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PENNDOT

EVALUATION OF SEALCOAT IN PAVEMENTS

University-Based Research, Education, and Technology Transfer Program
AGREEMENT NO. 359704, WORK ORDER 24

FINAL REPORT

October 2001

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16. Abstract

Application of seal coat is one of the efficient and economical periodic maintenance activities used for the extension of the service life of pavements. This work is based on the study results on polymer modified emulsion application on test track and on public highway. For durable pavement resealing works two variables: (1) construction-related, and (2) material-related variables were studied.

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Prepared for

Commonwealth of Pennsylvania
Department of Transportation

By

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and
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1. INTRODUCTION

1.1 Background

The Pennsylvania Department of Transportation (PENNDOT) is responsible for the design, construction, operation, and maintenance of the state owned system of 40,500 miles of highways and 25,000 bridges, a system first established in 1911 linking counties with over 8,835 miles of road networks. With the large road network and limited financial resources, it was necessary to extend the service life of the pavements as long as possible. Most of the pavements on this roadway network have served well under Pennsylvania's severe climate and generally poor soils with difficult drainage conditions. The well-coordinated and timely performance of maintenance activities will extend the service life of pavements.

Application of seal coat is one of the most efficient and economical periodic maintenance activities used for the extension of the service life of pavements. PENNDOT have developed specifications, policies, and guidelines as well as a design method for the maintenance purpose. In spite of all these efforts and extensive personal training, the service life of some seal coats has been shorter than desirable, often resulting in a severe loss of skid resistance through flushing of the surface.

PENNDOT has periodically made performance evaluations (surveys) of its seal coat programs. Although considerable attention has been given to design procedures, very little attention has been given to construction and traffic control variables.

In general, seal coats have experienced premature failures and a better understanding of the effect of certain construction variables is needed to maximize the effectiveness of seal coat as a maintenance activity.

1.2 Objectives

Surveys by PENNDOT have repeatedly shown a great deal of variability in seal coat performance. A much more controlled set of conditions is required to evaluate the different effects of variation in materials, construction, and/or traffic variables. This research study was initiated to investigate the effect of selected construction and pavement condition variables on the performance of seal coat.

The primary objective of the project was to construct and evaluate the performance of a number of seal coat sections at The Pennsylvania State University Pavement Facility (test track) and on a public highway in order to determine the variables required for the durable pavement resealing works for cost efficiency and performance.

These test sections incorporated a number of construction and material variables, including:

- Rolling patterns.
- Length of time between the application of the emulsion and the traffic.
- Severity of any rutting in the existing pavement.
- Use of the leveling course and its age before a seal coat is applied.
- Emulsion application rate.

1.3 Research Plan

Based on the literature search, construction and material related variables that concern PENNDOT the most and that are likely to affect the seal coat performance were identified. The study was divided into two parts: (1) a primary construction-related variable experiment and (2) a secondary material-related variables experiment. The PENNDOT project review panel selected the variables that were studied. The following variables were included in the primary (construction variables) experiment:

- Number of roller passes.
- Emulsion application rate.
- Existing pavement surface characteristics.
- Time of traffic control.

The variables included in the secondary (material variables) experiment were emulsion type, aggregate gradation, and age of the leveling course.

VARIABLES	OPTION AVAILABLE	CLASSIFICATION
Pavement Condition	Worn, New	Construction
Emulsion Type	E3, E3 polymer modified	Material
Emulsion Rate	As selected	Construction
Aggregate Type	Gravel, Crushed Stone	Material
Aggregate Gradation	Graded, Single size	Material
Aggregate Rate	As selected	Material
Pre-coating of Aggregate	Yes, No	Material
Roller Type	Pneumatic, Steel Wheel	Construction
Roller Passes	As selected	Construction
Time Between Emulsion and Cheap Spread	As selected	Construction
Time Between Cheap Spread and Rolling	As selected	Construction
Environmental	Air/Pavement Temperature, Humidity, Wind, Cloud Cover	-

Three different aggregate spread rates were used: graded aggregate at the Pavement Durability Facility, single-size stone at the Pavement Durability Facility, and one, graded aggregate for Route 64. Normal construction practice was used to maintain the fixed factors and the construction and material variables at their target levels.

2. APPROACH

2.1 Materials

A single aggregate source and emulsion were used for the primary study at the Pavement Durability Facility. The secondary study at Route 64 included four polymer-modified emulsion as well as the same unmodified emulsion that was used for the primary study. The same aggregate was used for the entire project except that a single-size gradation was used in three test sections at the Pavement Durability Facility.

2.1.1 Emulsion

A standard E-3 (ASTM CRS-2) emulsion manufactured by Koch Asphalt was used in the construction of all primary test sections and as a control for the polymer-modified sections. The properties of the base asphalt cement that was used to manufacture the E-3 emulsion are given in table 1*. Four modifiers were used in a secondary study at Route 64 to modify the base asphalt cement.

- Neoprene, 2.8 percent.
- Styrene-butadiene-styrene from manufacturer 1, SBS-1, 2.8 percent.
- Styrene-butadiene-styrene from manufacturer 2, SBS-2, 3.0 percent.
- Styrene-butadiene-co-polymer, SBR, 2.8 percent.

The routine test properties of the emulsified asphalt, E-3, are shown in table 2, along with the properties of the other polymer-modified emulsions. Each of these emulsions meets the PENNDOT specification requirements for an E-3 emulsion.

2.1.2 Aggregate

The aggregate supplied to the project, selected by PENNDOT personnel is a heterogeneous siliceous, glacial gravel produced at the Fairfield township operation of the Lycoming Silica Sand Company. The aggregate meets the grading requirements of TB stone that is to be used for seal coat work. The percentage of material passing the No. 200 sieve was less than 1 percent. All other specification criteria were met by this aggregate. Data for the aggregate are shown in table 3.

*These tables are reproduced from the available data and are presented separately in appendix B (due to extensive nature).

To provide a single-sized stone for the secondary materials experiment, a sufficient quantity of job aggregate was scalped at a batch plant located in the State College, Pennsylvania area to remove all materials passing the No. 4 sieve. The gradation for the graded and single-sized stone is shown in figure 1.

2.2 Pre-construction Evaluation

The rut depths and surface texture of the pavement on the Pavement Durability Facility were evaluated prior to the seal coat construction. The rut depths in both of the inner and outer wheel paths were measured with a 4-ft straightedge and a scale and were recorded in the Rut Depth Measurement table 4.

A leveling course was applied to several sections of the Pavement Durability Facility between 1987 and 1988, as part of the primary and secondary experiment. The surface texture of the worn and leveled sections was evaluated by visual examination. All of the surfaces were categorized into one of the five categories listed in the PENNDOT Seal Coat Design Method (Bulletin 27). The worn ID-2 wearing surface was classified as a "smooth, non-porous surface"-category 2. The two leveled surfaces, though not oxidized, were classified as a " slightly pocked, porous, and oxidized surface"-category 4

Pavement Surface Texture Classification Categories (PENNDOT Bulletin 27) is as follows:

Category No.	Description
1	Flushed asphalt surface
2	Smooth, non-porous surface
3	Slightly porous, oxidized surface
4	Slightly pocked, porous, and oxidized surface
5	Badly pocked, porous, and oxidized surface

Rut depths were measured on straightedge and scale in the same manner as at the Pavement Durability Facility. Measurements were obtained in the inner and outer wheel tracks at two locations for each test section.

The pavement condition survey for route 64 revealed two distinct surfaces. The first, a 3-year old seal coat, was characterized by minor transverse cracking (the cracks were not sealed prior to the application of the seal coat). Occasional skin patches, which were placed prior to the construction of the 3-year-old seal coat, had caused bleeding. The second surface condition was represented by the 1-year-old overlay. This surface was relatively free of transverse cracking and showed no tendency for bleeding or flushing. It was classified as a category 3 surface. The sections are identified in tables 5 and 6 according to the two surface conditions.

2.3 Seal Coat Design

The emulsion and aggregate application rates were determined using the procedure described in the PENNDOT Bulletin No 27. Details of calculations for the materials and conditions encountered for the project (from Bulletin No. 27) are presented in appendix A.

The PENNDOT procedure utilizes the existing pavement condition, spread modulus (D_{50}) of the aggregate, ADT, and absorption capacity of the aggregate as the variables necessary to calculate the application rates. Aggregate whip-off for this project was assumed to be 10 percent.

The design was basically based on the following factors:

- Rut depth for the inner and outer wheel paths.
- Existing pavement characteristics.
- Whip off-10 percent .
- ADT.
- Bitumen-Type (emulsion).
- D_{50} Value.
- Loose Unit Weight.

Emulsion application rates, calculated using the PENNDOT design procedure (Bulletin No. 27) for the condition at the Pavement Durability Facility and Route 64, are shown in table 7. The two design conditions at the Pavement Durability Facility represent a real field condition, where seal coat is to be applied to an old worn pavement with intermediate sections that have received an ID-2 leveling course.

To compare PENNDOT's design with other seal coat design procedures, several procedures were selected from the literature and applied to the conditions at Route 64.

These procedures are described in table 8, and range from simple methods (3, 5, and 6) to sophisticated procedures that are based on more comprehensive set of design parameters as indicated in methods 1, 2, 4, and 7.

Three simpler procedures (method 3, 5, and 6) give unrealistic estimates of the application rates for both the emulsion and aggregate and the results from these procedures were discontinued. The three remaining procedures give nearly identical application rates for the aggregate, which agreed well with the PENNDOT procedure.

The surface categories listed in the Seal Coat Mix Design manual, Bulletin No. 27, do not include categories that are specific to worn seal coats or to fresh, untrafficked leveling courses. In fact, Bulletin No. 27 does not make any specific reference to seal coat surfaces or seal coat surfaces in different states of wear and/or degree of flushing. A comparison of the PENNDOT design procedures with the other design procedures suggests that the PENNDOT procedure may result in slightly high emulsion application rates.

PENNDOT selected the aggregate spread rate used at the test site on the basis of local practice with the aggregate. This resulted in a spread rate less than the design value obtained from the PENNDOT design procedure. Thus, the application rate for the emulsion and the aggregate was based upon local experience with the job aggregate.

2.4 Construction Activity

During the construction at the Pavement Durability Facility and Route 64, several construction activities were documented including: the aggregate application rate, emulsion application rate, quantity of whip-off of aggregate, and the environmental conditions during the construction. Documented construction activities included the number of roller passes and the time between the emulsion and chip application and between chip application and rolling activities. All construction activities and equipment calibration were done under the control of PENNDOT personnel. No attempt was made to alter the normal construction technique and the experimental procedure of the project was designed to minimize any disturbance to the normal construction procedures.

2.4.1 Emulsion Application Rate

The emulsion application rate for the Pavement Durability Facility and Route 64 was determined with two different methods: ASTM D 2995 "Standard Recommended Practice for Determining Application Rate of Bituminous Distributors" and a procedure whereby fabric patches were placed on the pavement. The patch method is described as followed:

1. A 2-by-2-ft reweighed, geo-textile patch was placed on the pavement surface prior to the application of the emulsion.

2. Immediately after the application of the emulsion, but before the spreading of the aggregate, the fabric was carefully removed and placed in a pre-weighed plastic trash bag.

3. The trash bag containing the emulsion soaked fabric was returned to the laboratory, opened and placed in an oven at 140° F for 24 to 48 hrs. to allow evaporation of water.

4. The asphalt-soaked fabric and the trash bag were weighed and the quantity of emulsion in gallons-per-square-yard was calculated using the water content of the emulsion and the specific gravity of the emulsion.

The geo-textile patch method offers a simple easy-to-perform procedure for determining the emulsion application rate (see table 9). It has the drawback that it cannot be readily used to determine the variation in application rate across the width of the pavement. Neither the ASTM method nor the geo-textile patch procedure is suitable as a quality control test due to the turn-around time required to obtain the test results.

ASTM D 2995 "Standard Recommended Practice for Determining Application Rate of Bituminous Distributors" can be used to measure the traverse uniformity of the emulsion application rate, but it is more tedious to perform. The procedure consists of placing a series of cotton pads across the pavement width. The pads are weighed before and after the emulsion are applied to the pavement, and the application rates are calculated in the same manner as for the patch method. The ASTM method was used for six of the test sections, and results of the measurements are presented in table 10.

Statistical analyses were used to evaluate the variability and to compare the different test sections. The results of analysis are presented in tables 11 and 12.

In summary, the variability of the emulsion application rate was quite reasonable; and the repeatability of the geo-textile patch test is sufficient such that the test is warranted for use as a control test as long as three or more test samples are used for each determination.

2.4.2 Aggregate Application Rate and Whip-Off

The aggregate application rate at the Pavement Durability Facility and Route 64 was determined in triplicate by the following method:

1. A 22-by-22 inch pan was placed between the wheel paths of the pavement immediately after the emulsion was applied.

2. After the chip spreader passed over the pan, the pan was removed to the side of the pavement.

3. The collected aggregate was transferred to a pre-weighed bucket and was dried in an oven at 140° F ± 5° F for 24 hrs.

4. The dried aggregate was weighed and the aggregate application rate in pounds-per-square-yards was calculated.

The results of the aggregate application rate measurements are given in table 13. As for the emulsion application rate measurements, the measurements spanned several test sections representing a continuous pass of the chip spreader.

The aggregate not captured by the emulsion film (and susceptible to whip off under traffic) was estimated for each test section by the following method:

1. The test was conducted approximately 20 to 50 minutes after rolling the aggregate, when the bulk of water in the emulsion had evaporated.

2. One square yard template was placed between the wheel paths of the test section.

3. All loose chips within the template area were collected by carefully brooming the pavement surface. These chips were placed in a plastic bag for transport to the laboratory.

4. The aggregate was dried in an oven at 140° F ± 5° F for 24 hr. weighed, and the aggregate whip-off in pounds per square yard was calculated.

Tables 14 and 15 show the target and the measured aggregate application rate for the individual test sections. Also shown in these tables is the aggregate whip-off as estimated by the brooming test. Subtracting the brooming loss from the actual aggregate application rate results in an estimated in-place aggregate application rate.

The excess and deficiency in applied stone can be observed in the brooming loss. The brooming loss represents the whip-off aggregate (the aggregate not firmly seated into the emulsion film) that will be immediately lost to traffic.

2.4.3 Documentation of Construction Variables

The following construction variables were documented for each section at the Pavement Durability Facility and Route 64:

- Number of roller passes.
- Time (in seconds) between the application of the emulsion and the aggregate.
- Time (in seconds) between the spreading of the aggregate and rolling.
- Delay time between rolling and the application of traffic.
- Emulsion application temperature.

The above data are summarized in tables 16, 17, and 18. Similarly, at the time of construction, the following environmental conditions were documented for each section:

- Air temperature.
- Relative humidity.
- Wind condition.
- Rain on four consecutive days beginning with one day prior to construction.
- Pavement temperature.

It was observed that the rain was not a factor in the performance of any of the seal coat section. Overall, the construction at the Pavement Durability Facility and at the Route 64 site proceeded very well, especially given the number of test sections and at the Pavement Durability Facility, their short length. Except for the excessive aggregate applied at the Pavement Durability Facility and the streaking observed for some of the test sections, the quality of the construction was accepted given the short test sections and the number of test variables included in the construction.

3. PERFORMANCE EVALUATION

In order to evaluate the relative performance of sealcoat sections, the following three experiments were performed:

- A primary experiment to evaluate the effects of design and construction factors.
- A secondary experiment to evaluate the effects of selected modifiers, single-sized stone, and worn leveling courses.
- An experiment on Route 64 to evaluate the effects of roller passes and of selected modifiers exposed to field conditions.

3.1 Experiments at the Pavement Durability Facility

Four variables were included in the primary construction variable experiment. Twenty-four test sections were required to accommodate each of the 24 variable combinations and are summarized in table 19. Similarly, figure 2 presents a plan view of the seal coat sections as constructed at the Pavement Durability Facility, while sections 1 through 24 contain the 24 construction variable test sections. These 24 test sections were constructed in three groups of eight, resulting in three sections. Figure 3, 4, and 5 illustrate the method used to incorporate variables into each of the traffic section.

3.2 Secondary Material Variable Experiment

As shown in figure 2, sections 1-1 and 3-3 through S-14 were constructed as part of the secondary material-related variable experiment. The variables included in this experiment were emulsion type, aggregate gradation, and the age of leveling course (see table 20). These sections were constructed on a recently constructed leveling course except for test sections S-1, S-3, and S-4. All secondary test sections were subjected to one roller pass except for test sections S-3 and S-13, which received three passes. A control section containing the E-3 control emulsion was constructed to provide a more direct comparison of the modified emulsion with the control E-3.

3.2 Route 64 Experiments

The experiment plan for Route 64 seal coats incorporated both construction and material variables, including:

- Emulsion type.
- Number of roller passed.
- Existing pavement surface condition.
- Time of traffic control.

A total of 18 test sections were constructed on Route 64. The general layout is shown in figure 6 and table 21 summarizes the variables incorporated into each test section.

The following techniques were used to monitor the performance of the seal coat sections at a regular interval:

- Sandpatch method.
- Skid resistance.
- Visual evaluations.
- Sterophotographs.
- Geo-textiles.

The performance measurements obtained in this investigation are presented in the appendices.

Table 22 includes a summary of the parameters that were obtained and the frequency, number, and location of measurement for each of these techniques. This table also summarizes the advantages and disadvantages of each technique in terms of evaluating the performance of seal coats.

4. FINDINGS ON SEAL COAT OPERATION

The different phases involved in the placement of seal coat operations could be broken down as follows:

1. Determination of surface preparation.
2. Materials selection and specification.
3. Seal coat design (determination of emulsion application rate and aggregate application rate).
4. Construction procedures.
5. Quality control.
6. Post-construction evaluation.

4.1 Surface Preparation

After the decision to apply the surface treatment has been made, one of the three options is generally followed:

- A seal coat may be applied to the existing surface (option 1).
- A thin leveling (or scratch) course may be applied prior to applying the seal coat (option 2).
- A slightly thicker leveling course (or thin overlay) may be applied exclusively as a surface treatment (option 3).

The investigation showed that option 1 should be followed unless rutting is severe enough to create a traffic hazard or to make road maintenance difficult. Application of a leveling course to a surface having 1-in or less of rutting did not extend the life of a seal coat. A freshly placed leveling course generally has greater macro-texture than an older surface. Also, because leveled surfaces are generally less stiff than older surfaces that have been oxidized, more embedment can be expected on leveled surfaces, which implies that the expected life of a seal coat is less on leveled surfaces.

The only failure observed on the seal coat section tested were caused due to de-bonding between the leveling course and the underlying surface, which resulted in shoving of the leveling course mixture. Adequate placement of a thin leveling course can be difficult because such a small volume of material loses heat quickly and may not be able to transfer it to the underlying surface sufficiently to insure proper bonding.

4.2 Materials Selection and Specification

After the decision has been made to apply a seal coat, appropriate materials must be selected and specified. The following aggregate characteristics are generally considered to be important for seal coat application:

- Maximum size and gradation.
- Resistance to breakdown and wear.

The emulsion characteristics that are generally considered to be important are as follows:

- Compatibility with the aggregate.
- Spray-ability at specified application temperature.
- Viscosity at service temperature.
- Breaking characteristics.

Adequate specifications must be established to ensure that the materials have suitable characteristics to meet performance requirements and construction constraints. The findings of this investigation indicated that although aggregate meeting PENNDOT's current specification can and, in fact, did perform satisfactorily in most of the sections tested. This extended the seal coat life and a lower incidence of seal coat failures may be achieved if harder, larger, more uniform aggregates are used.

It can also be reasoned that seal coats constructed from larger aggregate will last longer than those constructed using smaller stone. Because the larger aggregate has a higher macro-texture, it will take longer for traffic to wear the aggregate to the point when the surface of the pavement is smooth and eventually loses skid resistance. It can also be expected that larger aggregates will not be embedded as readily as the smaller stone (see figure 7). The drawback of using larger stone is that more emulsion is required for adequate seal coat construction. The amount of emulsion required is roughly proportional to the size of the aggregate. Also, larger aggregate increases the potential for windshield breakage.

Little difference was observed in the performance of the control emulsion, E3, and the modified emulsions. Claims for modified emulsions include better chip retention at low temperature, improved chip retention on corners, improved resistance to bleeding, and the ability to retain larger emulsion percentage without bleeding. Claims such as improved chip retention at the intersections and on corners, especially immediately after construction, were not studied and therefore, these claims cannot be verified.

4.3 Seal Coat Design

The design of a seal coat involves the determination of the following:

- The emulsion application rate to obtain optimum performance from a particular aggregate on a particular surface.

- The aggregate spread rate required to insure that a maximum amount of aggregate is retained without excessive waste.

This investigation showed that the use of a proper emulsion application rate is probably the single most important factor in determining the long-term performance of a seal coat. Therefore, it is extremely important that the design procedure results in the best possible estimate of the optimum emulsion application rate. Clearly, a complete review of the steps involved in the design procedure is fully warranted in order to determine if any improvement can be made.

The following steps are used to determine the emulsion application rate:

1. A gradation analysis is performed to determine the nominal aggregate absorption.

2. The pavement surface is visually rated on a scale of 1 to 5 according to its porosity and absorption characteristics (one having the least porosity and absorption).

3. Design charts were used to determine the emulsion application rate using the nominal size of the aggregate and the numerical rating of the surface.

4. The determined rate is then adjusted if the aggregate is considered absorptive.

The findings of the investigation showed that PENNDOT's existing design charts would give reasonable estimates of the most appropriate emulsion application rates for the aggregate and surface tested.

It should be noted that, regardless of the system used, the emulsion application rate determined from the design phase is simply an estimate. Therefore, a field check should always be made during construction to ensure that the emulsion application rate results in the proper film thickness for the aggregate being used and the amount of expected embedment. The reason is because the actual absorption of a particular surface cannot be exactly determined.

4.4 Construction Procedure

Except for the air and pavement temperature at the time of construction, the construction procedures appear to have little effect on the performance of the seal tested. Lower air and pavement temperatures reduce the aggregate retention. Based on the observations made at the test site, they suggest that 70°F may be a more appropriate minimum pavement and air temperature at the time of construction.

It is also observed that the number of roller passes applied with a pneumatic roller does not affect the performance of the seal coat sections, nor the amount of aggregate retained on the section, i.e., no effect on whip-off.

4.5 Quality Control

The findings clearly showed that much closer attention must be paid to the equipment calibration in the field. It was observed that the variability between the design and actual emulsion application rates was very significant.

Significant differences were observed between design and actual aggregate spread rates. For aggregate spread rates in excess of the 10 percent allowed whip-off, the aggregate was wasted. Aggregate spread rates lower than the design values resulted in inferior seal coats.

It is suggested that the current procedures for calibrating and monitoring both distributors and chip spreaders should be reevaluated. Distributors should be calibrated such that, existing specification range for emulsion application rate (±10 percent of design) is met in all cases. Similarly, chip spreaders should be calibrated to the greatest degree possible.

In addition to improving calibration procedures, PENNDOT should attempt to establish a field monitoring system to enable the field crew to make necessary adjustments to the emulsion application rates as the section is being constructed.

4.5 Post Construction Evaluation

After construction, a series of post-construction evaluations were performed at each site. The following post-construction evaluations were recorded for each site and treatment:

- Stereo-photographs.
- Mean Texture Depth Testing (Sand Patch Test).
- Skid Resistance Level Testing.
- Visual examinations.
- Geo-textiles.

To obtain a proper evaluation of a seal coat, it was found that two measurements were needed: a direct or indirect measurement of texture and a visual evaluation or description of the pavement. The texture measurement provides a measure or indication of the pavements frictional resistance as well as a basis for objectively comparing seal coats.

The mean texture depth was found to give the best indication of expected seal coat life and an excellent parameter for comparing well-constructed seal coats on a relative basis. It was also found to be the most sensitive measure of texture changes during most of the seal coat life (Figure 8). The geo-textile used on this investigation was found to be unsuitable for recovering seal coat samples for evaluation during the life of the seal coat. The geo-textile could not be recovered from the pavement after traffic was applied, and they clearly affected the performance of the seal coat.

5. CONCLUSIONS

Based on this work, the following conclusions may be drawn regarding the adequacy of existing seal coat operation:

Worn surfaces should not be leveled prior to applying a seal coat. It should not be applied in addition to a leveling course, if a high quality mixture can be placed and compacted properly to level the entire lane. If not, then a seal coat should be used in addition to the leveling course. For this case, the emulsion application rate should be determined on the basis of the surface characteristic of the leveling course.

Good seal coat can be produced using aggregates, which meet PENNDOT's current specification. The use of larger aggregate (1/2-in maximum size) would extend seal coat life and reduce the incidence of seal coat failure. The existing LA Abrasion specification of 40 percent maximum should be reduced to a maximum of 30 percent in areas, where exposure to snow plows and street-wheeled buggy traffic is severe.

Results shows that the modifiers used in the study did not enhanced the low temperature performance of emulsion; similarly, modifiers had no effect on the low temperature properties of the residue. However, their use could be continued where early chip retention is desired. For better evaluation of the effects of modifiers on emulsion, further testing must be done under other traffic conditions or with asphalt concrete.

Existing design charts give reasonable estimates of the most appropriate emulsion application rates for the graded aggregate. Ten percent whip-off appeared to be an appropriate value for determining aggregate application rates for the graded aggregate. As recommended in the specification, zero percent whip-off should be assumed for shoulder work. The existing method of visually rating pavement surface is inadequate. A more objective method to rate pavement surfaces for seal coat design should be developed.

When 8 ton pneumatic rollers are used, no more than one roller pass need be specified for proper seal coat compaction and no more than two hours of traffic control need be specified after construction before a seal coat is open to traffic. As far as possible, seal coat should only be placed when the pavement and air temperatures are 70° F or higher.

Maximum effort must be put forth to ensure that both the distributor and the chip spreader are properly calibrated. For the measurement of emulsion application rates, for calibration purpose, the geo-textile patch method should be used. The practicality of developing and using a device for measuring emulsion film thickness during construction should be investigated.

A Mean Texture Depth (MTD) Measurement along with a visual rating to evaluate seal coat performance should be used, and similarly, MTD measurement should be obtained as part of the post construction evaluation. Aggregate wear rated should be correlated to laboratory properties for use in the prediction model. The model itself should be updated and calibrated as field data are collected.

APPENDIX A - DETERMINATION OF EMULSION AND AGGREGATE APPLICATION RATE

DETERMINATION OF EMULSION AND AGGREGATE SPREAD RATES--TEST TRACK

PROJECT: The Design, Construction, and Performance of Bituminous Seal Coats

PROJECT NO.: 87-02

REFERENCE: PennDOT Bulletin No. 27, Appendix E

I. Aggregate Gradation

The purpose of the gradation analysis is to determine the spread modulus, D_{50}, of the aggregate gradation. Three representative samples of the job aggregate were collected and a sieve analysis performed. The results of the analysis are summarized in table 20. The average of the three gradations was plotted. The D_{50} was determined to be 0.268 inches.

Table 20. Summary of gradation analysis on job aggregate.

	Percent Passing			
Sieve	Sample No. 1	Sample No. 2	Sample No. 3	Average Percent Passing
1/2"	100	100	100	100
3/8"	92	86	90	89
#4	24	22	16	21
#8	10	8	7	8
#16	8	7	2	4
#30	8	7	2	4

II. Loose Unit Weight of Aggregate

The loose unit weight of the job aggregate was determined in triplicate by the procedure outlined in DTM 609. The findings are:

Sample No. 1: 90.3 lb/cu. ft.
Sample No. 2: 90.5 lb/cu. ft.
Sample No. 3: 90.4 lb/cu. ft.
Average loose unit weight: 90.4 lb/cu. ft.

III. Average Daily Traffic (ADT)

For the purpose of the analysis, the ADT for the track was classified as >2000 vehicles per day.

IV. Aggregate Absorption Characteristics

The job aggregate is classified as absorptive with an absorption of 2.15 percent.

V. Surface Condition

Two distinct pavement surfaces exist at the test track: 1) the old ID2 wearing surface from Research Cycle IV and 2) the new leveling course material applied to various locations at the track. These surfaces are classified within the context of Bulletin 27 as:

Old ID2: "Smooth, non-porous surface"
New Scratch: "Slightly pocked, porous, and oxidized surface"

VI. Type of Bitumen to Use

Emulsions will be used in the construction.

VII. Summary of Input Variables

D_{50}:	0.268 inches (See figure 7.)
Loose Unit Weight:	90.4 lb/cu. ft.
ADT:	>2000 vehicles/day
Absorptive Aggregate:	Yes
Bitumen Type:	Emulsion
Surface Condition:	
Old ID2:	Smooth, non-porous
Scratch:	Slightly pocked, porous
Whip-off:	Use 10 percent

VIII. Determination of Aggregate Spread Rate

The aggregate spread rate for the input variables was determined using "Quantity of Stone Required" from PennDOT Bulletin No. 27. Inputting the D_{50} = 0.268 inches and a loose unit weight = 90.4 lb/cu. ft. for a 10 percent whip-off condition, a spread rate of 22 lb/sq. yd. was determined. (See figure 8.)

IX. Determination of Emulsion Spread Rate

The emulsion spread rate for the input variables was determined using "Quantity of Bitumen Required" from PennDOT Bulletin No. 27. Inputting the D_{50} = 0.268 inches, the two pavement conditions to be considered, and adding 0.30 gal/sq. yd. to adjust for the aggregate absorption, the following emulsion spread rates were determined. (See figure 9.)

Old ID2 surface: 0.27 gal/sq. yd.
Leveled surface: 0.35 gal/sq. yd.

TR-303 (10-81)

FIG. 1 GRADATION CHART

DISTRICT 2-0 COUNTY Centre L.R. Test Track SECTION ______

AGGREGATE TYPE Aggregate Gravel SUPPLIER Lycoming Silica & Sand

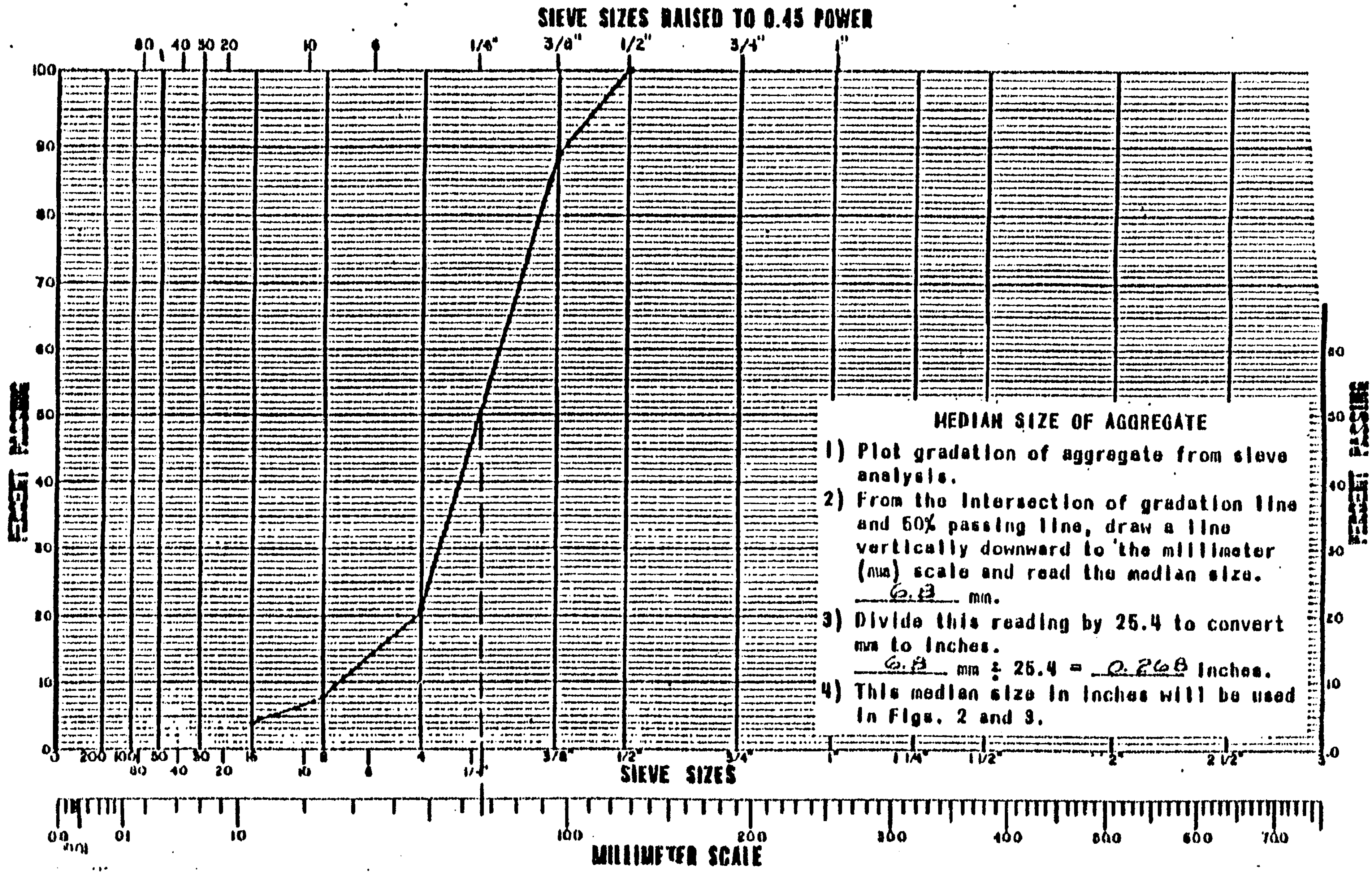

Figure 7. Gradation chart to determine D50.

R-304 (10-83)

FIG. 2

QUANTITY OF STONE REQUIRED

1) Determine the median size of the stone (inches) from Fig. 1.
2) Enter Quadrant 1 on the left and go horizontally to the right to Line A or B (Line A = 0% whip-off and Line B = 10% whip-off).
3) Proceed vertically downward to read quantity of stone (cu ft/sq yd).
4) Proceed downward to Quadrant 2 to intersection with applicable lb/cu ft line. Interpolate, if required.
5) Proceed horizontally to left to find the spread in lb/sq yd.
6) Continue horizontally to the left and into Quadrant 3 to intersection with applicable line for spread width.
7) Proceed vertically upward or downward to find tons of stone per station or lineal feet per ton.

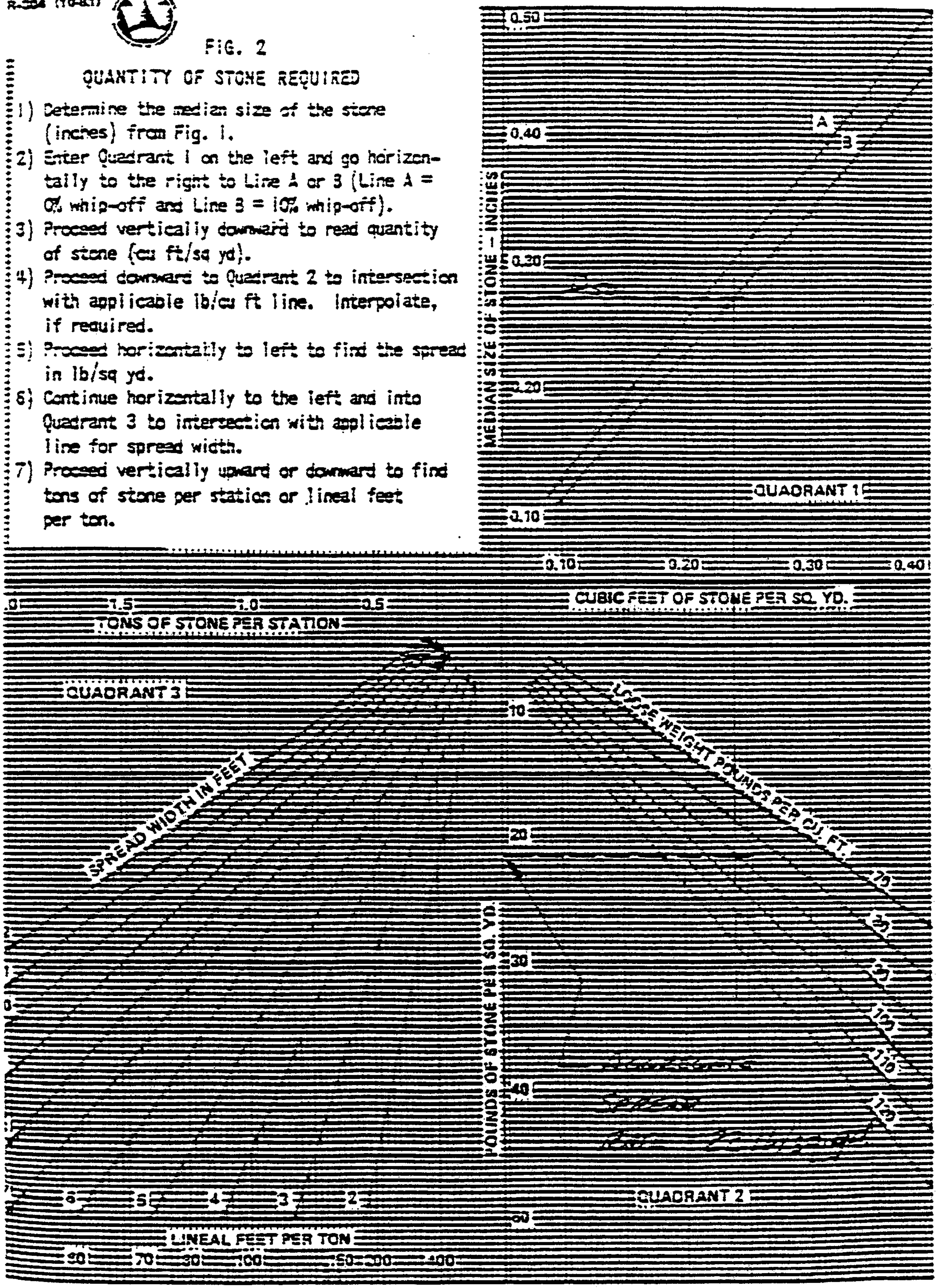

Figure 8. Determination of aggregate spread rate.

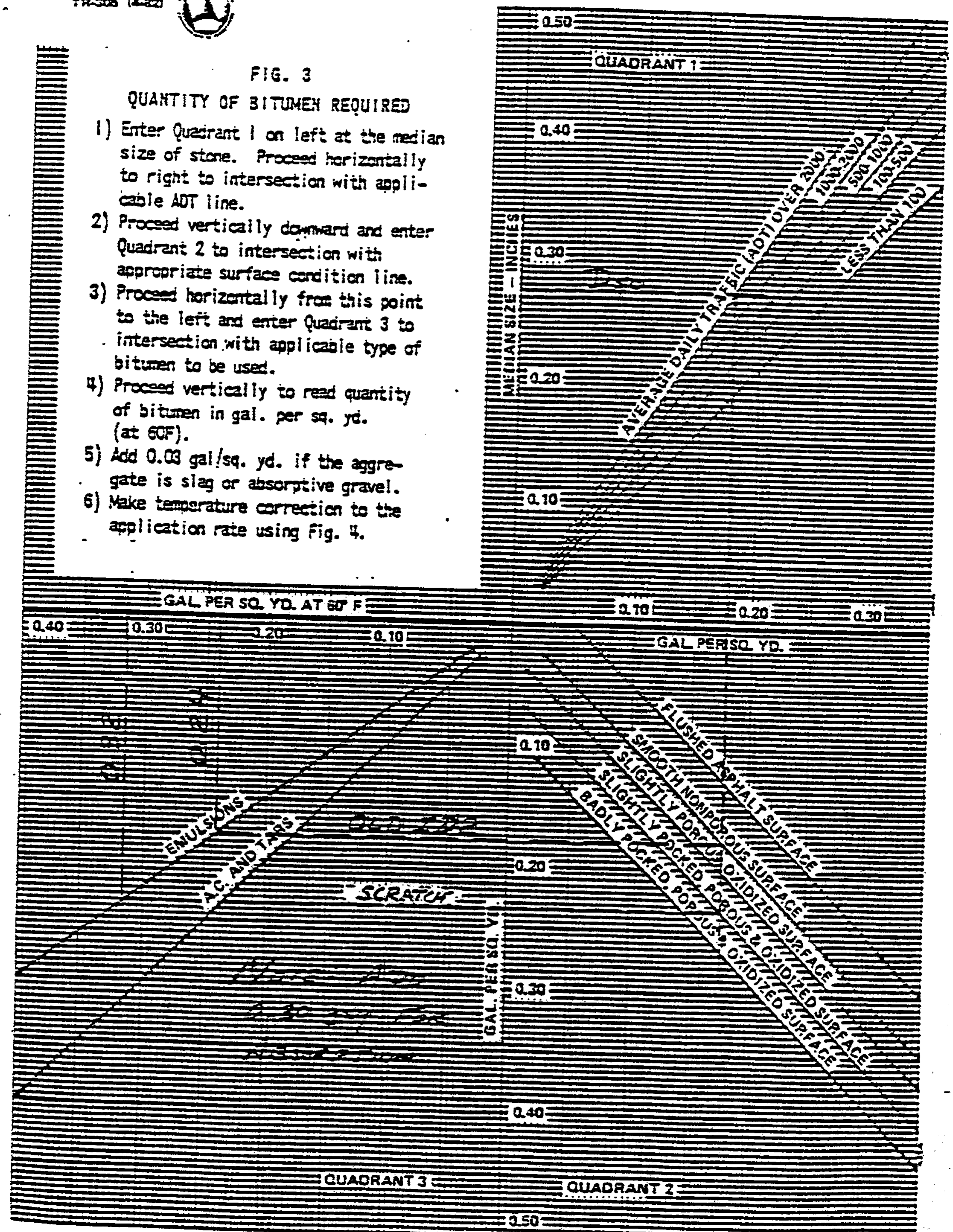

Figure 9. Determination of quantity of bitumen required.

Figure No. 1

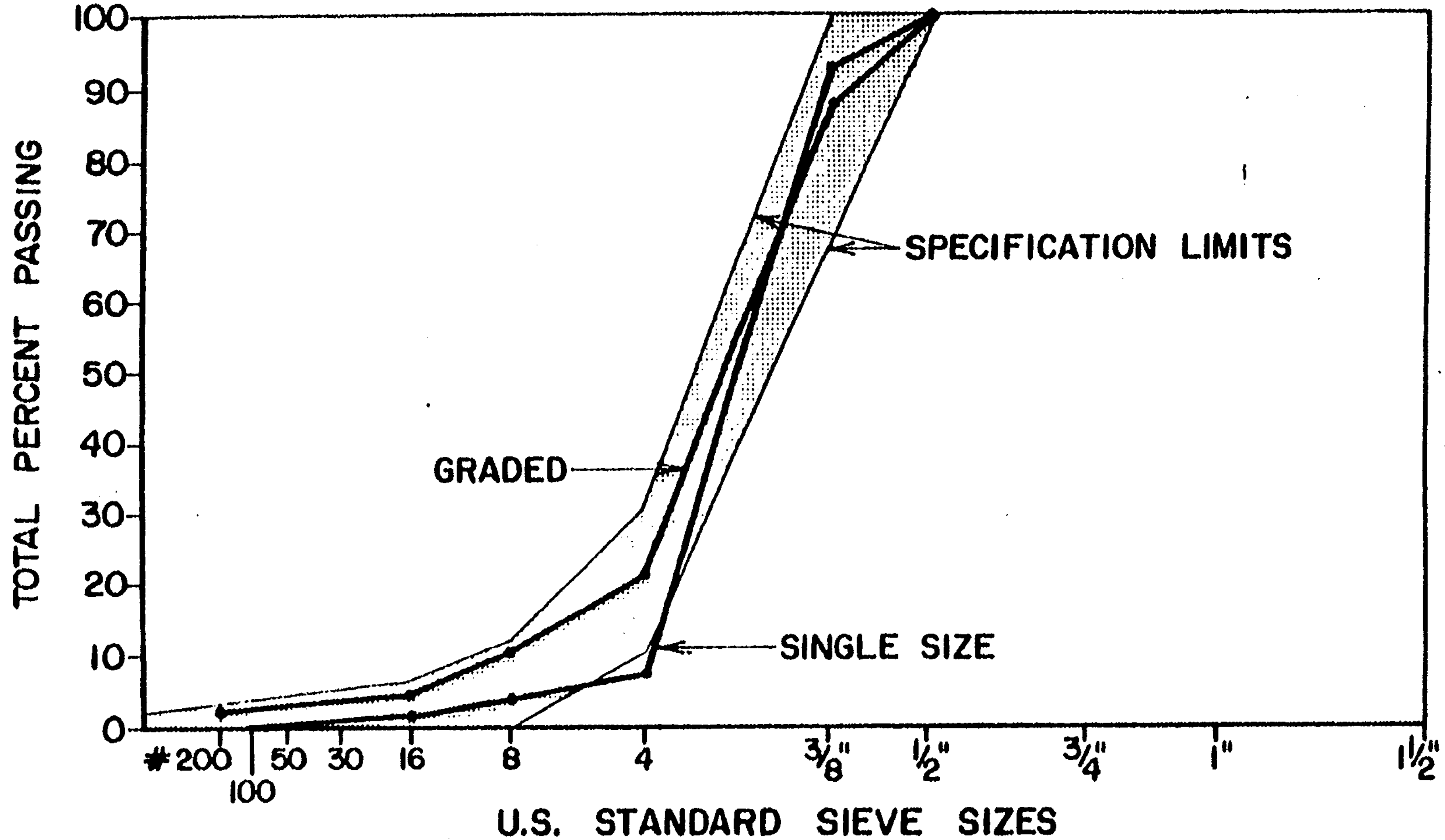

Figure 2.16. Gradation of crushed stone used for project.

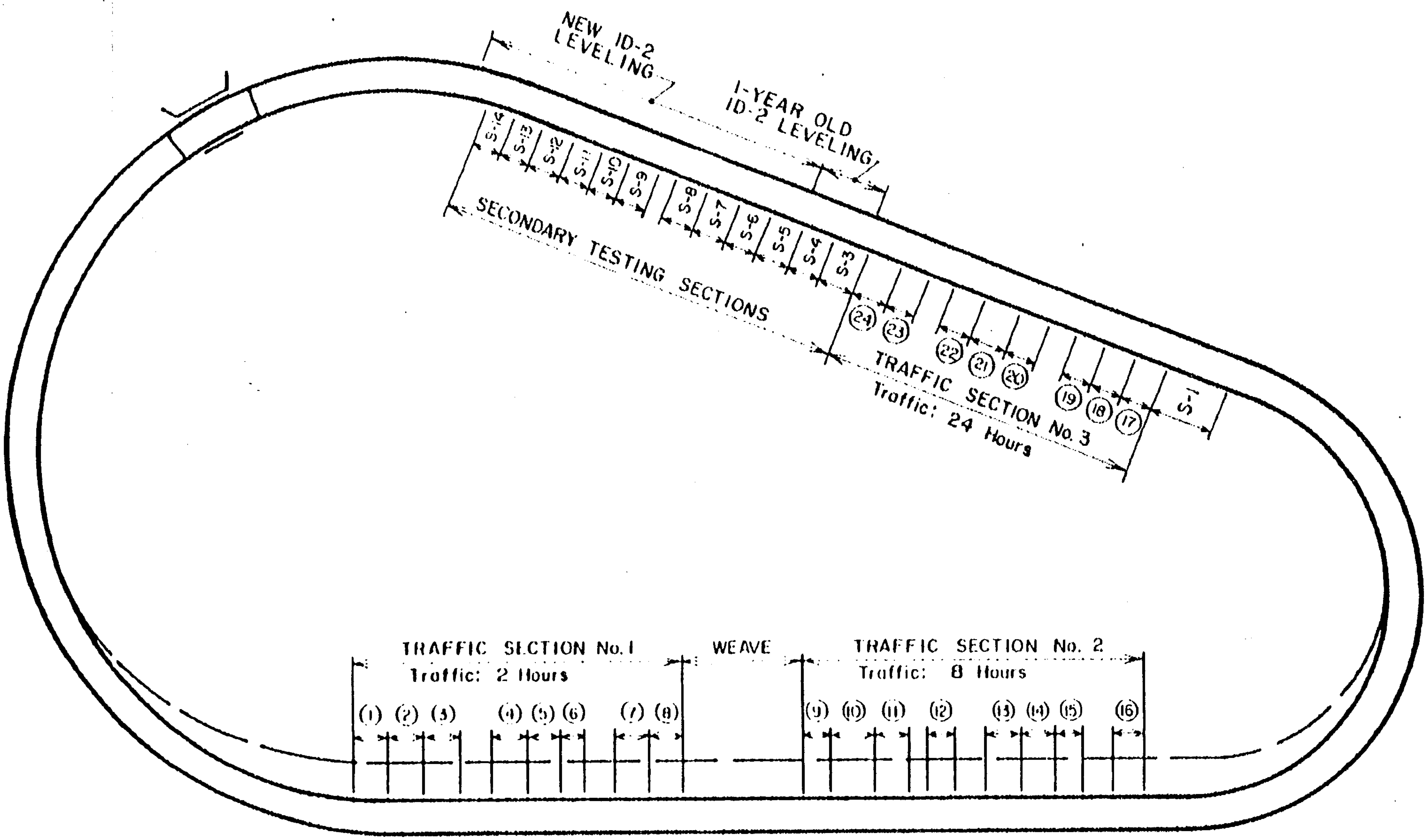

Figure 1.1. Overview of the test sections at the Pavement Durability Facility.

Figure No. 3

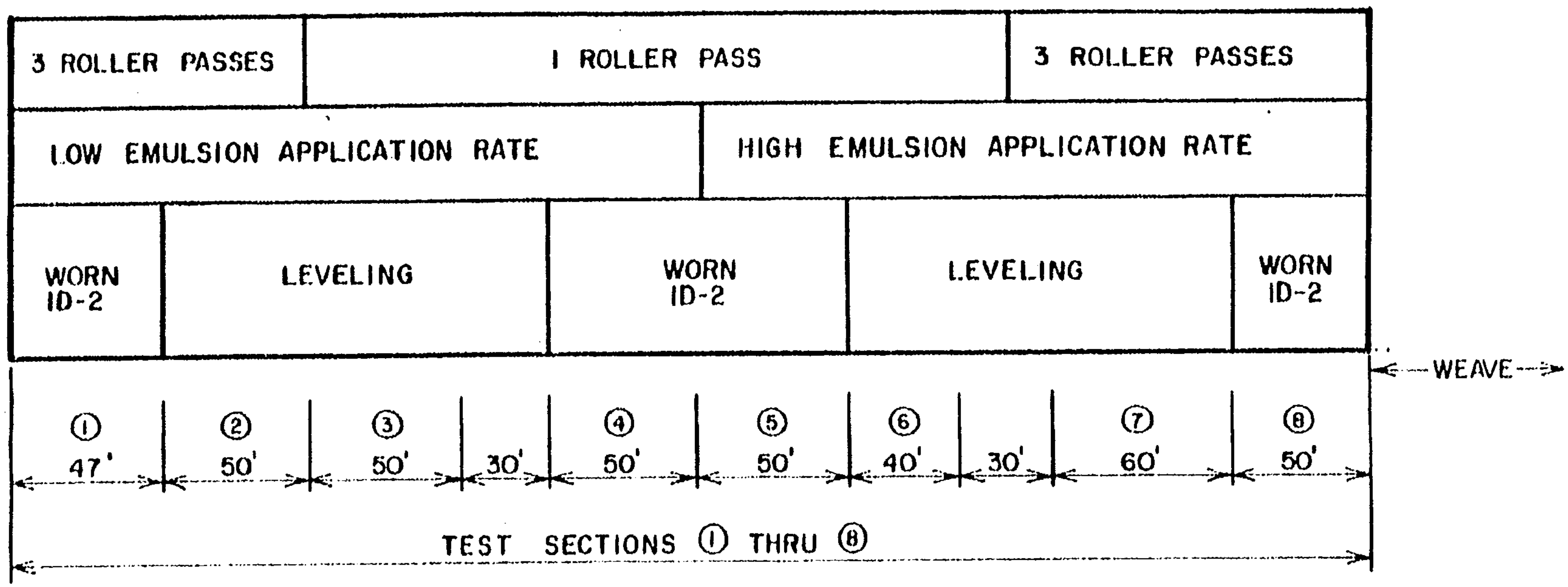

Figure 1.2. Distribution of test variables for sections having 2-h traffic control--test track.

Figure No. 4

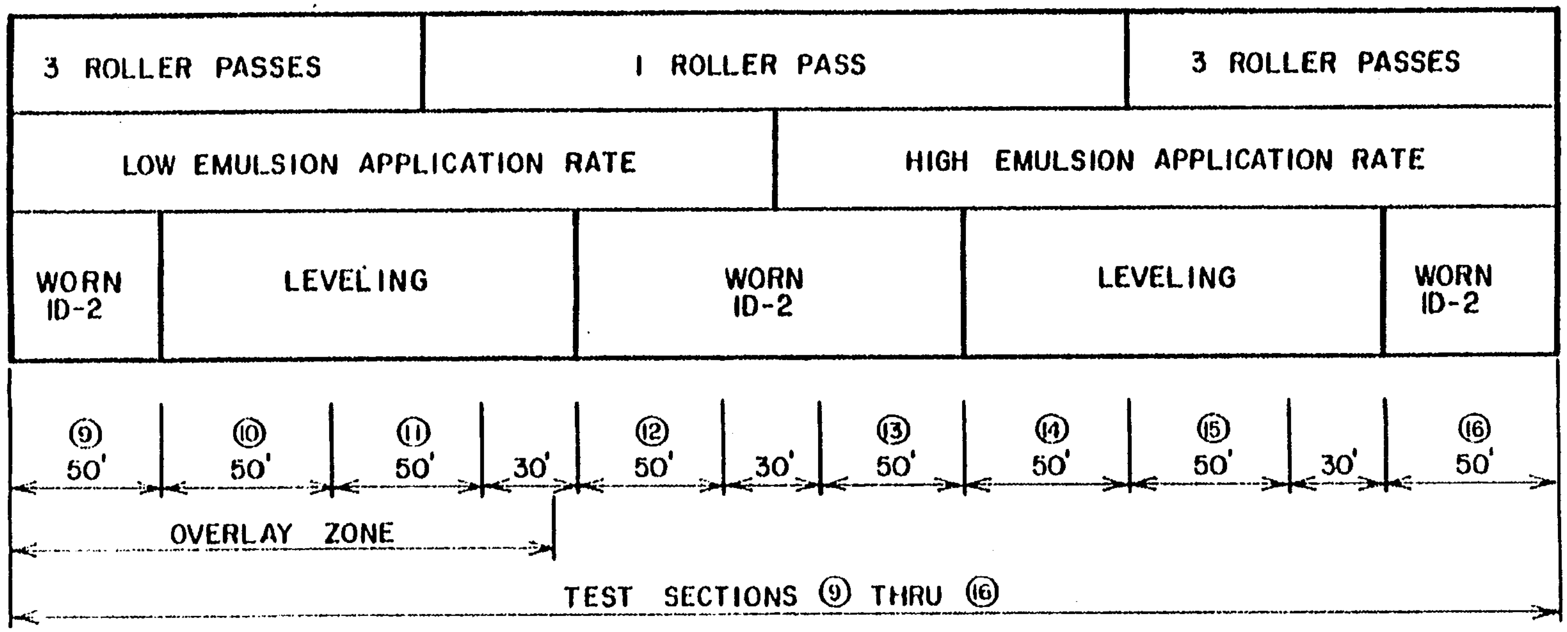

Figure 1.3. Distribution of test variables for sections having 8-h traffic control--test track.

Figure No. 5

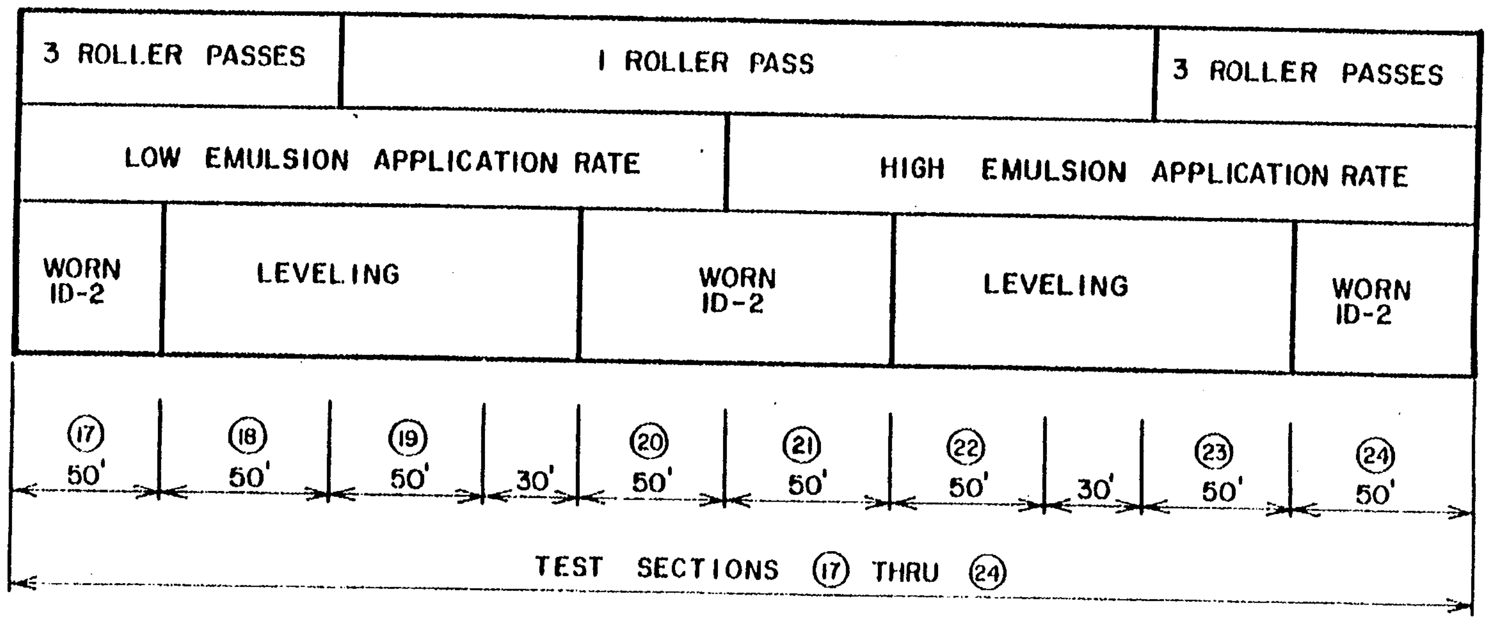

Figure 1.4. Distribution of test variables for sections having 24-h traffic control--test track.

North Bound Lane	Sect No.	4b	4a	3b	3a	2b	2a	1b	1a	Control
	Modifier	SBS-2	SBS-2	SBS-1	SBS-1	SBR	SBR	Neo	Neo	E-3
	Roller	2 Pass	1 Pass	2 Pass	1 Pass	2 Pass	1 Pass	2 Pass	1 Pass	1 Pass
	Traffic delay	2 hr	2 hr	4 hr	4 hr	4 hr	4 hr	2 hr	2 hr	2 hr

South Bound Lane	Sect No.	2d	2c	1d	1c	4d	4c	3d	3c	Control
	Modifier	SBR	SBR	Neo	Neo	SBS-2	SBS-2	SBS-1	SBS-1	E-3
	Roller	1 Pass	2 Pass	1 Pass	2 Pass	1 Pass	2 Pass	1 Pass	2 Pass	1 Pass
	Traffic delay	2 hr	2 hr	4 hr	4 hr	4 hr	4 hr	2 hr	2 hr	4 hr

Figure 1.5. General layout of test sections--Route 64.

Figure No. 6

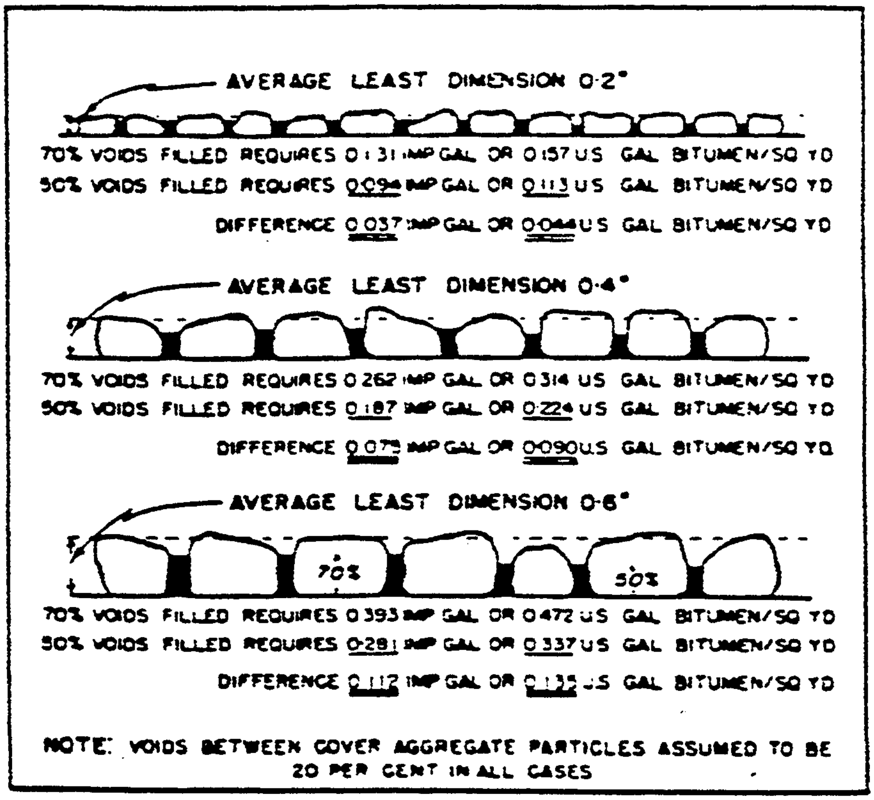

Figure 6.1. Influence of cover aggregate size on the critical range of bitumen quantity required for seal coats [9].

Figure No. 8

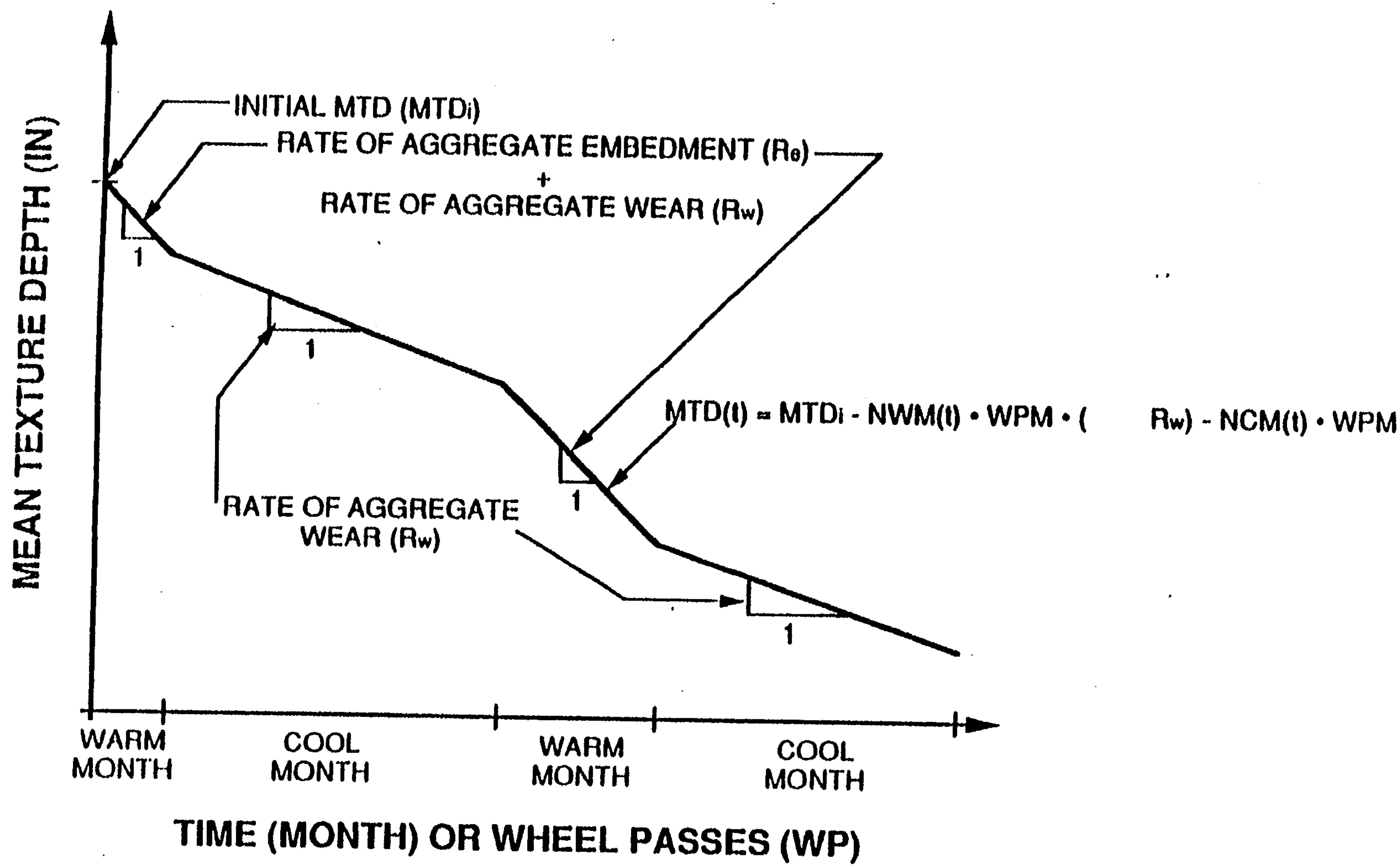

Figure 6.5. MTD as a function of wheel passes and time.

APPENDIX B – TABLES WITH DATA ON SEAL COAT

Table No. 1

Table 2.1. Properties of base asphalt.

Property	Value	AC-10 Specification
Absolute Viscosity, 140 °F, Poises	1034	1000 ± 200
Kinematic Viscosity, 140 °F, cSt	300	min, 150
Penetration, 77 °F, 100 g, 5 s, 0.01 mm	122	min, 70
Specific Gravity		
Thin Film Oven Test Residue		
Absolute Viscosity, 140 °F, Poises	2754	max, 5000
Ductility, cm	100+	min, 50
Penetration, 100 °F, 100 g, 5 s, 0.01 mm	74	---
Percent Mass Loss on Heating	0.036	---
Absolute Viscosity Ratio: Aged/Unaged	2.66	---

Table No 2

Table 2.2. Test results for as-delivered emulsion and emulsion residue, distillation method.

Property	E-3 Control	Neoprene	SBS-1	SBS-2	SBR	PennDOT Specifications Min	PennDOT Specifications Max
Emulsions:							
Residue, %	66.4	66.7	70.3	66.9	69.7	65	-
Demulsibility, %	96.7	78.4	97.6	91.8	88.1	-	-
Viscosity, Saybolt-Furol Seconds, 122 °F	395	212	243	345	114	100	400
Residue:							
Penetration, 77 °F, 0.01 mm, 100 g, 5 s	109	110	104	116	104	100	250
Softening Point, °F	112	118	118	116	124	-	-
Absolute Viscosity, 140 °F, Poises	1,260	1,770	2,000	1,600	2,890		-
Kinematic Viscosity, 275 °F, cSt	346	---	606	493	721	-	-

Table No. 3

Table 2.7. Aggregate properties--aggregate testing.

1) Gradation of Aggregate

Sieve Analysis

Sieve Size	Percent Passing 1B	Percent Passing Single-Sized
1/2	100	100
3/8"	89	92
#4	21	8
#8	8	4
#16	4	3.5
#30	4	--
#200	1	1

2) Hydrometer Analysis, percent finer than given size expressed as percent of total aggregate.

.025 mm	0.55
.008 mm	0.29
.001 mm	0.13

3) Flakiness Index

Average Least dimension .2 in

4) Los Angeles Abrasion

Percent Wear 30 %
(40 % max)

5) Crush Count

Percent Crushed Faces 94 %

6) Bulk Specific Gravity 2.62

7) Absorption 2.15 %

Table 3.1. Rut depths for the inner and outer wheel paths--test track.

Section No.	Average Rut Depth (in)	
	Inner Wheel Path	Outer Wheel Path
1	0.30	0.70
2	Leveling*	Leveling
3	Leveling	Leveling
4	0.30	0.30
5	0.25	0.35
6	Leveling	Leveling
7	Leveling	Leveling
8	0.25	0.25
9	0.45	0.25
10	Leveling	Leveling
11	Leveling	Leveling
12	0.90	0.85
13	1.05	0.95
14	Leveling	Leveling
15	Leveling	Leveling
16	0.45	0.25
17	0.50	0.40
18	Leveling	Leveling
19	Leveling	Leveling
20	0.35	0.20
21	0.25	0.10
22	Leveling	Leveling
23	Leveling	Leveling
24	0.65	0.35
S-1	0.5	0.25
S-3	Leveling	Leveling
S-4	Leveling	Leveling
S-5	Leveling	Leveling
S-6	Leveling	Leveling
S-7	Leveling	Leveling
S-8	Leveling	Leveling
S-9	Leveling	Leveling
S-10	Leveling	Leveling
S-11	Leveling	Leveling
S-12	Leveling	Leveling
S-13	Leveling	Leveling
S-14	Leveling	Leveling

* Rut depth for sections with leveling course was essentailly equal to zero.

Table No. 5

Table 3.3. Rut depths for the inner and outer wheel paths--Route 64.

Section No.	Average Rut Depth (in) Inner Wheel Path	Outer Wheel Path
Control North	.35	.40
Control South	.25	.25
1a	.35	.40
1b	.40	.35
1c	.25	.20
1d	.20	.15
2a	.45	.35
2b	.25	.30
2c	.25	.30
2d	.25	.40
3a	.30	.20
3b	.30	.25
3c	.30	.20
3d	.35	.25
4a	.30	.25
4b	.30	.30
4c	.25	.20
4d	.20	.10

Table No. 6

Table 3.4. Summary of existing pavement characteristics by test section--Route 64.

Existing Pavement Characteristic	Test Section
Three-year-old seal coat	Control North, Control South 1a,b, 2a,b, 3c,d, 4c,d
One-in overlay	3a,b, 4a,b, 1c,d, 2c,d

Table No. 7

Table 3.5 Summary of design and recommended emulsion and aggregate spread rates, Pavement Durability Test Facility and Route 64.

Location	Surface	PennDOT Surface Classification	PennDOT Bulletin 27 Design Emulsion Application Rate (gal/yd^2)	Emulsion Application Rate Recommended by PennDOT (gal/yd^2)
Pavement Durability Test Facility	Worn ID-2	Smooth non-porous surface (2)	.27	Low 0.27* High 0.35**
	New ID-2 Leveling	Slightly pocked, porous, and oxidized surface (4)	.35	
Route 64	Flushed portion of seal coat surface	Flushed asphalt surface (1)	.20	0.30**
	Non-flushed portion of seal coat surface	Smooth, non-porous surface (2)	.27	
	1-year-old ID-2 overlay	Slightly porous, oxidized surface (3)	.30	

* Chosen by project panel.
** Recommended by district maintenance personnel.

Table No. 8

Table 3.6. Comparison of various seal coat design procedures.

Design Method		Design Parameters* Considered	Design Application Rate	
			Aggregate (lb/yd^2)	Emulsion (gal/yd^2)
No. 1	PennDOT	1, 4, 6-10	22	0.30
2	McLeod	1, 4, 6-10, 12	22	0.28
3	ASTM	1, 8, 10	15	0.19
4	Asphalt Institute	1, 4, 6, 10	22.5	0.23
5	Asphalt Road Materials	1, 6, 7, 9, 10	15	0.20
6	Bituminous Materials	1, 6, 7, 10	15	0.22
7	Chevron	1-6, 10	22.5	0.28
	Average		19.1	0.24

* Design Parameters:

1. Aggregate Type (crushed slag, gravel, or sand)
2. Aggregate Condition (wet or dry, dirty or clean)
3. Aggregate Compatibility (w/ existing pavement, emulsion)
4. Emulsified Asphalt Type (based on set time, application temperature)
5. Emulsion Compatibility (w/ existing pavement, aggregate)
6. Existing Pavement Condition
7. Traffic Amount (ADT)
8. Application Type (single or double)
9. Application Temperature (of asphalt)
10. Field Conditions (of reconstruction site--rain, dry...)
11. Climate (of reconstruction site--wet, dry, humid...)
12. Flakiness Index
13. One-sized versus graded stone

Table No. 9

Table 4.1. Measured emulsion application rates.

Location	Test Section	ASTM Method, Average	Geotextile Patch No. 1	2	3	Average	Target
			Emulsion Application Rate (gal/yd²)				
Pavement Durability Facility	1-4	0.27	0.27	0.27	----	0.27	0.27
	5-8	0.38	0.41	0.42	----	0.40	0.35
	9-12	0.23	----	----	----	0.23	0.27
	13-16	0.35	0.36	----	----	0.36	0.35
	17-20	0.22	0.23	0.25	----	0.23	0.27
	21-24	0.34	0.39	0.37	----	0.37	0.35
	S-1	----	0.23	----	----	0.23	0.30
	S-3,S-4,S-5	----	0.34	0.35	0.36	0.35	0.35
	S-6	----	0.34	0.37	0.38	0.36	0.35
	S-7*	----	0.35	0.33	0.32	0.34	0.35
	S-8	----	0.25	0.28	0.25	0.26	0.35
	S-9*	----	0.31	0.33	0.35	0.33	0.35
	S-10	----	0.37	0.35	----	0.36	0.35
	S-11*	----	0.31	0.31	0.31	0.31	0.35
	S-12*	----	0.31	0.28	----	0.30	0.35
	S-13,S-14	----	0.42	0.43	0.42	0.42	0.38
Route 64	Control N	----	0.31	0.30	0.32	0.31	0.30
	Control S	----	0.30	0.30	0.29	0.30	0.30
	1a, 1b*	----	0.27	0.27	0.27	0.27	0.30
	1c, 1d*	----	0.30	0.26	0.29	0.28	0.30
	2a, 2b*	----	0.29	0.30	0.29	0.29	0.30
	2c, 2d*	----	----	0.29	0.29	0.29	0.30
	3a, 3b*	----	0.34	0.31	0.31	0.32	0.30
	3c, 3d*	----	0.30	0.31	0.32	0.31	0.30
	4a, 4b*	----	0.29	0.29	0.28	0.29	0.30
	4c, 4d*	----	0.29	0.29	0.30	0.29	0.30

* These sections represent the modified emulsion which was applied with a second application truck.

Table 4.2. Emulsion application rate across pavement.

Pad No.	Emulsion Application Rate (gal/yd²) 1-4	5-8	9-12	13-16	17-20	21-24
1						
2						
3						
4					.22	
5		.36	.23	.37	.22	.31
6	.29	.43		.33	.21	.35
7	.28	.37	.24	.35	.23	.37
8	.25	.41	.23	.38	.26	.33
9	.28		.22	.34	.25	.32
10	.25	.40	.21	.36	.24	.33
11	.26	.37	.21	.36	.25	.33
12	.26	.35	.22	.36	.24	.32
13	.25	.38	.25	.35	.19	.36
14	.28	.38	.22	.36	.20	.34
15			.23			.31
16	.28	.38	.26		.24	
17	.25	.39	.24	.34	.24	.31
18	.27	.38	.20	.37	.24	.32
19	.26	.43	.23	.34	.25	.31
20	.27	.38			.20	.36
21	.28	.34	.23	.34	.24	
22	.28	.46	.23	.36	.21	.35
23			.25	.34	.23	.34
24		.35	.20	.37	.23	.31
25	.25	.42	.24	.35	.19	.31
26	.27	.36	.19	.36	.23	.36
27	.29	.39	.23	.37	.22	.36
28	.25	.38	.23	.36	.24	.33
29	.26	.38	.25	.36	.21	.36
30	.26	.39		.33	.24	.35
31		.37		.37		.36
32		.38		.36		.34
33						.31
34						.34
35						
36						

Table 4.3. Design and actual emulsion application rates for the test track and Route 64.

Section No.	Location	Emulsion Application Rate (gal/yd^2) Design	Allowable Range[a]	Target	Measured
1	Test Track	0.27	0.24 - 0.30	0.27	0.27
2	Test Track	0.35	0.24 - 0.30	0.27	0.27
3	Test Track	0.35	0.24 - 0.30	0.27	0.27
4	Test Track	0.27	0.24 - 0.30	0.27	0.27
5	Test Track	0.27	0.32 - 0.39	0.35	<0.41>[b]
6	Test Track	0.35	0.32 - 0.39	0.35	<0.41>
7	Test Track	0.35	0.32 - 0.39	0.35	<0.41>
8	Test Track	0.27	0.32 - 0.39	0.35	<0.41>
9	Test Track	0.27	0.24 - 0.30	0.27	<0.23>
10	Test Track	0.35	0.24 - 0.30	0.27	<0.23>
11	Test Track	0.35	0.24 - 0.30	0.27	<0.23>
12	Test Track	0.27	0.24 - 0.30	0.27	<0.23>
13	Test Track	0.27	0.32 - 0.39	0.35	0.36
14	Test Track	0.35	0.32 - 0.39	0.35	0.36
15	Test Track	0.35	0.32 - 0.39	0.35	0.36
16	Test Track	0.27	0.32 - 0.39	0.35	0.36
17	Test Track	0.27	0.24 - 0.30	0.27	<0.23>
18	Test Track	0.35	0.24 - 0.30	0.27	<0.23>
19	Test Track	0.35	0.24 - 0.30	0.27	<0.23>
20	Test Track	0.27	0.24 - 0.30	0.27	<0.23>
21	Test Track	0.27	0.32 - 0.39	0.35	0.37
22	Test Track	0.35	0.32 - 0.39	0.35	0.37
23	Test Track	0.35	0.32 - 0.39	0.35	0.37
24	Test Track	0.27	0.32 - 0.39	0.35	0.37
S-1	Test Track	NA[c]	-- --	0.30	0.23
S-3	Test Track	0.35	0.32 - 0.39	0.35	0.35
S-4	Test Track	0.35	0.32 - 0.39	0.35	0.35
S-5	Test Track	0.35	0.32 - 0.39	0.35	0.35
S-6	Test Track	0.35	0.32 - 0.39	0.35	0.36

[a]Allowable range = design ± 10% of design as per PennDOT specifications, Bulletin 27.
[b]Emulsion application rates that were outside the allowable range are indicated by < >.
[c]The PennDOT design procedure is not applicable to the single-sized stone.

Table No. 12

Table 4.3. Design and actual emulsion application rates for the test track and Route 64 (continued).

Section No.	Location	Emulsion Application Rate (gal/yd²)			
		Design	Allowable Range[a]	Target	Measured
S-7	Test Track	0.35	0.32 - 0.39	0.35	0.34
S-8	Test Track	0.35	0.32 - 0.39	0.35	<0.26>
S-9	Test Track	0.35	0.32 - 0.39	0.35	0.33
S-10	Test Track	0.35	0.32 - 0.39	0.35	<0.36>[b]
S-11	Test Track	0.35	0.32 - 0.39	0.35	<0.31>
S-12	Test Track	0.35	0.32 - 0.39	0.35	0.30
S-13	Test Track	NA	NA	0.38	0.42
S-14	Test Track	NA	NA	0.38	0.42
CN	Route 64	0.27	0.24 - 0.30	0.30	<0.31>
CS	Route 64	0.27	0.24 - 0.30	0.30	0.30
1a	Route 64	0.27	0.24 - 0.30	0.30	0.27
1b	Route 64	0.27	0.24 - 0.30	0.30	0.27
1c	Route 64	0.30	0.27 - 0.33	0.30	0.28
1d	Route 64	0.30	0.27 - 0.33	0.30	0.28
2a	Route 64	0.27	0.24 - 0.30	0.30	0.29
2b	Route 64	0.30	0.27 - 0.33	0.30	0.29
2c	Route 64	0.30	0.27 - 0.33	0.30	0.29
2d	Route 64	0.30	0.27 - 0.33	0.30	0.29
3a	Route 64	0.30	0.27 - 0.33	0.30	<0.32>
3b	Route 64	0.30	0.27 - 0.33	0.30	<0.32>
3c	Route 64	0.27	0.24 - 0.30	0.30	0.29
3d	Route 64	0.27	0.24 - 0.30	0.30	0.29
4a	Route 64	0.30	0.27 - 0.33	0.30	0.29
4b	Route 64	0.30	0.27 - 0.33	0.30	0.29
4c	Route 64	0.27	0.24 - 0.30	0.30	0.29
4d	Route 64	0.30	0.27 - 0.33	0.30	0.29

[a]Allowable range = design ± 10% of design as per PennDOT specifications, Bulletin 27.
[b]Emulsion application rates that were outside the allowable range are indicated by < >.
[c]The PennDOT design procedure is not applicable to the single-sized stone.

Table No. 13

Table 4.5. Measured aggregate application rates.

Location	Test Sections	Application Rates (lb/yd^2)			Average Rate (lb/yd^2)	Target
Pavement Durability Facility	Traffic Section 1 (1-8)	24.5	24.2	26.3	25.0	22
	Traffic Section 2 (9-16)	23.2	22.4	25.6	23.7	22
	Traffic Section 3 (17-24)	26.1	22.4	25.5	24.7	22
	Neoprene (S-7) [S3-S5]*	23.0	23.6	22.7	23.1	22
	SBR (S-9) [S-6]	21.0	20.7	20.6	20.8	22
	SBS-1 (S-11) [S-8]	34.5	34.6	33.6	34.2	22
	SBS-2 (S-12) [S-10]	28.9	27.6	27.8	28.1	22
	Single Size (S-13, 14)	27.5	30.0	28.6	28.7	20
	Single Size (S-1)	25.5	26.0	24.4	25.3	20
Route 64	Control North	16.7	15.9	16.0	16.2	18
	Control South	19.8	17.8	19.0	18.9	18
	Neoprene (a, b)	17.8	18.9	19.5	18.7	18
	Neoprene (c, d)	19.4	18.0	16.9	18.1	18
	SBR (a, b)	17.1	17.2	17.6	17.3	18
	SBR (c, d)	17.9	13.8	17.0	17.4	18
	SBS-1 (a, b)	17.8	19.6	18.6	18.7	18
	SBS-1 (c, d)	16.9	19.0	20.0	18.6	18
	SBS-2 (a, b)	17.9	17.6	17.0	17.5	18
	SBS-2 (c, d)	17.1	15.1	17.4	16.5	18

* Numbers in brackets indicate that the bracketed sections were included in the same application as the sections in parentheses. Actual measurements were made in the sections enclosed in parentheses.

Table No. 14

Table 4.6. Summary of target and measured aggregate application rates, brooming loss, and estimated remaining aggregate.

Section	Location	Target Aggregate Application Rate (lb/yd²)	Measured Aggregate Application Rate (lb/yd²)	Brooming Loss (lb/yd²)	Remaining Aggregate (lb/yd²)
1	P.D.F.*	22	25.0	5.7	19.3
2	P.D.F.	22	25.0	8.1	16.9
3	P.D.F.	22	25.0	8.6	16.4
4	P.D.F.	22	25.0	5.3	19.7
5	P.D.F.	22	25.0	5.1	19.9
6	P.D.F.	22	25.0	5.8	19.2
7	P.D.F.	22	25.0	4.2	20.8
8	P.D.F.	22	25.0	3.5	21.5
9	P.D.F.	22	23.7	5.6	18.1
10	P.D.F.	22	23.7	10.6	13.1
11	P.D.F.	22	23.7	7.4	16.3
12	P.D.F.	22	23.7	5.0	18.7
13	P.D.F.	22	23.7	5.7	18.0
14	P.D.F.	22	23.7	4.6	19.1
15	P.D.F.	22	23.7	5.7	18.0
16	P.D.F.	22	23.7	5.0	18.7
17	P.D.F.	22	24.7	4.5	20.2
18	P.D.F.	22	24.7	6.0	18.7
19	P.D.F.	22	24.7	6.3	18.4
20	P.D.F.	22	24.7	7.6	17.1
21	P.D.F.	20	24.7	7.0	17.7
22	P.D.F.	22	24.7	5.1	19.6
23	P.D.F.	22	24.7	5.1	19.6
24	P.D.F.	22	24.7	4.7	20.0
S-1	P.D.F.	22	25.3	5.0	20.3
S-3	P.D.F.	22	23.1	7.0	16.1
S-4	P.D.F.	22	23.1	7.6	15.5
S-5	P.D.F.	22	23.1	6.5	16.6
S-6	P.D.F.	22	20.8	6.7	14.1
S-7	P.D.F.	22	23.1	4.3	18.8
S-8	P.D.F.	22	34.2	14.2	20.0
S-9	P.D.F.	22	20.8	6.7	14.1
S-10	P.D.F.	22	28.1	4.4	23.7
S-11	P.D.F.	20	34.2	14.8	19.4
S-12	P.D.F.	20	28.1	8.0	20.1

*Pavement Durability Facility

Table No. 15

Table 4.6. Summary of target and measured aggregate application rates, brooming loss, and estimated remaining aggregate (continued).

Section	Location	Target Aggregate Application Rate (lb/yd²)	Measured Aggregate Application Rate (lb/yd²)	Brooming Loss (lb/yd²)	Remaining Aggregate (lb/yd²)
S-13	P.D.F.	20	28.7	3.6	25.1
S-14	P.D.F.	20	28.7	4.0	24.7
CN	Route 64	18	16.2	0.6	15.6
CS	Route 64	18	18.9	1.9	17.0
1a	Route 64	18	18.7	0.5	18.2
1b	Route 64	18	18.7	1.7	17.0
1c	Route 64	18	18.1	0.8	17.3
1d	Route 64	18	18.1	0.6	17.5
2a	Route 64	18	17.3	2.7	14.6
2b	Route 64	18	17.3	3.0	14.3
2c	Route 64	18	17.4	2.1	15.3
2d	Route 64	18	17.4	0.8	16.6
3a	Route 64	18	18.7	3.2	15.5
3b	Route 64	18	18.7	4.1	14.6
3c	Route 64	18	18.6	2.6	16.0
3d	Route 64	18	18.6	0.8	17.8
4a	Route 64	18	17.5	1.8	15.7
4b	Route 64	18	17.5	1.9	15.6
4c	Route 64	18	16.5	1.1	15.4
4d	Route 64	18	16.5	1.3	15.2

[a]Pavement Durability Facility

Table No. 16

Table 4.7. Summary of the construction variables documented during the seal coat construction at the Pavement Durability Facility and Route 64.

Section	Emulsion Type	No. of Roller Passes	Traffic Control Applied Hours	Emulsion Appl. Temp. (°F)	Time Between Emulsion-Aggregate (s)	Time Between Aggregate-Rolling (s)
1	E-3	3	2.5	165	30	30
2	E-3	3	2.5	165	30	30
3	E-3	1	2.5	165	30	180
4	E-3	1	2.5	165	30	180
5	E-3	1	2.5	165	30	30
6	E-3	1	2.5	165	30	30
7	E-3	3	2.5	165	30	30
8	E-3	3	2.5	165	30	30
9	E-3	3	7.0	174	26	22
10	E-3	3	7.0	174	26	22
11	E-3	1	7.0	174	26	22
12	E-3	1	7.0	174	26	22
13	E-3	1	7.0	174	28	24
14	E-3	1	7.0	174	28	24
15	E-3	3	7.0	174	28	24
16	E-3	3	7.0	174	28	24
17	E-3	3	25.5	170	30	30
18	E-3	3	25.5	170	30	30
19	E-3	1	25.5	170	30	30
20	E-3	1	25.5	170	30	30
21	E-3	1	25.5	170	30	30
22	E-3	1	25.5	170	30	30
23	E-3	3	25.5	170	30	30
24	E-3	3	25.5	170	30	30
S-1	E-3	1	2.5	160	103	25
S-3	E-3	3	6.5	170	40	80
S-4	E-3	1	6.5	170	40	80
S-5	E-3	1	6.5	170	40	80
S-6	E-3	1	2.0	150	30	30
S-7	Neoprene	1	2.0	165	60	40
S-8	E-3	1	2.25	160	50	20

Table No. 17

Table 4.7. Summary of the construction variables documented during the seal coat construction at the Pavement Durability Facility and Route 64 (continued).

Section	Emulsion Type	No. of Roller Passes	Traffic Control Applied Hours	Emulsion Appl. Temp. (°F)	Time Between Emulsion-Aggregate (s)	Time Between Aggregate-Rolling (s)
S-9	SBR	1	2.0	160	30	30
S-10	E-3	1	2.0	165	30	30
S-11	SBS 1	1	2.0	160	25	25
S-12	SBS 2	1	2.0	160	30	30
S-13	E-3	3	2.0	165	24	111
S-14	E-3	1	2.0	165	24	111
CN	E-3	1	2.0	170	30	28
CS	E-3	1	4.0	165	27	90
1a	Neoprene	1	2.0	165	30	32
1b	Neoprene	2	2.0	165	30	32
1c	Neoprene	2	4.0	165	28	82
1d	Neoprene	1	4.0	165	28	82
2a	SBR	1	4.0	160	120	80
2b	SBR	2	4.0	160	120	80
2c	SBR	2	2.0	160	20	30
2d	SBR	1	2.0	160	20	30
3a	SBS 1	1	4.0	170	55	55
3b	SBS 1	2	4.0	170	55	55
3c	SBS 1	2	2.0	170	25	80
3d	SBS 1	1	2.0	170	25	80
4a	SBS 2	1	2.0	160	30	30
4b	SBS 2	2	2.0	160	30	30
4c	SBS 2	2	4.0	160	30	30
4d	SBS 2	1	4.0	160	30	30

Table No. 18

Table 4.4. Emulsion application temperatures.

Material	Location	Section(s)	Emulsion Temperature (°F)	Average Emulsion Temperature (°F)
E-3	Durability Facility	1-8	165	
		9-16	174	
		17-24	170	
		S-1	160	
		S-3, S-4, S-5	170	
		S-6	150	
		S-8	160	
		S-10	165	
		S-13, S-14	165	164
	Route 64	Control North	170	
		Control South	165	167
Neoprene	Durability Facility	S-7	165	
	Route 64	1a, 1b, 1c, 1d	165	165
SBS-1	Durability Facility	S-11	160	
	Route 64	3a, 3b, 3c, 3d	170	165
SBR	Durability Facility	S-9	160	
	Route 64	2a, 2b, 2c, 2d	160	160
SBS-2	Durability Facility	S-12	160	
	Route 64	4a, 4b, 4c, 4d	160	160

Table No. 19

Table 1.2. Variables included in the construction variable experiment at the Pavement Durability Facility.

Primary Study Variable	Variable	No. of Levels
Pavement Condition	Worn ID-2, New ID-2 Leveling	2
Emulsion Rate	High, Low	2
No. of Roller Passes	1, 3	2
Traffic Control, delay before application of traffic	2, 8, 24	3

Total number of test sections: 2 x 2 x 2 x 3 - 24

Table no. 20

Table 1.4. Summary of the characteristics for each test section for the secondary material variable experiment at the Pavement Durability Facility.

Section No.	Emulsion Type	Aggregate Gradation	No. of Roller Passes	Pavement Condition
S-1	E-3	Single-Size	1	Worn ID-2
S-3	E-3	Graded	3	Worn ID-2 Leveling*
S-4	E-3	Graded	1	Worn ID-2 Leveling
S-5	E-3	Graded	1	New ID-2 Leveling
S-6	E-3	Graded	1	New ID-2 Leveling
S-7(S-5)**	Neoprene	Graded	1	New ID-2 Leveling
S-8	E-3	Graded	1	New ID-2 Leveling
S-9(S-6)	SBR	Graded	1	New ID-2 Leveling
S-10	E-3	Graded	1	New ID-2 Leveling
S-11(S-8)	SBS 1	Graded	1	New ID-2 Leveling
S-12(S-10)	SBS 2	Graded	1	New ID-2 Leveling
S-13	E-3	Single-Size	3	New ID-2 Leveling
S-14	E-3	Single-Size	1	New ID-2 Leveling

* Worn ID-2 Leveling was placed in 1987 with no traffic until after the seal coat was applied.

**Numbers in parentheses correspond to the control for the sections that were constructed with modified binders.

Table No. 21

Table 1.5. Summary of characteristics of seal coat test sections constructed on Route 64.

Section No.	Emulsion Type	No. of Roller Passes	Traffic Control (hours)	Existing Pavement Condition
Control North	AC-10 Control	1	2	3-Year Seal Coat
Control South	AC-10 Control	1	4	3-Year Seal Coat
1a	Neoprene	1	2	3-Year Seal Coat
1b	Neoprene	2	2	3-Year Seal Coat
1c	Neoprene	2	4	Thin Overlay
1d	Neoprene	1	4	Thin Overlay
2a	SBR	1	4	3-Year Seal Coat
2b	SBR	2	4	3-Year Seal Coat
2c	SBR	2	2	Thin Overlay
2d	SBR	1	2	Thin Overlay
3a	SBS	1	4	Thin Overlay
3b	SBS	2	4	Thin Overlay
3c	SBS	2	2	3-Year Seal Coat
3d	SBS	1	2	3-Year Seal Coat
4a	SBS	1	2	Thin Overlay
4b	SBS	2	2	Thin Overlay
4c	SBS	2	4	3-Year Seal Coat
4d	SBS	1	4	3-Year Seal Coat

Table 5.1. Evaluation of performance measurements for seal coats.

Technique	Parameter Obtained	Frequency	Number Per Section (location)	Advantages	Disadvantages	Remarks
Sand Patch	Mean Texture Depth (MTD)	Monthly	4 (outer wheel path)	Objective, sensitive	Small test area; distress mode not identified	May become less sensitive as macrotexture is reduced.
Skid Resistance	Skid Number (SN)	Monthly	5 (wheel path)	Covers entire section length, microtexture and microtexture may be evaluated	Lacks sensitivity early, affected by temperature and contamination, distress mode not identified	Becomes more sensitive as macrotexture is reduced.
Visual Examination	Three performance ratings: overall; bleeding; aggregate retention	Monthly	3 Evaluators (entire section)	Covers entire section; identifies failure mode	Subjective, lacks sensitivity, affected by lighting and environment	Unsuitable for ranking the sections or for detailed analysis.
Stereophotos	None	Monthly	1 (outer wheel path)	Visual record of changes with time at one location	Small test area.	Unsuitable for detailed analysis, since no parameter is obtained.
Geotextiles	None	---	---	---	Appear to affect performance	Did not work (could not be recovered from sections