 1.0. The difference approaches zero at the outer ends of the curve, as expected. Because the most important region of the curve is in the vicinity of the balance point, more runs were devoted to this zone.

In inspecting the results of the computer runs of the simulation model, it is important to remember that they have a level of significance of 95 percent and a confidence interval of 5 percent of the estimate of the mean value. Some results are therefore apt to be somewhat higher or lower than the expected value. This is confirmation of the randomness of the result computed by the simulation model and, in fact, the real-life situation as well.

In order to demonstrate the application of this method and to show how the results will differ from the conventional method, consider the combination of a 13-cu yd shovel and 50-ton dump trucks as described in Mr. Lee's paper. If the shovel (7 bank cu yd) loads a truck (25 bank cu yd) in 4 passes, the average bucket load will be 6.25 bank cu yd $\left(= \frac{25}{4}\right)$. Therefore, the average production of the shovel will be

$$P_s = \frac{50}{0.44} \times 6.25 = 710 \text{ bank cu yd/hr}$$

rather than 796 as given in Table 1 of Mr. Lee's paper. However, $\frac{0.10}{0.44}$ or 22.7 percent of the total shovel cycle time will be spent in moving the shovel. This is a total of 11.35 min out of each 50-min hour. The shovel cannot load trucks while moving, so the trucks will be able to load only 38.65 min out of the 50-min hour. The average production of 1 truck will be

$$P_t(1) = \frac{38.65}{11.4} \times 25 = 84.76 \text{ bank cu yd/hr}$$

The number of trucks to balance shovel production will then be

$$M_b = \frac{P_s}{P_t(1)} = \frac{710}{85} = 8.35 \text{ trucks}$$

TABLE 12

COST OPTIMIZATION FOR 4 PASSES OF SHOVEL

M	P_s	$P_t(M)$	I	D	P	Total Cost, $	Unit Cost, $
5	710	424	1.67	0.000	424	287.54	0.678
6	710	509	1.39	0.015	501	316.18	0.632
7	710	593	1.20	0.048	565	344.82	0.610
8	710	678	1.05	0.087	619	373.46	0.603
9	710	763	0.93	0.081	652	402.10	0.617
10	710	848	0.84	0.065	664	430.74	0.649
11	710	932	0.76	0.052	673	459.38	0.682

TABLE 13

COST OPTIMIZATION FOR 3 PASSES OF SHOVEL

M	P_s	$P_t(M)$	I	D	P	Total Cost, $	Unit Cost, $
5	796	368	2.16	0.000	368	287.54	0.780
6	796	442	1.80	0.000	442	316.18	0.717
7	796	516	1.54	0.004	514	344.82	0.671
8	796	589	1.35	0.021	577	373.46	0.648
9	796	663	1.20	0.048	631	402.10	0.637
10	796	737	1.08	0.078	680	430.74	0.633
11	796	810	0.98	0.098	718	459.38	0.639
12	796	884	0.90	0.077	735	488.02	0.664
13	796	957	0.83	0.065	744	516.66	0.695
14	796	1031	0.77	0.053	754	545.30	0.723
15	796	1104	0.72	0.045	760	573.94	0.755

This is reasonably close to Mr. Lee's figure of 8.1. It is now possible to recompute the system production using D-factors and to optimize the unit cost with Mr. Lee's cost assumptions. Table 12 gives the results of these computations.

It is evident from inspection of this table that the optimum number of trucks is 8, system production is approximately 619 bank cu yd/hr, and unit cost will be about $0.60 per bank cu yd. As a matter of interest it was decided to investigate cost and production if the shovel made 3 passes and loaded 21 bank cu yd in a truck instead of 4 passes for 25 yd. Table 13 gives the results of these computations.

In this latter case, shovel production is maximized by carrying a full bucket (7 bank cu yd) but not completely filling with 3 passes (21 bank cu yd). The optimum number of trucks is increased to 10, production increases to 680 bank cu yd/hr (up from 619), while unit cost is about $0.63 per bank cu yd (up $0.03). This is a good demonstration of Caterpillar's Load Growth Theory where the system production has been enhanced by loading less into the carriers. Comparing the results for 10 trucks given in Tables 2 and 3, it is readily observable that unit cost is down ($0.633 versus $0.649) and production is up (680 versus 664) if the shovel makes 3 passes instead of 4. Figure 4 shows the unit costs plotted for this situation. It is interesting to note that, if you started out with 10 trucks and 3 passes, and 2 trucks broke down, it would improve production to go to 4 passes with the shovel.

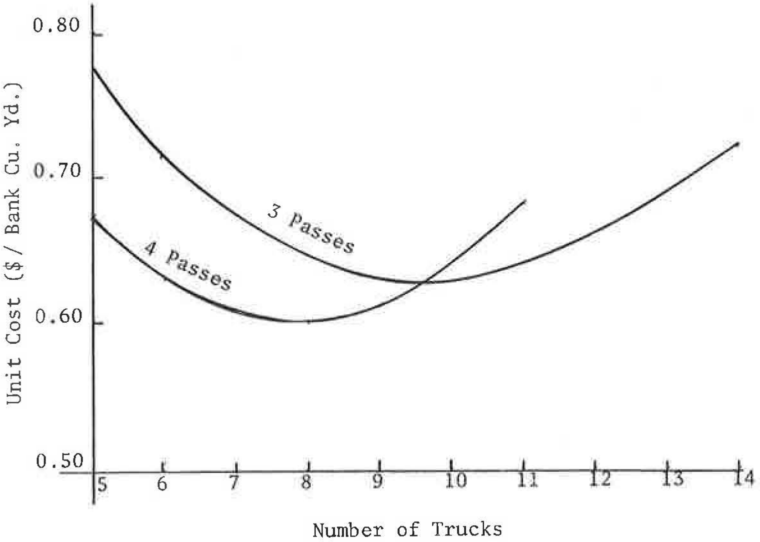

Figure 4.

The manual method just demonstrated is tedious and time consuming, but little more so than the conventional methods of solution of these same problems. The best answer lies in solution by computer so that the construction manager has the time to consider many alternatives instead of a few. Technical Report 111 (6), recently published by the Stanford Construction Institute, is a compilation of several models, both queuing and simulation, for the solution of problems of varying degrees of complexity. Computer programs in this report are written in FORTRAN IVH for running on the IBM 360/67 computer. Some use previous Stanford Simulation Programs and some utilize IBM's General Purpose Systems Simulator (GPSS). The chief advantages of computer analysis are, of course, speed and low cost. It seldom takes more than about 3 min of computation time to run one of these programs (at $600 per hour for computation, that is only $30). In that time, the computer can easily perform computations requiring a year to perform manually.

These solutions by Mr. Lee have amply demonstrated the disadvantage of improper matching of loader to carrier. Many simulation studies show that the carrier should generally be 6 to 8 times the capacity of the shovel. Carriers should be selected so that they are loaded by an integral number of full buckets. Manufacturers are responsible for this balance in design and should make sure that matching components are available. Today's problem: What will you load with a 24-yd bucket? Computations on systems of unmatched equipment such as the 13-yd shovel and the R-50 trucks reveal the fallacy in this kind of selection. The K-W Dart 600 loader is nicely matched to the K-W Dart 125-ton truck. Here a 15-yd bucket is matched to a 75-yd hauler, 5 full buckets to load. We need more of this kind of thinking!

Probably the greatest disadvantage of conventional estimating by average cycle times is that it discounts the interaction of equipment and the large number of variables present in the real-life problem. The assumption of 0.1 min for moving the shovel plus the 50-min efficiency hour has the effect of withdrawing a block of 36 percent of the total time. These losses cause waiting lines to form at the shovel, bunching on the haul road, and other internal delays in the system. They can all be considered for their separate effects by computer simulation. In cases where several "servers" (i.e., 2 or 3 loaders or shovels) are involved, the conventional method is incapable of providing accurate answers. The interaction between the various machines, especially where constraints are imposed about passing and double loading, renders the average time methods unsatisfactory.

And so, we are grateful to Mr. Lee for introducing this subject and affording an opportunity to examine some new ways to solve these problems. Generally it can be said that using the conventional method of average cycle times will tend to overestimate production and, hence, underestimate cost.

In conclusion, I would like to emphasize that the methods I have mentioned are here and available now. Computers are commonplace, available everywhere. Many contractors and engineers own them. I know it is hard to accept new ideas until they have proven their worthiness. Somehow people must be persuaded to use these new tools for construction management. I hope I have stimulated you to move in this direction.

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Computer Simulation for Quality Assurance in Asphaltic Concrete Production

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The New York State Department of Transportation's Engineering Research and Development Bureau has developed a computer simulation of asphaltic concrete production for evaluation and improvement of quality assurance. As far as can be determined, this is the first simulation directed toward formulating a quality assurance program for blending of bulk materials. The model consists of a set of random data generators simulating hot-bin and final-mix gradations. Drift from the plant mean caused by production fluctuations can be introduced into the process, with the drift's starting point, duration, and magnitude determined randomly. Operating characteristics are determined for any quality assurance method by simulating numerous and different plants—representative of normal production—and by adjusting quality assurance parameters for various testing strategies. With the increasing complexity of testing schemes, evaluation by simulation is the only feasible method of analysis. This technique is used to develop operating characteristic data for a quality assurance program as applied to standard top-course mix. The basic model is in generalized form, with all mix characteristics entered by the user. It is applicable to any mix for which proper distributions can be formulated. The program is written in FORTRAN IV and, with only minor file card adjustments, may be run on either the Burroughs B5500 or the IBM 360 computers. This discussion briefly covers the background of the computer simulation and evaluation of one proposed quality assurance program. A full report on building the simulation model, along with program listings, is also available for the engineer who is familiar with statistical methods.

•IN RECENT YEARS, state highway departments have become increasingly interested in developing quality assurance programs for construction materials. The blending of aggregates for asphaltic concrete has been of special concern, as it is the most critical aspect of production. The Engineering Research and Development Bureau, in cooperation with the U. S. Bureau of Public Roads, has been studying asphaltic concrete uniformity and quality assurance since 1960. An earlier paper (1) presented the results of the first study. The limitations of that study prompted the present research.

In the past, quality assurance methods for asphaltic concrete evolved through trial-and-error procedures using actual data. Although this approach is often inefficient and suboptimal, it was the only method available because of the nature of the production process. Variation in plant operation complicates analysis of the process to such an extent as to preclude a strict analytical treatment.

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Fluctuation in the rate of production is a major influence on gradation uniformity. Production surges occur frequently during plant start-up in the morning and in the afternoon when many trucks are waiting to be loaded with mix. As plant production approaches capacity, more and more aggregate must be separated by the vibrating screens, and thus screen efficiency drops and material "carry-over" increases. The latter occurs either when smaller material is trapped and carried along by larger stone, or when the screens become plugged. In both cases, the aggregate is not allowed to drop into the proper hot bin. Torn and worn screens will influence production uniformity, by permitting oversized particles to drop into the wrong hot bin. Finally, one plant can be producing several different mixes for various customers in random order. This keeps production from ever reaching a steady state for any one mix.

Specifically, 3 major aspects of the process—production drift, interdependence of gradation between sieves, and sampling limitations—restrict the analysis.

1. Drifting of production from the plant mean, caused primarily by process fluctuations, was found to occur in over 50 percent of the plants sampled.
2. Because the sample gradation must total 100 percent, variations in any one aggregate size must induce corresponding opposite variations in the other sizes. Thus, if a sample fails specifications on one size, the probability increases that it will also fail on another size. Consequently, between-sieve independence cannot be assumed.
3. It would be too expensive and time-consuming to take enough samples for adequate evaluation of the operating characteristics of any quality assurance program that is developed.

Only 2 other possible routes remained for developing a realistic quality assurance method—the test plant or the simulation approach. Use of a test plant was ruled out because it would be impossible to duplicate all possible process characteristics with only 1 plant. Simulation, then, was the method chosen for this study.

FORMULATING AND OPERATING THE MODEL

Choice of the Basic Model

Various available mathematical modeling strategies and their uses were reviewed. Only the Monte Carlo method was deemed practical for this process. Many authors (9) use the term "simulation" to denote the application of proposed specifications to sample data; this should not be confused with the simulation approach developed here.

The adopted approach—simulation of plant output utilizing Monte Carlo techniques—entails use of cumulative frequency distributions for generation of aggregate gradations in each hot bin. The individual batches are then simulated by randomly selecting gradation values from the cumulative distributions, adjusting them for inherent process variation, and combining them into the final mix. This approach has many advantages; it is a static or nontemporal method of simulation that eliminates the need either for trying to determine starting conditions for all variables or for sensing when the system has reached "steady state." To calibrate this model, samples need be obtained only at the hot-bin area, where sampling facilities are normally provided. The effect of local variables can be reduced by using distributions developed from samples taken at many different plants throughout the state.

The simulation method permitted us to provide for the 3 major factors that precluded an analytical approach to the problem. Drifting of the plant production mean could be simulated by systematically shifting the mean gradation about which the production output varies. Interdependence of sieves could be compensated for by correlation equations relating the bin's primary size aggregate to other sieves in the bin. Finally, all the "samples" needed to evaluate the operating characteristics of any quality assurance testing strategy could be generated efficiently at a minimal cost.

Data Collection for Model Calibration

To identify and quantify plant variables affecting product uniformity, and to develop distributions of the gradations that typify plant production, it was essential that sufficient samples be taken from a wide cross section of asphaltic concrete plants. Between 1961 and 1964, the Engineering Research and Development Bureau sampled production of 29 plants producing top-course mix to study variation of gradation. The data were used to calculate the testing limits contained in the state's quality assurance manual (3). However, on the average, only 17 samples were obtained at each plant, and, although these data were adequate for project objectives, they could not give the true picture of production trending that is required for system simulation.

In 1967, as part of this simulation research, a pilot study was conducted to determine the practicality of the extensive sampling needed to gather data for a simulation. After successful completion of the pilot study, the 1961-1964 and 1967 data were used as the basis of a feasibility study of computer simulation of an asphaltic concrete plant, performed under contract by Rensselaer Polytechnic Institute. When the simulation approach proved feasible, an ambitious sampling program was instituted to secure data suitable for calibration and validation of a simulation model.

During the summer of 1968, Bureau personnel visited 46 of the approximately 120 asphaltic concrete plants throughout New York State, and 39 were sampled. Samples were taken as the aggregate dropped from the hot bins into the weigh hopper and also at the individual cold feeds. Sample processing was a major undertaking in itself. Drying (for cold-feed samples), splitting, and sieving of the 15,000 samples took 18 months.

Twenty-one plants sampled were producing top-course mix. Their hot-bin samples were used to determine both the magnitude and the source of variation in asphaltic concrete production needed for this research. The other 18 plants were producing different mixes, and their data are earmarked for subsequent uniformity and simulation projects. Likewise, the cold-feed samples will be used to investigate the possibility of establishing a quality assurance procedure for the cold feed, using simulation techniques. Observations recorded at the plants not sampled reinforced the other data when plant parameters and system variables had to be postulated.

It was decided that a day's production could be adequately represented by 30 sets of hot-bin samples taken at 10- to 15-min intervals. These data were used not only to develop the variable distributions for the simulation model, but also the fixed time interval between samples facilitated recognition of any tendency of the process to drift from its mean. This is the first time that extensive time series data, required for a simulation, have ever been obtained at numerous asphaltic concrete plants.

Two different sampling procedures were employed. In 17 of the 21 plants producing top-course mix, a "regular sampling strategy" was used. Thirty sets of samples were taken from each of the 3 hot bins, for a total of 90 samples per plant. These samples were dry-sieved, and means and standard deviations were calculated for the percent-retained on each sieve in each bin. In 4 different plants, an "intensive sampling strategy" was applied. Duplicate samples were taken from each hot bin until the desired 30-sample sets (180 samples) were obtained. These were used to determine the adjustment of the percents-retained needed to compensate for sampling and testing errors within the data.

Formulation of the Model

Numerous plant operating procedures and general characteristics were evaluated, and the following ones, which influenced mix production or sampling results, were quantified:

1. Correlation of individual sieve data within a bin,
2. Correlation between sample variation and percentage of predominant size aggregate in each bin,
3. Variation between the job mix formula (JMF) and plant gradation means,
4. Distribution of batch variation about the plant gradation mean,
5. Process drift from the gradation mean, and
6. Errors in sampling and testing affecting final gradation.

Parameters 1 and 2 were determined by regression analysis, 3 and 4 from analysis of the distributional form of the sample data, 5 from plots of the primary size data and from run tests, and 6 from analysis of variance.

Although most of the process characteristics are self-explanatory, drift does need some explanation. This behavior was recognized in our first study of uniformity. It is attributed mainly to changes in plant operating speed, causing carry-over in the bins.

A program was written to plot and apply run tests (4) to each of the sample gradations taken in the individual plants. These tests indicated some drifting from the mean present in 12 of the 21 plants sampled. An analysis of the plots showed that gradation drift from the plant mean tended to be parabolic and was most evident on the predominant size materials. Drift was found to occur once or twice a day either (a) when a queue of trucks developed and plant production increased, causing the predominant size to decrease (negative drift), or (b) when production slowed down drastically and the predominant size increased (positive drift).

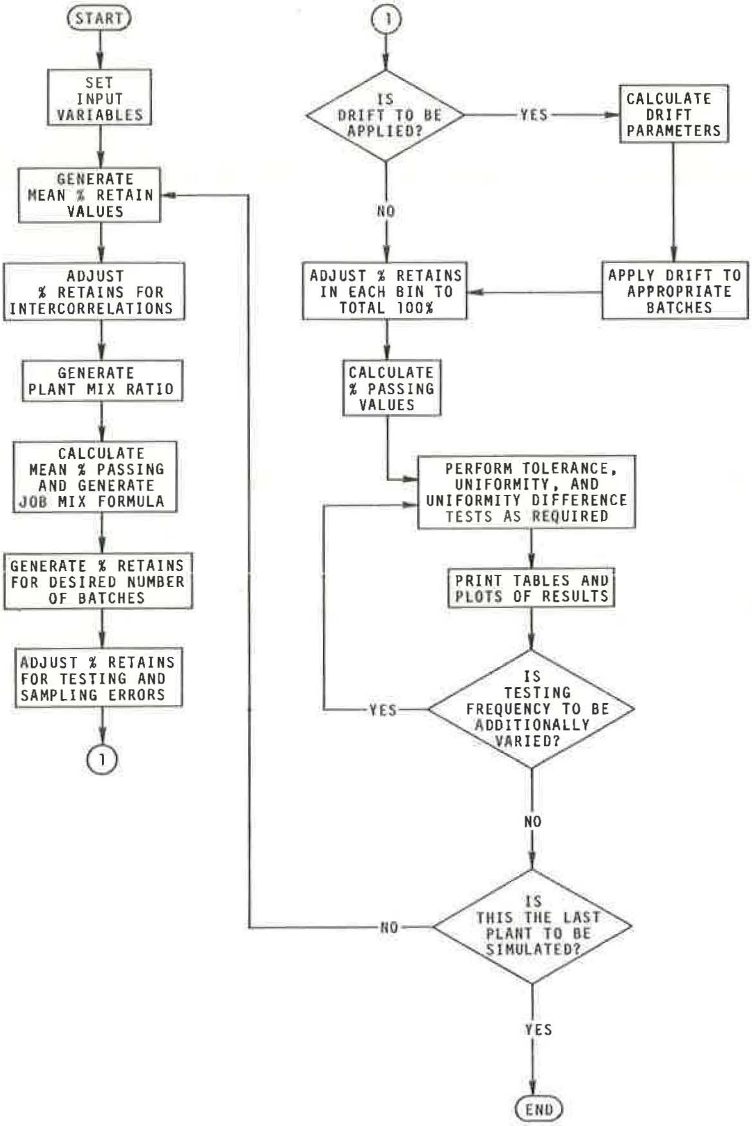


Figure 1. Simplified flow diagram.

After all the necessary intercorrelation and adjustment procedures were formulated and the sample distributional form was characterized by the W-Statistic developed by Shapiro and Wilk (8), the basic model was written and programmed. A simplified flow chart of the program is shown in Figure 1, and a sample program output is given in the Appendix.

Program Operations

Simulated production of a plant begins with the computer randomly choosing the mean gradation around which all batches will vary. Cumulative frequency plots of statewide percent-retained values for each bin and sieve are input to the computer. The plots were developed from the sample data after the drifting samples had been removed. Uniform random numbers between 0.0 and 1.0 are then generated, and a mean percent-retained value is chosen for each bin and sieve combination.

Figure 2 shows this generation process using the percent-retained on the ⅛-in. sieve in bin 1 (predominately ¼-in. stone) as an example. Choosing a random number, we enter on the y-axis at that random number, and the corresponding value on the x-axis is the percent-retained for that sieve and bin. Picking 0.60 for the random number yields a 15.4 mean percent-retained for the ⅛-in. sieve in bin 1. This procedure is repeated for each sieve in each bin to generate percent-retained values. The final mean gradations are obtained by adjusting these values for intercorrelations within the bin.

The program then starts production of the new mix by randomly choosing a plant mix ratio (PMR)—the percentage of aggregate dropped from each hot bin—for bin 2 (predominately ⅛-in. stone) from a statewide distribution of values. Using this value, a prediction equation determines the PMR for bin 3 (fines bin), and finally bin 1 is set to make the PMR values total 100 percent. From these data, the mean percent-passing for the mix is calculated. The job mix formula (JMF)—the target percent-passing the producer is aiming for—is then generated with random variation from the plant mean. This JMF must be within the state's acceptable band before the simulation may proceed.

Mixed production is handled by generating gradation data for each hot bin. This is the mean gradation with random normal or lognormal variations superimposed. These gradations are further modified by random testing and sampling errors, producing the samples as seen by an inspector. Finally, they are combined according to the PMR into the final mix.

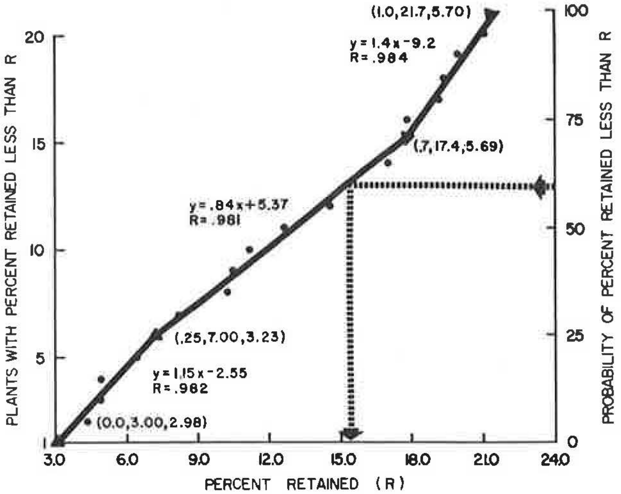


Figure 2. Cumulative frequency plot of percent-retained on ⅛-in. sieve of bin 1.

The testing scheme incorporated in the program is a variation of the method proposed by our 1967 paper. This sampling scheme compares the percentage passing each sieve with the plant's JMF, supplemented by "red flag" procedures that monitor the primary size percentage in each hot bin. The producer may have any JMF that suits his raw materials, as long as it falls within a general range for the mix-type being made.

At the start of a day's production, the plant inspector would perform a complete hot-bin analysis by sieving out samples from each bin, and weighting them mathematically with the PMR to calculate a final mix. The inspector checks the calculated mix to see that it is within acceptable JMF tolerances.

If the hot-bin analysis is acceptable, then the inspector can shift over to the uniformity and uniformity-difference mode of gradation testing. Here, he checks the percent-retained primary size in the hot bins against uniformity limits to see that it is above minimal standards. The percent-retained primary size must be above a minimum value for coarse aggregate and within a tolerance band from the last hot-bin analysis for all aggregates.

The reasoning behind the uniformity and uniformity-difference tests is quite simple. To produce a uniform mix, the primary size of the hot bins should be about the minimum specified for that aggregate size in the stockpiles. Also, it should not vary too much from that for the last acceptable mix, or it will probably throw the final mix out of specifications. When the uniformity tests fail, the inspector immediately checks the mix with a complete hot-bin analysis.

Once the desired number of batches have been simulated, the drift option may be called. If drift is desired, the program first performs testing without drift, prints the results, then goes back and applies drift to the generated samples, and retests with the same scheme. The drift routine is one of the most important parts of the program, in that it adds realism to the simulation. It is also required to evaluate the sensitivity of a testing scheme in detecting drifts from the plant mean.

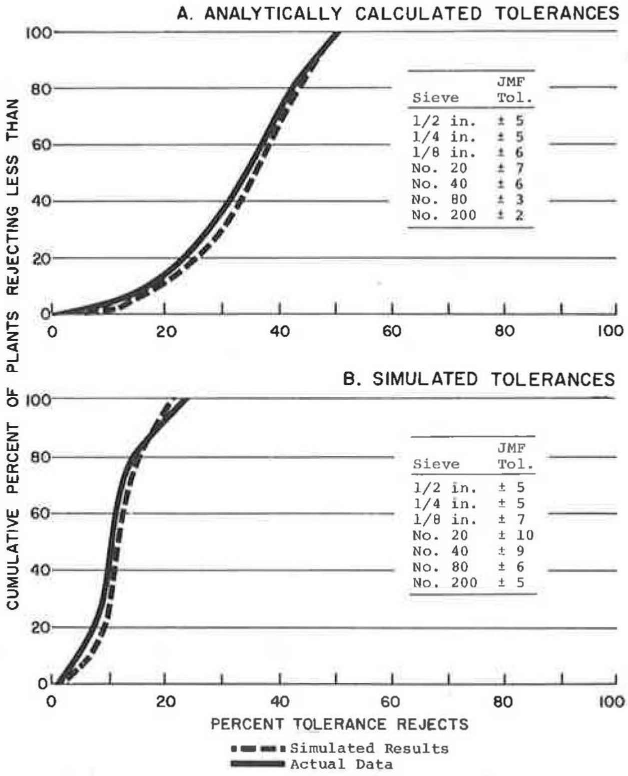
Model Efficiency

The simulation program is designed to be as efficient and flexible as possible. Several modes of operation are possible and the subroutines developed are applicable for use in any program. It was written in FORTRAN IV because of this language's ready acceptance by most programmers and computers; in fact, the present program will run on both the IBM 360 and the Burroughs B5500 with only minor revisions in input and output files. To give an idea of the machine time required for the program, the model simulates 200 nondrifting batches with 2.04 min of processor time and 0.33 min of input-output time. When drift is included, these increase to 3.00 and 0.65 min respectively. The program is designed either to simulate and test data generated internally, or to accept and test actual plant data for validation purposes. There are 3 modes of operation.

1. The simulation mode is used when batches are to be simulated and considerable output is required. The various plant parameters are either input or generated, and the required number of batches are simulated and tested.
2. The production mode does the same calculations as the simulation mode, but the printed output is substantially reduced. This mode is used when many plants are to be simulated sequentially and it is advantageous to limit the output volume.
3. The validation mode utilizes actual field cumulative weights-retained that are read in. This mode bypasses the simulation portion of the program and enters the testing section directly.

Computer Model Validation

Before any simulated data can be analyzed, one must determine whether the simulation model adequately represents operation of an asphaltic concrete plant. A model is usually considered valid when the results agree closely with actual data from the system being simulated (6). Further, a model may be required either to duplicate past results or to predict future results. Because only past data were available for this study, model validation was based solely on ability to reproduce historical results. This



A. ANALYTICALLY CALCULATED TOLERANCES

Sieve	JMF Tol.
1/2 in.	± 5
1/4 in.	± 5
1/8 in.	± 6
No. 20	± 7
No. 40	± 6
No. 80	± 3
No. 200	± 2

B. SIMULATED TOLERANCES

Sieve	JMF Tol.
1/2 in.	± 5
1/4 in.	± 5
1/8 in.	± 7
No. 20	± 10
No. 40	± 9
No. 80	± 6
No. 200	± 5

Figure 3. Percentage of tolerance rejects, using analytical and simulated tolerances.

concept of verifying the model with hot-bin data originally used to calibrate the same model may be confusing. It should be realized that the model is made up of a group of equations predicting various individual plant parameters. Even though the logic behind each of these relationships is sound, the generated parameters may not interact properly to simulate the operation of the entire system.

To begin the validation procedure, hot-bin field data from the sample plants were input to the program, utilizing the validation mode of operation. Two different tolerance testing schemes were applied to the samples, and the percentage outside of the specifications was calculated for each plant. The first tolerances were derived analytically for the 1A top mix by our 1967 paper (1). The others were formulated by the simulation. Both sets of tolerances were used to test 100 plants with 200 simulated batches per plant to find how well simulated data compared with actual field samples. The comparison is shown in Figure 3. Of course, no model can be expected to duplicate the existing data perfectly and there was some minor deviation, but this was attributed primarily to the difference in numbers of plants and batches being tested. Because the model was performing well with the application of both sets of tolerances, further calibration was not necessary and the model was considered valid.

DEVELOPING THE QUALITY ASSURANCE PROGRAM

Tolerance Test

The first step in formulating a realistic quality assurance program is balancing the tolerance test rejection rate on each separate sieve. The JMF tolerance limit describes the acceptance band about the JMF. For example, if a producer picks a target JMF of 50 percent passing the ⅛-in. sieve, with the tolerances proposed by our 1967 paper, he may produce acceptable material anywhere from 44 to 56 percent passing (±6 percent about the JMF of 50 percent). Table 1 gives a 7-level simulated experiment designed to optimize the tolerances, using the tolerances proposed in our 1967 paper as the median level. Twenty plants were simulated at each strategy level. Two hundred batches were generated and tested with no drift applied. The ½-in. sieve was not varied because little aggregate of that size is found in top-course mix. For convenience, it was kept at the 5 percent level.

TABLE 1

EXPERIMENT TO EVALUATE TOLERANCES

Item	JMF Tolerance Limits, ±						
	More Stringent			Proposed in 1967	Less Stringent		
	1	*2*	*3*	*4*	*5*	*6*	*7*
Sieve							
½ in.	5.0	5	5	5	5	5	5
¼ in.	0.5	3	4	5	6	7	8
⅛ in.	1.0	3	5	6	7	8	9
No. 20	1.0	4	6	7	8	10	12
No. 40	1.0	3	5	6	8	10	11
No. 80	0.5	1	2	3	4	6	8
No. 200	0.5	1	2	2	4	5	6
Uniformity limit	85	80	75	70	65	60	55
Uniformity difference limit	4	8	10	12	14	16	20

Note: Italics indicate successive strategy levels.

The tolerance test rejection rate for each tolerance level was calculated, and Figure 4A shows the percentage of samples that would be out of specification on the separate sieves when various tolerance limits were imposed. A good quality assurance program should balance the rejection rate on each sieve so that none is rejecting more than its share of batches. Any line drawn parallel to the Figure 4A abscissa will intersect the sieve plots at levels to achieve a balanced rejection rate over all sieves. For example, to obtain a balanced

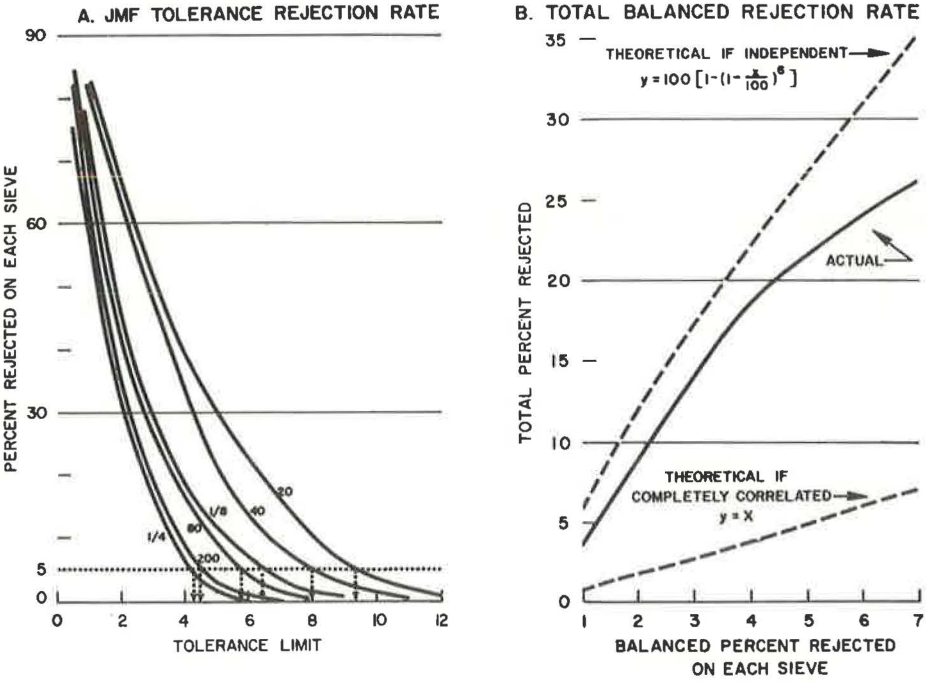


Figure 4. Development of a balanced tolerance rejection rate.

5 percent rejection rate on the 6 sieves, Figure 4A shows that tolerances should be set at the following levels:

Sieve	Tolerance
¼ in.	4.2
⅛ in.	6.3
No. 20	9.2
No. 40	8.0
No. 80	5.9
No. 200	4.4

However, an overall rejection rate of 5 percent will not be achieved by setting the individual sieve rejection rates at 5 percent, unless the 6 sieves are totally correlated or in a one-fail-all-fail situation. Likewise, if the percent-passing a given sieve is totally independent of all the others, setting individual rejection rates at 5 percent would lead to an overall rejection rate of 26.5 percent ($1-0.95^6$). This is not the case either, for if a higher-than-average percentage of the aggregate passes 1 sieve, a lower-than-average percentage must pass 1 or more of the lower sieves.

The actual overall tolerance rejection rate falls somewhere between these 2 theoretical extremes. The overall rejection rate associated with individual balanced rejection rates of from 1 to 7 percent was simulated. The average for 20 plants with 200 simulated batches per plant was considered the overall rejection rate at each level.

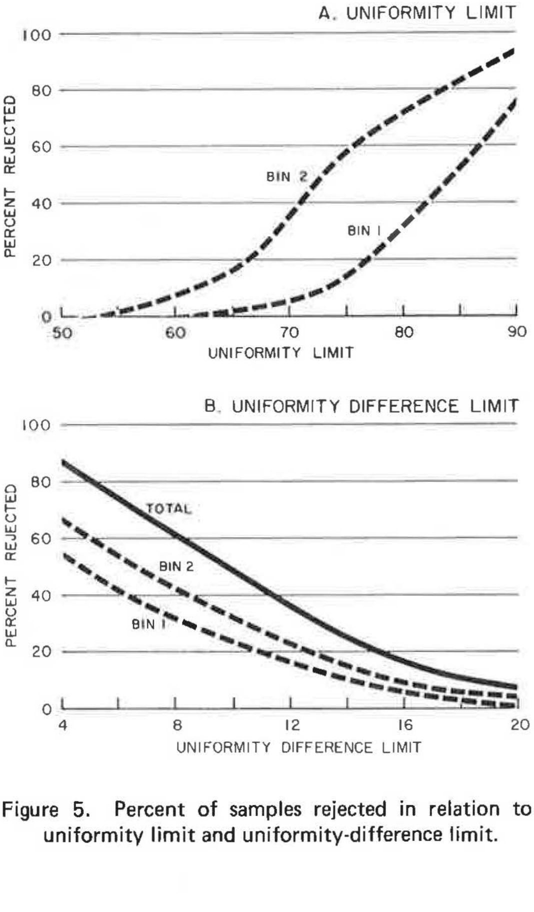


Figure 5. Percent of samples rejected in relation to uniformity limit and uniformity-difference limit.

Figure 4B shows plots of the actual rejection rate in relation to the 2 theoretical extremes. The actual rate tends to be more closely associated with the independent than correlated extreme, indicating that a relatively low percentage must be rejected on each sieve to obtain a reasonable overall rejection rate. To achieve a desirable 10 percent rejected, the individual sieve tolerances should be set at the balanced 2.2 percent level. To ensure that a true cross section of plants had been simulated, 100 additional plants were generated and tested at the balanced 2.2 percent individual rate and again a median 10 percent overall rejection rate was achieved. The balanced 2.2 percent limits extrapolated from Figure 4A and rounded to the nearest percent are as follows:

Sieve	Tolerance
¼ in.	5
⅛ in.	7
No. 20	10
No. 40	9
No. 80	6
No. 200	5

Uniformity Tests

The "red flag" uniformity and uniformity-difference tests also had to be balanced to ensure that an equal amount of material would be rejected in both bins 1 and 2. Figure 5A shows that a balanced rejection rate of about 7 percent in each bin can be obtained in the uniformity test if batches are out of specifications when the primary size in bins 1 or 2 falls below 70 or 60 percent respectively. Setting the uniformity limit at the knee of each distribution is advantageous in that both rejection curves slope sharply upward as more stringent testing limits are applied. No overall rejection rate is shown in Figure 5A because the plot would be meaningless with the bin rejection rates not balanced.

The simulated percents-rejected were also plotted against various uniformity-difference testing levels, with the results shown in Figure 5B. A uniformity-difference limit of ±16 percent will almost balance the individual bin rejection rates at about 9 percent. Again, this is a good level for setting the limit, because the total rejection rate rises sharply as lower, more stringent limits are applied.

Any uniformity and uniformity-difference limit chosen must also be consistent with acceptable levels of alpha and beta error. Figure 6 shows these errors associated with various testing levels. In these plots, an alpha-error reject is considered to be a sample that passes the tolerance test with the selected tolerances imposed, but is rejected by either the uniformity or uniformity-difference tests.

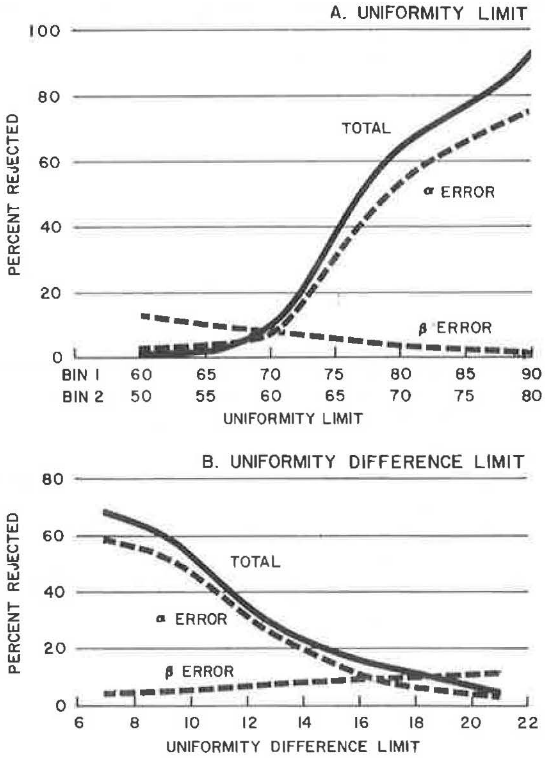


Figure 6. Operating characteristic curves for uniformity test and uniformity-difference test.

The optimum uniformity limit was found by determining in Figure 6A the point where total alpha and beta errors were equal. At a uniformity limit of 70 percent for bin 1 and 60 percent for bin 2, the alpha and beta errors will be balanced at an acceptable 8 percent level and the overall uniformity rejects will be 11 percent. The same procedure is repeated, and the uniformity-difference limit shown in Figure 6B is optimized at ±16 percent, with 10 percent alpha and beta errors and 14 percent total uniformity-difference rejects.

Testing Strategy Evaluation

Thus far, the simulation has produced batches that have not drifted from the plant mean. Any acceptable quality assurance method must also detect this phenomenon promptly so that corrective action may be instituted. Fifty plants were simulated with and without drift and the simulated testing limits imposed. The simulated data indicated that the tolerance test percent-rejects increased when drift was included. Also, as the percent-rejects without drift in a plant rise, the number of rejects with drift also increases. This implies that drifting in a nonuniform plant will cause the most problems.

The uniformity test was excellent at detecting negative drift in plants, with a relatively low percent-retained in any primary size. The uniformity-difference test performed well at identifying both positive and negative drift.

Fifty additional drifting plants were simulated with 500 batches per plant. Various sampling frequencies were employed, and the resulting percentage of batches rejected was tabulated. The efficiency of each testing scheme dropped substantially as the time between samples increased.

A study of 9 asphaltic concrete plants in New York State (2) indicated that a modern, efficiently run asphalt plant produces about 60 batches per hour. It would be physically impossible to test every batch as the computer simulation can. The uniformity test requires about 20 min, while a complete hot-bin analysis would take over 45 min. Therefore, the minimum testing frequency physically possible for 1 man would be every 20 batches for the uniformity tests and every 45 batches for the hot-bin analysis. Plotting simulated results indicated that a uniformity and uniformity-difference testing frequency of every 80 batches would be most effective because the percent-rejected dropped rapidly after this point. Because the percents-rejected between tolerance tests do not increase drastically as the time between samples increases and there is good correlation between the tolerance and uniformity tests, a tolerance test every 400 batches, together with uniformity tests every 80 batches, is a realistic testing frequency for this type of sampling plan.

CONCLUSIONS

1. This study has illustrated the evaluation of one quality assurance program for asphaltic concrete, utilizing computer simulation procedures. Computer simulation has proved to be an effective, flexible tool in developing testing strategies. Although development of the simulation package was an exercise in programming logic involving such statistical techniques as experimental design, regression analysis, and analysis of variance, anyone can use the program by merely inputing it to the computer with a list of descriptive plant parameters.

2. The methodologies presented in this paper can also be used to analyze other, more complicated sampling plans that are too complex to evaluate analytically. Also, the technique may be modified to ascertain the quality assurance aspects of many other types of construction materials such as portland cement concrete.

3. The simulation model of aggregate flow can be expanded in 2 directions. It can be expanded backward toward the raw materials so that the gradation in the cold bin can be predicted from the simulated hot-bin data, and a testing program for the cold feed may thus be instituted. Testing at the cold feed would allow "real time" control so that corrective action can be taken to remedy out-of-control production before the material leaves the plants. The model can also be expanded forward to the roadway, in that the characteristics of the mix actually placed can be simulated from the hot-bin data. This would be extremely useful in ascertaining the economics of adjusting the bid price on the basis of the quality level of the material received, as advocated by several construction agencies (5, 7).

ACKNOWLEDGMENTS

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Another publication on this investigation (10) presents greater technical detail for the quality control engineering and asphalt paving technologist familiar with statistical methods, and discusses the building of the simulation model, statistical analysis of the sample data, program listings with sample input and output, and quality assurance testing. Both Research Report 70-1 and this paper were extracted in part from N. F. Bolyea's 1969 dissertation at Rensselaer Polytechnic Institute.

The work reported was performed under the administrative supervision of William C. Burnett. The project's feasibility study was conducted under contract at Rensselaer Polytechnic Institute by R. M. Lewis, J. W. Wilkinson, and N. F. Bolyea. Invaluable assistance by James M. Hill in programming the simulation model is gratefully recognized. Special acknowledgment is due to Jerome J. Thomas, who was responsible for the conception of this study; his comments on various drafts of the project's publications have been most helpful.

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Appendix

Sample program output is given on the following pages.

```
P L A N T   N O .  1

        RANDOM NUMBER SEEDS USED FOR THIS PLANT TO INITIALIZE RANDOM NUMBER GENERATORS ARE-
NORRN= 424692154368. PCRRN= 494487470080, DRFN=      66544111, JMFRN= 409756237824, PMRRN= 154694238336



          NO. OF      NO. OF      NO. OF      NO. OF
          BATCHES      BINS       SIEVES       STEPS
             18          3           7           0


          SAMPLES ARE OBTAINED FROM EVERY BATCH.


          PLANT MIX RATIOS HAVE BEEN GENERATED.

          PLANT MIX RATIOS
          BIN      PERCENT

           1         24.2
           2         30.0
           3         45.8


                                            IMPOSED
          SIEVE    STATE JMF LIMITS        TOLERANCE
           1/2        100.-  95.              5.0
           1/4         85.-  65.              5.0
           1/8         65.-  32.              8.0
           N20         39.-  15.             11.0
           N40         25.-   7.              9.0
           N80         12.-   3.              7.0
          N200          6.-   2.              5.0

          UNIFORMITY AND UNIFORMITY DIFFERENCE LIMITS

          THE UNIFORMITY DIFFERENCE LIMIT IS 14.0 PERCENT.
          THE UNIFORMITY LIMITS AND THE PRIMARY SIZE SIEVES BY BIN ARE-
                             UNIFORMITY
                   SIEVE       LIMIT
             BIN 1   1/4        70.0
             BIN 2   1/8        40.0

          DRIFT HAS BEEN SPECIFIED FOR THIS PLANT.
```

```
MEANS AND STD. DEVIATIONS USED            CORRELATION MATRIX USED IN CALCULATION
FOR CALCULATION OF JOB MIX FORMULA        OF MEAN PERCENT RETAINED FOR THE PLANT

SIEVE    MEAN    STD.DEV.                 BIN 1    BIN 2    BIN 3
 1/2     0.00     0.00                     0.00     0.00     0.00
 1/4    -0.13     0.57                     0.00     0.00     0.00
 1/8    -0.04     1.01                    -0.93     0.00     0.00
 N20     0.14     1.20                    -0.11    -0.81     0.00
 N40    -0.06     0.94                     0.00    -0.08    -0.42
 N80    -0.14     0.73                     0.00    -0.03    -0.59
N200     0.21     0.65                     0.00    -0.02    -0.10
 PAN     0.00     0.00                     0.00    -0.02     0.00

         MEAN PERCENT RETAINED                       MEAN PERCENT       JOB MIX
              FOR THE PLANT                            PASSING          FORMULA
SIEVE    BIN 1      BIN 2      BIN 3               FOR THE PLANT    FOR THE PLANT    DIFFERENCE
 1/2      0.96       0.02       0.00                   99.76            99.76            0.00
 1/4     80.05       9.08       0.00                   77.67            78.00            0.33
 1/8     15.86      74.31       0.32                   51.39            52.05            0.66
 N20      2.48      16.58      39.76                   27.61            29.95            2.34
 N40      0.22       0.02      18.96                   18.86            20.06            1.19
 N80      0.16       0.00      24.00                    7.83             8.66            0.82
N200      0.09       0.00       6.63                    4.78             3.65           -1.13
 PAN      0.19       0.00      10.33                    0.00             0.00            0.00

                        MEAN PERCENT PASSINGS AND IMPOSED TOLERANCES

       MEAN PERCENT  MEAN PERCENT
         PASSING       PASSING       CALCULATED     CALCULATED     CALCULATED      IMPOSED       IMPOSED        IMPOSED
SIEVE  FOR THE PLANT (ALL BATCHES)   TOLERANCE      LOWER LIMIT    UPPER LIMIT    TOLERANCE    LOWER LIMIT    UPPER LIMIT

 1/2      99.76         99.63          0.78           98.98         100.00          5.00         94.76         100.00
 1/4      77.67         77.68          4.02           73.98          82.02          5.00         73.00          83.00
 1/8      51.39         50.71          4.47           47.58          56.52          8.00         44.05          60.05
 N20      27.61         28.19          6.48           23.47          36.43         11.00         18.95          40.95
 N40      18.86         19.84          5.66           14.40          25.72          9.00         11.06          29.06,
 N80       7.83          7.94          3.55            5.11          12.21          7.00          1.66          15.66
N200       4.78          4.85          4.49            0.00           8.14          5.00          0.00           8.65

ALL  18 BATCHES EXAMINED.

                                   TABLE OF RESULTS

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*    TEST     * NUMBER  * NUMBER  * PERCENT * * NUMBER * PERCENT* * NUMBER * PERCENT* * NUMBER * PERCENT* * NUMBER * PERCENT* *
*             * ACCEPTS * REJECTS * REJECTED* * ACC-ACC* ACC-ACC* * REJ-REJ* REJ-REJ* * ACC-REJ* ACC-REJ* * REJ-ACC* REJ-ACC* *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*             *         *         *         * *        *        * *        *        * *        *        * *        *        * *
*  TOLERANCE*    17.    *    1.   *    5.56 * *        *        * *        *        * *        *        * *        *        * *
*             *         *         *         * *        *        * *        *        * *        *        * *        *        * *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*             *         *         *         * *        *        * *        *        * *        *        * *        *        * *
* UNIFORMITY*    17.    *    1.   *    5.56 * *   16.  *  88.89 * *    0.  *   0.00 * *    1.  *   5.56 * *    1.  *   5.56 * *
*             *         *         *         * *        *        * *        *        * *        *        * *        *        * *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*             *         *         *         * *        *        * *        *        * *        *        * *        *        * *
* UNIFORMITY*    14.    *    3.   *   17.65 * *   13.  *  76.47 * *    0.  *   0.00 * *    3.  *  17.65 * *    1.  *   5.88 * *
* DIFFERENCE*           *         *         * *        *        * *        *        * *        *        * *        *        * *
*             *         *         *         * *        *        * *        *        * *        *        * *        *        * *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                 PERCENT REJECTS BY SIEVE AND BIN

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*    TEST     * SIEVE * SIEVE * SIEVE * SIEVE * SIEVE * SIEVE * SIEVE *
*             *  1/2  *  1/4  *  1/8  *  N20  *  N40  *  N80  * N200  *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*             *       *       *       *       *       *       *       *
*  TOLERANCE*   0.0  *  0.0  *  0.0  *  0.0  *  0.0  *  0.0  *  5.6  *
*             *       *       *       *       *       *       *       *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*             * BIN 1 * BIN 2 *
* * * * * * * * * * * * * * * *
*             *       *       *
* UNIFORMITY*   5.6  *  0.0  *
*             *       *       *
* * * * * * * * * * * * * * * *
*             *       *       *
* UNIFORMITY*         *       *
* DIFFERENCE*   0.0  * 17.6  *
*             *       *       *
* * * * * * * * * * * * * * * *

DRIFT HAS BEEN SPECIFIED FOR THIS PLANT.

INFORMATION ON THE DRIFT SPECIFICATIONS FOLLOW-


DRIFT WILL BE APPLIED BEFORE BATCH   2.
MAXIMUM POSSIBLE DRIFT DURATION (IN BATCHES) IS   7.


             NO. OF BINS    START OF                        END OF
              DRIFTING       DRIFT                           DRIFT

1ST DRIFT        1             2        BIN 2  NEG. DRIFT     7

2ND DRIFT        2             6        BIN 1  POS. DRIFT    12
                                        BIN 2  NEG. DRIFT    11


DRIFT IS ENCLOSED IN PARENTHESIS () AND
IS LOCATED TO THE RIGHT OF THE PRIMARY SIZE FOR THE BINS ON WHICH IT WAS APPLIED.


               PERCENT PASSING                                  PERCENT RETAINED

                           PERCENT
BATCH   1       SIEVE      PASSING                  SIEVE        BIN 1          BIN 2              BIN 3
                 1/2        99.27                    1/2          2.91           0.07               0.00
                 1/4        81.61                    1/4         72.97           0.00               0.01
                 1/8        51.34                    1/8         23.26          82.15               0.00
                 N20        27.11                    N20          0.00          16.99              41.77
                 N40        20.38                    N40          0.40           0.00              14.48
                 N80         9.55                    N80          0.05           0.00              23.63
                N200         5.03                   N200          0.00           0.00               9.86
                 PAN         0.00                    PAN          0.41           0.79              10.26

                           PERCENT
BATCH   2       SIEVE      PASSING                  SIEVE        BIN 1          BIN 2              BIN 3
                 1/2        99.08                    1/2          3.53           0.00               0.14
DRIFT ON         1/4        77.80                    1/4         76.92           8.88               0.00
                 1/8        49.55                    1/8         18.91          78.94(-4.44)        0.00
                 N20        27.11                    N20          0.00          10.22              42.30
                 N40        20.90                    N40          0.19           1.65              12.37
                 N80         6.51                    N80          0.20           0.00              31.33
                N200         3.41                   N200          0.24           0.31               6.43
                 PAN         0.00                    PAN          0.00           0.00               7.44
```

```
                    PERCENT PASSING                        PERCENT RETAINED
                        PERCENT
BATCH   3       SIEVE   PASSING      SIEVE     BIN 1           BIN 2            BIN 3
                  1/2     99.97        1/2      0.00            0.03             0.04
DRIFT ON          1/4     79.99        1/4     67.19           12.41             0.00
                  1/8     54.13        1/8     28.39           63.29(-7.10)      0.00
                  N20     29.59        N20      4.03           23.75            35.89
                  N40     20.16        N40      0.00            0.00            20.58
                  N80      7.09        N80      0.12            0.51            28.14
                 N200      2.39       N200      0.00            0.00            10.28
                  PAN      0.00        PAN      0.27            0.00             5.07

                        PERCENT
BATCH   4       SIEVE   PASSING      SIEVE     BIN 1           BIN 2            BIN 3
                  1/2     99.31        1/2      2.72            0.12             0.00
DRIFT ON          1/4     75.28        1/4     78.63           16.45             0.00
                  1/8     47.56        1/8     10.73           81.66(-7.99)      1.38
                  N20     28.42        N20      6.40            0.00            38.40
                  N40     23.21        N40      1.00            0.00            10.85
                  N80      9.03        N80      0.46            0.00            30.72
                 N200      5.42       N200      0.07            1.58             6.80
                  PAN      0.00        PAN      0.00            0.00            11.84

                        PERCENT
BATCH   5       SIEVE   PASSING      SIEVE     BIN 1           BIN 2            BIN 3
                  1/2     98.83        1/2      4.47            0.31             0.00
DRIFT ON          1/4     77.26        1/4     70.86           14.72             0.00
                  1/8     47.27        1/8     18.72           84.86(-7.10)      0.00
                  N20     26.44        N20      4.23            0.00            43.26
                  N40     16.40        N40      1.26            0.00            21.26
                  N80      7.88        N80      0.29            0.00            18.45
                 N200      6.26       N200      0.00            0.12             3.46
                  PAN      0.00        PAN      0.16            0.00            13.58

                        PERCENT
BATCH   6       SIEVE   PASSING      SIEVE     BIN 1           BIN 2            BIN 3
                  1/2     99.79        1/2      0.83            0.02             0.01
DRIFT ON          1/4     74.28        1/4     85.65           15.93             0.00
                  1/8     54.92        1/8     10.60           56.01(-4.44)      0.00
                  N20     31.66        N20      1.04           22.66            35.39
                  N40     21.97        N40      0.79            4.87            17.54
                  N80      8.49        N80      0.26            0.51            28.97
                 N200      4.54       N200      0.83            0.00             8.18
                  PAN      0.00        PAN      0.00            0.00             9.91

                        PERCENT
BATCH   7       SIEVE   PASSING      SIEVE     BIN 1           BIN 2            BIN 3
                  1/2     99.35        1/2      2.68            0.00             0.00
DRIFT ON          1/4     77.83        1/4     76.20           10.22             0.03
                  1/8     48.58        1/8     20.73           79.86( 0.00)      0.60
                  N20     27.54        N20      0.00            9.78            39.53
                  N40     17.80        N40      0.00            0.00            21.28
                  N80      8.02        N80      0.00            0.15            21.26
                 N200      6.42       N200      0.26            0.00             3.35
                  PAN      0.00        PAN      0.13            0.00            13.95

                        PERCENT
BATCH   8       SIEVE   PASSING      SIEVE     BIN 1           BIN 2            BIN 3
                  1/2     99.97        1/2      0.00            0.03             0.04
DRIFT ON          1/4     73.40        1/4     90.83( 3.86)    15.29             0.01
                  1/8     51.27        1/8      7.99           62.37(-4.54)      3.25
                  N20     20.19        N20      0.89           22.14            52.88
                  N40     13.72        N40      0.00            0.00            14.13
                  N80      4.56        N80      0.29            0.00            19.85
                 N200      3.03       N200      0.00            0.13             3.25
                  PAN      0.00        PAN      0.00            0.04             6.59

                        PERCENT
BATCH   9       SIEVE   PASSING      SIEVE     BIN 1           BIN 2            BIN 3
                  1/2     99.75        1/2      0.85            0.06             0.06
DRIFT ON          1/4     75.40        1/4     81.84( 5.79)    15.14             0.00
                  1/8     54.15        1/8     11.48           60.49(-6.06)      0.71
                  N20     32.99        N20      4.03           23.45            28.71
                  N40     23.59        N40      1.39            0.32            19.60
                  N80      9.43        N80      0.01            0.17            30.80
                 N200      3.96       N200      0.35            0.00            11.75
                  PAN      0.00        PAN      0.05            0.38             8.38

                        PERCENT
BATCH  10       SIEVE   PASSING      SIEVE     BIN 1           BIN 2            BIN 3
                  1/2    100.00        1/2      0.00            0.00             0.00
DRIFT ON          1/4     74.71        1/4     80.32( 5.79)    19.51             0.00
                  1/8     50.74        1/8     15.07           66.42(-4.54)      0.86
                  N20     26.39        N20      2.96           12.54            43.39
                  N40     18.53        N40      1.34            0.87            15.89
                  N80      8.29        N80      0.04            0.00            22.32
                 N200      8.29       N200      0.00            0.00             0.00
                  PAN      0.00        PAN      0.27            0.67            17.53

                        PERCENT
BATCH  11       SIEVE   PASSING      SIEVE     BIN 1           BIN 2            BIN 3
                  1/2    100.00        1/2      0.00            0.00             0.00
DRIFT ON          1/4     77.02        1/4     81.72( 3.86)    10.69             0.00
                  1/8     52.21        1/8     14.97           70.62( 0.00)      0.00
                  N20     30.11        N20      3.31           17.46            35.06
                  N40     21.89        N40      0.00            1.08            17.24
                  N80      7.56        N80      0.00            0.00            31.29
                 N200      5.09       N200      0.00            0.15             5.28
                  PAN      0.00        PAN      0.00            0.00            11.12

                        PERCENT
BATCH  12       SIEVE   PASSING      SIEVE     BIN 1           BIN 2            BIN 3
                  1/2     98.99        1/2      3.92            0.00             0.12
DRIFT ON          1/4     77.87        1/4     76.24( 0.00)     9.58             0.00
                  1/8     48.63        1/8     13.39           85.99             0.00
                  N20     26.48        N20      5.70            2.24            43.89
                  N40     18.38        N40      0.06            1.61            16.61
                  N80      7.94        N80      0.43            0.00            22.56
                 N200      3.34       N200      0.27            0.45             9.61
                  PAN      0.00        PAN      0.00            0.14             7.20

                        PERCENT
BATCH  13       SIEVE   PASSING      SIEVE     BIN 1           BIN 2            BIN 3
                  1/2     99.62        1/2      1.47            0.03             0.04
                  1/4     78.69        1/4     72.52           11.23             0.02
                  1/8     48.80        1/8     19.74           82.32             0.91
                  N20     26.17        N20      5.54            6.43            42.26
                  N40     16.63        N40      0.00            0.00            20.83
                  N80      5.08        N80      0.54            0.00            24.94
                 N200      1.34       N200      0.00            0.00             8.17
                  PAN      0.00        PAN      0.18            0.00             2.82

                        PERCENT
BATCH  14       SIEVE   PASSING      SIEVE     BIN 1           BIN 2            BIN 3
                  1/2     99.49        1/2      1.98            0.01             0.06
                  1/4     74.25        1/4     87.36           13.66             0.01
                  1/8     49.33        1/8      8.89           75.69             0.14
                  N20     25.41        N20      0.00            9.13            46.24
                  N40     17.43        N40      0.75            0.86            16.46
                  N80      7.98        N80      0.51            0.66            19.94
                 N200      6.32       N200      0.00            0.00             3.62
                  PAN      0.00        PAN      0.51            0.00            13.54
```

```
                  PERCENT PA   NG                                              PERCENT RETAINED
                               PERCENT
BATCH  15         SIEVE        PASSING                   SIEVE          BIN 1          BIN 2          BIN 3
                   1/2          99.93                     1/2            0.00           0.04           0.13
                   1/4          78.26                     1/4           76.97          10.14           0.00
                   1/8          54.32                     1/8           20.14          61.87           1.10
                   N20          27.44                     N20            1.80          26.88          40.14
                   N40          18.14                     N40            0.70           0.55          19.58
                   N80          11.70                     N80            0.00           0.16          13.95
                  N200           5.85                    N200            0.06           0.00          12.74
                   PAN           0.00                     PAN            0.34           0.36          12.36

                               PERCENT
BATCH  16         SIEVE        PASSING                   SIEVE          BIN 1          BIN 2          BIN 3
                   1/2          99.99                     1/2            0.00           0.00           0.03
                   1/4          77.01                     1/4           90.06           3.94           0.01
                   1/8          52.65                     1/8            7.20          70.10           3.46
                   N20          28.76                     N20            0.00          25.81          35.26
                   N40          23.26                     N40            1.57           0.00          11.18
                   N80           6.54                     N80            0.30           0.15          36.26
                  N200           3.05                    N200            0.00           0.00           7.62
                   PAN           0.00                     PAN            0.87           0.00           6.19

                               PERCENT
BATCH  17         SIEVE        PASSING                   SIEVE          BIN 1          BIN 2          BIN 3
                   1/2         100.00                     1/2            0.00           0.00           0.00
                   1/4          74.95                     1/4           84.73          15.13           0.02
                   1/8          50.57                     1/8           14.00          69.97           0.00
                   N20          34.24                     N20            0.59          12.69          27.02
                   N40          22.07                     N40            0.00           1.75          25.44
                   N80          10.68                     N80            0.40           0.19          24.54
                  N200          10.54                    N200            0.28           0.00           0.16
                   PAN           0.00                     PAN            0.00           0.28          22.82

                               PERCENT
BATCH  18         SIEVE        PASSING                   SIEVE          BIN 1          BIN 2          BIN 3
                   1/2          99.96                     1/2            0.00           0.03           0.08
                   1/4          79.29                     1/4           71.05          10.84           0.01
                   1/8          51.43                     1/8           22.03          73.87           0.80
                   N20          31.78                     N20            5.60          13.76          30.94
                   N40          22.84                     N40            0.00           0.19          19.39
                   N80           6.80                     N80            0.24           0.00          34.89
                  N200           3.05                    N200            0.16           0.13           8.03
                   PAN           0.00                     PAN            0.03           1.19           5.86



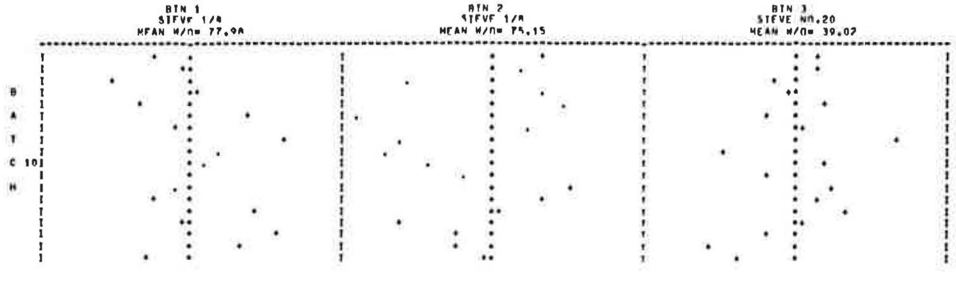
              P E R C E N T   R E T A I N E D   W I T H   D R I F T   A R O U N D   M E A N   W / O   D R I F T
                                             (FOR PRIMARY SIZES AND NO. 20)

NUMBER OF DRIFTS FOR THIS PLANT IS 2.
1ST DRIFT STARTS AT BATCH   2.
2ND DRIFT STARTS AT BATCH   8.

1ST DRIFT
            DRIFT ON BIN 2 ENDS ON BATCH   7.

2ND DRIFT
            DRIFT ON BIN 1 ENDS ON BATCH  12.
            DRIFT ON BIN 2 ENDS ON BATCH  11.

EACH COLUMN IS EQUAL TO 1 PERCENT.
A + REPRESENTS THE PERCENT RETAINED FOR A BATCH WITHOUT THE APPLICATION OF DRIFT.
A , REPRESENTS THE PERCENT RETAINED FOR A BATCH WITH THE APPLICATION OF DRIFT.
```



```
                                        T O L E R A N C E   T E S T


PRINT TOLERANCE ACCEPT-REJECT MATRIX.
A REJECT IS DENOTED BY REJ, AN ACCEPT BY A BLANK IN THE MATRIX.
A REJECT IS OBSERVED IF THE FINAL PERCENT PASSING OF A SIEVE
FOR A BATCH IS OUTSIDE THE TOLERANCE BAND FOR THE SIEVE.

SAMPLE   SIEVE    SIEVE    SIEVE    SIEVE    SIEVE    SIEVE    SIEVE
  NO.     1/2      1/4      1/8      N20      N40      N80      N200
    1
    2
    3
    4
    5
    6
    7
    8
    9
   10
   11
   12
   13
   14
   15
   16
   17                                                           REJ
   18


ALL  18 BATCHES EXAMINED.
```

```
                                        U N I F O R M I T Y   T E S T

 TEST ON UNIFORMITY OF SAMPLES WITH PRIMARY SIZE PERCENT PASSING AS FOLLOWS-
       BIN 1    70.0
       BIN 2    60.0


 SAMPLE NO.    BIN 1  BIN 2
      1
      2
      3          REJ
      4
      5
      6                 REJ
      7
      8
      9
     10
     11
     12
     13
     14
     15
     16
     17
     18

 PERCENT REJECTS BY BIN WHICH HAVE A PRIMARY SIZE.
 BIN 1      5.56
 BIN 2      5.56


ALL  18 BATCHES EXAMINED.
                          U N I F O R M I T Y   D I F F E R E N C E   T E S T


TEST ON DIFFERENCE BETWEEN SAMPLES
DIFFERENCE MUST BE EQUAL OR LESS THAN  14.0.

SAMPLE NOS.  BIN 1  BIN 2
  1-   2
  2-   3
  3-   4             REJ
  4-   5
  5-   6             REJ
  6-   7             REJ
  7-   8             REJ
  8-   9
  9-  10
 10-  11
 11-  12
 12-  13
 13-  14
 14-  15
 15-  16
 16-  17
 17-  18

PERCENT REJECTS BY BIN WHICH HAVE A PRIMARY SIZE.
BIN 1      0.00
BIN 2     23.53
 FREQUENCY PLOT TITLE - NO. OF BINS A SAMPLE IS REJECTED-UNIFORMITY DIFFERENCE

 FREQUENCY      4       0
************************
     4        ***
     3        * *
     2        * *
     1        * *
------------------------
NO. OF BINS    1       2

 FREQUENCY PLOT TITLE - TOTAL NO. OF REJECTS BY EACH BIN

 FREQUENCY     0       4
************************
     4               ***
     3               * *
     2               * *
     1               * *
************************
            BIN 1   BIN 2

ALL  18 BATCHES EXAMINED.
                                          T A B L E   O F   R E S U L T S

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*    TEST    * NUMBER  * NUMBER  * PERCENT * * NUMBER * PERCENT* * NUMBER * PERCENT* * NUMBER * PERCENT* * NUMBER * PERCENT* *
*            * ACCEPTS * REJECTS * REJECTED* * ACC-ACC* ACC-ACC* * REJ-REJ* REJ-REJ* * ACC-REJ* ACC-REJ* * REJ-ACC* REJ-ACC* *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*            *         *         *         * *        *        * *        *        * *        *        * *        *        * *
*  TOLERANCE*    17.   *    1.   *    5.56 * *        *        * *        *        * *        *        * *        *        * *
*            *         *         *         * *        *        * *        *        * *        *        * *        *        * *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*            *         *         *         * *        *        * *        *        * *        *        * *        *        * *
* UNIFORMITY*    16.   *    2.   *   11.11 * *   15.  *  83.33 * *    0.  *   0.00 * *    2.  *  11.11 * *    1.  *   5.56 * *
*            *         *         *         * *        *        * *        *        * *        *        * *        *        * *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*            *         *         *         * *        *        * *        *        * *        *        * *        *        * *
* UNIFORMITY*    13.   *    4.   *   23.53 * *   12.  *  70.59 * *    0.  *   0.00 * *    4.  *  23.53 * *    1.  *   5.88 * *
* DIFFERENCE*          *         *         * *        *        * *        *        * *        *        * *        *        * *
*            *         *         *         * *        *        * *        *        * *        *        * *        *        * *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


                 P E R C E N T   R E J E C T S   B Y   S I E V E   A N D   B I N

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*    TEST    * SIEVE * SIEVE * SIEVE * SIEVE * SIEVE * SIEVE * SIEVE *
*            *  1/2  *  1/4  *  1/8  *  N20  *  N40  *  N80  * N200  *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*            *       *       *       *       *       *       *       *
*  TOLERANCE*  0.0  *  0.0  *  0.0  *  0.0  *  0.0  *  0.0  *  5.6  *
*            *       *       *       *       *       *       *       *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*            * BIN 1 * BIN 2 *
* * * * * * * * * * * * * * * *
*            *       *       *
* UNIFORMITY*  5.6  *  5.6  *
*            *       *       *
* * * * * * * * * * * * * * * *
*            *       *       *
* UNIFORMITY*       *       *
* DIFFERENCE*  0.0  * 23.5  *
*            *       *       *
* * * * * * * * * * * * * * * *

                                   ******************************************
                                   *                                        *
                                   *ASPHALT PLANT SIMULATION EXITED NORMALLY*
                                   *                                        *
                                   ******************************************


          RANDOM NUMBER SEEDS AT END OF RUN ARE AS FOLLOWS-
NORRN= 125118185172, PCHRN= 892874208140, ORFN= 187309228032, IMERN= 208530309140, PHRRN= 378317832192
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Screenless Plant Operation With Cold Feed Control

J. L. FARRELL and W. H. WRIGHT, Kansas Highway Commission

This report describes the procedures used in the transition to "screenless plant operations" with control of the proportioning at the cold feed. The cold feeder must have the desired precision and the hot bins should be modified to function as only one bin for temporary storage between batches. The information was obtained on 3 projects constructed during the transition by contractors with high-production automatic batch plants. Correlation samples were taken at the cold feed, dry batch samples at the pugmill, and bituminous mix samples for extraction. Comparison of the results of these samples is evidence that desired precision in proportioning can be obtained with the newer types of cold feeders. Tables of means and standard deviations summarize the results obtained and are a basis of comparison since the values for standard deviation are a measure of variability. Extraction gradation results are indicative of the uniformity of the bituminous mix produced with this method. The control of proportioning at the cold feed is advantageous from the sampling standpoint and has none of the drawbacks of the hot bin or dry batch pugmill-mixed method of sampling. The desired screening efficiency can best be accomplished during individual aggregate production.

•ONE OF THE PROBLEMS associated with bituminous plant mix construction has been the variability of the test results taken at various points in the construction process. This variability was often reflected by differences in appearance of the bituminous mix in short periods of time such as the comparison of one truck load with the next or even one batch with the next.

Another primary purpose in this work was the need to increase our testing efficiency to correspond with the increasing capacity of the new automatic types of plants.

First, let us give the history of the evolution of the sampling techniques of our plant-mixed bituminous mixes.

HISTORY OF PLANT SAMPLING

Prior to 1964, batch plants were sampled by taking hot bin samples of the dried aggregate being discharged into the weigh hopper. Variability in aggregate gradation was apparent at this point in the production process, particularly in the fine bin. Hot bin gradation results were frequently not reproducible, and the variability was frequently greater than could be attributed to the variation of the aggregates at the cold feed. Regardless of the causes of this variability, its very existence resulted in noticeable variability in the resultant bituminous mix.

Another drawback to the hot bin sampling method was the need to conduct a complete sieve analysis on each bin sample before obtaining the final results. At best, this method gave only a theoretical combination and a speedier, more direct procedure was desired.

Paper sponsored by Committee on Construction Practices—Flexible Pavement and presented at the 49th Annual Meeting.

Figure 1. Cold feed blending plant.

In 1964, to streamline the sampling procedure, a dry pugmill-mixed combined sample was adopted as the basis of acceptance. Plant operations were interrupted while a clean-out batch was run through the pugmill, and the following batch was used for sampling. Several types of samplers were developed for this purpose, and most were erected in an empty truck bed. Because of limited capacity without overflowing of the samplers, a partial or fraction of a batch was used. Possible errors in using a fraction of a batch for sampling, handling of a cumbersome sampler, and extremely dirty conditions surrounding the pugmill discharge were disadvantages of this method. The contractors with high production plants were opposed to the interruption of production for this type of sampling and the loss of processed aggregate for the pugmill clean-out batch and the sampled batch.

Among the advantages of this method was obtaining the final gradation results with only one sample in place of the 3 or 4 samples required with the hot bin method.

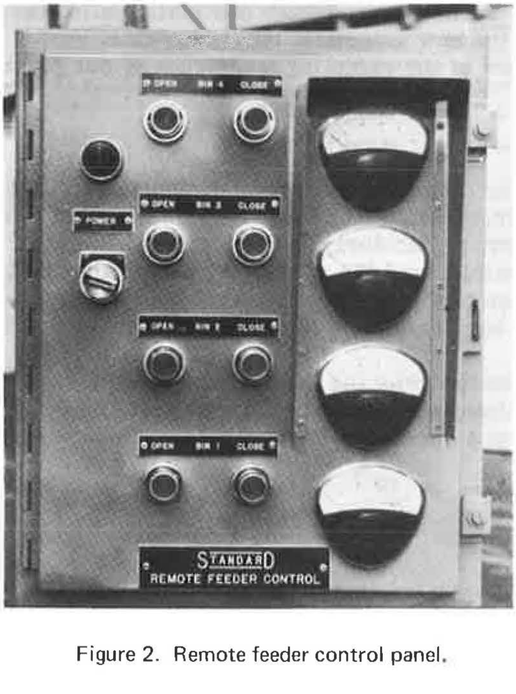

Figure 2. Remote feeder control panel.

SCREENLESS PLANT OPERATION

During a panel discussion at the Kansas University Asphalt Conference in 1966, the question of "screenless plant operation" having the ultimate controls placed at the cold feed was discussed. This type of control would permit continuous operation that is essential to uniformity and would not waste processed aggregate during sampling.

Newer types of cold feeders that permitted accurate positive control of the proportioning of the individual aggregates were appearing on the projects. Cold feeders with individual belt feeders for each bin and with a variable speed feeder drive controlled by electrically operated actuators greatly improve the accuracy of the proportioning of the individual aggregates (Fig. 1). Adjustments in the proportioning can be made by simple push buttons and position indicators that indicate that the desired percentages are being maintained and are in constant view of the plant operator and the inspector (Fig. 2).

FIRST EXPERIMENTAL PROJECT— US-54 NEAR TORONTO

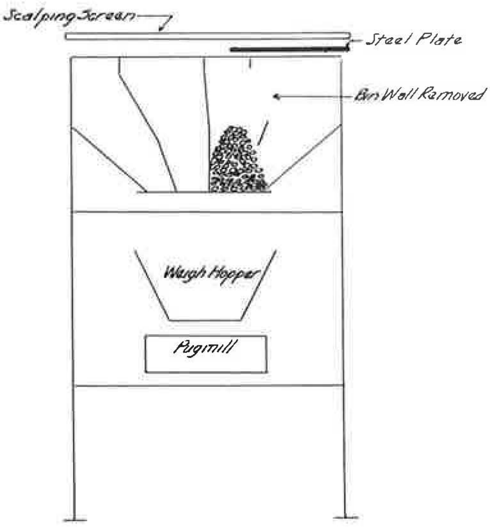

Figure 3. Bin partition and screen removal.

During the summer of 1967, a progressive and cooperative contractor requested permission to try this method on an experimental basis. The contractor had a new automatically controlled plant with a cold feeder having the features described previously. This method was tried for a period of 6 days producing both base course and surface course mixes on one project. Modification of the plant consisted of removing the screens from the screening unit with the exception of the scalper screen and placing a steel plate over approximately one-half of the bottom deck so the aggregate from the hot elevator would be delivered to and drop directly into the area being drawn off for weighing. The No. 2 bin was selected because it was more nearly centered over the weigh hopper and would permit the weighing of a full batch into the weigh hopper. Production was regulated so that the hot bin was not used for storage and was completely emptied each time a batch was weighed out. This method was chosen to prevent any segregation that might occur in the bin (Fig. 3).

Corresponding samples were taken at the cold feed and of the combined pugmill-mixed dry batch as well as samples of the bituminous mix for extraction.

The results of this experimental work were gratifying. The gradation results were comparable between the cold feed samples and the combined pugmill samples. More important, however, was the apparent uniformity of the mix from batch to batch. The uniformity of the cold feed samples as indicated by the values for standard deviation proved that excellent precision could be obtained in the proportioning of the individual aggregates with this type of cold feeder. This apparent uniformity is further borne out by the remarkable uniformity of the gradation of the extraction samples (Tables 1 and 2). We were so pleased with all aspects of this experimental operation that we began looking for a means to experiment with this type of plant processing and inspection control on an entire project.

SECOND EXPERIMENTAL PROJECT—K-68 NEAR LOUISBURG

The portion of the Standard Specifications that encourages new methods and new equipment was utilized to obtain permission to produce the bituminous base and sur-

TABLE 1

BASE COURSE MIX (ACB-3) WITHOUT SCREENS—US-54 NEAR TORONTO

Screen	Cold Feed (n = 12)		Pugmill (n = 12)		Extraction (n = 12)		Standard Deviations		
	Range	Mean	Range	Mean	Range	Mean	Cold Feed	Pug-mill	Extraction
¾	2 to 5	3.1	1 to 4	1.8	0 to 4	1.1	0.91	0.85	1.17
⅜	22 to 31	26.7	20 to 31	24.8	16 to 27	21.8	2.75	3.41	3.33
4	42 to 51	47.2	40 to 52	46.3	38 to 51	44.8	2.59	4.35	3.74
8	59 to 65	62.7	59 to 68	63.5	58 to 65	62.3	1.73	3.20	2.00
16	71 to 75	73.2	71 to 79	75.3	71 to 75	73.5	1.13	2.58	1.45
30	79 to 82	80.3	80 to 85	82.9	78 to 82	80.7	0.91	1.51	1.17
50	83 to 86	84.4	84 to 89	86.9	82 to 86	84.6	0.80	1.31	1.00
100	86 to 88	87.1	88 to 91	89.8	84 to 88	87.4	0.52	0.95	1.17
200	88 to 90	89.0	90 to 93	91.8	87 to 90	89.5	0.60	0.85	0.91

TABLE 2

SURFACE COURSE MIX (HM-3) WITHOUT SCREENS—US-54 NEAR TORONTO

Screen	Cold Feed (n = 17)		Pugmill (n = 17)		Extraction (n = 15)		Standard Deviations		
	Range	Mean	Range	Mean	Range	Mean	Cold Feed	Pug-mill	Ex-traction
⅜	12 to 25	19.8	11 to 20	16.1	14 to 19	16.3	3.16	2.35	1.44
4	38 to 47	42.2	30 to 42	37.7	37 to 43	40.5	2.84	3.67	1.73
8	52 to 60	56.2	47 to 57	52.8	54 to 58	56.1	2.32	3.20	1.42
16	63 to 69	66.0	59 to 67	63.5	64 to 68	66.3	1.73	2.72	1.10
30	73 to 78	75.1	71 to 77	74.2	73 to 77	75.7	1.32	1.80	1.17
50	83 to 87	84.6	83 to 86	85.0	83 to 86	85.1	1.00	1.12	0.96
100	88 to 91	88.9	88 to 92	90.8	89 to 92	90.4	0.97	1.20	0.84
200	90 to 92	90.8	91 to 94	93.1	90 to 93	92.1	0.79	0.87	0.80

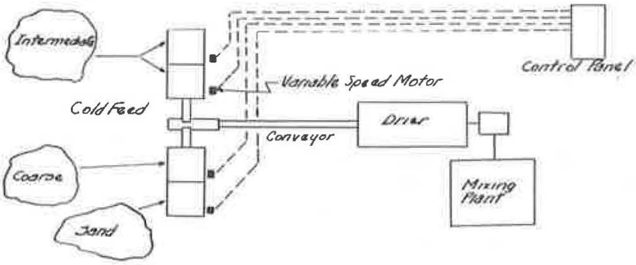

Figure 4. Asphalt plant layout.

face on a 9-mile project with the automatic batch plant and the precision cold feeder previously described. A written description of the method of plant production was submitted by the contractor and approval was granted on a performance basis. This project was constructed during the summer of 1968.

For the convenience of sampling the cold feeder, the contractor installed a stub conveyor between the blending conveyor of the cold feeder and the auxiliary conveyor leading to the dryer. This permitted the plant inspectors to take a cross section of the blended aggregates at any time without any delay or stoppage of the plant production (Figs. 4 and 5).

The batching arrangement through only one hot bin was as previously described; and again production was regulated so this bin was not used for storage, and it was emptied each time a batch was weighed out.

We were again pleased with the results of this "screenless plant operation" on an entire project. Dry, combined pugmill samples were the basis of acceptance but, with the correlation that was being obtained between the cold feed samples taken from the stub conveyor and the pugmill samples, the frequency of pugmill sampling was reduced to 2 samples per day.

The gradation results were acceptable from either location and, in terms of standard deviations, the cold feed samples were more uniform than the pugmill samples. With exceptions on only 2 screens, the standard deviation of the cold feed samples is lower or smaller than the standard deviation of the pugmill samples.

The overall variance as determined by the average or mean percentage retained on each sieve was not as great as had been expected. The only significant variation was the stack loss amounting to essentially one percent on the No. 200 sieve. The

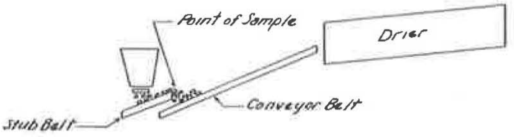

Figure 5. Cold feed sampling arrangement.

correlation samples demonstrated that adjustments can be made in the cold feed proportioning if necessary to compensate for any altering of the aggregate during plant processing (Tables 3 and 4).

The pleasing appearance and the uniformity of surface texture plus the smoothness as determined by roughometer readings were evidence that highly desirable bituminous pavements can be constructed with this method.

THIRD EXPERIMENTAL PROJECT—US-59 NEAR CHETOPA

Another project was constructed early in 1969, using the new methods and new equipment option as previously described. The same type of automatic batch plant and with variable speed cold feeder drives having remote controls was used, but the plant was owned by a different contractor. The aggregate used was a siliceous chert (commonly known as chat) and would not be subject to degradation in the drier or the pugmill. The base course aggregates were accepted at the cold feed, and pugmill samples were taken only for correlation purposes.

Control of the base course was equally as good at the cold feed as were the correlating pugmill samples.

In terms of normal distribution and standard deviations, the gradation of the extraction samples was the best, followed in this order by the cold feed and then the pugmill samples (Table 5). The gradation of the extraction samples was remarkably uniform as they had been on every project using the "screenless plant" and cold feed control. This was also indicative of the uniformity of the bituminous mix being produced with this method.

STANDARD SPECIFICATIONS

A Special Provision to the Standard Specifications was published early in 1969, and was included in the contracts beginning in June 1969. Screenless plant operation is optional with the contractor and is on a performance basis.

TABLE 3

BASE COURSE MIX (ACB-3) WITHOUT SCREENS—K-68 NEAR LOUISBURG

Screen	Cold Feed (n = 46)		Pugmill (n = 46)		Extraction (n = 7)		Standard Deviations		
	Range	Mean	Range	Mean	Range	Mean	Cold Feed	Pug-mill	Ex-trac-tion
3/8	19 to 34	23.3	15 to 29	21.0	17 to 21	19.1	2.63	3.81	1.47
4	40 to 56	47.7	38 to 54	45.6	41 to 44	42.7	2.80	3.79	1.35
8	54 to 70	64.8	51 to 70	64.0	59 to 61	60.1	2.50	3.46	0.92
16	62 to 79	75.0	60 to 79	75.3	70 to 73	71.7	2.39	3.04	0.91
30	68 to 84	81.4	67 to 85	81.8	77 to 80	78.7	2.25	2.71	0.91
50	80 to 88	85.3	80 to 88	85.8	82 to 83	82.6	1.15	1.61	0.57
100	87 to 90	88.3	86 to 91	88.9	85 to 86	85.6	0.76	1.24	0.57
200	89 to 92	90.2	88 to 93	90.9	87 to 89	88.1	1.87	1.08	0.71

TABLE 4

SURFACE COURSE MIX (HM-3) WITHOUT SCREENS—K-68 NEAR LOUISBURG

Screen	Cold Feed (n = 26)		Pugmill (n = 26)		Extraction (n = 6)		Standard Deviations		
	Range	Mean	Range	Mean	Range	Mean	Cold Feed	Pug-mill	Ex-trac-tion
3/8	17 to 27	22.0	14 to 25	20.2	16 to 22	17.8	2.57	3.21	2.57
4	40 to 47	43.3	36 to 45	41.3	39 to 41	40.2	1.88	2.56	0.77
8	51 to 59	55.2	49 to 59	53.7	52 to 54	52.8	1.66	2.62	0.77
16	60 to 67	63.4	58 to 68	61.9	60 to 62	61.2	1.77	2.37	0.77
30	67 to 73	70.4	66 to 74	69.6	67 to 70	68.5	1.57	1.81	1.00
50	78 to 86	81.8	78 to 86	82.0	77 to 84	80.2	2.78	2.55	2.79
100	89 to 92	90.2	86 to 93	90.7	88 to 91	89.7	1.08	1.37	1.00
200	91 to 93	92.4	89 to 95	93.1	91 to 93	92.0	0.20	1.17	0.63

TABLE 5

BASE COURSE MIX (ACB-1) WITHOUT SCREENS—US-59 NEAR CHETOPA

Screen	Cold Feed (n = 45)		Pugmill (n = 26)		Extraction (n = 21)		Standard Deviations		
	Range	Mean	Range	Mean	Range	Mean	Cold Feed	Pug-mill	Ex-traction
3/8	0 to 1	0.04	0 to 1	0.42	0 to 1	0.33	0.20	0.49	0.45
4	14 to 23	18.24	15 to 28	21.62	17 to 22	19.62	2.27	2.64	1.32
8	33 to 46	41.60	38 to 53	46.31	42 to 47	43.86	2.63	3.71	1.28
16	51 to 67	59.98	57 to 73	64.58	60 to 65	61.86	2.78	3.68	1.47
30	68 to 79	74.22	73 to 84	78.92	74 to 79	75.62	1.86	2.93	1.50
100	83 to 91	88.80	88 to 95	92.58	89 to 92	90.33	1.32	1.70	0.87
200	89 to 93	92.02	91 to 97	95.27	92 to 95	93.57	0.78	1.40	0.67

Individual Aggregates

The contractor shall establish gradation limits and the proportions in the final mix of each individual aggregate he proposes to furnish. The resulting combined gradation will automatically meet the gradation requirements specified in the contract. Individual aggregate shall be fed through a separate feeder that can be easily and accurately calibrated and be capable of maintaining a constant and uniform flow throughout the range of its calibration.

Combined Aggregates

A provision is required to obtain a sample of the combined aggregates prior to entering the drier. The sampling device and procedures used shall be such that the continuity of the operation will not be interrupted.

In order to determine the amount of aggregate breakdown through the drier and also to determine the stack loss, the engineer will take samples of either the dried aggregate or the mixed bituminous material. The results of tests on these samples shall be used as a basis for adjusting cold feed proportions in order to produce the required combined gradation.

Samples will be taken until a satisfactory correlation between the cold feed and the final product is obtained. Thereafter, random samples will be taken in order to verify the process. The intent of this specification is to encourage continuous production by requiring processed aggregates that can be combined with the desired precision at the cold feed. Initial correlation tests are taken to determine the alteration taking place in the plant processing, and, when this is once established, the acceptance would be based on the blended aggregate samples taken at the cold feed.

Plant Operation

Batch Plants—The discharge into the weigh hopper shall be made from one bin only, which shall discharge into the center of the weigh hopper. The amount of storage in the bin at any one time shall not exceed one batch in weight and shall be fed into the bin in such a manner so as to prevent sluffing or segregation.

Continuous Flow Plants—The storage in each bin being used shall be limited in amount so that sluffing or segregation will not occur. Each bin used shall be equipped with 2 indicators, one of which will indicate the position of the aggregate at the lower quarter points and the other will indicate the position of the aggregates in the upper quarter points.

If more than one bin is used by either type of plant, separation shall be accomplished in such a manner so as to ensure uniform flow to each bin and to preclude segregation of the total material as obtained from the individual bins.

CONCLUSIONS

On the high production plants, we believe the drier capacity and the aggregate flow exceeds the capacity of the screening unit to efficiently screen uniform sizes of aggregates in the various hot bins. Under these conditions of inefficient screening, it is detrimental to the uniformity of the bituminous mix if segregation occurs in the hot bins.

We believe the desired screening efficiency can best be accomplished at the individual aggregate production site and the desired proportioning can be accomplished with the precision of the variable speed feeder drives controlled by electrically operated actuators. The plant only processes the ingredients of the mix and necessarily turns out what is put into it.

The hot bin is necessary only for temporary storage between batches and should be emptied each time a batch is weighed out.

Continuous plant operations are essential to the uniformity of the bituminous mix. The aggregate is maintained at a more uniform temperature by continuous production.

Extraction gradation results are indicative of the uniformity of the bituminous mix produced with this method. On each project the extraction gradation results were the most uniform in terms of normal distribution and standard deviation.

The procedures used were a smooth transition to "screenless plant operations" with correlation samples being taken to ensure that the required combined gradation was being obtained. Correlation samples have demonstrated that equally consistent results can be obtained with cold feed control when compared with control by pugmill sampling.

The Special Provision to the Standard Specifications requires the contractor to furnish processed aggregate of such gradation that the resulting combined gradation will automatically meet the gradation requirements specified in the contract. These processed aggregates must be stored properly so there will be no appreciable segregation in handling or stockpiling. Keeping the aggregate stockpiles separated and orderly is good practice for any type of bituminous plant construction.

Several major projects with this Special Provision were under construction in late 1969.

REFERENCE

Evaluation of Construction Control Procedures—Interim Report. NCHRP Rept. 34, 1967.

A Study of Cessation Requirements for Constructing Hot-Mix Asphalt Pavements

CHARLES R. FOSTER, National Asphalt Pavement Association

Currently, placing of hot-mix asphalt pavement is stopped when the air temperature falls below a certain value. A more logical requirement would be to stop placing when conditions are such that the contractor will not have a "reasonable time" to compact the pavement before it cools to where it cannot be compacted. Corlew and Dickson developed a mathematical model of the loss of heat from a mat that considers laydown temperature, mat thickness, air temperature, base temperature, wind velocity, and solar flux. The model was used to produce cooling curves for mat thicknesses from ½ to 8 in., laydown temperature from 225 to 300 F, and a range of environmental conditions. The mathematical model shows that laydown temperature and mat thickness are far more important in determining how fast the mat will cool than the environmental conditions. A method is suggested whereby these data can be used to establish cessation requirements that would permit paving when the contractor would have a reasonable time to apply rolling before the mat cools and would stop paving when he does not have enough time. The suggested cessation requirements show that a requirement based on a single limiting air temperature is not adequate to ensure that paving is permitted only when conditions are satisfactory. Laydown temperature and mat thickness must be considered as well as the environment. The data also show clearly the need to apply breakdown rolling as quickly as practicable to ensure quality pavements.

•CURRENTLY CESSATION REQUIREMENTS for constructing hot-mix asphalt pavements are based on air temperature (except for a very few agencies that use base temperature); paving is permitted when the temperature is above a certain value and stopped when the temperature is below a certain value. These requirements are based on historical experience and are intended to regulate construction so that paving is permitted only when conditions are favorable for obtaining a satisfactory job. The principal criteria for a satisfactory job are smoothness, including surface texture, and density. To obtain satisfactory density, the mat must be rolled before it has cooled too much.

There is ample evidence in the technical literature to show that the initial or breakdown rolling produces most of the density. It is also a fact of life that it takes a certain time to apply the breakdown rolling. The National Asphalt Pavement Association proposes that cessation requirements based on conditions that will ensure that the contractor has a "reasonable time" to apply the breakdown rolling would be much more logical than cessation requirements based only on air or base temperature.

This paper describes the procedures being used to explore this new concept in cessation requirements and illustrates the procedure.

NECESSARY DATA

To prepare cessation requirements based on a "reasonable time" to apply the breakdown rolling, one needs information on (a) the rate at which the mat cools; (b) what is a "reasonable time" for applying breakdown rolling; and (c) the temperature below which breakdown rolling is not effective in producing compaction.

Paper sponsored by Committee on Construction Practices—Flexible Pavement and presented at the 49th Annual Meeting.

AVAILABLE DATA

TABLE 1

RELATIONSHIP OF BASE TEMPERATURE, AIR TEMPERATURE, AND SOLAR FLUX

Base Temperature (deg F)	Air Temperature (deg F)	Solar Flux (Btu/sq ft/hr)
10	10	50
20	20	50
30	30	50
40	40	50
50	50	50
60	60	50
80	70	100
100	80	200
120	90	200

Corlew and Dickson (1) developed a mathematical model of the loss of heat from a mat. The model considers laydown temperature, mat thickness, air temperature, temperature on which the mat is being placed (called base temperature in this paper), wind velocity, solar flux (heat from sun), specific heat of the layers, and transfer coefficients between the mat and the underlying layer and between the mat and the air. The model was checked with actual measurements, and there was good agreement.

Corlew and Dickson's work shows that laydown temperature and mat thickness are far more important in determining the time it will take for a mat to cool than any of the other variables, and these are the primary variables in this study. Thicknesses from ½ to 8 in. and laydown temperatures from 225 to 300 F were selected to cover the range of anticipated values.

Base temperature was selected as the other principal variable, and air temperature and solar flux fitted the base temperature as given in Table 1. It is believed that air temperature and solar flux given in Table 1 will generally be more favorable than the values for a given base temperature. For example, the solar flux of 50 Btu/sq ft/hr shown for base temperatures below 60 F is the flux that would occur under a complete cloud cover during the winter. To achieve base temperatures in the 80 to 120 F range, it is necessary to have higher solar fluxes, as indicated in the table, and the base temperature will be higher than the air temperature. A wind velocity of 10 knots was selected as the average condition; however, 20 knots was used in certain computations. Higher velocities were not considered as construction activities would probably be stopped when the wind exceeded about 30 knots.

Average values were selected for the specific heat and transfer coefficients as suggested by Corlew and Dickson.

The Colorado School of Mines has made the computations of cooling curves for the conditions described. The curves will be presented in a technical paper by Corlew and Dickson in another journal and are thus not repeated here. The paper by Corlew and Dickson will give details on the mathematical model, selected coefficients, and methods of computations.

In November 1968, a questionnaire was circulated to members of the NAPA Quality Improvement Committee and NAPA Governors requesting information on the time, temperature, and number of passes applied in breakdown rolling. Replies were received from 25 states. These are given in Table 2.

TABLE 2

SURVEY ON BREAKDOWN ROLLING

Condition	Surface Binder, Leveling		Hot-Mix Asphalt Base	
	Range	Avg.	Range	Avg.
Time—laydown to first pass, min				
Normal	0.5 to 15	6	—	—
Minimum practicable	0.5 to 8	3	—	—
Temperature, deg F				
At start of rolling	225 to 300	273	200 to 300	265
At end of rolling	130 to 275	223	130 to 260	214
Roller passes for breakdown	1 to 7	3.1	1 to 6	3.4
Time required to apply rolling, min				
Normal	3 to 60	11	3 to 120	21
Minimum practicable	2 to 10	6	2 to 90	15

REASONABLE TIME FOR APPLYING BREAKDOWN

The replies to the questionnaire (Table 2) indicate that breakdown rolling ranges from 1 to 7 passes and averages about 3 passes. In the meeting of the Quality Improvement Committee held February 2, 1969, it was concluded that the amount of rolling applied during breakdown should increase with the thickness of lift and as a start 2 roller passes would be used for lifts $1\frac{1}{4}$ in. in thickness or less and 3 roller passes for thicker lifts. A roller pass is defined as the entire roller going by a given spot in the lane.

The respondents to the questionnaire indicated the average minimum time to complete breakdown rolling was 9 min (3 min before the first pass and 6 min to apply rolling). In the NAPA Quality Improvement Committee deliberations on February 2, 1969, it was felt 2 times would be reasonable; a long time that could be used for normal and thick lift construction and a shorter time that would be applicable to thin lift construction. It was recognized the shorter time might require multiple breakdown rollers or reduced paver speeds. After considerable deliberation it was concluded that 15 min (3 min before application of the first pass and 12 min to apply the rolling) was reasonable for the longer time period. For the shorter time period, it was the consensus that 5 min for application of the rolling was about as fast as could be expected. There was also discussion regarding reducing the 3 min interval between the laydown and first pass, but after considerable discussion it was decided to retain the 3-min time interval. Thus, the "reasonable times to apply breakdown rolling" selected by the NAPA Quality Improvement Committee were 15 min for thicker lifts and 8 min for thinner lifts. As it turns out no specific delineation is needed because the 8-min time could be used for any thickness of lift if rollers were available that could accomplish the required compaction in 8 min.

CUT-OFF TEMPERATURE

The respondents to the questionnaire indicated that on the average breakdown rolling was completed by the time the mat had cooled to 223 F. This temperature appears to be high when the cooling curves and time for rolling are considered. Also, such a high cut-off temperature is not believed warranted. Kilpatrick and McQuate (2) show a curve of density versus average breakdown temperature. Density did not increase much when the average breakdown temperature exceeded 200 F. It should be noted that this was the average, not the value at the end of breakdown rolling.

The members of the NAPA Quality Improvement Committee discussed this subject at length and finally agreed to suggest a 175 F cut-off temperature for initial consideration.

ILLUSTRATION

The method of developing cessation requirements under this new concept is illustrated in the remainder of this paper. It is emphasized that the figures present an illustration of the concept and not recommended cessation requirements. It is NAPA's desire in presenting this illustration to stimulate state highway departments to conduct field trials to check the validity of cessation requirements based on these new concepts.

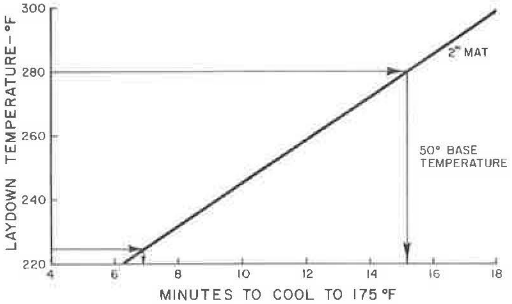

Figure 1. Effect of laydown temperature.

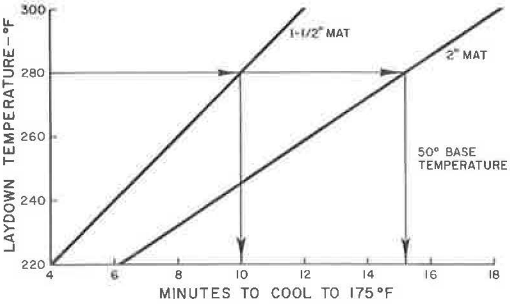

Figure 2. Effect of mat thickness.

Figure 1 shows a plot of laydown temperature versus time to cool to 175 F for a 2-in. mat at a 50-deg base temperature replotted from the curves prepared by Corlew and Dickson that illustrate the effect of laydown temperature. For example, if the mat hits the road at 280 F, a normal temperature, it will take a little better than 15 min for it to cool to 175 F. If, however, laydown is delayed by truck or paver breakdown or any other reason so that the mat hits the road at 225 F, an often quoted lower allowable limit, it will cool to 175 F in about 7 min, half the time as before. It is obvious that laydown temperature is an important variable in determining the time available to apply rolling before the mat cools so much that it cannot be compacted.

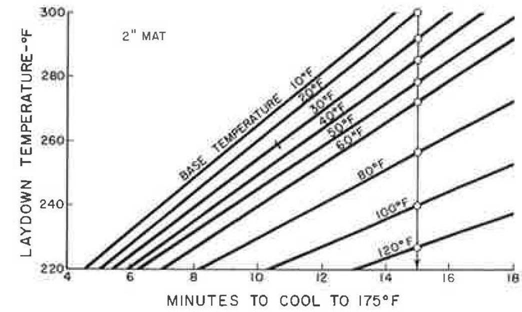

Figure 3. Effect of base temperature.

Figure 2 shows a plot of cooling curves for $1\frac{1}{2}$- and 2-in. mats that illustrate the importance of mat thickness on time available for rolling before the mat cools. The 2-in. curve is the same as shown in Figure 1. For the same conditions of laydown temperature and base temperature, the contractor will have considerably longer to roll the 2-in. mat than the $1\frac{1}{2}$-in. mat before both cool so much they cannot be compacted. For a 280-deg laydown temperature the difference is about 5 min.

Figure 3 shows the effect of base temperature on the time required for a 2-in. mat to cool to 175 F. A 10-deg change in base temperature will produce about a one-minute change in the time for the mat to cool to 175 F when the laydown temperature is in the order of 280 deg. (The circles shown in Figure 3 will be explained later.)

Figure 4 shows the effect of wind velocity on time required for a 2-in. mat placed on a 50-deg base to cool to 175 deg. It can be seen that a 20-knot wind reduces the time by only about 2 min. All the remaining data presented in this discussion are for a 10-knot wind velocity.

Figures 3 and 5 together show the method of preparing cessation requirements. The illustration is for a 2-in. mat and a 15-min rolling time. Each of the circles shown in Figure 3 represents a condition of laydown temperature and base temperature that will provide 15 min before the mat cools to 175 F. The conditions of laydown temperature and base temperature at each of the circles shown in Figure 3 were replotted in Figure 5 with laydown temperature plotted against base temperature. The points line up almost in a straight line. The deviations from the straight line are caused by use of 200-Btu/sq ft/hr solar flux for both 100 and 200 F base temperatures. The straight line shown in

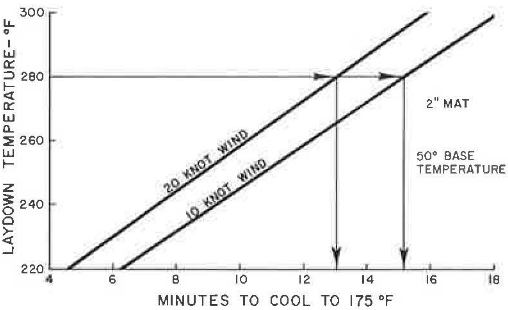

Figure 4. Effect of wind velocity.

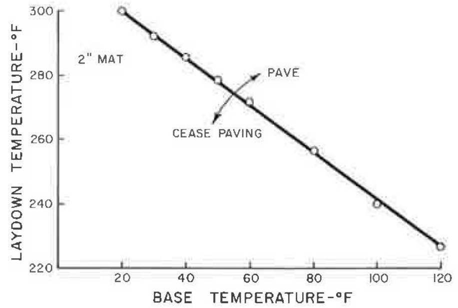

Figure 5. Illustration of suggested cessation requirements—15-min rolling time, 2-in. mat.

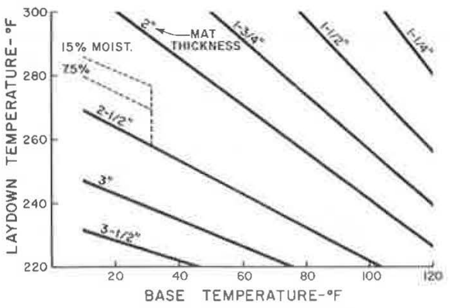

Figure 6. Illustration of suggested cessation requirements—15-min rolling time, various mat thicknesses.

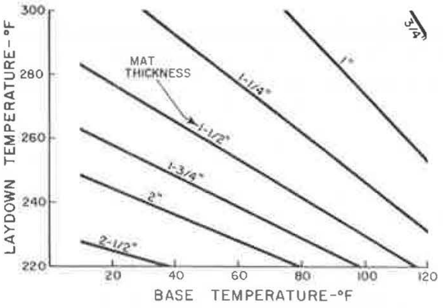

Figure 7. Illustration of suggested cessation requirements—8-min rolling time, various mat thicknesses.

Figure 5, which was fitted to the points by eye, represents laydown and base temperatures that will result in 15 min before the mat cools to 175 F. Conditions above the line will provide more than 15 min, and the contractor should have a high probability of achieving satisfactory density; hence, this area is designated as "pave." Combinations of laydown temperature and base temperature below the line will result in a condition where the mat will cool to 175 F in less than 15 min, and thus the chances of obtaining adequate density are poor. Thus, the area below the line is designated as "cease paving."

Figures 6 and 7 show suggested cessation requirements for a range of mat thicknesses. Figure 6 shows "15-min" rolling time and Figure 7 shows "8-min" rolling time. The 8-min rolling time may require multiple rollers if high paver speeds are achieved. The line for each mat thickness represents a suggested cessation requirement for that mat thickness; paving would be permitted for laydown and base temperatures above the line, but paving would be stopped when the combination of base temperature and laydown temperature fell below the line.

The solid lines shown in Figures 6 and 7 below 32 F represent laydown temperatures where the mat is placed on an existing pavement or dense hot-mix asphalt base that contains no frozen moisture. Since the paper was prepared, computations have been made for frozen subgrades and bases containing frozen moisture. Additional heat is necessary in the form of higher laydown temperatures for these cases. The dashed lines in Figure 6 show that the laydown temperature for a $2\frac{1}{2}$-in. mat must be raised about 10 deg for a moisture content of 7.5 percent (typical of a base course) and almost 20 deg for a moisture content of 15 percent (typical of a subgrade).

It may be noted that Figure 7 shows that mats less than 1 in. thick will cool to below 175 deg in 8 min even when placed on very warm bases. At the present time we are not able to establish tentative cessation requirements for very thin lifts. We would like to point out that miles of thin lifts are built each year and they generally give satisfactory service. Possibly a lower cut-off temperature or fewer passes of the breakdown roller would be adequate for very thin lifts. There is also the distinct possibility that very thin lifts are not compacted thoroughly during construction. Construction rolling on thin lifts may be primarily a smoothing operation with actual compaction left to traffic. The raveling that occurs fairly frequently in thin lifts placed late in the construction season lends credence to this latter thought.

SUMMATION

This paper illustrates a suggested method of establishing cessation requirements that incorporates the very important factors of laydown temperature and mat thickness. This illustration is presented primarily to stimulate state highway departments to conduct trials of this new concept.

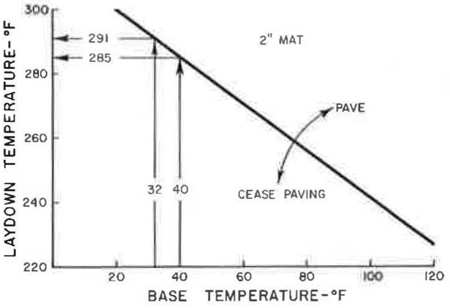

Figure 8. Illustration of change in laydown temperature required to compensate for change in base temperature.

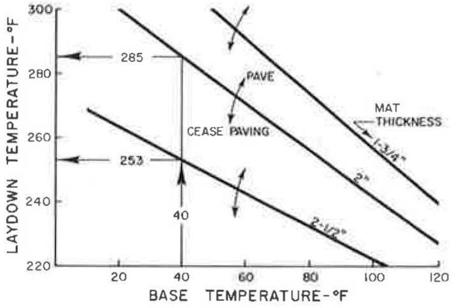

Figure 9. Illustration of change in laydown temperature required to compensate for change in mat thickness.

Although this paper is presented as an illustration, even a casual study of the data will show that cessation requirements based on air temperature or base temperature alone are not reasonable. For example, Figure 8 shows that when the base and air temperature are at 40 deg a 2-in. mat can be placed at 285 deg. By raising the laydown temperature only 6 deg, to 291 deg, the mat could be placed at 32 deg and the contractor would still have the same time to apply breakdown rolling before the mat cools.

The inadequacy of a single limiting air temperature, in this case 40 deg, is further shown in Figure 9 for 2½-, 2-, and 1¾-in. mats. The 2½-in. mat could be placed as low as 253 deg, whereas the 2-in. mat would have to be placed at 285 deg. The 1¾-in. mat would have to be placed at 308 deg, which would probably be impossible because of limitations on mixing temperatures.

It is apparent that cessation requirements are needed that include consideration of the laydown temperature and mat thickness as well as the environment. It is believed that the concept we are proposing has merit. It is further believed that the model developed by Corlew and Dickson has sufficient validity at the present time to warrant moderate modifications in existing cessation requirements such as permitting thick lift placement in cold weather.

Finally, we believe this study will bring home to the contractor, and all concerned, the necessity to apply the breakdown rolling as rapidly as practicable to ensure quality pavements.

REFERENCES

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2. Kilpatrick, M. J., and McQuate, R. G. Bituminous Pavement Construction—A Compilation of Data and Conclusions from Staff Research Studies of Bituminous Pavement Compaction Equipment, Construction Methods, and Nondestructive Test Procedures. U.S. Department of Transportation, June 1967.

The Effect of Paver Speed on Roller Requirements

CHARLES R. FOSTER, National Asphalt Pavement Association

The specifications of many agencies base the number of rollers required on an asphalt paving job on the tons of mix laid per hour. Others have shown that thick lifts are easier to compact than thin lifts, and thus additional rollers are not needed just because the lift is thick, a common condition that produces a high rate of laydown in terms of tonnage. Other authorities have noted that, if density is to be obtained during rolling, the initial rolling, usually called the breakdown rolling, must be applied before the mat has cooled below a certain temperature. Thin mats cool faster than thick mats; also, thin mats permit faster paving speeds than thick mats for a given number of tons per hour of production. It appears logical that roller requirements should ensure that the mat can be rolled before it cools too much. The time required to roll a given area of pavement with a roller operating at a given speed can be computed. Because the paver operation is continuous, the paver moves ahead while the mat just laid is being rolled out. If the paver is moving slow enough the roller can keep up, but if the paver is moving too fast it will leave the roller behind. A formula is presented for mating the paver speed with the roller so that the roller can just keep up with the paver. Charts are presented, based on the formula, for applying 2, 3, and 4 passes of breakdown rolling with 1, 2, and 3 rollers within time periods up to 18 minutes (most mats will have cooled too much by then). The findings by others cited in the paper plus the computations presented in the paper justify the conclusion that roller requirements should be based on paver speeds rather than tonnage rates.

•THE SPECIFICATIONS on hot-mix bituminous pavements used by many agencies call for additional rollers when the rate of laydown exceeds a certain number of tons per hour. These requirements may have been justified before thick lifts came into the picture but Beagle (1), Minor (2), and others have shown that thick lifts are easier to compact than thin lifts. Therefore, thick lifts that produce high rates of laydown do not require additional rollers.

Data reported by Kilpatrick and McQuate (3), Zube (4), and others show that most of the density obtained during rolling of hot-mix pavement is produced by the breakdown rolling and that breakdown rolling is effective only if applied before the mat has cooled below a certain temperature. It appears logical that roller requirements should ensure that the mat can be rolled the desired number of passes before it cools. Expressing roller requirements in terms of paver speed will ensure that rolling can be accomplished within a given period of time.

Paper sponsored by Committee on Construction Practices—Flexible Pavement and presented at the 49th Annual Meeting.

This paper presents theoretical computations that show the dependence of roller requirements on area laid per unit of time rather than tonnage per unit of time. The case is illustrated in terms of paver speed as "area laid per unit of time."

PAVER SPEED VERSUS AVAILABLE ROLLING TIME

The theoretical time required to roll a given length of hot asphalt pavement being laid by a paving machine can be computed as follows:

$$T = \frac{LrM}{Rs} + V \tag{1}$$

where

T = time, min, to roll length, Lr;
Lr = length being rolled, ft;
M = total number of times the roller moves length, Lr, in applying the required number of roller passes;
Rs = roller speed, ft/min; and
V = time, min, spent in reversing the roller.

Normally, the roller moves ahead with each pass; however, in these computations it is assumed that the length being rolled, Lr, is rolled out before the roller advances. Rolling time is dependent only on the length being rolled, the time spent in reversing the roller, and roller speed. Rolling out a length before advancing the roller would increase the time between the laydown and application of the first pass of the roller but would not increase the rolling time.

The paver operation is continuous, at least the paving crew tries to keep the paver moving continuously, so the paver moves ahead while rolling is being applied. The distance the paver moves ahead while length, Lr, is being rolled out is simply the product of the paver speed and the time required to roll out length, Lr.

$$Lp = PsT \tag{2}$$

where

Lp = length paver moves while length, Lr, is being rolled out, ft;
Ps = paver speed, ft/min; and
T = time, min, required to roll out length, Lr.

If Lp is less than Lr, the roller will have time to apply the required number of passes and sit idle for a few moments; but if Lp is larger than Lr, the paver will go off and leave the roller. The paver and roller can be mated, at least theoretically, by setting

$$Lr = Lp$$

Then Eq. 1 becomes

$$T = \frac{PsTM}{Rs} + V \tag{3}$$

which reduces to

$$T = \frac{VRs}{Rs - PsM} \tag{4}$$

Computations of theoretical relationships between paver speed and available rolling time are presented for the conditions listed in subsequent paragraphs.

Roller and Lane Width

This author has previously reported (5) that the 8- to 10-ton tandem steel roller is used more for breakdown rolling than any other roller; therefore, these computations are based on the use of an 8- to 10-ton tandem roller. They could be made for any other breakdown roller. The normal width of the rolls on the 8- to 10-ton tandem roller is 54 in. This means that 3 roll widths are required for any lane width more than 9 ft and less than 13.5 ft. Because this covers the widths used most frequently, these computations are based on the assumption that 3-roll widths will be required to cover the lane being paved. With this assumption, the width of the lane being rolled is not important, and only one dimension of area, the length, is used in the presentations.

Roller Passes for Breakdown

This author has also reported (5) that breakdown rolling required by the various agencies ranges from 1 to 7 passes and averages 3.2. Computations are presented here for 2, 3, and 4 passes. A roller pass is defined as one movement of the roller past a given spot on the pavement. Because the computations are for a tandem roller, this means that each spot will be hit with 2 roller drums.

Roller Speed

Most agencies limit the roller speeds to 3 or 4 mph, and a speed of 3.5 mph is used in these computations. This is a speed of 308 ft/min. The effect of speeds of 3 and 4 mph is illustrated in one case.

Total Number of Roller Movements

At first glance it would appear that the total number of movements of the roller would be 3 times the required number of passes because 3 drum widths are required to go across the lane. This is true for an odd number of passes, but for an even number of passes the roller completes the rolling away from the paver and the roller has to deadhead back to start rolling a fresh length. This adds an additional pass.

Multiple rollers present an interesting problem. The shortest rolling time occurs when the rolling is equalized, to the extent possible, among the rollers and no rollers have to deadhead back. Rolling patterns were developed where the required number of passes over each spot in the lane could be applied with the following total movements of the roller making the most movements. Possibly more efficient plans can be developed.

Passes Over Each Spot	Number of Rollers	Total Roller Movements
4	1	13
	2	7
	3	5
3	1	9
	2	5
	3	3
2	1	7
	2	3
	3	3

Reversal Time

The number of reversals the roller must make is always one less than the total number of roller movements. In these computations it is assumed that each reversal adds 1/6 min to the rolling time.

COMPUTATION OF PAVER SPEED VERSUS ROLLING TIME

The appropriate values for each of the conditions listed can be put into Eq. 4 for computation of paver speed versus rolling time. The case for 3 passes over each spot with 2 rollers is used for illustration.

M, total roller movements = 5
V, reversal time, 4 reversals × $\frac{1}{6} = \frac{4}{6} = \frac{2}{3}$ min
Rs, roller speed = 308 ft/min

$$T = \frac{\frac{2}{3} \times 308}{308 - 5Ps},\ T = \frac{205.33}{308 - 5Ps},\ T = \frac{41.07}{61.6 - Ps}$$

Inspection of this formula reveals that, when the paver speed reaches 61.6 ft/min, T becomes infinity so this sets an absolute upper limit on paver speed. Also, when the paver speed is zero, $T = \frac{2}{3}$ min, the time allotted for reversals.

Figure 1 shows the relationship between paver speed and available rolling time for the case being illustrated, 3 passes applied with 2 rollers. The bold curve is for a roller speed of 3.5 mph; the 2 partial curves are for 3 and 4 mph. Combinations of paver speeds and rolling times below any one curve will result in conditions where the rollers can more than keep up with the paver, but combinations of paver speeds and rolling times above a specific curve will result in the paver going off and leaving the rollers. For example, assume a rolling time of 5 min and a roller speed of 3.5 mph. At a paver speed of 40 ft/min the paver will move 200 ft while the rollers are applying the required 3 passes to each spot in the lane. As noted previously, one roller has to apply 5 passes to accomplish this, which requires 4 reversals. The reversals use up 0.67 min of the rolling time. So the roller has to make 5 passes, each 200 ft long or 1,000 ft in 4.33 min. At 3.5 mph the roller makes 308 ft/min and in 4.33 min can travel 1,333 ft, well beyond the amount required. For an example above the curve, consider a paver speed of 60 ft/min and a time of 5 min. In 5 min the paver will move 300 ft, and the roller will have to roll 1,500 ft in 4.33 min. It cannot do this at 3.5 mph (308 ft/min × 4.33 = 1,333 ft), and the paver will go off and leave the roller.

The partial curves for 3 and 4 mph indicate that a change in roller speed of ½ mph is about the same as a change in paver speed of from 7 to 8 ft/min.

Figures 2, 3, and 4 show plots similar to Figure 1 for 4, 3, and 2 passes over each spot in the lane at a speed of 3.5 mph. The scale of paver speeds up to 100 ft/min was used to illustrate that even with multiple rollers the curve flattens out indicating a maximum paver speed. The scale for rolling time was cut off at 18 min because the curves had flattened out at this time, and using a large scale for rolling time gave better definition of the curve at short times. It is believed the paver speeds and rolling

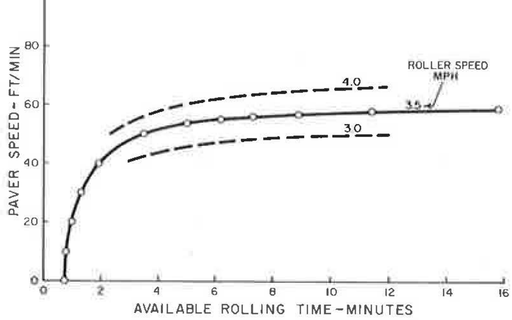

Figure 1. Maximum paver speed versus available rolling time—3 passes over each spot in lane, 2 breakdown rollers.

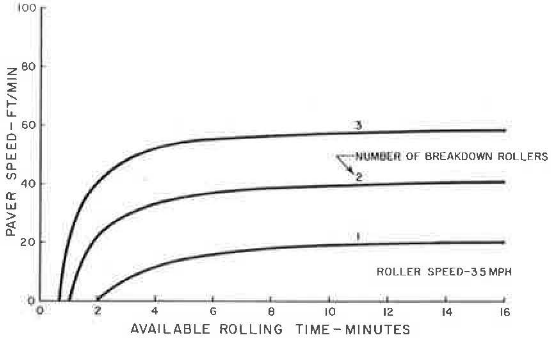

Figure 2. Maximum paver speed versus available rolling time—4 passes over each spot in lane.

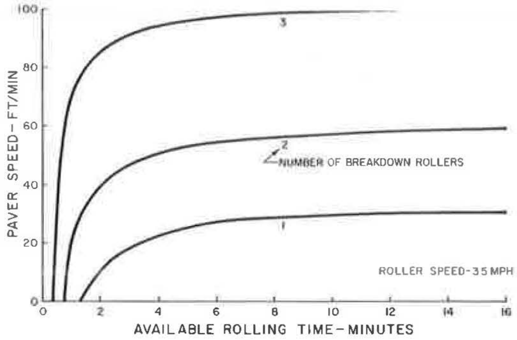

Figure 3. Maximum paver speed versus available rolling time—3 passes over each spot in lane.

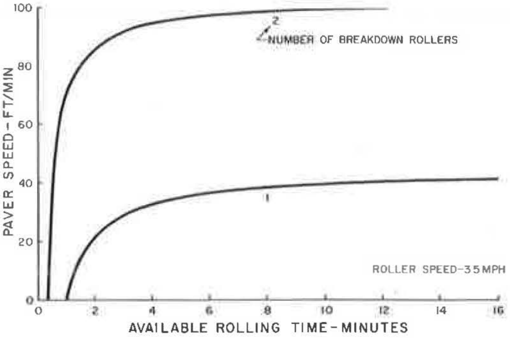

Figure 4. Maximum paver speed versus available rolling time—2 passes over each spot in lane.

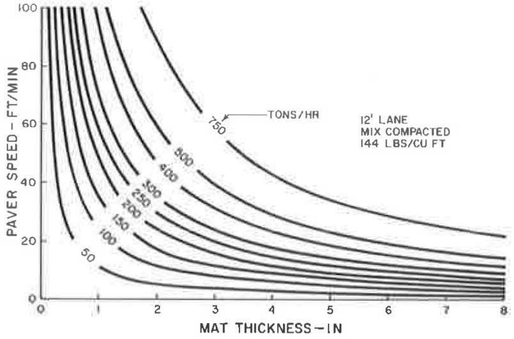

Figure 5. Maximum paver speed versus mat thickness.

times shown on the figures cover the range of conditions that will be pertinent in actual construction.

The curves in Figures 2 through 4 show fairly dramatically that if the mat is to be rolled within a given time period then roller requirements are dependent on paver speed. For example, in Figure 3, if only one breakdown roller is used, the roller will fall behind if the paver speed exceeds about 30 ft/min. If 2 breakdown rollers are used, they can keep up at paver speeds in the order of 55 to 60 ft/min, and with 3 rollers, the paver can go all out.

The paver speed for this purpose should be considered the average paver speed, which would include time spent in short stops because the roller does not normally stop when the paver makes a short stop.

PAVER SPEED—MAT THICKNESS—TONNAGE

Figure 5 shows the relationship between paver speed and mat thickness for selected tonnage rates ranging from 50 to 750 tons per hour presented in the manner suggested by Masters (6). Tonnage rates normally range from 50 to about 300 tons per hour for one laydown machine. The rate of 750 tons per hour is probably beyond the capacity of laydown with a single machine because of logistic problems of getting the mix delivered into one machine.

Figure 5 shows that high paver speeds cannot be maintained for thick lifts. For example, to place a 4-in. lift at even 20 ft/min requires in the order of 350 tons per hour. However, high paver speeds can be maintained for thin lifts. For example, 200 tons per hour will supply mix for laying a $\frac{3}{4}$-in. mat at a little better than 60 ft/min. The data shown in Figure 5 together with the data previously presented illustrate that thick lifts do not require additional rollers to complete compaction before the mat cools.

CONCLUSION

The findings presented by others that thick lifts are easier to compact than thin lifts, that breakdown rolling produces most of the density, and that breakdown rolling has to be applied before the mat cools to be effective plus the computations presented here justify the conclusion that roller requirements should be based on "area laid per units of time" such as paver speeds rather than tonnage rates.

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Effect of Aggregate Type on the Properties of Shrinkage-Compensating Concrete

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Expansive cement concretes, if adequately restrained by reinforcing steel, can minimize or prevent the development of cracks due to drying shrinkage. Such concretes are referred to as shrinkage-compensating. Reported are results of an investigation undertaken to determine the effect of aggregate type on the properties of shrinkage-compensating concretes. Included in this study were 3 types of natural aggregates and one lightweight aggregate. Two types of cement were used. One was the shrinkage-compensating cement that was a blend of 15 percent by weight of calcium sulfoaluminate expansive component and 85 percent of type V portland cement. The second cement used in the control concretes was 100 percent type V portland cement. The expansion and shrinkage characteristics of the shrinkage-compensating concretes were determined for both restrained and unrestrained prisms. Compressive strength and modulus of elasticity were determined for unrestrained cylindrical specimens. All concretes had a cement content of 5.5 scy and a water-cement ratio of 0.58 by weight. With these fixed mix proportions, the slump of the concretes with the 4 different types of aggregate varied from 2 to 4 in. From the results of this investigation it is concluded that the aggregate type is an important factor in the properties of a shrinkage-compensating concrete. Shrinkage-compensating concrete mixes must be so designed that their restrained expansion is of sufficient magnitude to compensate for the potential shrinkage of the concrete containing a certain type of aggregate. The expansion and shrinkage behavior of a shrinkage-compensating concrete is related to its modulus of elasticity. Concretes of high elastic modulus exhibit a larger expansion than do concretes of lower modulus of elasticity.

•SHRINKAGE-COMPENSATING CEMENTS, now being produced by several manufacturers in the United States, are used in various types of concrete construction. California, Connecticut, Ohio, and Wisconsin have constructed concrete pavement sections with shrinkage-compensating cement (1). Other uses of concrete utilizing shrinkage-compensating cement included, for example, a folded-plate roof in Yuba City, California (2), floors of several large commerical buildings, a motel, and a municipal pumping station (3). The expansive cement developed by Alexander Klein (4), of the University of California at Berkeley, is designated by ACI Committee 223 as type K. A number of review papers and reports covering the properties and uses of expansive cement concretes have been published (5, 6, 7). ACI Committee 223 is currently preparing a comprehensive report on expansive cement concretes (8) that will be published by the American Concrete Institute.

The benefits obtained from the use of shrinkage-compensating cements are derived from the expansion of the concrete. If this expansion, which takes place during the early ages of curing, is restrained by reinforcing steel, the steel goes into tension and

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the concrete into compression. On drying the concrete shrinks causing a relief of the precompression rather than the development of tensile stresses as is the case in conventional concrete. When the drying shrinkage is essentially complete, a properly designed shrinkage-compensating concrete will remain under a slight compression thus reducing cracking.

The rate and magnitude of expansion are influenced by several factors including the chemical composition and fineness of the expansive cement, richness of mix, conditions of curing, and degree and type of restraint. These and other factors have been investigated and reported (9). One of the most important factors affecting not only the expansion characteristics of the concrete but also its drying shrinkage is the aggregate. Carlson (10) has shown that the drying shrinkage of concrete, which is but a fraction of that of neat cement paste, is greatly influenced by the compressibility of the aggregate and the volume change of aggregate due to drying. The maximum size, grading, shape, and surface texture of the aggregate also have an effect on the shrinkage of the concrete. Pickett (11) has developed an equation for shrinkage of concrete as a function of the shrinkage of the cement paste, volume of aggregate in the mix, and the elastic constants of the aggregate and of the concrete mix. Hansen and Nielsen (12) have extended this theory by including the effect of shrinkage of aggregate and modulus of elasticity of cement paste and aggregate.

SCOPE OF INVESTIGATION

The objective of this investivation was to evaluate the influence of the nature of aggregate used on the physical and mechanical properties of shrinkage-compensating concrete. Three types of natural aggregates and one lightweight aggregate were employed. To permit a direct evaluation of the effect of type of aggregate, all concretes employed contained the same volume of aggregate per unit volume of concrete. The expansion of the concrete during its 14-day curing period and the drying shrinkage during storage at 50 percent relative humidity and 70 F was determined for restrained as well as unrestrained concrete prisms. Compressive strength and modulus of elasticity were determined for each concrete at ages of 3, 7, 14, and 28 days. As a control mix for each type of aggregate a type V portland cement was used. The strength and drying shrinkage of the concrete made using this cement were determined and used as a reference.

Although only a single concrete mixture (identical cement factor, w/c ratio, and aggregate volume) was employed, similar trends as those reported in this study should be expected for other mixes.

MATERIALS AND TEST SPECIMENS

Cements

Two types of cement were used. One was the shrinkage-compensating cement that was a blend of 15 percent by weight of calcium sulfoaluminate expansive component, made at the University of California (4, 13), and 85 percent of type V portland cement of the following compound composition: C3S = 55 percent, C2S = 25 percent, C3A = 3.4 percent, and C4AF = 8.9 percent. A portland cement low in C3A content was selected, as previous research (9) has established that the lower the C3A content of the portland cement (15) the greater the expansion of the expansive cement. Furthermore, the composition and expansion of the shrinkage-compensating cement used in this study are similar to the commercially produced shrinkage-compensating cement.

The second cement, which was used for the control concrete mixes, was 100 percent type V portland cement of the same composition as that used in the shrinkage-compensating cement.

Aggregates

Three natural coarse aggregates of $^3/_4$-in. maximum size and a lightweight aggregate of $^5/_8$-in. maximum size were used. The natural coarse aggregates were selected on the basis of their influence on the shrinkage characteristics of concrete. One of these coarse aggregates was crushed granite, which produces concretes of low shrinkage

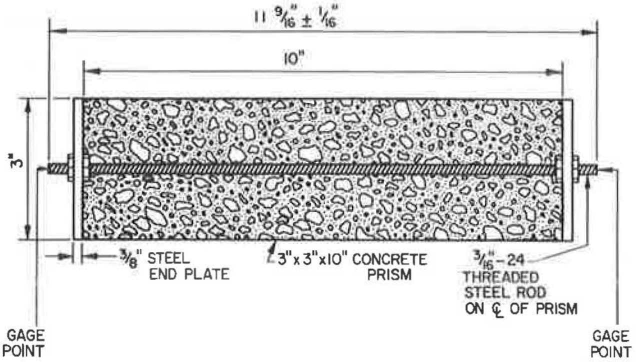

Figure 1. Restrained concrete prism.

characteristics. Its specific gravity was 2.87 and its absorption was 0.9 percent. The second coarse aggregate, also producing concretes of low shrinkage characteristics, was a river gravel of relatively smooth rounded shape. Its specific gravity was 2.80 and absorption was 0.7 percent. The main rock types present in this aggregate were basalt, andesite, dacite, and quartz. The fine aggregate used with these 2 coarse aggregates was a well-graded quartz sand with an F. M. of 2.76, specific gravity 2.60, and absorption of 1.3 percent. The third natural aggregate, both coarse and fine (F. M. 2.60), was a partially crushed river aggregate, primarily sandstone and graywacke, which produces concretes of relatively high shrinkage characteristics. Its specific gravity was 2.67, and its absorption was 1.4 percent. These 3 natural aggregates are hereinafter designated as granite, river gravel, and sandstone aggregate.

The lightweight aggregate, both coarse and fine, was an expanded shale produced by calcining crushed shale in a rotary kiln, resulting in a rounded hard-coated product. The 5/8-in. maximum size coarse aggregate had a specific gravity of 1.28 and absorption of 14.5 percent; and the fine expanded shale aggregate (F. M. 2.18) had a specific gravity of 2.12 and absorption of 10.5 percent. This expanded shale aggregate is hereinafter designated as lightweight aggregate.

Concretes

In designing the concrete mixes for the 4 different types of aggregates, it was essential to select proportions resulting in a fixed volume of aggregate per unit volume of concrete to permit a direct comparison of the effect of type of aggregate on properties of shrinkage-compensating concrete. The final mix selected had a cement content of 5.5 scy and water-cement ratio of 0.58 by weight. With the fixed volumes of aggregate, cement, and water, the slump was allowed to vary from 2 to 4 in. (3.0 ± 1 in.). The nominal unit weight of the concretes containing the natural aggregates was 152 pcf and of the lightweight aggregate concretes 105 pcf.

Test Specimens

The expansion and the drying shrinkage characteristics of the concrete were determined on both restrained and unrestrained 3- by 3- by 10-in. prisms. The restrained prisms, as shown in Figure 1, had an embedded 3/16-in. threaded rod (24 threads per in.) with end plates providing 0.30 percent of steel in the longitudinal direction.

The ends of the threaded rod were furnished with a gage point for length measurements. The unrestrained prisms had only a gage plug in each end for length measurements. After casting, the prisms were stored in a fog room, the sides of the prism molds were removed at age 8 hours, an initial length measurement was taken, and the prisms on their base plates (to prevent damage to the weak concrete) were stored in lime-saturated water. The base plates were removed after 24 hours. All prisms were water-cured for 14 days and then transferred to a low humidity room maintained at 70 F and 50 percent relative humidity. Measurements of expansion during water-curing and shrinkage during storage in the low humidity room were taken at frequent intervals.

Compressive strength and modulus of elasticity were determined on unrestrained 3- by 6-in. cylindrical specimens at ages of 3, 7, 14, and 28 days. After casting, these specimens were stored in a fog room, molds removed after 24 hours, and the specimens then stored in lime-saturated water up to age of test.

TEST RESULTS

Summarized herein are the test results obtained for shrinkage-compensating concretes made with 4 different aggregates and for corresponding control mixes containing type V portland cement. Included are compressive strength, modulus of elasticity, and the expansion and shrinkage behavior of the shrinkage-compensating concretes. A minimum of 3 specimens was used to determine the relationships presented for any one mixture. The cement content of all concretes was 5.5 scy, the water-cement ratio was 0.58 by weight, and their slump was 3 ±1 in.

Compressive Strength

Results of compressive strength tests on the concretes up to age 28 days are shown in the upper 2 diagrams of Figure 2. The diagram on the right gives results for the

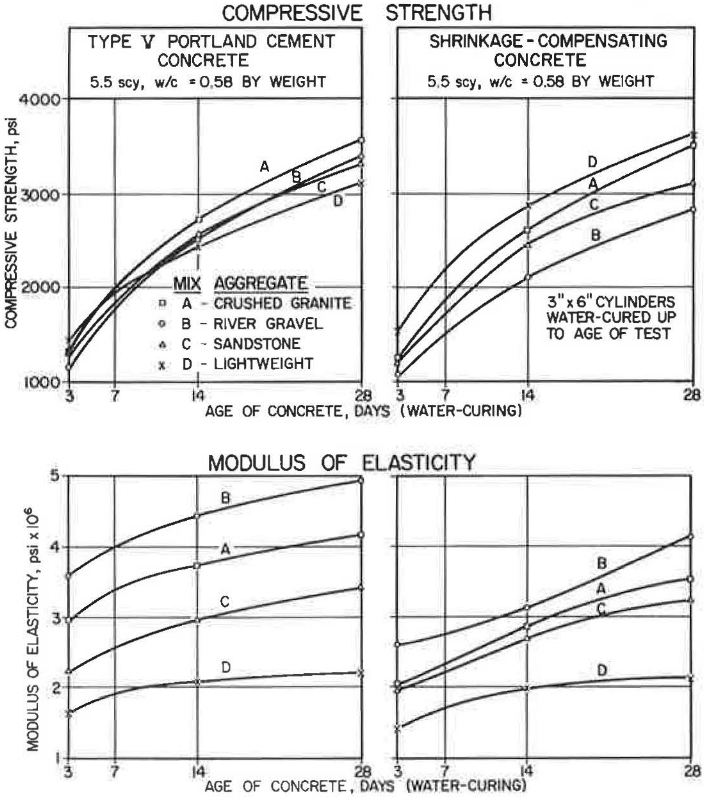

Figure 2. Compressive strength and modulus of elasticity of concretes.

shrinkage-compensating concrete mixes and the one on the left for the corresponding control mixes made with type V portland cement. The nominal 28-day compressive strength of these concretes was 3,000 to 3,500 psi. Compressive strength was determined on 3- by 6-in. unrestrained specimens cured in lime-saturated water up to the age of test.

In making comparisons of data obtained on the shrinkage-compensating concretes and the type V cement concretes, it should be recognized that the type of aggregate has a marked influence on the expansion behavior of the shrinkage-compensating concretes, and this influences their compressive strengths. The greater the expansion of the concrete is, the lower should be its strength. Unrestrained expansion data for these shrinkage-compensating concretes are shown in Figure 3. Note that the expansion of the concrete is almost completed within 14 days of curing and that about 85 to 90 percent of this expansion occurs during the first 7 days.

Referring to Figures 2 and 3, the lightweight aggregate shrinkage-compensating concrete (curves D), which had the lowest expansion, had the highest strength, whereas the river gravel concrete (curves B), which exhibited the largest expansion, had the lowest strength.

The surface texture and angularity of an aggregate may have a more important influence on the strength of shrinkage-compensating concretes than the magnitude of expansion. The rougher the surface texture is, the better the bond between paste and aggregate, thus resulting in higher strength. The crushed granite (curve A) not only produced a concrete of relatively high expansion (Fig. 3) but also a concrete of high strength (Fig. 2). Even after expansion has taken place, its rough textured angular shaped particles will provide better bond than a smooth textured rounded aggregate. This is clearly demonstrated when comparing the results obtained with the river gravel and crushed granite concretes. Inasmuch as the expansion (Fig. 3) of the crushed granite concrete (curve A) was only slightly lower (7 percent) than that of the river gravel concrete (curve B), it might be expected to have a somewhat higher strength. However, the rough textured angular shape of the granite aggregate produced a concrete of much higher strength (25 percent) than the river gravel. It may therefore be concluded that the compressive strength of shrinkage-compensating concrete is influenced by 2 factors: (a) the

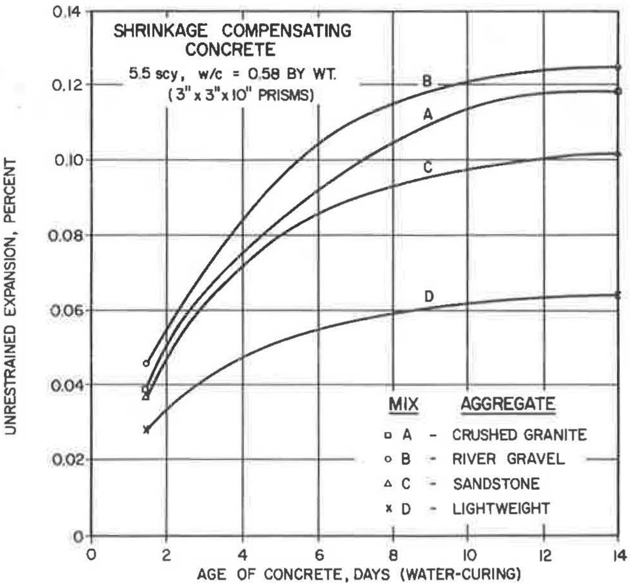

Figure 3. Unrestrained expansion of concretes.

surface texture and shape of the aggregate that influences the bond between paste and aggregate, and (b) the magnitude of expansion.

The small difference in strength observed for the control concretes made with type V cement (Fig. 2) can be attributed primarily to the surface texture and angularity of the aggregate. The lower 28-day strength of the lightweight aggregate concrete is to some degree due to the lower strength of the aggregate itself. The slightly higher 3-day strength of this concrete is probably due to the internal curing, at an early age, provided by the water held in the pores of the lightweight aggregate.

Modulus of Elasticity

Modulus of elasticity was determined at ages of 3, 7, and 28 days on 3- by 6-in. concrete specimens cured in lime-saturated water up to the age of test. Results obtained on the shrinkage-compensating concretes and on the control concretes made with type V cement are shown in the lower 2 diagrams of Figure 2.

For all ages and aggregates investigated, the shrinkage-compensating concretes had a lower modulus of elasticity than the corresponding concrete containing type V cement. This difference in modulus of the concrete is primarily due to the difference in the modulus of the paste, the structure of which is altered during expansion. The higher the expansion is, the lower the modulus. The lightweight aggregate shrinkage-compensating concrete, which had the lowest expansion (curve D, Fig. 3), had a 28-day modulus of elasticity (Fig. 2) only 4 percent lower than that of the corresponding type V cement control mix, whereas for the river-gravel concrete (curve B), which exhibited the largest expansion, the loss in modulus of elasticity was 16 percent.

Referring to the lower diagrams of Figure 2, it can be seen that the type of aggregate has a significant influence on the modulus of elasticity of the type V cement concretes, ranging from 2.2×10^6 psi for the lightweight aggregate mix to 4.9×10^6 psi for the river gravel mix. A much smaller difference in modulus can be observed for the shrinkage-compensating concretes that ranged from 2.1×10^6 psi for the lightweight aggregate mix to 4.1×10 psi for the river gravel mix. This smaller effect of type of aggregate on modulus of elasticity is due to the different expansion characteristics of these concretes. A low modulus concrete has a lower expansion and thus a smaller reduction of modulus than does a high modulus concrete that has a much larger expansion. Thus the effect of aggregate type on modulus of elasticity of the concrete is being masked by the expansion of the paste that reduces its modulus.

Expansion-Shrinkage Characteristics

A shrinkage-compensating concrete is subject to as much drying shrinkage as a portland cement concrete. However, if its expansion is restrained by reinforcing steel, a slight compression is developed in the concrete. On drying the shrinkage of this concrete will reduce the magnitude of the precompression. A properly designed shrinkage-compensating concrete mix will remain under a slight compression even after long periods of drying. By preventing development of tensile stresses during drying, the formation of drying-shrinkage cracks can be avoided. As shown by test results herein reported, the aggregate has a significant effect on expansion as well as on drying shrinkage and is therefore a major factor in the mix design of a shrinkage-compensating concrete.

The expansion characteristics up to 14 days of water-curing and subsequent drying shrinkage up to age of one year of the shrinkage-compensating concretes made with the 4 different types of aggregates are shown in Figure 4. These volume changes were determined on 3- by 3- by 10-in. prisms. Data for unrestrained prisms are shown in the upper diagram of Figure 4, and data for the prisms restrained with reinforcement ($p = 0.3$ percent) are shown in the lower diagram. It should again be pointed out that a shrinkage-compensating concrete can only be effective if restrained. The tests on unrestrained prisms were made for comparison purposes only.

To evaluate the effect of type of aggregate used in this investigation on the shrinkage of concrete, drying shrinkage was determined for the control concrete mixes employing the type V portland cement. Results of these tests, for both restrained ($p = 0.3$ percent)

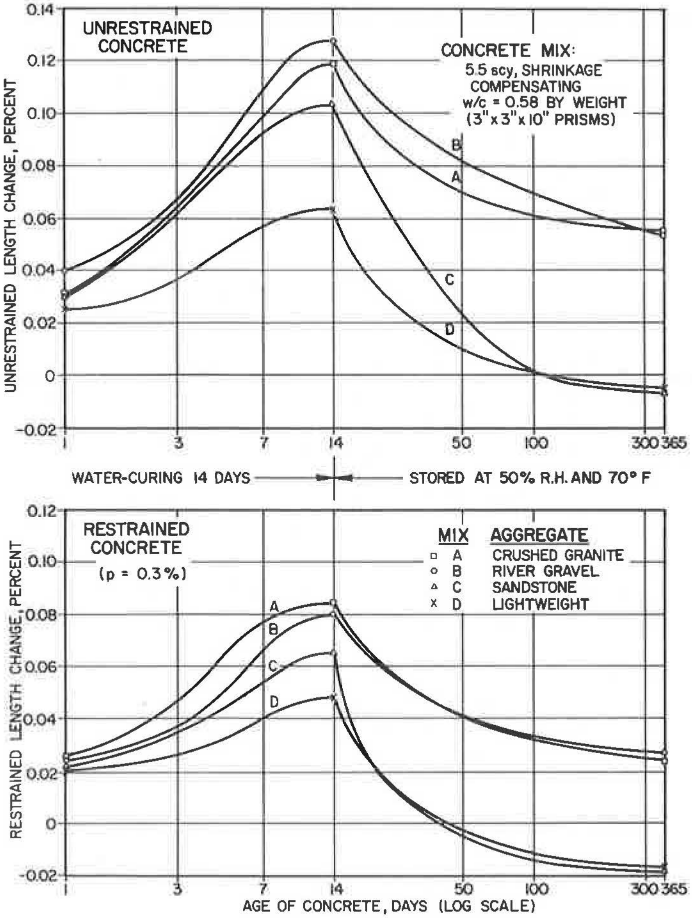

Figure 4. Effect of aggregate type on length change of shrinkage-compensating concrete.

and unrestrained 3- by 3- by 10-in. prisms are shown in the 2 diagrams of Figure 5. These concretes were water-cured for 14 days prior to storage in a room at 50 percent relative humidity and 70 F. These data clearly demonstrate the significant influence of the type of aggregate on drying shrinkage of concrete. For the unrestrained concretes the one-year shrinkage ranged from 0.058 percent for the river gravel mix to 0.108 for the sandstone aggregate. The crushed granite mix had about the same shrinkage characteristics as the river-gravel mix. The one-year unrestrained shrinkage of the lightweight aggregate concrete was 0.065 percent. As is to be expected the drying shrinkage of prisms restrained with reinforcing steel is lower than that of unrestrained prisms. As shown in Figure 5, the one-year shrinkage of the restrained concretes ranged from 0.044 percent for the river-gravel mix to 0.075 percent for the sandstone aggregate concrete. This is about a 30 percent reduction as compared to the shrinkage of the unrestrained concretes.

Referring to Figure 4, the 14-day expansion of the shrinkage-compensating concretes ranged from 0.064 to 0.128 percent for the unrestrained prisms and from 0.048 to 0.084 percent for the restrained prisms. The low expansion values were for the lightweight aggregate and sandstone aggregate concretes and the large expansions for the river-gravel and crushed-granite concrete mixes. Unrestrained concrete made with the river

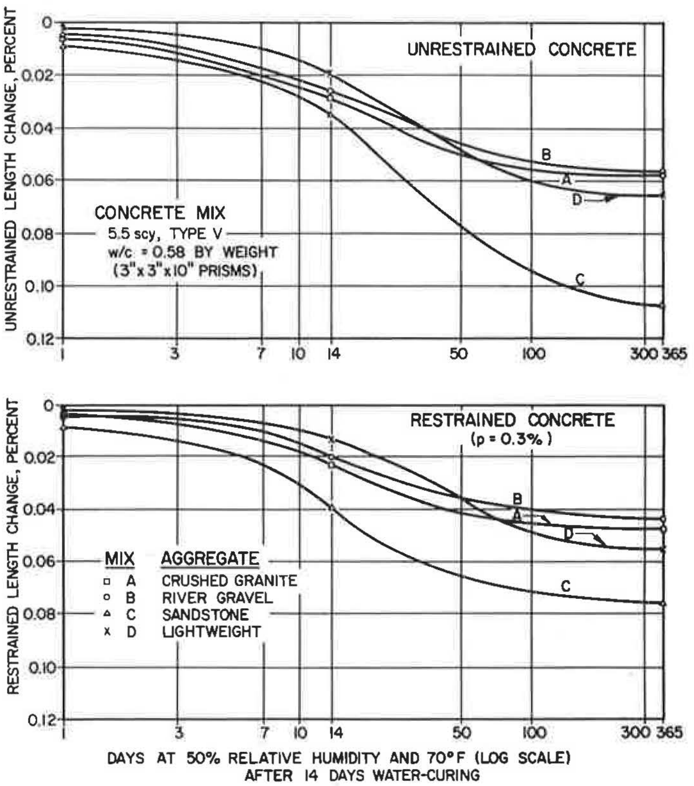

Figure 5. Effect of aggregate type on shrinkage of type V portland cement concrete.

gravel had a somewhat higher expansion than the concrete made with crushed granite; however, the reverse is true for the restrained prisms. No reason other than testing variation can be given for this small discrepancy between restrained and unrestrained prisms. In general, however, the higher the elastic modulus of the concrete is, the larger its expansion.

Data for the restrained prisms (lower diagram of Fig. 4) clearly show that the river-gravel and crushed granite mixes have some residual compression even after one year of drying. This is not true for the sandstone aggregate or lightweight aggregate concretes, which lost all of the precompression after about 40 days of drying. To produce a true shrinkage-compensating concrete with these 2 types of aggregate, a different mix design would need to be employed that would increase the expansion characteristics of the concrete. This could be accomplished either by increasing the expansive cement content of the concrete or by using a cement of higher expansion characteristics. It is therefore essential that in evaluating the behavior of a shrinkage-compensating concrete the same type of aggregate be employed as that which will be used in the structure.

Discussion of Results

Results of this investigation demonstrate that aggregate type is an important variable in the properties of shrinkage-compensating concretes. For a concrete mix of a given cement content and water-cement ratio, the aggregate type controls its strength, elastic modulus, and its expansion and shrinkage behavior. Concretes made with aggregate types producing a high elastic modulus expand more than those of lower modulus. For the normal weight concrete mixes investigated, the magnitude of shrinkage was inversely proportional to the elastic modulus of the concrete (Figs. 2 and 5). Thus the expansion and shrinkage characteristics of the normal weight concrete are related to the modulus of elasticity of the aggregate. A low modulus aggregate that is easily compressed under load will produce a mix of low expansion and high shrinkage, whereas the reverse will be true for a high modulus aggregate.

Compressive strength is lowered by expansion of the concrete, but not by an amount directly proportional to the expansion of the concrete. Aggregate shape and surface texture play a part in determining how much strength is lost because of expansion.

Modulus of elasticity of the shrinkage-compensating concrete was always lower than that of the corresponding concrete made with the type V portland cement. The higher the expansion of a concrete is, the lower its modulus.

From the results of this study it is evident that in the design of a shrinkage-compensating concrete mix the selection of aggregate type must be carefully considered. Aggregates that produce low shrinkage in conventional concretes are more suitable for use in shrinkage-compensating concretes than are aggregates responsible for high shrinkage of concretes. In general, aggregates producing low shrinkage concretes include quartz, limestone, dolomite, granite, and some basalts, whereas those producing high shrinkage concretes include sandstone, slate, and some basalts or other aggregates of low rigidity or which shrink considerably by themselves. Should an aggregate be selected that is known to produce concretes of high shrinkage characteristics, an increase in expansive cement content, or the use of a cement of higher expansion potential, needs to be considered. It should be recognized, however, that an increase in expansion will tend to reduce the strength and modulus of elasticity of the concrete. It is therefore essential that the properties of a shrinkage-compensating concrete be fully evaluated employing the aggregate type selected for use in a particular structure or project.

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The Application of Time-Lapse Photography in Work Simplification Studies of Construction Operations

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ABRIDGMENT

•THE REPORT describes the use of time-lapse photography in work simplification studies of concrete bridge deck construction. The investigation was funded by the Indiana State Highway Commission through the Purdue Joint Highway Research Project, and was performed with the cooperation of several bridge construction contractors. Its findings indicated that commonly used methods for bridge deck construction contained inefficiencies that warranted formal work simplification studies and could benefit therefrom. Analyses in support of this conclusion are included in the research report.

The investigator recommends that construction managers be encouraged to make use of time-lapse photography as a basis for work simplification studies of selected construction operations. Generalized work simplification findings are of questionable value to construction managers because of the changing nature of their work. However, specific applications of work simplification techniques can be of substantial benefit to each construction organization. The report includes, as an appendix, a guide manual for the application of time-lapse photography to work method studies of construction operations.

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