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# AMERICAN OIL COMPANY

## RESEARCH AND DEVELOPMENT DEPARTMENT

# LABORATORY TEST TRACK INVESTIGATION OF THE SKID RESISTANCE OF BITUMINOUS PAVEMENTS COMPOSED OF HARD TYPE FINE AGGREGATES

T. L. SPEER

FINAL REPORT

RESEARCH PROJECT FOR MICHIGAN STATE HIGHWAY DEPARTMENT,
OFFICE OF TESTING AND RESEARCH

JULY, 1965

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AMERICAN OIL COMPANY

RESEARCH AND DEVELOPMENT DEPARTMENT
WHITING, INDIANA

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T. L. SPEER
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Findings of a contract research project for Michigan State Highway Department, Office of Testing and Research

ABSTRACT

Twelve thin deslicking surface course mixtures were built and tested for overall slipperiness characteristics and relative resistance to polishing action in the laboratory test track traffic machine. Four types of minerals, aggregate sizes from 3/8 inch to passing the Number 30 screen sieve, three types of binder and both commercial and experimental sources for pavement materials were included in these studies. Sliding coefficients, measured at 7 and 30 mph were used to rank and rate mixture performance. 3.5 million machine wheel coverages were operated during a two and one half month test period. Factors related the improvement of pavement skidding resistance are summarized. Maximum mixture aggregate size is important. The contribution of mineral type was found to have a smaller effect with sandstone outperforming the more widely used conventional paving materials employed in this experiment. Future development effort with laboratory scale pavements is justified. Experiments designed to study and control sand deslicking mixture erosion are proposed for future projects.

## INTRODUCTION

Ideal bituminous pavements are durable, they are stable and they do not become slippery under the scuffing actions of dense wheel traffic. Many motorists are involved in highway accidents each year. While the vast majority of these unfortunate, often death dealing, events are the fault of individual drivers judgment errors, today far too many are caused by unsafe driving surfaces(1). Providing adequate pavement skid resistance is as important to the progressive highway engineer as achieving safe roadway alignments, developing adequate mixture strength or attaining slab longevity.

### Skid Resistance

Pavement surface slipperiness characteristics that have absolute physical meanings are the prime factors which control skidding improvements with deslicking overlays. Highway engineers seek skid design properties which are analogous to strength, stability or hardness in structural materials. Unfortunately, a single parameter cannot describe resistance to skidding adequately(2).

The ratio of the force or resistance to sliding in the plane of contact between the tire and road to the wheel load normal to this plane is the coefficient of road friction. The coefficient is not an absolute number. Also, it is not a simple material property. Rather, it is an identity which is meaningful and valid numerically for a set of specific conditions. A sliding coefficient represents the combined frictional effects of a test procedure, a measuring instrument, the road surface itself and the environment at the time the coefficient was evaluated. Thus, friction coefficients describe all of the aspects of a performance quality or value.

Exhaustive studies into the exact nature of pavement slipperiness phenomena, conducted over the past 30 to 35 years in the United States and Europe, clearly demonstrate that the simplest evaluations of pavement friction and skidding hazards are complicated by the interaction of many factors. Some 15 different variables contribute to large differences in pavement friction. In addition, more than 15 vehicle operation and tire friction factors play significant roles in skidding accidents on slippery pavements[3].

Geometric and molecular properties of the road surface largely determine the obtainable sliding coefficient. Surface geometry may be described by:

(1) the average number of discrete particles per unit area,
(2) their average size, distribution and
(3) their average shape.

Road surface factors affecting skid resistance include:

(1) the type - asphalt, concrete, brick, surface treatment or plant mix,
(2) the condition - wet, dry, or ice,
(3) the maintenance - new, worn, sealed or deslicked,
(4) the aggregate - mineral type, size, gradation and hardness,
(5) the binder - its type and amount,
(6) the texture - dense graded, open graded, sandpaper finish or glazed,
(7) the roughness - smooth, corrugated, ravelling, scaling or warped,
(8) the contamination - sand, dust, oil grease or mud,
(9) the water wetting - rain water, ground water, municipal water and film thickness,
(10) the scouring action - of traffic, rain, grits and chlorides,
(11) the weather-oxidation, freezing, thawing, wetting or drying,
(12) the time or age - daily, monthly or seasonal,
(13) the temperature - ambient, solar gradient or tire tread induced,
(14) the traffic - its weight, volume, compaction and abrasiveness,
(15) the highway - its design curvature, grade, crown, super elevation and intersection alignment.

Vehicle operating factors which affect skid resistance are:

(1) vehicle speed, size, weight distribution, accelerating and braking characteristics, and
(2) the tire size, tread pattern, load, road contact area, inflation pressure and component design features.

## Skid Resistance Research in Michigan

The State of Michigan has been active in fostering pavement surface skid resistance design and construction improvements for many years. Active non-skid experiments began in 1947-48 with a State Highway Department field study of several pavement projects constructed during the late 1930's and early 1940's in the Upper Peninsula[4,5]. In 1954 non-skid research was expanded to include a segment of the automotive industry. A cooperative survey project covering about 150 sites was undertaken with the General Motors Proving Ground Administration[4]. A towed trailer of the general type described by P. C. Skeels[6] was used to determine skid resistance levels of a spectrum of highway surface types and physical conditions[5]. Data from this program demonstrate that definite difference exist in surface friction-wear patterns for portland cement concrete, bituminous concrete, sheet asphalt and bituminous surface treatment types of pavement. They also demonstrate that speed is a very important factor in wet-surface skid resistance and that some types of paving materials can be expected to lose up to 60% of their 20 mph coefficient at 40 mph.

One general conclusion of Michigan's research program: skid resistance standards must be a key feature in overall pavement design procedures and deslicking of slippery, unsafe surfaces is an important and economical construction activity whenever full surface course thickness is not needed for ride smoothing or geometric design improvement. Analysis of Michigan's data suggest a 40 mph towed trailer coefficient not less than 0.35-0.40 is required to ensure reasonably safe stopping distances at all speeds under wet driving conditions and that "consideration be given --- designs employing thin fine-aggregate deslicking surface courses to achieve the desired --- friction standard". To implement this objective, a one-mile section of experimental bituminous surface, incorporating seven fine aggregate mixtures, was built in June, 1958. These deslicking materials were compacted to one-half inch thickness or less. Skid resistance level was measured periodically.

## Purpose and Scope of the Laboratory Test Track Investigation

The present investigation is an extension of Michigan's experimental bituminous field test project. Its objective was to obtain realistic skid resistance performance records for use in 1965 of several hard type aggregates which are not presently available commercially in finer aggregate particle gradations but are sizes which could be produced economically if superior deslicking performance was achieved with them.

The circular laboratory test track technique was selected for the investigation because:

(1) relatively small quantities of experimental fine-graded aggregates were used for pavement construction,
(2) the aggregate required could be easily produced in a short time in a laboratory-scale rock crusher,

(3) the controlled environment of the laboratory machine could be used to accelerate and duplicate the aging experienced by real roads after many years of service, and
(4) several million passages of vehicular wheels could be operated over the pavements and skid resistance coefficient responses determined prior to the start of the 1965 pavement construction season.

Twelve primary and one secondary or reserve skid resistance mixtures were designed for the traffic laboratory program. Three commercial gradations, eight fine deslicking and a seal coat treatment were selected for inclusion in the project. Ten of the twelve primary test pavements were made with 60-70 penetration asphalt cement, one with Wyton resin binder and one with epoxy seal binder. Periodic surface skid resistance determinations were made during a test period of about 3,500,000 wheel passages. Slipperiness test were conducted with two portable instruments; one operated at a varying speed which averaged about 7 mph and the other at constant speeds of 7 and 30 mph.

## EXPERIMENTAL CONSIDERATIONS

Project experimental activity logically divides into four independent, interrelated phases. During the initial operation twelve primary and one secondary or spare deslicking mixture overlay pavements were constructed. This phase was followed by the laboratory traffic operation employing environmental conditions and situations designed to encourage rapid wheel polishing action. Concurrently, variations in slipperiness characteristics of wheel and non-wheel path portions of pavement surfaces were measured with the standard portable British pendulum skid tester. The final step involved development and operation of a high speed skid test device to supplement the 7 mph, average speed, British instrument; all pavements were evaluated after passage of 3,498,500 wheels for their sliding coefficients at constant speeds of 7 and 30 mph with a bicycle wheel apparatus mounting the pendulum head and rubber slider on its perimeter.

Excepting the two pavement slipperiness testers, all subgrade preparation, mix plant operations, slab laydown work, traffic testing to polish surface aggregate and final pavement condition measurements were performed with machines, devices and instruments normally available and in regular use at the Highway Engineering Research and Development Laboratory of American Oil Company at Whiting, Indiana. Detailed information regarding the full capabilities of the laboratory and its testing equipment are given in References 7 through 11. Since, in the interest of brevity, only those characteristics of the apparatus which apply particularly to deslicking mixtures and their proper performance evaluations will be mentioned in the remainder of this section, all "detail-oriented" readers are encouraged to study the five References.

Pavement Construction

Test pavements 24 x 44 inches in size were selected for this experiment. A group of twelve sections is needed to make up the complete circular test track in the variable speed traffic test machine; this is the second traffic device built at the Whiting Laboratory and it has been engaged in essentially continuous base course testing for the past eighteen months. However, the normal tracking and torquing arrangements of the four wheels of the machine was modified as outlined below for this skid resistance study.

Significant deflection or rutting of the test slabs was not permitted because these actions tend to slow aggregate polishing and possibly would be detrimental to project testing efficiency. To accomplish these objectives thick, semi-rigid bases were designed and constructed as follows: first a 21 inch thick subbase of crushed limestone, Illinois Highway Department gradation specification No. 8 which is frequently used to build waterbound macadam bases, was placed in lifts having a compacted thickness of 6 inches; next the subbase was covered with a 5 inch thickness of gravel aggregate, portland cement concrete base; and, finally, the concrete was given a spray tack coat of liquid RC-70 asphalt at an application rate of 0.05 gpsy. The deslicking mixture was machine spread, tamped and screeded on top of the concrete. Steel and rubber tire rolling produced a final overlay thickness of 5/8 inch. The completed test section, including the specimen container, weighed approximately 2500 pounds.

Details of mixture formulas for the twelve primary and a spare skid resistance test sections are:

| | Material | | Filler | | Binder | |
|---|---|---|---|---|---|---|
| Mix No. | Type | Amount, % | Type | Amount, % | Type | Amount, % |
| 1 | 31A Blend (P 3/8) | 92.2 | Fly ash | 2.0 | Asphalt | 5.8 |
| 2 | 3BC Blend (P8) | 93.5 | | | Asphalt | 6.5 |
| 3 | 2NS Blend (P 3/8) | 93.7 | | | Asphalt | 6.3 |
| 4 | Sturgeon Quartzite (P8) | 93.0 | | | Asphalt | 7.0 |
| 5 | Sturgeon Quartzite (P8 R16) | | | | Epoxy | Seal |
| 6 | Chocolay Quartzite (P4) | 94.3 | | | Wyton | 5.7 |
| 7 | Chocolay Quartzite (P4) | 94.3 | | | Asphalt | 5.7 |
| 8 | Rhyolite (P8) | 94.3 | | | Asphalt | 5.7 |
| 9 | Trap Rock (P8) | 94.3 | | | Asphalt | 5.7 |
| 10 | Dune Sand (P30) | 91.5 | Asbestos (7M06) | 2.0 | Asphalt | 6.5 |
| 11 | Slag Sand, 3BCS (P4) | 92.0 | | | Asphalt | 8.0 |
| 12 | Sandstone (P 3/8) | 92.5 | | | Asphalt | 7.5 |
| 10A | 2MS Sand (P8) | 93.5 | | | Asphalt | 6.5 |

Mix numbers indicated above will be used throughout the remainder of this report to identify individual test pavements. Pavement 10A is a spare and was not traffic tested. The notation P 3/8 etc. means passing the indicated screen sieve and R means retained on the sieve. Pavement 5 was a seal coat treatment using sized Sturgeon Quartzite cover chips. All of the aggregate for the test pavements were produced, sized and blended to exact gradations required by Michigan at the Testing Laboratory Division, Ann Arbor. This Laboratory also furnished the epoxy seal coat and Wyton binder for pavements 5 and 6. The asphalt cement for the remaining 10 test and the spare pavement was a 60-70 penetration grade supplied by American Oil Company from current Whiting, Indiana refinery production; the crude was normal for this service, consisting of a blend of about 70% Y and 30% C sources. Results of inspections made on this asphalt are summarized in Table I. A large sample of this asphalt was sent to Ann Arbor for confirmation property tests.

Blended aggregates were received from the Testing Laboratory Division in Michigan State Highway Department canvas sample bags. One full and a fraction of another bag, obtained with a riffles type sample splitter, were blended together to make up a sample batch weighing about 100 pounds. This aggregate was divided into 2 metal cans, placed in an electric laboratory oven and brought to a uniform temperature of 303 ± 2 F. Batch size quantities of the asphalt were put into and stored in 12 metal cans from a single laboratory melt; one of these cans was heated for each pavement to a uniform temperature of 276 ± 2 F in a second electric oven. Temperature for pavement 6 aggregate was 320 ± 2 F and the Wyton binder 280 ± 2 F. Aggregates plus the formulation quantity of binder were mixed for 60 seconds in the laboratory planetary mixer. The bowl and paddle were preheated to the temperature of the aggregate; bowl sides were scrapped free of adherence at the midpoint and at the end of the mixing cycle.

The laboratory deslicking surface courses were machine placed and compacted with laydown equipment which duplicates normal field practice, as shown in Figure 1. A hot tamper-screeder finishing machine, Figure 2, was used to lay each mixture, excepting the epoxy seal treatment, on top of its tack coated concrete base. Loose mixture material was spread after a 5 minute post mixing storage period in an electric oven controlled at the aggregate temperature. Two 12 inch wide passes of the tamper-screeder, Figure 2, covered the width of the test pavement; a third finishing pass was made down the center of the pavement to eliminate center joint effects, Figure 3. Laydown machine travel speed was varied from 10 to 30 feet per minute depending on mixture handling characteristics. Following screeding, 9 passes of the steel wheel roller, Figure 4 were applied to compact the pavement; for initial passes the loading was 34 pounds per inch width of the roller and final passes were at 118 pounds. A pneumatic rubber tire roller, Figure 5, was operated at light loads to erase all texture evidence of the center line construction joint. Rubber rolling was not used with several mixtures because the steel roller removed joint line markings satisfactorily.

Samples of the loose mix were retained and shipped in metal cans each day pavements were fabricated to the Chicago Testing Laboratory. This organization obtained mixture composition data after extracting the asphalt; their findings were reported directly to the State of Michigan Highway Department. Chunks of compacted mixture, stripped from the concrete end blocks which support compaction rollers at the end of each pass, were shipped to the Testing Laboratory Division for further analysis. Results are tabulated in the Appendix.

Pavement 5 was designed as an epoxy surface treatment with Sturgeon quartzite chips, passing No. 8 and retained on No. 16 sieve screen . First, a 5/8 inch thick overlay was laid on the concrete base using crushed limestone and natural silica sand aggregates conforming to I 11, Mixture B surface course specifications of the Illinois Highway Department (this is the regular surface course normally used at the Whiting Traffic Laboratory). Next, a large mechanical scrubbing machine was operated over the new surface; it was polished until all asphalt was worn off the exposed portions of the larger aggregate particles (several scrubbings were necessary and between them, the pavement was chilled to 20 F to improve scrubber efficiency). Finally, the "worn" surface was coated with the epoxy at an application rate of 3 pounds psy; it was then covered with the quartzite chips, using a mechanical spreader, at a uniform application rate of 5 pounds psy within 5 minutes after the epoxy was applied.

Each pavement section was photographed following fabrication. Figures 6, 7 and 8 identify and depict the surface textures produced by the various deslicking mixtures. None of the experimental materials was difficult to lay and all of them produced surface features acceptable for high speed, high density traffic.

## Laboratory Traffic and Slipperiness Testing

The twelve deslicking overlay pavements were assembled into a test track set in the variable speed laboratory traffic test machine, Figure 9. A smooth and level traffic surface was established by appropriate raising or lowering of six levelling jack screws, some are visible in the foreground of Figure 9 atop the "Unistrut" posts, provided on each specimen container. A rigid arm, temporarily fastened to the machine turntable, mounting a dial gauge reading to ± 0.001 inch was used to facilitate this operation. The pavement surface of the test track was leveled to ± 0.003 inch and was releveled periodically as required during traffic testing to ± 0.005 inch.

After track assembly each pavement was gauged for flatness of its surface with the laboratory profilometer, Figure 10. With this device, the distance from the fixed reference plane to 110 individual points (5 cross section profiles and 22 locations per profile) on the surface of the pavement is measured to ± 0.001 inch. From the data, 27 (5 + 22) surface contours are evaluated and the average deviation from a flat surface is computed. During the progress of traffic testing, measurements were repeated to chart the change in surface smoothness.

The initial slipperiness of each wet pavement was measured with the standard British portable pendulum type skid resistance tester, Figure 11. A small rubber slider reacts against the road surface; it is 3 inches wide, Figure 12 (the dark rectangle near the center of the pendulum arm head), and the height of the instrument is adjusted until the length of its slide is 5 inches ± 1/8 inch. The slider is mounted on a shaft which provides sufficient rotation to allow the slider to orient its face parallel to the roadway surface. A spring loading system terminates at this shaft and exerts a static load in the axis of the pendulum arm of 2.15 pounds. During the experimental work with this tester, it was observed that the static load increases significantly in operation because of a centrifugal force effect. This factor is considered when the effect of skid test speed is discussed in a later section of this report. Actually, only the narrow upper edge, a strip less than 1/8 inch wide, of the rubber slider contacts the pavement surface during the pendulum skid. In addition, all skid resistance evaluations were made on freshly wet pavements and the work was carried out inside the plastic environmental control tent of the traffic machine. Skid test results are snesitive to variations in the temperature at the time the data are obtained, Operating procedures for the instrument are standardized(12) and significant correlations with field skid performance are reported(13).

Portable tester measurements of skid resistance were made at six locations on each pavement surface prior to traffic test machine operations over them. Three were in the center of the wheel path, at its midpoint and near the two ends of each test section, and three were outside this path. The specific testing locations are indicated in Figure 13. Locations 1, 2, 4 and 6 were rechecked periodically during the traffic testing to chart slipperiness performance characteristics.

Laboratory test track operating conditions were selected to provide maximum acceleration of actions which tend to produce pavement slipperiness. The usual environmental situations (see reference 8, pages 510-511 and 513-154 for details and numerical control levels) were modified for skid testing. Procedural changes adopted were designed to accelerate abrasion of asphalt films from surface aggregate particles, to induce coarse aggregate polishing, i.e., edge type wear, and to lower skidding resistance as much as possible. Modifications include the following:

(1) Only two of the four wheels were torqued; a force of 200 foot pounds was used; one wheel was accelerated while the other was braked.
(2) The two remaining wheels ran in the freewheeling condition .
(3) The pair of nontorqued wheels were offset inward towards the center of the traffic machine a distance equal to one half the width of the test tire; thus, each wheel overlapped the preceeding and following wheel by 2 inches and the tire kneading action which resulted was effective in reorienting coarser aggregates parallel to the roadway surface.
(4) Slick faced tires, Figure 9, were used to obtain a uniform pavement polish across the wheel path; however, it was observed that the free-wheeling portion did not become as slippery as the torqued part of the path even though many of the pavements appeared to obtain a uniform polish.

(5) Aging of pavement binder material was accomplished with 275 watt erythermal ultraviolet sunlamps, Figure 9; the 12 sections of pavement were exposed to the full radiation of 90 lamps which operated on a 30 minute on-off cycle.
(6) Surfaces of all test pavements were sprayed with water to duplicate the action of rain water which removes particles from roadways; spacing of wetting cycles varied from time to time to accommodate specified testing schedules and the normal 8 am to 4:30 pm laboratory work shift.
(7) Inside the test machine plastic tent the air temperature was controlled at 35 ± 1.5 F; when the sunlamps operated the deslicking course temperature, measured 1/2 inch below the pavement surface, was 42 ± 1.5 F.
(8) Test machine wheel pressure was 30 ± 2 psi as determined by measurement of wheel load and tire contact area.
(9) Tire inflation pressure was 40 ± 1 psi.

Once traffic test work was underway, full project attention was directed to the problem of developing a high speed portable laboratory skid resistance tester. A preliminary literature search yielded several suggestions; upon detailed examination, all of the devices were too bulky and/or heavy for use in the laboratory test track tent. Progress in planning a new test concept and device was relatively tedious because:

(1) The needed apparatus had to fit and operate in a space 1.5 x 2.5 x 3.0 ft.
(2) It had to be readily demountable and should not damage pavement surfaces as it was supported by them during a test run.
(3) The measuring device was expected to operate over small laboratory pavements at speeds up to about 50 mph.
(4) Surface scuffing action of the device must be appreciably milder than rubber tire wheel polishing to avoid affecting skid test evaluations since a large number of individual trials had to be taken at the same pavement location.

The instrument illustrated by Figure 14 evolved after preliminary mock-ups of several other types had to be rejected as impracticable for environmental test tent conditions. It consists of the standard pendulum instrument head which is mounted on the perimeter of a 20 inch diameter bicycle rear wheel and coaster brake axle assembly. A counterweight was attached to the wheel rim opposite the testing head to provide a balancing momentum force. The wheel was mounted in a variable height support frame; the rubber slider pavement contact length was adjusted to the normal 5 inch distance employed for the standard pendulum tests. A lifting handle permitted removal and repositioning of the slider on the test section without varying the slide distance. With this technique, major adjustments in wheel speed could be made while the wheel and slider spun in air and only the last, fine speed adjustments had to be made while the slider contacted a pavement surface. The instrument was operated successfully to 385 rpm (30 mph); the only controlled variable speed motor available while traffic testing was in progress did not develop enough power for faster trials. It should be noted that the rubber slider made a 5 inch long slide on the pavement for each revolution of the wheel. A constant flow of water moved across the test pavement in the direction of the slide; it was supplied by the plastic tube illustrated at the left end of the instrument base plate test hole, Figure 14, in controlled amounts which were adequate to wet the pavements uniformly during the high speed tests. Hydroplaning of the slider was controlled at speeds to 30 mph by water film thickness adjustments.

Instrumentation developed to measure the power consumed to overcome road friction at selected slider operating speeds is illustrated in Figure 15. The rotational speed was measured with the General Radio Company Model 1531-A Strobotac Unit. The speed of the wheel and its slider was adjusted and held constant by a Model C25, G. H. Heller motor controller unit which furnished electric power to a Model 6T, 60-20, G. H. Heller variable speed DC motor. Line voltage from the controller to the motor was measured with the Simpson Model 260 test meter and the current flowing with the Hewlett-Packard Model 428A clip-on milliameter.

The operating sequence for the constant high speed skid tester consisted of three separate steps. First, two sets of power consumption data were obtained. The wheel was run free of the pavement in air at 7 and 30 mph and then at these two speeds on each of the twelve pavement surfaces. The differential power consumptions for each speed were determined and horizontal friction forces were calculated.

Initial computations of tester head dynamics for the wheel type test conditions indicated the slider load would vary significantly with the (1) speed, due a centrifugal force effect of the wheel and (2) road texture because of impact conditions as the slider force transferred from the slider support to the test section surface. To overcome these difficulties, 7 and 30 mph slider loads were measured; a Kistler quartz crystal pressure transducer was mounted in a protective anvil for these determinations. The crystal pressure signal was displayed on the Tektronix Company Type 581 Oscilloscope and photographed with the Polaroid camera. Typical center location, 30 mph slider load oscillograms are illustrated in Figure 16.

The third or final step was concerned with computation of sliding coefficients. Using the appropriate friction forces and vertical slider loads, coefficients were obtained at 7 and 30 mph for each of the twelve test pavement sections.

## SKID TEST RESULTS

Laboratory traffic testing was in progress over the deslicking mixture pavements from January 19, 1965 to April 2, 1965. During the 74 day interval, 3,498,500 wheel coverages were tallied over each of the twelve test track pavement sections. All twelve of the deslicking pavements survived the full traffic exposure period. The general appearance of their surfaces at the end of the experiment is illustrated by Figures 17, 18 and 19.

As the test traffic wheel coverages accumulated approximately 1,200 standard portable skid resistance, 48 special constant 7 and 30 mph skid resistance and 180 surface roughness evaluations were obtained at intervals of varying lengths. Detailed numerical results are tabulated and the findings are summarized in the remainder of this report. Three major technical conclusions are developed from an analysis of project data.

### Standard Skid Tester Pavement Slipperiness

The standard portable skid test instrument measures the amount of energy required to move the small rubber slider probe, Figure 12, across a 5 inch length of road surface at an average speed of 6.9 mph. Initially, the friction of the main pendulum arm bearing is adjusted until a pointer carried by the arm moves exactly to zero on the scale as the head swings freely in air. The physical quantity measured by this tester is termed "skid resistance" or the "BPN" (British Pendulum Number). The scale of the instrument is numbered from 0 to 150 BPN. The higher the BPN the more skid resistant the pavement surface. Instrument instructions[12] suggest: a test value of + 65 BPN "fulfills all traffic requirements", + 55 BPN "all but the most difficult conditions encountered on roads", readings from 45 to 55 BPN are "satisfactory only in favorable circumstances" and values below 45 BPN mean "potentially slippery or dangerous pavements". Following the scale calibration and prior to actual skid testing, the condition of the rubber slider edge contact is checked by operating the tester on a wet glass plate; when a reading of 14 ± 1 BPN was not obtained, the old slider was replaced. All new sliders were given several light hand strokes across a fine texture pavement surface to condition their contact edge and they also were checked on the wet glass plate.

BPN readings were obtained prior to initial traffic testing, at 23 spaced intervals during the traffic testing period and a final set after operations were shut down. Each pavement was evaluated at several locations, see Figure 13. In addition pavements 1, 4, 7 and 10 were checked for BPN at several other times in the early phase of traffic testing. All BPN data are reported in Table II; each reported value represents the average of at least 5 individual pendulum slides.

Significant wheel path rutting did not occur, Table III, under the imposed traffic stress and environmental conditions of this experiment; the dune sand, pavement 10, eroded appreciably in the wheel path but the laboratory profilometer did not detect any evidence of surface bulging outside the traffic area. Thus, the evidence obtained suggests all of the deslicking materials tested had adequate mixture stability with the possible exception of pavement 10.

Pavement BPN values may be converted to sliding coefficients with the methods and equations developed by H. W. Kummer(14). Average wheel path coefficients computed from the BPN data obtained for three locations checked on each pavement are presented in Table IV; these data are graphed in Figures 20, 21 and 22.

Sliding coefficients representing pavement slipperiness of new surfaces and after 3,500,000 wheel coverages are:

| Test Pavement | | Surface Sliding Coefficient Computed From BPN, After Kummer | |
|---|---|---|---|
| No. | Mixture | New | Trafficked |
| 1 | 31A Blend (P 3/8) | 0.69 | 0.47 |
| 2 | 3BC Blend (P8) | 0.70 | 0.51 |
| 3 | 2NS Blend (P 3/8) | 0.68 | 0.50 |
| 4 | Sturgeon Quartzite (P8) | 0.99 | 0.53 |
| 5 | Sturgeon Quartzite (P8R16)-Epoxy Seal | 1.10 | 0.69 |
| 6 | Chocolay Quartzite (P4)-Wyton | 0.88 | 0.54 |
| 7 | Chocolay Quartzite (P4) | 0.80 | 0.52 |
| 8 | Rhyolite (P8) | 0.86 | 0.50 |
| 9 | Trap Rock (P8) | 0.88 | 0.50 |
| 10 | Dune Sand (P30) | 0.57 | 0.65 |
| 11 | Slag Sand, 3BCS (P4) | 0.87 | 0.47 |
| 12 | Sandstone (P 3/8) | 0.96 | 0.57 |

New condition sliding coefficients ranged from a low of 0.57 for dune sand to a high of 1.10 for epoxy seal treatment; after traffic, they varied from 0.47 for 31A aggregate and slag sand to 0.69 for the epoxy seal. Eleven of the twelve deslicking mixtures experienced significant increases in slipperiness while one, the dune sand, became less slick as traffic testing progressed. Sliding coefficient losses varied from a minimum of 0.18 for the 2NS aggregate to a maximum of 0.46 for crusher run Sturgeon quartzite (pavement 4). The dune sand with asbestos pavement wore or eroded severely under wheel traffic. At one point near the traffic exit end, in the torqued wheel portion of the wheel path, the full 5/8 inch overlay thickness was removed, exposing the concrete base. The slipperiness of the dune sand mixture decreased during the testing from an initial sliding coefficient of 0.57 to a terminal value of 0.65.

Relative comparative deslicking mixture performance is illustrated with bar graphs in Figure 23; moving from left to right within each group of 4 bars, the 0, 0.5, 1.5 and 3.5 million wheel coverage sliding coefficients are indicated for each of the twelve pavements. Examined together, the 48 bar graphs categorize the slipperiness histories of these twelve deslicking mixtures under laboratory traffic exposure and they provide a base for predicting variations in field serviceability.

## Effect of Speed on Pavement Slipperiness

Slipperiness data discussed in the preceeding section inherently represent slow and non-uniform speed conditions. The portable tester rubber slider changes velocity during the 5 inch slide length because the work needed to overcome road friction is constantly being subtracted from the total kinetic energy of the falling pendulum instrument head. With the deslicking pavements, its average speed was 6.94 mph; the Data Graph Polaroid camera was used to measure the motion and large variations of incremental speed, both above and below this average are evident in the records.

Many investigators working with several different types of test devices and many forms of instrumentation, report pronounced variations in pavement slipperiness characteristics as vehicle speed varies. Frequently, large loss in the sliding coefficient is observed with increasing speed. M. G. Brown and E. A. Finney (reference 5, pages 451 and 452) indicate "different surface types have distinct speed-coefficient relationships"; the following data were selected from this reference to illustrate:

| | | Sliding Coefficients | | |
|---|---|---|---|---|
| Pavement Type | Location | 7 mph | 30 mph | change |
| Bituminous concrete | US27-1958 | 0.68 | 0.57 | -0.11 |
| Sheet asphalt | Sec. 2 | 0.65 | 0.51 | -0.14 |
| Portland cement concrete | US27-1952 | 0.74 | 0.57 | -0.17 |
| High type pavement average | | 0.69 | 0.55 | -0.14 |
| RC-4 asphalt surface treatment | Washtenaw Co. Test Road | 0.38 | 0.31 | -0.07 |

Somewhat more generalized information on the nature of the speed-coefficient relationship was developed by the General Tire and Rubber Company(15). At 7 mph, wet coefficients reported range from 0.55 to 0.70 and at 30 mph, from 0.40 to 0.53. Detailed examination of their wet pavement slipperiness data indicate the speed effect on coefficients is very different in the velocity ranges 0 to 60 and 60 to 100 mph. The 10 mph incremental coefficient loss averages 0.06 for the 0 to 60 and 0.025 for the 60 to 100 mph velocities. Theoretical considerations also suggest the numerical level of the measured sliding coefficients vary significantly with rubber friction(16).

Work with the constant speed bicycle wheel skid test instrument on this project was limited to speeds of 7 and 30 mph. At higher velocities the present experience indicates the standard pendulum head with its spring supported rubber slider probe bounced excessively; this type of loading mechanism cannot be expected to provide a uniform contact force for all types of polished and worn pavement surfaces.

The differential power, i.e., the increment of power consumed to overcome road friction, was measured for each of the twelve pavements at the two speeds after the traffic test had ended. Results are presented in Table V. This power was then converted to a horizontal friction force at the road surface. The method used and the results are also summarized in Table V.

For the particular conditions of the bicycle wheel tester, the average load on the pendulum head slider, during its 5 inch travel on the pavement surface was, 17.5 pounds at 7 mph and 41 pounds at 30 mph. Pavement sliding coefficients were obtained by dividing the measured friction force by slider load for each of the two test speeds. Results after 3,480,500 wheel coverages are:

| Test Pavement | | Surface Sliding Coefficient (Constant Speed Conditions) | |
|---|---|---|---|
| No. | Mixture | 7 mph | 30 mph |
| 1 | 31A Blend (P 3/8) | 0.54 | 0.37 |
| 2 | 3BC Blend (P8) | 0.30 | 0.39 |
| 3 | 2NS Blend (P 3/8) | 0.29 | 0.31 |
| 4 | Sturgeon Quartzite (P8) | 0.36 | 0.33 |
| 5 | Sturgeon Quartzite (P8R16)-Epoxy Seal | 0.44 | 0.51 |
| 6 | Chocolay Quartzite (P4)-Wyton | 0.28 | 0.39 |
| 7 | Chocolay Quartzite (P4) | 0.42 | 0.38 |
| 8 | Rhyolite (P8) | 0.46 | 0.34 |
| 9 | Trap Rock (P8) | 0.26 | 0.37 |
| 10 | Dune Sand (P30) | 0.29 | 0.28 |
| 11 | Slag Sand, 3BCS (P4) | 0.45 | 0.35 |
| 12 | Sandstone (P 3/8) | 0.40 | 0.46 |

The constant 7 mph slipperiness data do not correlate with the standard portable tester results at an average speed, for these twelve pavements, of 6.9 mph. A certain range of differences should be expected between constant and variable speed instruments. However, the present variability between the two methods is large enough that the findings of this project should be considered exploratory and final conclusions should not be made until additional experimental work is undertaken with the bicycle wheel device. However, the preliminary data at 30 mph are interesting. They yield a rather different picture of skid resistance performance from that discussed above for the 7 mph standard portable tester. The epoxy seal treatment still ranks best with a coefficient of 0.51; it is followed by sandstone with a coefficient of 0.46 and the commercial 3 BC blend and the Wyton pavements at 0.39. Dune sand is poorest with a coefficient of 0.28.

## Factors for Improved Skid Resistance

The relative effect of various deslicking mixture variables on slipperiness is evident when average sliding coefficients for pavements having different (1) maximum aggregate sizes, (2) types of minerals, (3) binder adhesions and (4) source features such as commercially available or experimental material are compared as is done in Table VI.

Regarding the size of the maximum aggregate, within the range passing the 3/8 inch to passing the No. 8 screen sieve, new pavement surface coefficients increase from 0.78 for the 3/8 in. to 0.86 for the No. 8 size aggregate. However, after 3,500,000 wheel coverages each of the three sizes had average coefficients of 0.51 and the new pavement size effect on slipperiness disappears.

Regarding the effects of mineral type, excluding the two sands, new pavement coefficients exhibit significant differences over the range from 0.80 to 1.10 and the ranking from best to poorest is Sturgeon quartzite, sandstone, trap rock, rhyolite and Chocolay quartzite; if the four quartzites are averaged the rankings become sandstone, quartzite, trap rock and rhyolite. Following 3,500,000 wheel passages, significant slipperiness differences almost vanish; the range is 0.69 to 0.50 and the rankings are Sturgeon quartzite, epoxy seal, sandstone, Chocolay quartzite and trap rock = rhyolite. Averaging four quartzite the rankings reduce to two: sandstone = quartzite and trap rock = rhyolite (the = means materials have same coefficients). Regarding the two sand materials, slag outperforms dune sand in new pavement surfaces with respective coefficients of 0.87 and 0.57. The old road performance of the slag is disappointing with the coefficient at 0.47; likewise, the coefficient for dune sand after 3,500,000 wheel coverages is fairly good at 0.65, but the deep erosion discussed earlier presents a major problem.

Regarding the effect of pavement binder type, the epoxy surface deslicking treatment is superior to all other mixtures, both in new and old road surfaces; compare the worn epoxy surface at coefficient 0.69 with the Wyton at 0.54 or the ten asphalt pavement average of 0.52. Also, at coefficient 0.54 the worn Wyton binder pavement offers at best only a slight improvement over many asphalt surfaces.

Finally, the effect of source, either commercial or experimental, appears to be significant for both new and old road surface slipperiness; average new surface coefficients are 0.69 for commercial and 0.88 for experimental with trafficked surface at 0.49 for commercial and 0.55 for experimental sources.

## CONCLUSIONS

Major conclusions suggested from the implications of the research effort completed during the conduct of the present Michigan pavement skid resistance improvement project include:

(1) Aggregate mineral type selection does not appear to be the optimum method for eliminating pavement slipperiness because much of the difference in sliding coefficient observed among a group of pavements built with a variety of available materials vanishes as millions of wheel passages polish their surfaces; large variations in slipperiness characteristics in well constructed old pavement apparently are unusual.

(2) Epoxy seal surface treatments of quartzite chips and thin resurfacings of the sandstone deslicking mixture have more skid improvement potential than any of the other more usual deslicking materials tested.

(3) The differential power consumption technique for constant speed friction measurements was successful and deserves thorough study; the existing bicycle tester is not rugged enough for testing at velocities above 30 mph and measurement of the vertical slider loads is very difficult.

## RECOMMENDATIONS

A field correlation investigation with the standard portable tester is proposed. The objective is to obtain an accurate comparison between high and variable speed sliding coefficients obtained with the skid trailer and the 6.9 mph pendulum over pavements built of the same types of aggregates employed in the present laboratory project; field projects should include pavements having large differences in total traffic exposure. The instrument used for the laboratory skid work was made available to the Michigan State Highway Department, Testing Laboratory Division, Ann Arbor on April 29, 1965 to facilitate implementation of this recommendation.

The full benefits which can be obtained by varying deslicking mixture aggregate size are not pinpointed by available technical knowledge or the results of this project. Much more detailed studies are needed. A program to develop performance data for sands having carefully selected top sizes and gradations is proposed. Particular emphasis is needed on sizes from the No. 8 to the No. 30 sieve screens. Identical blends of sandstone, quartzite and slag sands should be compared for slipperiness characteristics. Sands of these sizes possibly may not polish or become slippery and they also may control the critical erosion losses experienced with the dune sand evaluated in the present investigation.

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TLS:jeh
Enclosures - 6 Tables, 23 Figures

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Table I

ASPHALT CEMENT INSPECTIONS

| Property Test | Inspection Value | Typical Whiting Value |
|---|---|---|
| I. Viscosities | | |
| At 140 F, poises | 1,951 | 1,969 (a) |
| At 275 F, SSF | 173 | 166 |
| At 275 F, Cs | 372 | 370 (a) |
| At 300 F, Cs | 194 | 180 |
| II. Miscellaneous | | |
| Penetration, 77 F | 62 | 65 |
| Penetration, 39.2 F | 18 | 22 |
| Pen. Ratio | 29 | 34 (b) |
| Softening Point, F | 123 | 119 |
| Flash (COC), F | 595 | 620 |
| Spot Test | Neg. | Neg. |
| Solubility $CCL_4$, % | 99.7 | 99.7 |
| Specific Gravity, 77 F | 1.027 | 1.028 |
| Ductility, 77 F, 5 cm/min | 150+ | 150+ |
| Ductility, 60 F, 5 cm/min | 150+ | -- |
| Ductility, 39.2 F, 1 cm/min | 6.6 | 6.6 |
| III. Thin Film Oven | | |
| Weight Loss, % | 0.05 | 0.08 |
| Penetration, 77 F | 32.2 | 39 |
| Retained Pen., % | 52 | 60 |
| Viscosity, 275 F, CS | 568 | -- |
| Viscosity, 140 F, Poises | 5756 | 5300 (a) |
| Viscosity Ratio, 140 F | 2.95 | 2.7 (a) |
| IV. Detroit Recovery | | |
| Penetration, 77 F | 30 | 32 |
| Ductility, 77 F, 5 cm/min | 150+ | 86 |
| Retained Pen., % | 48.4 | 49.4 |

Notes: (a) Statistical value for Whiting 62 penetration asphalt.

(b) $\frac{39.2\text{ F Pen.}}{77\text{ F Pen.}} \times 100$

Table II

BRITISH PENDULUM NUMBERS
(Averages for minimum of 5 tests over wet pavement)

| Pavement | Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Material | 31A | 3BC | 2NS | S. Quartz | Epoxy | Wyton | C. Quartz | Rhyolite | Trap | Dune | Slag | Sandstone |
| Condition | | | | | | | | | | | | | |
| New, 0 WP | | | | | | | | | | | | | |
| Location | 1 | 62 | 59 | 58 | 88 | 92 | 75 | 70 | 77 | 75 | 48 | 77 | 84 |
| | 3 | 64 | 59 | 56 | 87 | 93 | 75 | 68 | 76 | 74 | 49 | 75 | 80 |
| | 5 | 61 | 60 | 59 | 85 | 91 | 75 | 68 | 79 | 74 | 47 | 75 | 83 |
| | Avg.* | 62 | 59 | 58 | 87 | 92 | 75 | 69 | 77 | 74 | 48 | 76 | 82 |
| | 2 | 57 | 59 | 58 | 84 | 92 | 75 | 68 | 72 | 74 | 49 | 74 | 81 |
| | 4 | 60 | 60 | 56 | 84 | 94 | 75 | 68 | 75 | 75 | 49 | 72 | 80 |
| | 6 | 59 | 61 | 59 | 85 | 92 | 75 | 68 | 73 | 75 | 48 | 75 | 82 |
| | Avg.** | 59 | 60 | 58 | 84 | 93 | 75 | 68 | 73 | 75 | 49 | 74 | 81 |
| 16,000 WP | | | | | | | | | | | | | |
| Location | 1 | 59 | | | 83 | | | | | | 44 | | |
| | 2 | 57 | | | 75 | | | | | | 48 | | |
| | 4 | 56 | | | 74 | | | | | | 48 | | |
| | 6 | 56 | | | 77 | | | | | | 48 | | |
| | Avg.** | 56 | | | 75 | | | | | | 48 | | |
| 28,200 WP | | | | | | | | | | | | | |
| Location | 1 | 59 | | | 82 | | | 71 | | | 45 | | |
| | 2 | 55 | | | 75 | | | 70 | | | 47 | | |
| | 4 | 54 | | | 74 | | | 70 | | | 47 | | |
| | 6 | 55 | | | 75 | | | 71 | | | 49 | | |
| | Avg.** | 55 | | | 75 | | | 70 | | | 48 | | |

Notes: WP Indicates total number of test machine wheel coverages
* Indicates average for points outside wheel path
** Indicates average for points in wheel path

Table II

BRITISH PENDULUM NUMBERS CONTINUED
(Averages for minimum of 5 tests over wet pavement)

| Pavement Number | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Material | | 31A | 3BC | 2NS | S. Quartz | Epoxy | Wyton | C. Quartz | Rhyolite | Trap | Dune | Slag | Sandstone |
| Condition | | | | | | | | | | | | | |
| 55,800 WP | | | | | | | | | | | | | |
| Location | 1 | 60 | 57 | 56 | 83 | 94 | 75 | 72 | 76 | 74 | 45 | 76 | 80 |
| | 2 | 53 | 54 | 55 | 73 | 81 | 70 | 70 | 75 | 75 | 45 | 66 | 74 |
| | 4 | 53 | 53 | 55 | 74 | 80 | 68 | 70 | 70 | 72 | 44 | 65 | -- |
| | 6 | 54 | 54 | 57 | 74 | -- | 69 | 71 | 71 | 71 | 46 | 65 | 74 |
| | Avg.** | 53 | 54 | 56 | 74 | 81 | 69 | 70 | 72 | 73 | 45 | 65 | 74 |
| 87,400 WP | | | | | | | | | | | | | |
| Location | 1 | 65 | | | 82 | | | 70 | | | 45 | | |
| | 2 | 54 | | | 74 | | | 70 | | | 47 | | |
| | 4 | 54 | | | 74 | | | 69 | | | 47 | | |
| | 6 | 54 | | | 75 | | | 70 | | | 47 | | |
| | Avg.** | 54 | | | 74 | | | 70 | | | 47 | | |
| 110,000 WP | | | | | | | | | | | | | |
| Location | 1 | 60 | 55 | 58 | 82 | 95 | 75 | 69 | 74 | 72 | 45 | 75 | 84 |
| | 2 | 51 | 50 | 53 | 69 | 85 | 69 | 65 | 68 | 69 | 45 | 59 | 70 |
| | 4 | 51 | 50 | 54 | 70 | 83 | 67 | 67 | 68 | 69 | 47 | 62 | 71 |
| | 6 | 52 | 51 | 55 | 70 | 84 | 67 | 66 | 68 | 67 | 45 | 60 | 72 |
| | Avg.** | 51 | 50 | 54 | 70 | 84 | 68 | 66 | 68 | 68 | 46 | 60 | 71 |
| 147,500 WP | | | | | | | | | | | | | |
| Location | 1 | 61 | | | 79 | | | 65 | | | 45 | | |
| | 2 | 50 | | | 67 | | | 62 | | | 47 | | |
| | 4 | 51 | | | 67 | | | 62 | | | 49 | | |
| | 6 | 51 | | | 67 | | | 62 | | | 45 | | |
| | Avg.** | 51 | | | 67 | | | 62 | | | 47 | | |

Table II

BRITISH PENDULUM NUMBERS CONTINUED
(Averages for minimum of 5 tests over wet pavement)

| Pavement Number | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Material | | 31A | 3BC | 2NS | S. Quartz | Epoxy | Wyton | C. Quartz | Rhyolite | Trap | Dune | Slag | Sandstone |
| Condition | | | | | | | | | | | | | |
| 165,300 WP | | | | | | | | | | | | | |
| Location | 1 | 60 | 57 | 55 | 84 | 94 | 74 | 66 | 75 | 74 | 46 | 80 | 85 |
| | 2 | 50 | 49 | 52 | 71 | 78 | 66 | 64 | 65 | 71 | 49 | 63 | 76 |
| | 4 | 52 | 52 | 54 | 72 | 80 | 65 | 64 | 69 | 72 | 55 | 63 | 75 |
| | 6 | 52 | 52 | 54 | 71 | 77 | 66 | 68 | 70 | 70 | 50 | 64 | 76 |
| | Avg.** | 51 | 51 | 53 | 71 | 78 | 66 | 65 | 68 | 71 | 51 | 63 | 76 |
| 193,300 WP | | | | | | | | | | | | | |
| Location | 1 | 60 | | | 80 | | | 65 | | | 44 | | |
| | 2 | 48 | | | 70 | | | 60 | | | 48 | | |
| | 4 | 50 | | | 70 | | | 63 | | | 50 | | |
| | 6 | 50 | | | 69 | | | 66 | | | 48 | | |
| | Avg.** | 49 | | | 70 | | | 63 | | | 49 | | |
| 230,600 WP | | | | | | | | | | | | | |
| Location | 1 | 60 | 55 | 57 | 79 | 96 | 72 | 70 | 74 | 74 | 44 | 73 | 81 |
| | 2 | 52 | 54 | 57 | 66 | 82 | 63 | 62 | 66 | 69 | 54 | 62 | 74 |
| | 4 | 52 | 53 | 55 | 69 | 84 | 63 | 64 | 68 | 70 | 57 | 62 | 75 |
| | 6 | 53 | 54 | 55 | 69 | 82 | 65 | 65 | 68 | 70 | 53 | 62 | 75 |
| | Avg.** | 52 | 54 | 56 | 68 | 83 | 64 | 64 | 67 | 70 | 55 | 62 | 75 |
| 331,200 WP | | | | | | | | | | | | | |
| Location | 1 | 56 | 53 | 52 | 78 | 87 | 69 | 65 | 70 | 69 | 44 | 71 | 80 |
| | 2 | 47 | 50 | 54 | 65 | 73 | 59 | 59 | 58 | 61 | 55 | 58 | 67 |
| | 4 | 48 | 50 | 51 | 64 | 71 | 58 | 59 | 60 | 62 | 54 | 58 | 70 |
| | 6 | 49 | 51 | 53 | 66 | 70 | 59 | 60 | 62 | 62 | 50 | 59 | 70 |
| | Avg.** | 48 | 50 | 53 | 65 | 71 | 59 | 59 | 60 | 62 | 53 | 58 | 69 |

Table II

BRITISH PENDULUM NUMBERS CONTINUED
(Averages for minimum of 5 tests over wet pavement)

| Pavement Number | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Material | | 31A | 3BC | 2NS | S. Quartz | Epoxy | Wyton | C. Quartz | Rhyolite | Trap | Dune | Slag | Sandstone |
| Condition | | | | | | | | | | | | | |
| 427,200 WP | | | | | | | | | | | | | |
| Location | 1 | 59 | 55 | 55 | 77 | 88 | 70 | 68 | 71 | 70 | 44 | 70 | 80 |
| | 2 | 49 | 52 | 54 | 60 | 71 | 60 | 58 | 59 | 58 | 56 | 57 | 69 |
| | 4 | 49 | 50 | 50 | 64 | 73 | 59 | 59 | 61 | 60 | 55 | 55 | 67 |
| | 6 | 50 | 50 | 50 | 63 | 71 | 60 | 60 | 60 | 61 | 54 | 58 | 68 |
| | Avg.** | 50 | 51 | 51 | 62 | 72 | 60 | 59 | 60 | 60 | 55 | 57 | 68 |
| 529,200 WP | | | | | | | | | | | | | |
| Location | 1 | 60 | 56 | 55 | 78 | 89 | 72 | 65 | 72 | 71 | 45 | 72 | 80 |
| | 2 | 50 | 52 | 55 | 65 | 69 | 61 | 60 | 60 | 59 | 59 | 56 | 66 |
| | 4 | 52 | 54 | 53 | 66 | 74 | 63 | 62 | 65 | 62 | 58 | 56 | 70 |
| | 6 | 51 | 55 | 54 | 69 | 74 | 61 | 62 | 62 | 62 | 55 | 60 | 72 |
| | Avg.** | 51 | 54 | 54 | 67 | 72 | 62 | 61 | 62 | 61 | 57 | 57 | 69 |
| 631,000 WP | | | | | | | | | | | | | |
| Location | 1 | 60 | 54 | 56 | 78 | 89 | 74 | 67 | 72 | 71 | 44 | 72 | 80 |
| | 2 | 50 | 51 | 55 | 64 | 71 | 60 | 59 | 60 | 57 | 56 | 56 | 65 |
| | 4 | 50 | 51 | 51 | 64 | 71 | 60 | 60 | 62 | 60 | 60 | 55 | 67 |
| | 6 | 50 | 56 | 53 | 66 | 71 | 61 | 61 | 61 | 60 | 62 | 56 | 65 |
| | Avg.** | 50 | 53 | 53 | 65 | 71 | 60 | 60 | 61 | 59 | 59 | 56 | 66 |
| 726,600 WP | | | | | | | | | | | | | |
| Location | 1 | 57 | 54 | 55 | 79 | 90 | 72 | 66 | 71 | 70 | 44 | 72 | 81 |
| | 2 | 47 | 50 | 53 | 62 | 75 | 60 | 56 | 57 | 60 | 58 | 53 | 65 |
| | 4 | 48 | 50 | 50 | 63 | 71 | 59 | 58 | 57 | 59 | 57 | 55 | 65 |
| | 6 | 47 | 50 | 50 | 65 | 73 | 60 | 61 | 59 | 60 | 57 | 56 | 66 |
| | Avg.** | 47 | 50 | 51 | 63 | 73 | 60 | 58 | 58 | 60 | 57 | 55 | 65 |

Table II

BRITISH PENDULUM NUMBERS CONTINUED
(Averages for minimum of 5 tests over wet pavement)

| Pavement | Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Material | 31A | 3BC | 2NS | S. Quartz | Epoxy | Wyton | C. Quartz | Rhyolite | Trap | Dune | Slag | Sandstone |
| Condition | | | | | | | | | | | | | |
| 834,200 WP | | | | | | | | | | | | | |
| Location | 1 | 58 | 54 | 55 | 80 | 91 | 74 | 64 | 70 | 70 | 44 | 74 | 80 |
| | 2 | 46 | 50 | 50 | 60 | 65 | 57 | 54 | 55 | 57 | 55 | 54 | 62 |
| | 4 | 45 | 49 | 50 | 61 | 70 | 58 | 56 | 56 | 58 | 57 | 55 | 65 |
| | 6 | 46 | 50 | 50 | 62 | 68 | 59 | 58 | 57 | 57 | 57 | 55 | 63 |
| | Avg.** | 46 | 50 | 50 | 61 | 68 | 58 | 56 | 56 | 57 | 56 | 55 | 63 |
| 932,200 WP | | | | | | | | | | | | | |
| Location | 1 | 59 | 54 | 56 | 79 | 88 | 73 | 68 | 74 | 69 | 45 | 76 | 80 |
| | 2 | 49 | 53 | 51 | 60 | 68 | 58 | 56 | 55 | 55 | 57 | 52 | 62 |
| | 4 | 48 | 51 | 49 | 60 | 70 | 56 | 57 | 56 | 55 | 57 | 53 | 62 |
| | 6 | 48 | 52 | 49 | 63 | 70 | 58 | 57 | 56 | 55 | 60 | 55 | 62 |
| | Avg.** | 48 | 52 | 50 | 61 | 69 | 57 | 57 | 56 | 55 | 58 | 53 | 62 |
| 1,032,400 WP | | | | | | | | | | | | | |
| Location | 1 | 57 | 54 | 53 | 75 | 88 | 70 | 65 | 70 | 68 | 44 | 70 | 79 |
| | 2 | 49 | 52 | 50 | 58 | 64 | 57 | 52 | 55 | 55 | 55 | 49 | 58 |
| | 4 | 48 | 50 | 46 | 57 | 69 | 55 | 54 | 53 | 55 | 57 | 50 | 60 |
| | 6 | 47 | 50 | 47 | 58 | 67 | 56 | 55 | 54 | 55 | 56 | 51 | 58 |
| | Avg.** | 48 | 51 | 48 | 58 | 67 | 56 | 54 | 54 | 55 | 56 | 50 | 59 |
| 1,234,200 WP | | | | | | | | | | | | | |
| Location | 1 | 60 | 55 | 55 | 77 | 88 | 72 | 65 | 70 | 70 | 46 | 70 | 79 |
| | 2 | 50 | 52 | 54 | 54 | 66 | 54 | 52 | 55 | 55 | 63 | 50 | 60 |
| | 4 | 49 | 53 | 51 | 60 | 68 | 55 | 55 | 57 | 60 | 65 | 55 | 65 |
| | 6 | 50 | 52 | 51 | 60 | 68 | 56 | 56 | 57 | 59 | 65 | 52 | 63 |
| | Avg.** | 50 | 52 | 52 | 58 | 67 | 55 | 54 | 56 | 58 | 64 | 52 | 63 |

Table II

BRITISH PENDULUM NUMBERS CONTINUED
(Averages for minimum of 5 tests over wet pavement)

| Pavement Number / Material | | 1<br>31A | 2<br>3BC | 3<br>2NS | 4<br>S. Quartz | 5<br>Epoxy | 6<br>Wyton | 7<br>C. Quartz | 8<br>Rhyolite | 9<br>Trap | 10<br>Dune | 11<br>Slag | 12<br>Sandstone |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Condition | | | | | | | | | | | | | |
| 1,438,300 WP | | | | | | | | | | | | | |
| Location | 1 | 60 | 57 | 57 | 80 | 90 | 77 | 68 | 74 | 75 | 47 | 75 | 84 |
| | 2 | 48 | 51 | 53 | 57 | 64 | 55 | 52 | 50 | 53 | 64 | 53 | 62 |
| | 4 | 49 | 55 | 52 | 61 | 72 | 55 | 57 | 56 | 57 | 67 | 55 | 67 |
| | 6 | 50 | 52 | 51 | 62 | 70 | 57 | 58 | 59 | 55 | 66 | 56 | 67 |
| | Avg.** | 49 | 53 | 52 | 60 | 69 | 56 | 56 | 55 | 55 | 66 | 55 | 65 |
| 1,616,300 WP | | | | | | | | | | | | | |
| Location | 1 | 57 | 54 | 55 | 78 | 88 | 70 | 63 | 68 | 68 | 45*** | 70 | 80 |
| | 2 | 46 | 47 | 50 | 45 | 64 | 47 | 45 | 44 | 45 | 55 | 45 | 50 |
| | 4 | 48 | 50 | 50 | 53 | 65 | 50 | 50 | 47 | 48 | 55 | 48 | 55 |
| | 6 | 48 | 50 | 48 | 53 | 65 | 51 | 50 | 47 | 46 | 55 | 49 | 54 |
| | Avg.** | 47 | 49 | 49 | 51 | 65 | 49 | 48 | 46 | 46 | 55 | 47 | 53 |
| 1,826,700 WP | | | | | | | | | | | | | |
| Location | 1 | 57 | 55 | 54 | 78 | 88 | 71 | 65 | 69 | 70 | 45 | 70 | 82 |
| | 2 | 45 | 46 | 46 | 45 | 63 | 46 | 45 | 42 | 45 | 57 | 45 | 47 |
| | 4 | 45 | 47 | 45 | 51 | 60 | 49 | 46 | 43 | 45 | 55 | 46 | 51 |
| | 6 | 46 | 49 | 47 | 52 | 60 | 50 | 48 | 46 | 45 | 55 | 46 | 50 |
| | Avg.** | 45 | 47 | 46 | 49 | 61 | 48 | 46 | 44 | 45 | 56 | 46 | 49 |
| 2,001,200 WP | | | | | | | | | | | | | |
| Location | 1 | 59 | 55 | 57 | 78 | 88 | 74 | 65 | 69 | 70 | 45 | 72 | 80 |
| | 2 | 44 | 47 | 47 | 49 | 61 | 49 | 44 | 42 | 42 | 57 | 43 | 48 |
| | 4 | 45 | 49 | 44 | 51 | 61 | 49 | 50 | 41 | 45 | 55 | 44 | 50 |
| | 6 | 45 | 47 | 45 | 53 | 62 | 53 | 50 | 44 | 44 | 57 | 45 | 50 |
| | Avg.** | 45 | 48 | 45 | 51 | 61 | 50 | 48 | 42 | 44 | 56 | 44 | 49 |

Note: *** concrete showing at certain spots due to erosion of deslicking dune sand mixture.

Table II

BRITISH PENDULUM NUMBERS CONTINUED
(Averages for minimum of 5 tests over wet pavement)

| Pavement Number | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Material | | 31A | 3BC | 2NS | S. Quartz | Epoxy | Wyton | C. Quartz | Rhyolite | Trap | Dune | Slag | Sandstone |
| Condition | | | | | | | | | | | | | |
| 2,203,500 WP | | | | | | | | | | | | | |
| Location | 1 | 58 | 55 | 55 | 78 | 88 | 72 | 63 | 69 | 69 | 45 | 70 | 80 |
| | 2 | 42 | 45 | 45 | 48 | 58 | 45 | 40 | 42 | 42 | 56 | 42 | 48 |
| | 4 | 43 | 47 | 42 | 50 | 59 | 47 | 44 | 41 | 41 | 55 | 44 | 50 |
| | 6 | 43 | 46 | 42 | 51 | 57 | 50 | 47 | 43 | 42 | 55 | 44 | 50 |
| | Avg.** | 43 | 46 | 43 | 50 | 58 | 47 | 44 | 42 | 42 | 55 | 43 | 49 |
| 2,403,200 WP | | | | | | | | | | | | | |
| Location | 1 | 60 | 55 | 56 | 80 | 88 | 73 | 65 | 72 | 71 | 45 | 73 | 79 |
| | 2 | 44 | 45 | 44 | 47 | 50 | 45 | 44 | 42 | 41 | 57 | 42 | 49 |
| | 4 | 45 | 47 | 42 | 49 | 58 | 47 | 46 | 42 | 43 | 57 | 44 | 51 |
| | 6 | 44 | 47 | 44 | 51 | 56 | 50 | 49 | 44 | 44 | 55 | 44 | 50 |
| | Avg.** | 44 | 46 | 43 | 49 | 55 | 47 | 46 | 43 | 43 | 56 | 43 | 50 |
| 2,599,300 WP | | | | | | | | | | | | | |
| Location | 1 | 59 | 55 | 56 | 79 | 89 | 73 | 65 | 71 | 70 | 45 | 73 | 80 |
| | 2 | 44 | 46 | 45 | 47 | 58 | 45 | 44 | 41 | 42 | 59 | 45 | 50 |
| | 4 | 41 | 46 | 43 | 50 | 59 | 48 | 45 | 41 | 44 | 57 | 45 | 52 |
| | 6 | 44 | 45 | 44 | 50 | 59 | 50 | 48 | 44 | 45 | 58 | 44 | 52 |
| | Avg.** | 43 | 46 | 44 | 49 | 59 | 48 | 46 | 42 | 44 | 58 | 45 | 51 |
| 2,799,300 WP | | | | | | | | | | | | | |
| Location | 1 | 56 | 55 | 55 | 78 | 89 | 72 | 64 | 70 | 68 | 45 | 70 | 81 |
| | 2 | 42 | 45 | 44 | 46 | 58 | 45 | 44 | 40 | 42 | 56 | 45 | 48 |
| | 4 | 42 | 45 | 43 | 50 | 60 | 48 | 44 | 40 | 43 | 57 | 43 | 50 |
| | 6 | 42 | 48 | 42 | 50 | 58 | 49 | 47 | 44 | 44 | 57 | 42 | 51 |
| | Avg.** | 42 | 46 | 43 | 49 | 59 | 47 | 45 | 41 | 43 | 57 | 43 | 50 |

Table II

BRITISH PENDULUM NUMBERS CONTINUED
(Averages for minimum of 5 tests over wet pavement)

| Pavement | Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Material | 31A | 3BC | 2NS | S. Quartz | Epoxy | Wyton | C. Quartz | Rhyolite | Trap | Dune | Slag | Sandstone |
| Condition | | | | | | | | | | | | | |
| 3,003,900 WP | | | | | | | | | | | | | |
| Location | 1 | 58 | 54 | 56 | 78 | 89 | 72 | 65 | 70 | 70 | 46 | 72 | 80 |
| | 2 | 43 | 44 | 42 | 46 | 58 | 45 | 43 | 40 | 40 | 57 | 40 | 50 |
| | 4 | 43 | 46 | 41 | 51 | 59 | 49 | 45 | 40 | 42 | 56 | 43 | 52 |
| | 6 | 42 | 45 | 42 | 50 | 60 | 49 | 47 | 44 | 44 | 57 | 42 | 51 |
| | Avg.** | 43 | 45 | 42 | 49 | 59 | 48 | 45 | 41 | 42 | 57 | 42 | 51 |
| 3,201,400 WP | | | | | | | | | | | | | |
| Location | 1 | 60 | 56 | 58 | 80 | 90 | 77 | 68 | 73 | 73 | 47 | 74 | 80 |
| | 2 | 42 | 45 | 44 | 48 | 60 | 47 | 45 | 41 | 42 | 60 | 44 | 50 |
| | 4 | 44 | 48 | 42 | 52 | 61 | 49 | 47 | 42 | 45 | 58 | 44 | 52 |
| | 6 | 44 | 45 | 44 | 53 | 59 | 51 | 49 | 44 | 45 | 56 | 44 | 51 |
| | Avg.** | 43 | 46 | 43 | 51 | 60 | 49 | 47 | 42 | 44 | 58 | 44 | 51 |
| 3,498,500 WP | | | | | | | | | | | | | |
| Location | 1 | 59 | 54 | 56 | 76 | 90 | 73 | 64 | 70 | 69 | 46 | 69 | 79 |
| | 2 | 41 | 44 | 43 | 43 | 60 | 45 | 43 | 41 | 42 | 57 | 40 | 47 |
| | 4 | 41 | 45 | 42 | 48 | 59 | 48 | 46 | 42 | 42 | 55 | 42 | 50 |
| | 6 | 41 | 44 | 44 | 48 | 59 | 49 | 47 | 45 | 45 | 57 | 41 | 51 |
| | Avg.** | 41 | 44 | 43 | 46 | 59 | 47 | 45 | 43 | 43 | 56 | 41 | 49 |

Table III

AVERAGE WHEEL PATH RUTTING
Inches

| Pavement Number<br>Material | 1<br>31A | 2<br>3BC | 3<br>2NS | 4<br>S. Quartz | 5<br>Epoxy | 6<br>Wyton | 7<br>C. Quartz | 8<br>Rhyolite | 9<br>Trap | 10<br>Dune | 11<br>Slag | 12<br>Sandstone |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Condition | | | | | | | | | | | | |
| 1,032,400 WP | 0.001 | 0.010 | 0.007 | 0.003 | 0.002 | 0.009 | 0.002 | 0.004 | 0.004 | 0.064 | 0.004 | 0.013 |
| 1,234,200 WP | | | | | | | | | | 0.230 | | |
| 1,616,300 WP | | | | | | | | | | 0.319 | | |
| 1,826,700 WP | | | | | | | | | | 0.320 | | |
| 2,001,200 WP | 0.004 | 0.015 | 0.011 | 0.004 | 0 | 0.011 | 0.005 | 0.005 | 0.007 | 0.328 | 0.006 | 0.014 |
| 2,599,300 WP | | | | | | | | | | 0.336 | | |
| 3,498,500 WP | 0 | 0.017 | 0.011 | 0.003 | 0 | 0.012 | 0.005 | 0.004 | 0.004 | 0.340 | 0.005 | 0.015 |

Table IV

AVERAGE WHEEL PATH SLIDING COEFFICIENTS
Wet Pavement Surface

| Pavement Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Material | 31A | 3BC | 2NS | S. Quartz | Epoxy | Wyton | C. Quartz | Rhyolite | Trap | Dune | Slag | Sandstone |
| Condition | | | | | | | | | | | | |
| New, 0 WP | 0.69 | 0.70 | 0.68 | 0.99 | 1.10 | 0.88 | 0.80 | 0.86 | 0.88 | 0.57 | 0.87 | 0.96 |
| 110,000 WP | 0.59 | 0.58 | 0.63 | 0.82 | 0.99 | 0.80 | 0.77 | 0.80 | 0.80 | 0.53 | 0.70 | 0.83 |
| 165,300 WP | 0.59 | 0.59 | 0.62 | 0.83 | 0.92 | 0.77 | 0.76 | 0.80 | 0.83 | 0.59 | 0.74 | 0.89 |
| 230,600 WP | 0.60 | 0.63 | 0.65 | 0.80 | 0.98 | 0.75 | 0.75 | 0.78 | 0.82 | 0.64 | 0.72 | 0.88 |
| 529,200 WP | 0.59 | 0.63 | 0.63 | 0.78 | 0.84 | 0.72 | 0.71 | 0.72 | 0.71 | 0.66 | 0.66 | 0.81 |
| 1,032,400 WP | 0.56 | 0.59 | 0.56 | 0.68 | 0.78 | 0.65 | 0.63 | 0.63 | 0.64 | 0.65 | 0.58 | 0.69 |
| 1,438,200 WP | 0.57 | 0.62 | 0.60 | 0.70 | 0.81 | 0.65 | 0.65 | 0.64 | 0.64 | 0.77 | 0.64 | 0.76 |
| 1,616,300 WP | 0.54 | 0.57 | 0.57 | 0.58 | 0.76 | 0.57 | 0.56 | 0.53 | 0.53 | 0.64 | 0.54 | 0.62 |
| 2,001,200 WP | 0.52 | 0.56 | 0.52 | 0.59 | 0.71 | 0.58 | 0.56 | 0.49 | 0.51 | 0.65 | 0.51 | 0.57 |
| 2,203,500 WP | 0.50 | 0.53 | 0.50 | 0.58 | 0.68 | 0.54 | 0.51 | 0.49 | 0.49 | 0.64 | 0.50 | 0.57 |
| 2,599,300 WP | 0.50 | 0.53 | 0.51 | 0.57 | 0.69 | 0.56 | 0.53 | 0.49 | 0.51 | 0.68 | 0.52 | 0.59 |
| 3,003,900 WP | 0.50 | 0.52 | 0.49 | 0.57 | 0.69 | 0.56 | 0.52 | 0.47 | 0.49 | 0.66 | 0.49 | 0.59 |
| 3,498,500 WP | 0.47 | 0.51 | 0.50 | 0.53 | 0.69 | 0.54 | 0.52 | 0.50 | 0.50 | 0.65 | 0.47 | 0.57 |

Table V

BICYCLE WHEEL PAVEMENT SLIPPERINESS
Wet Wheel Path After 3,498,500 Coverages

| Test Pavement | | Differential Power Watts | | Road Friction Force Pounds | |
|---|---|---|---|---|---|
| Number | Material | 7 mph | 30 mph | 7 mph | 30 mph |
| 1 | 31A Blend | 4.40 | 30.38 | 9.53 | 15.31 |
| 2 | 3BC Blend | 2.42 | 31.32 | 5.24 | 15.79 |
| 3 | 2NS Blend | 2.36 | 24.86 | 5.11 | 12.53 |
| 4 | Sturgeon Quartzite | 2.94 | 26.68 | 6.36 | 13.45 |
| 5 | Epoxy Seal | 3.53 | 41.57 | 7.64 | 20.95 |
| 6 | Wyton Binder | 2.23 | 31.41 | 4.83 | 15.83 |
| 7 | Chocolay Quartzite | 3.39 | 31.09 | 7.34 | 15.67 |
| 8 | Rhyolite | 3.72 | 27.63 | 8.05 | 13.92 |
| 9 | Trap Rock | 2.11 | 29.96 | 4.57 | 15.10 |
| 10 | Dune Sand | 2.34 | 22.57 | 5.07 | 11.38 |
| 11 | Slag Sand | 3.60 | 28.08 | 7.79 | 14.15 |
| 12 | Sandstone | 3.23 | 37.39 | 6.99 | 18.84 |

Notes: 1.0 foot pound = 0.738 watts per second
0.54 foot = slider contact length

7 mph = 1.49 rps of bicycle wheel
30 mph = 6.40 rps of bicycle wheel

$$\text{Friction force} = \frac{\text{watts}}{(0.738)(0.42)(\text{rps})}$$

$$= (2.165)(\text{watts}) \text{ at 7 mph}$$

and $= (0.504)(\text{watts})$ at 30 mph

Table VI

RELATIVE EFFECTS OF DESLICKING MIXTURE VARIABLES ON AVERAGE SLIDING COEFFICIENT

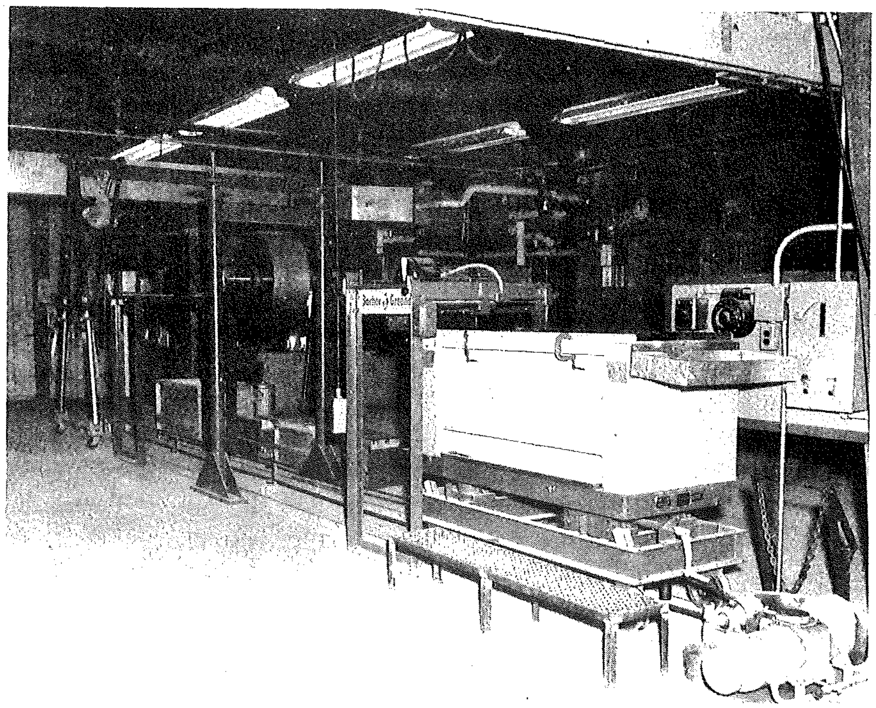
| | Number | Pavement Material | Coefficients Initial | Coefficients Final | Coefficients Change |
|---|---|---|---|---|---|
| I. Maximum Aggregate Size | | | | | |
| A. Passing 3/8" | 1 | 31A Blend | 0.69 | 0.47 | -0.22 |
| | 3 | 2NS Blend | 0.68 | 0.50 | -0.18 |
| | 12 | Sandstone | 0.96 | 0.57 | -0.39 |
| | Avg. | | 0.78 | 0.51 | -0.27 |
| B. Passing No. 4 | 6 | Wyton-Chocolay | 0.88 | 0.54 | -0.34 |
| | 7 | Chocolay Quartzite | 0.80 | 0.52 | -0.28 |
| | 11 | Slag Sand | 0.87 | 0.47 | -0.40 |
| | Avg. | | 0.85 | 0.51 | -0.34 |
| C. Passing No. 8 | 2 | 3BC Blend | 0.70 | 0.51 | -0.19 |
| | 4 | Sturgeon Quartzite | 0.99 | 0.53 | -0.46 |
| | 8 | Rhyolite | 0.86 | 0.50 | -0.36 |
| | 9 | Trap Rock | 0.88 | 0.50 | -0.38 |
| | Avg. | | 0.86 | 0.51 | -0.35 |
| D. Passing No. 30 | 10 | Dune Sand | 0.57 | 0.65 | +0.08 |
| II. Type of Aggregate Mineral | | | | | |
| A. Sturgeon Quartzite | 4 | | 0.99 | 0.53 | -0.46 |
| | 5 | Epoxy Seal | 1.10 | 0.69 | -0.41 |
| | Avg. | | 1.05 | 0.61 | -0.44 |
| B. Chocolay Quartzite | 7 | | 0.80 | 0.52 | -0.28 |
| | 6 | Wyton Binder | 0.88 | 0.54 | -0.34 |
| | Avg. | | 0.84 | 0.53 | -0.31 |
| C. Quartzite Average | | | 0.94 | 0.57 | -0.37 |
| D. Rhyolite | 8 | | 0.86 | 0.50 | -0.36 |
| E. Trap Rock | 9 | | 0.88 | 0.50 | -0.38 |
| F. Sandstone | 12 | | 0.96 | 0.57 | -0.39 |
| G. Dune Sand | 10 | | 0.57 | 0.65 | +0.08 |
| H. Slag Sand | 11 | | 0.87 | 0.47 | -0.40 |

Table VI

RELATIVE EFFECTS CONTINUED

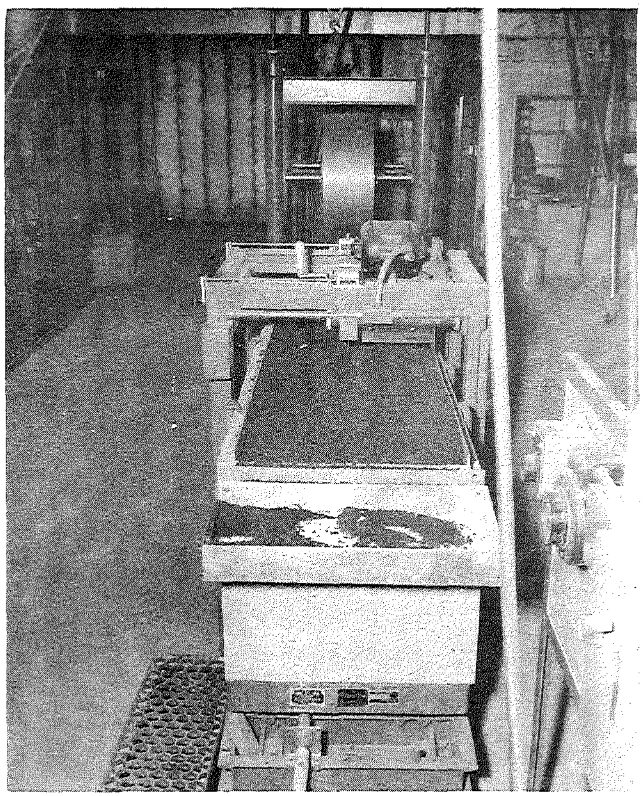
| | Pavement Number | Material | Coefficients Initial | Final | Change |
|---|---|---|---|---|---|
| III. Type of Binder | | | | | |
| A. Asphalt | 1 | 60-70 Penetration | 0.69 | 0.47 | -0.22 |
| | 2 | | 0.70 | 0.51 | -0.19 |
| | 3 | | 0.68 | 0.50 | -0.18 |
| | 4 | | 0.99 | 0.53 | -0.46 |
| | 7 | | 0.80 | 0.52 | -0.28 |
| | 8 | | 0.86 | 0.50 | -0.38 |
| | 9 | | 0.88 | 0.50 | -0.38 |
| | 10 | | 0.57 | 0.65 | -0.08 |
| | 11 | | 0.87 | 0.47 | -0.40 |
| | 12 | | 0.96 | 0.57 | -0.39 |
| | Avg. | | 0.80 | 0.52 | -0.28 |
| B. Wyton | 6 | Binder | 0.88 | 0.54 | -0.34 |
| C. Epoxy | 5 | Seal Treatment | 1.10 | 0.69 | -0.41 |
| IV. Type of Source | | | | | |
| A. Commercial Blends | | | | | |
| | 1 | 31A | 0.69 | 0.47 | -0.22 |
| | 2 | 3BC | 0.70 | 0.51 | -0.19 |
| | 3 | 2NS | 0.68 | 0.50 | -0.18 |
| | Avg. | | 0.69 | 0.49 | -0.20 |
| B. Experimental Materials | | | | | |
| | 4 | Sturgeon Quartzite | 0.99 | 0.53 | -0.46 |
| | 5 | Epoxy Seal | 1.10 | 0.69 | -0.41 |
| | 6 | Wyton Binder | 0.88 | 0.54 | -0.34 |
| | 7 | Chocolay Quartzite | 0.80 | 0.52 | -0.28 |
| | 8 | Rhyolite | 0.86 | 0.50 | -0.36 |
| | 9 | Trap Rock | 0.88 | 0.50 | -0.38 |
| | 10 | Dune Sand | 0.57 | 0.65 | +0.08 |
| | 11 | Slag Sand | 0.87 | 0.47 | -0.40 |
| | 12 | Sandstone | 0.96 | 0.57 | -0.39 |
| | Avg. | | 0.88 | 0.55 | -0.33 |

FIGURE I



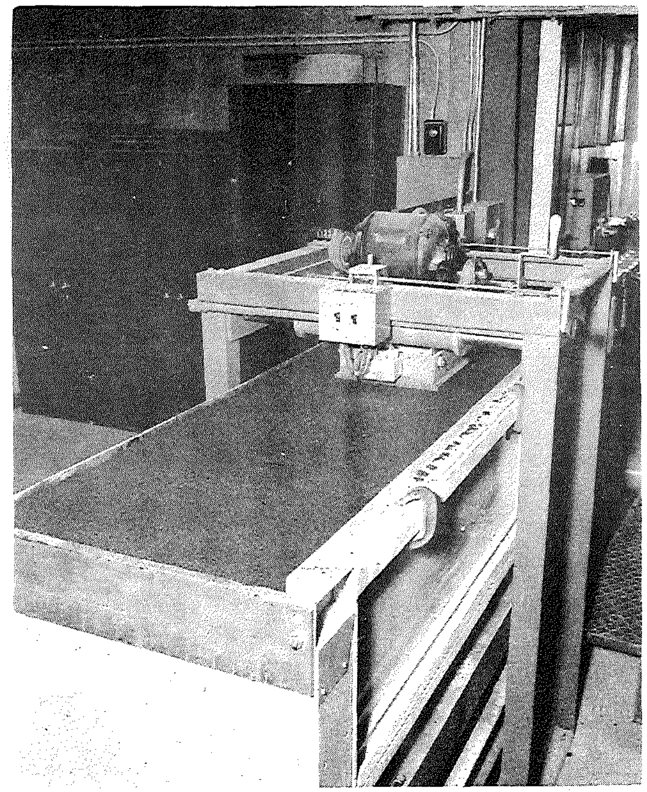
LABORATORY PAVEMENT
LAYDOWN EQUIPMENT

FIGURE 2



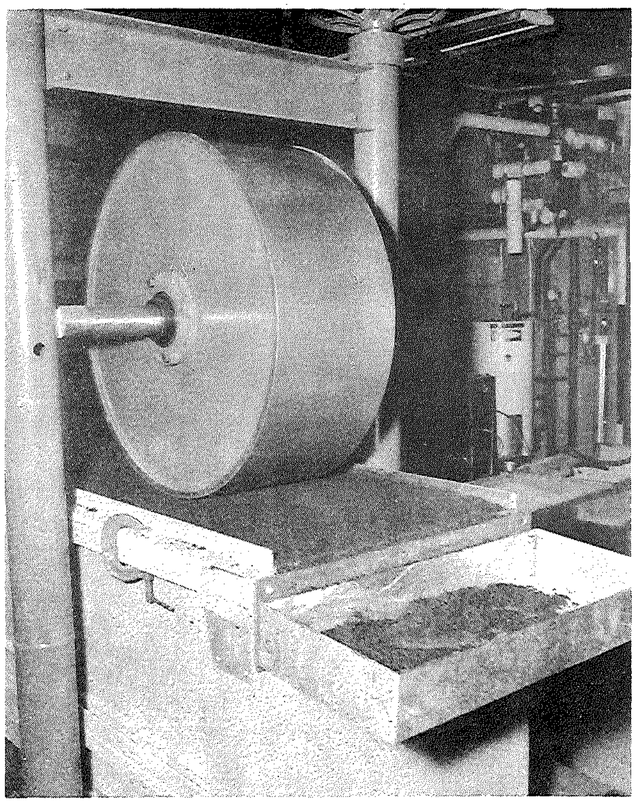
HOT TAMPER - SCREEDER
PAVEMENT FINISHING MACHINE

FIGURE 3



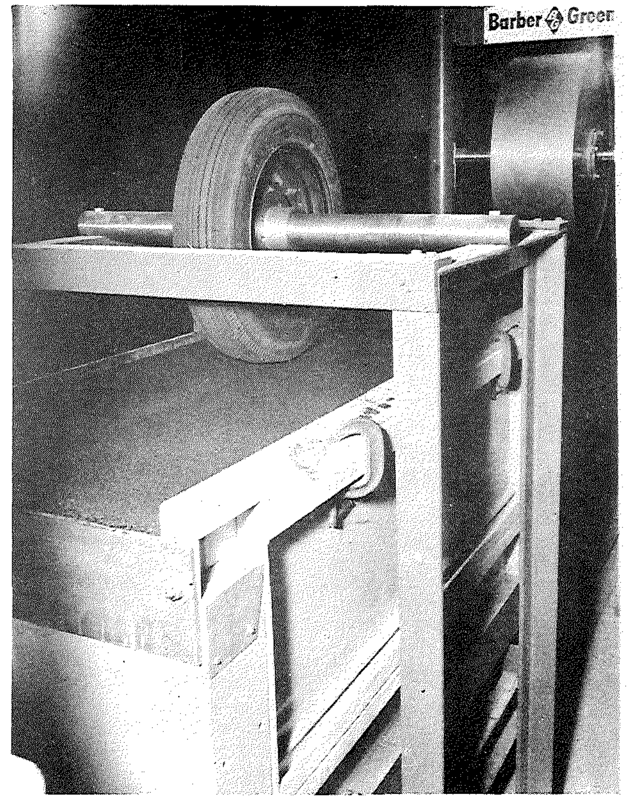
CENTER STRIP SCREED PASS

FIGURE 4



STEEL WHEEL
COMPACTION ROLLER

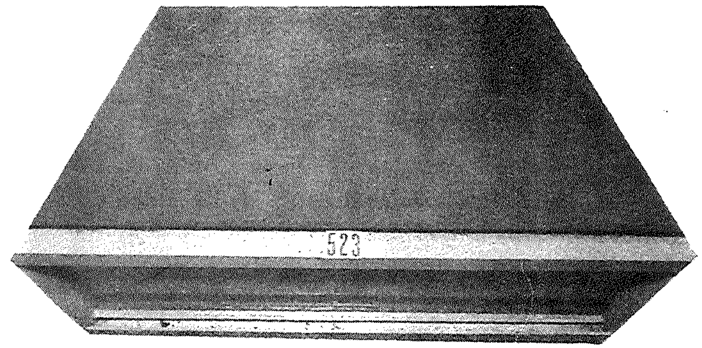
FIGURE 5



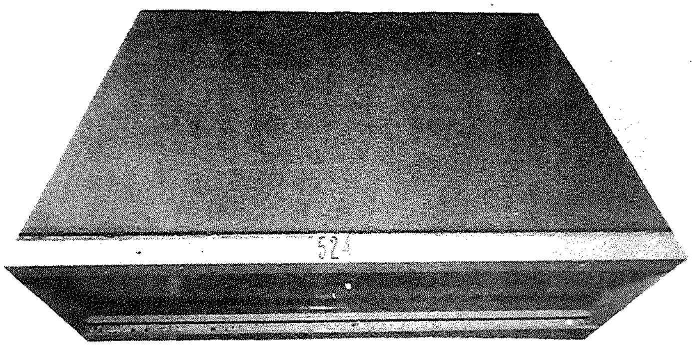
PNEUMATIC RUBBER
TIRE ROLLER

FIGURE 6

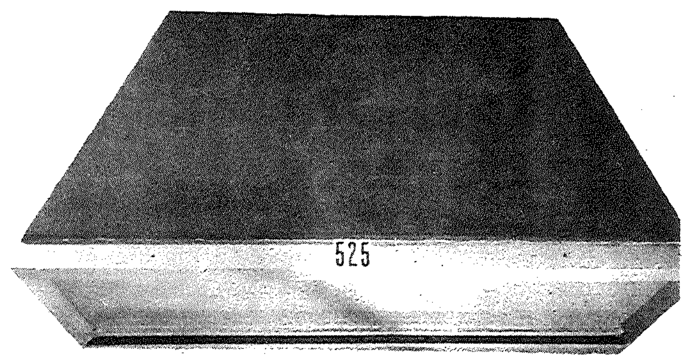

MIX 1 - 31A BLEND




MIX 2 - 3BC BLEND



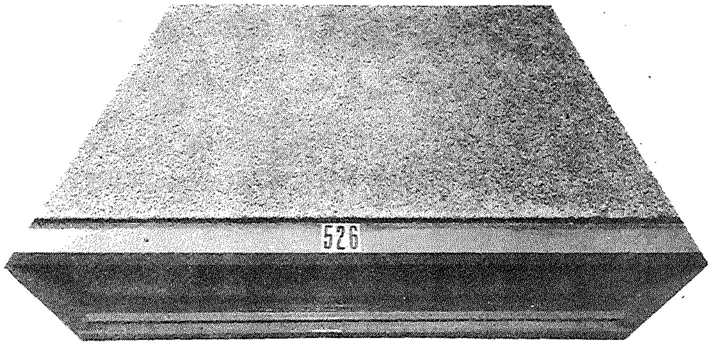
MIX 3 - 2NS BLEND



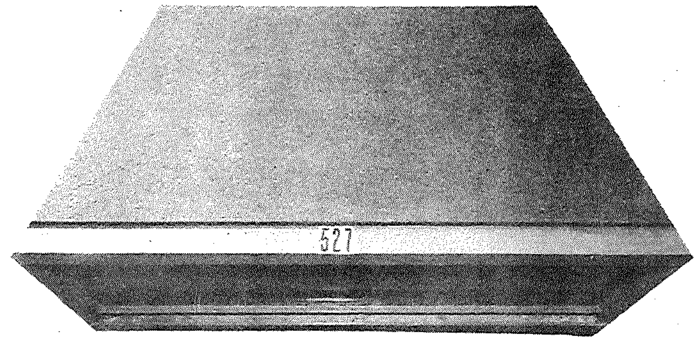

MIX 4 - STURGEON QUARTZITE

NEW PAVEMENT SURFACE TEXTURE

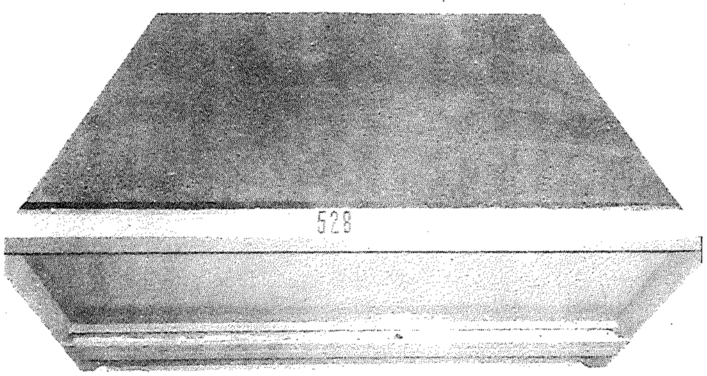
FIGURE 7



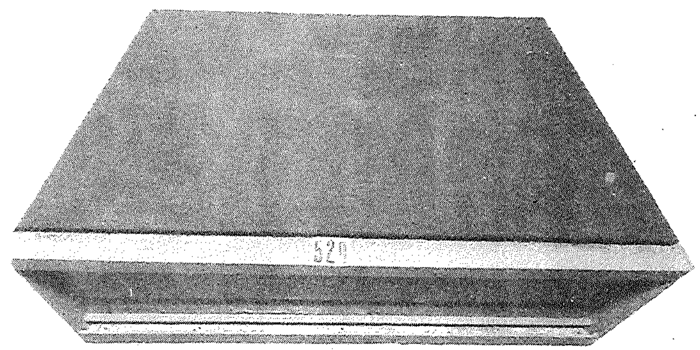

MIX 5 - EPOXY SEAL




MIX 6 - WYTON BINDER



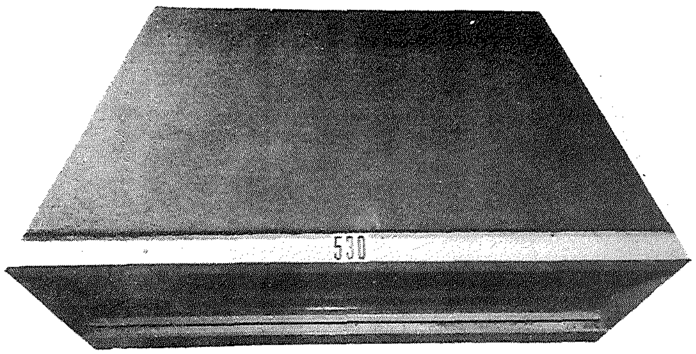

MIX 7 - CHOCOLAY QUARTZITE



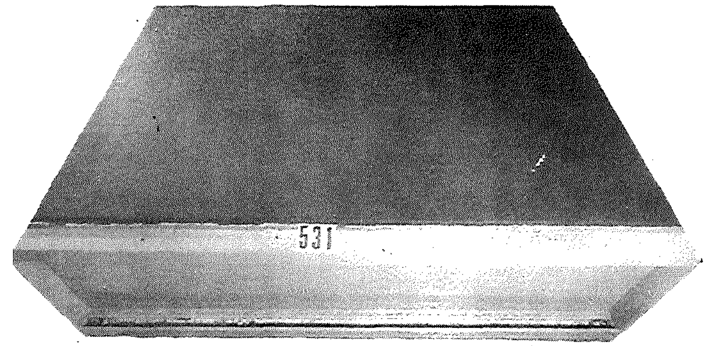
MIX 8 - RHYOLITE

NEW PAVEMENT SURFACE TEXTURE

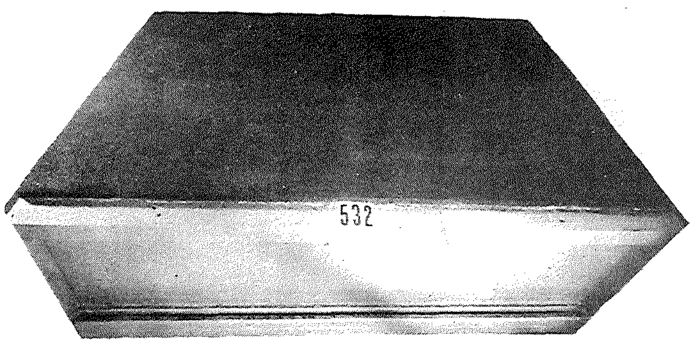
FIGURE 8



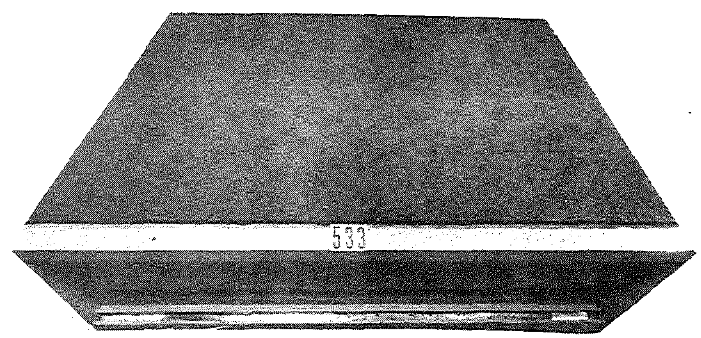

MIX 9-TRAP ROCK




MIX 10-DUNE SAND



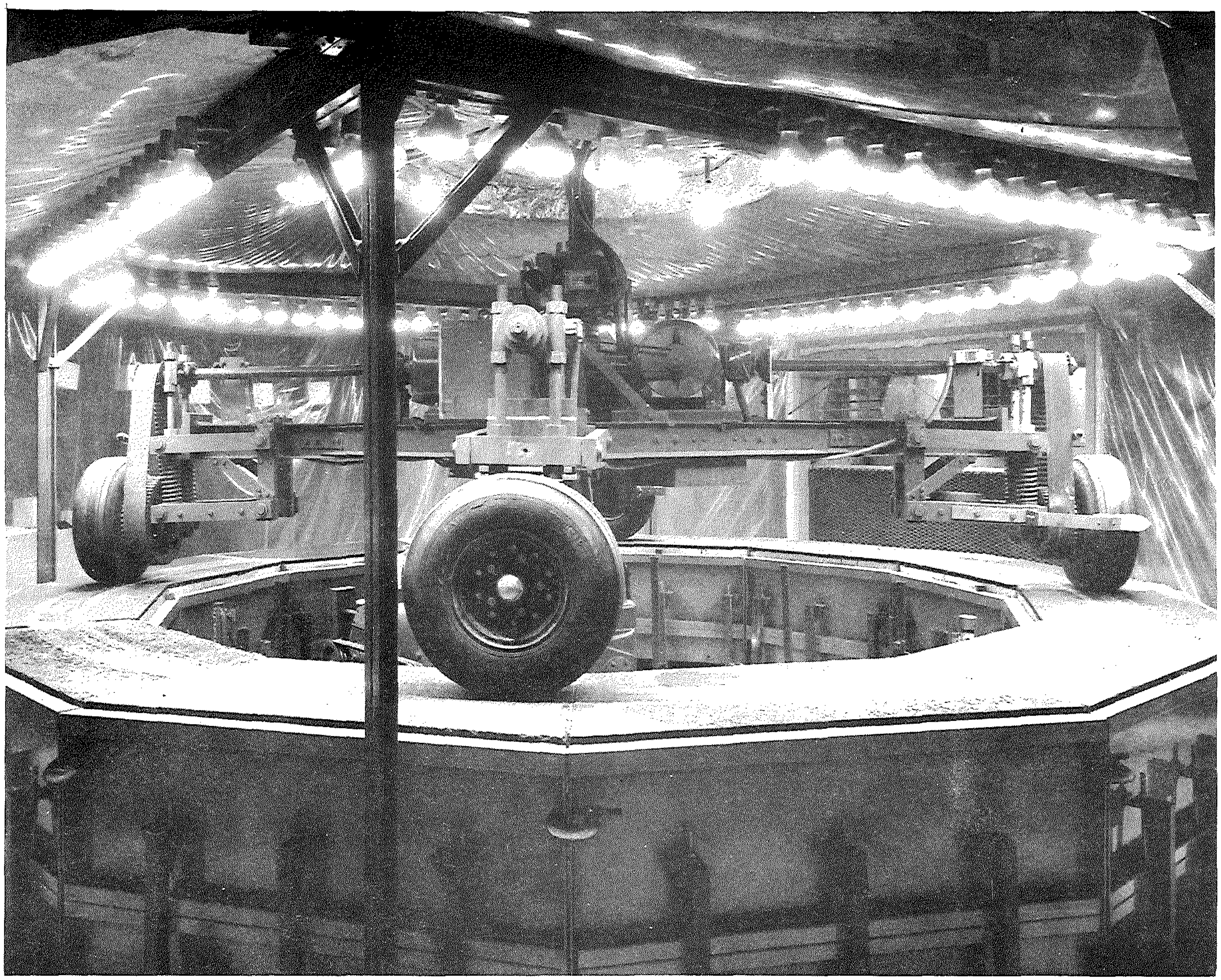

MIX 11-SLAG SAND




MIX 12-SANDSTONE

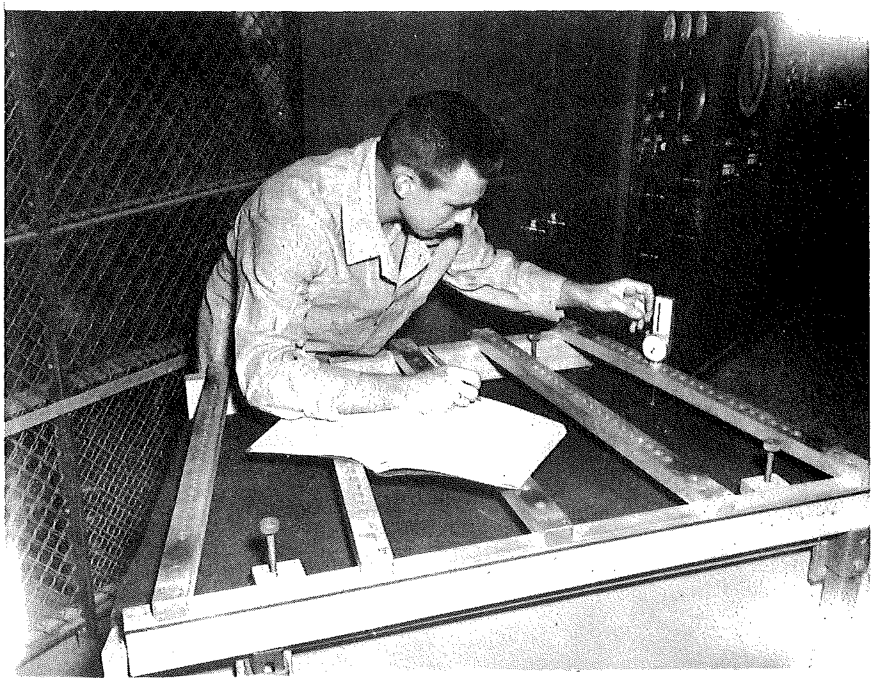
NEW PAVEMENT SURFACE TEXTURE

FIGURE 9



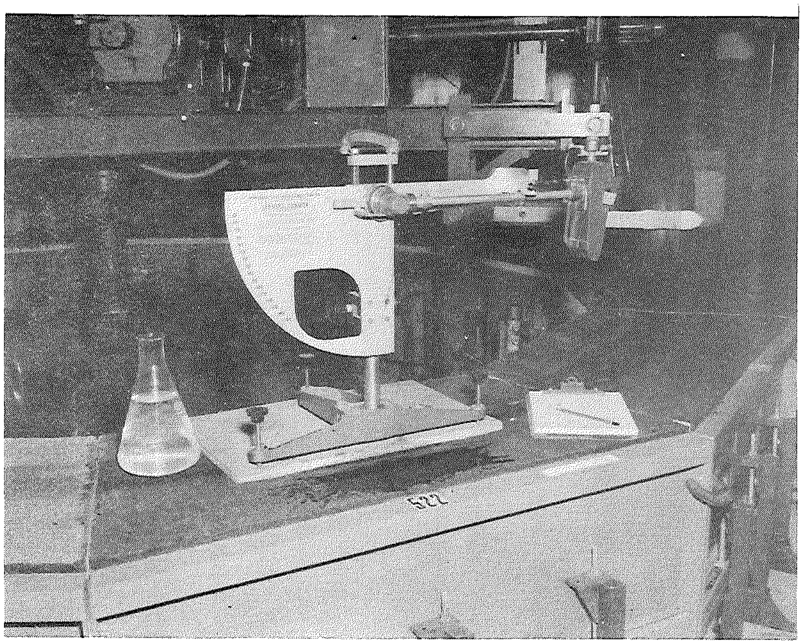
LABORATORY TEST MACHINE WITH MICHIGAN DESLICKING PAVEMENTS

FIGURE 10



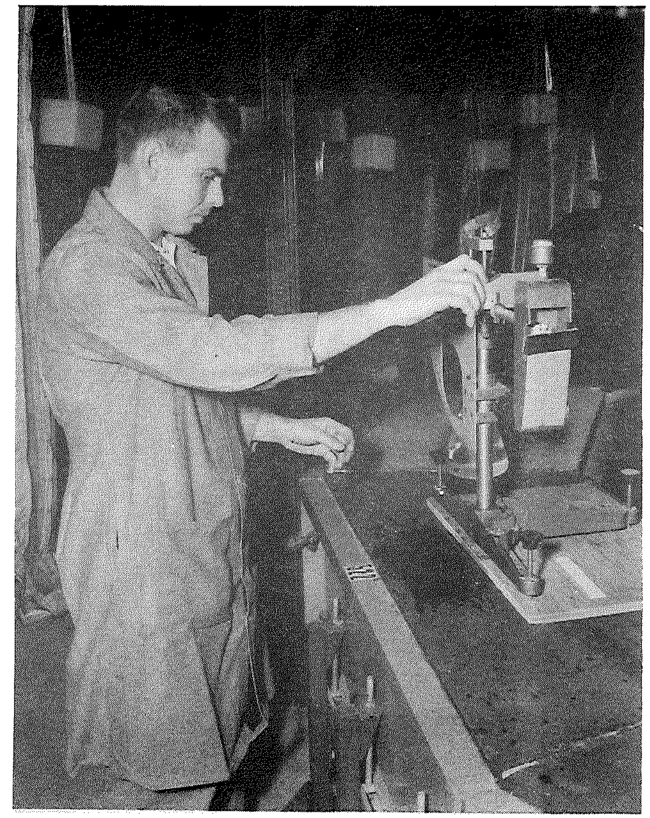
LABORATORY PAVEMENT
PROFILOMETER INSTRUMENT

FIGURE 11



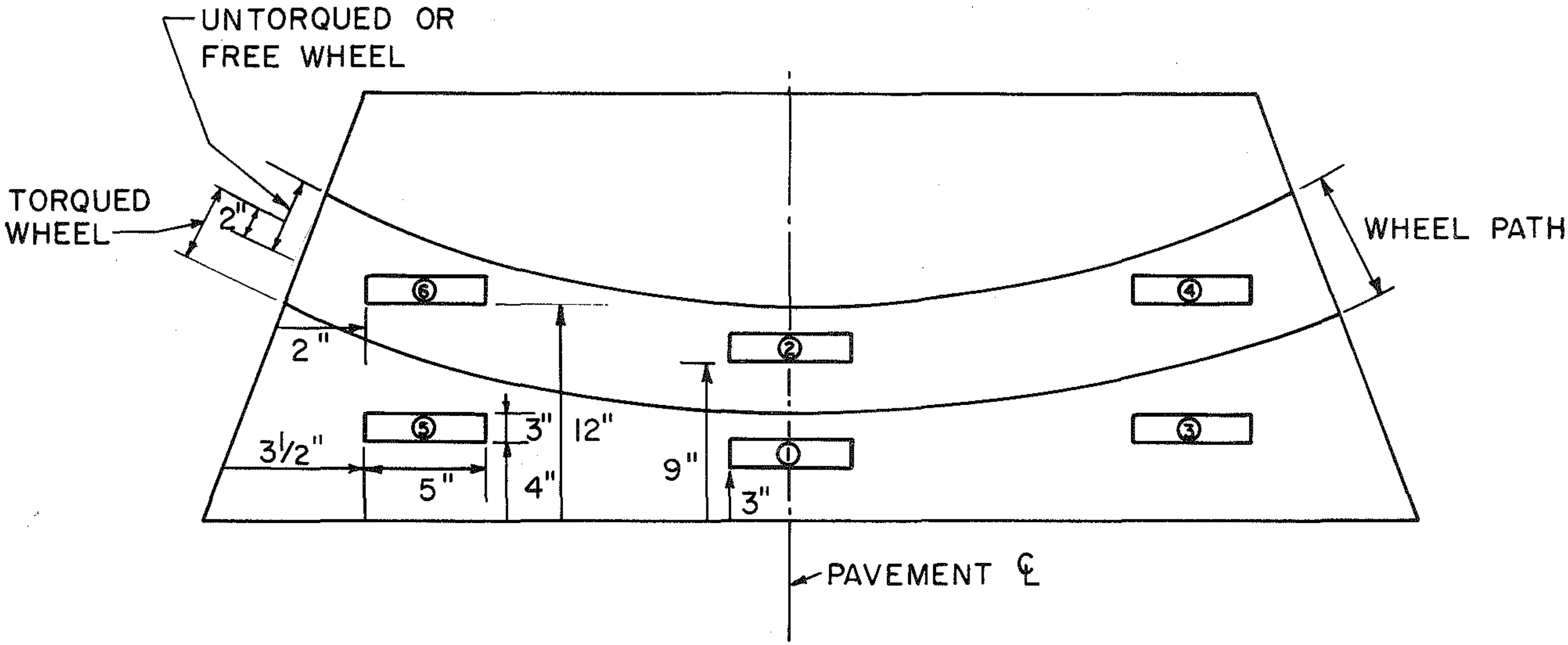
STANDARD PORTABLE SKID
RESISTANCE TESTER INSTRUMENT

FIGURE 12



PORTABLE SKID TESTER
RUBBER SLIDER

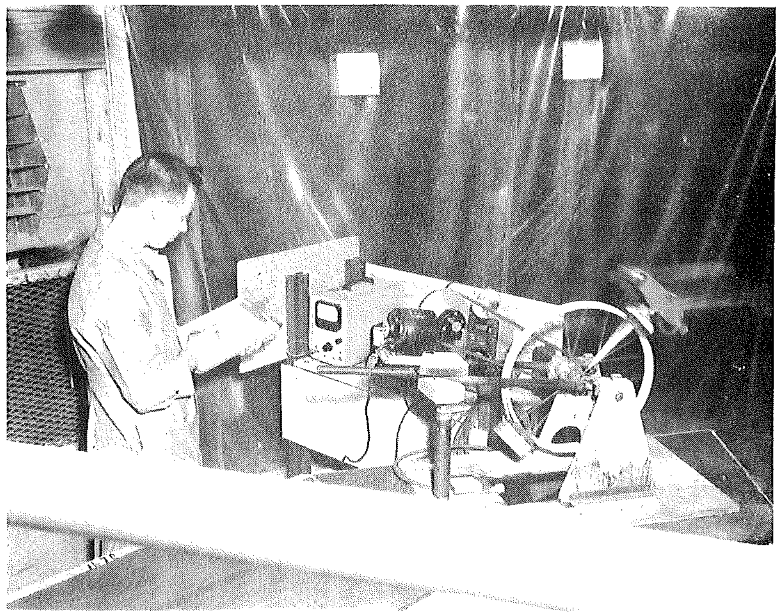
FIGURE 13




SKID TEST SITES ARE NUMBERED ① TO ⑥
PERIODIC TRAFFIC EFFECTS MEASURED AT ①, ②, ④ AND ⑥

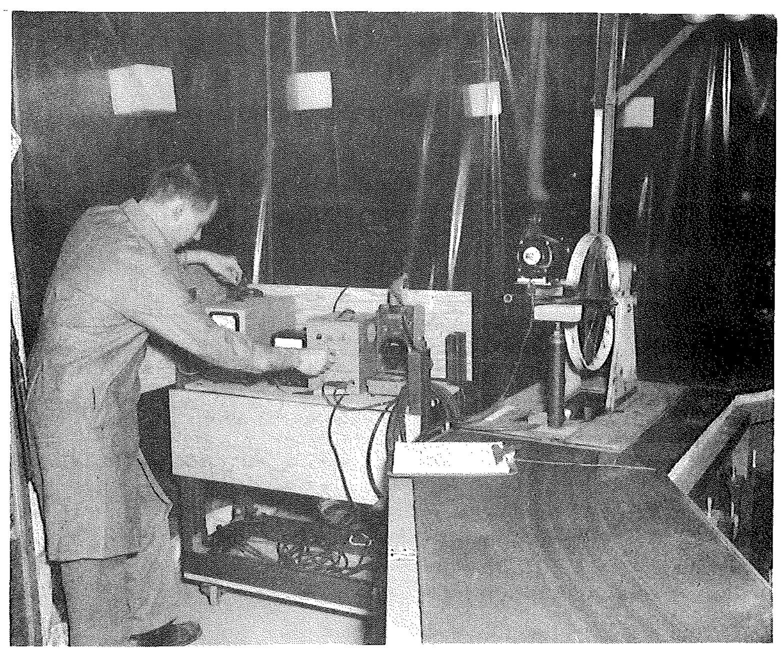
**PAVEMENT LOCATIONS FOR PORTABLE SKID TESTER MEASUREMENTS**

FIGURE 14



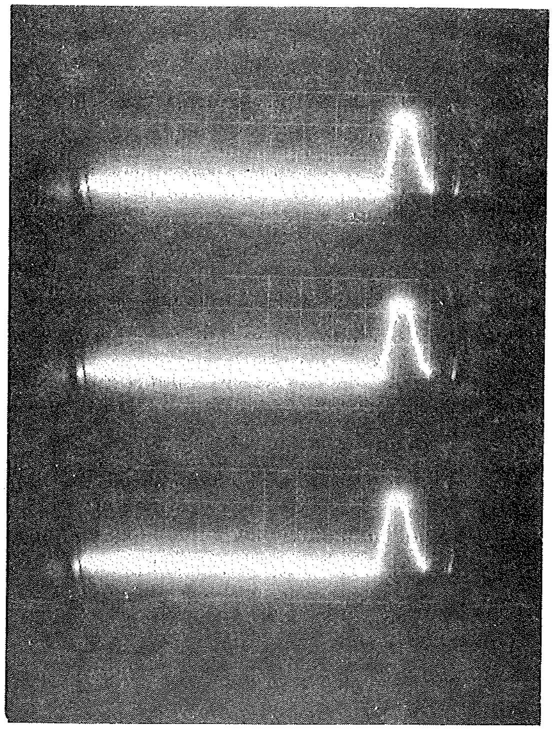
PORTABLE HIGH SPEED SKID RESISTANCE TESTER INSTRUMENT

FIGURE 15



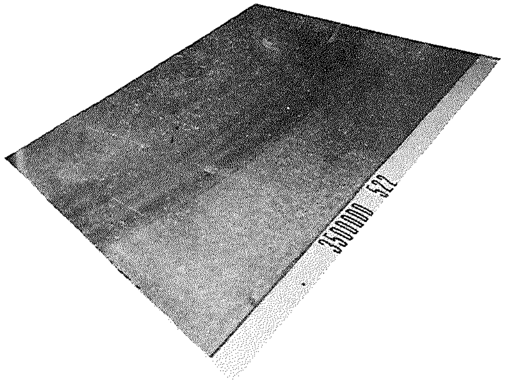
INSTRUMENTATION FOR HIGH SPEED POWER CONSUMPTION DETERMINATIONS

FIGURE 16

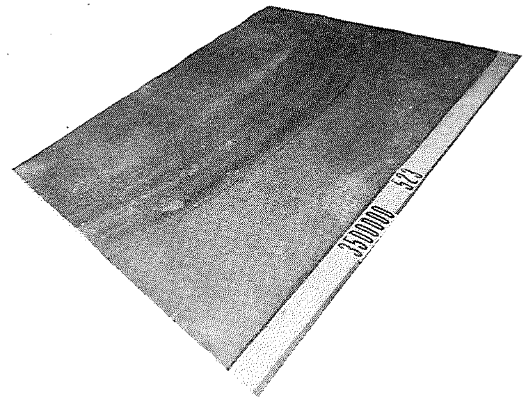


SLIDER LOAD OSCILLOGRAMS
FOR 30 MPH TESTER SPEED

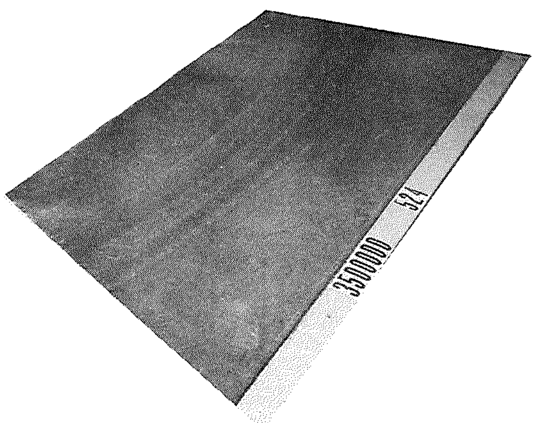
FIGURE 17



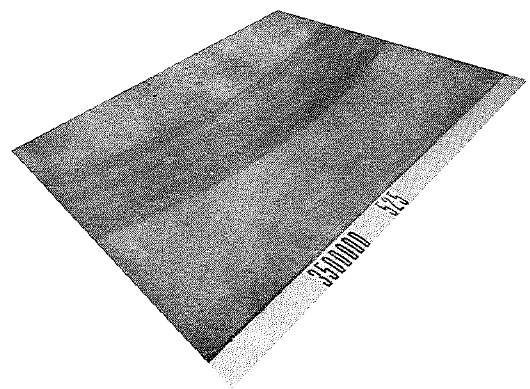

MIX 1 - 31A BLEND




MIX 2 - 3BC BLEND



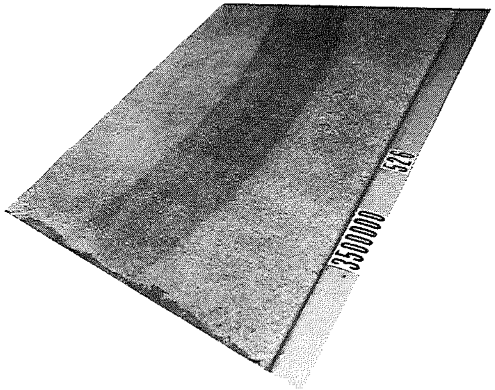

MIX 3 - 2NS BLEND



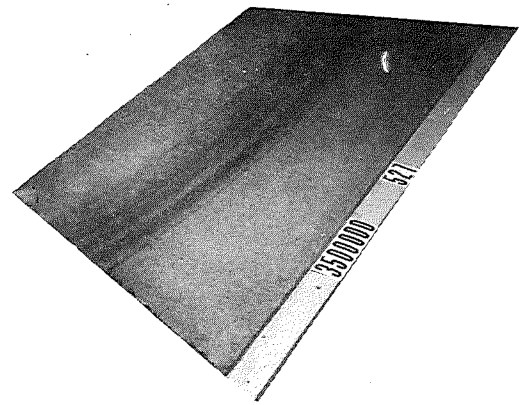

MIX 4 - STURGEON QUARTZITE

## END OF TEST PAVEMENT APPEARANCE

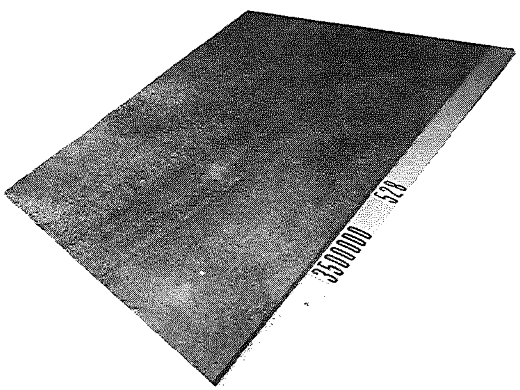
FIGURE 18



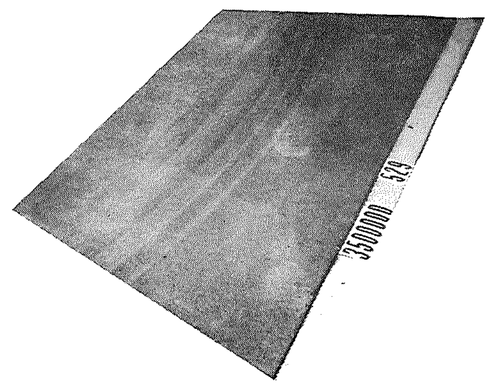

MIX 5 - EPOXY SEAL




MIX 6 - WYTON BINDER



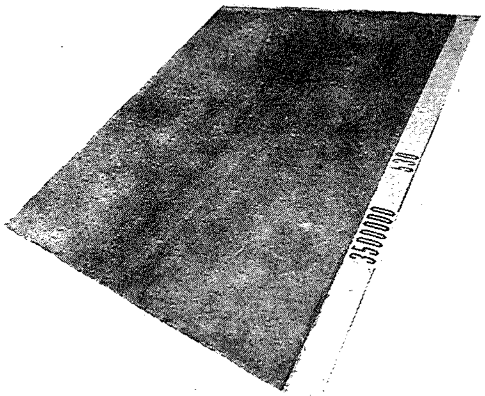

MIX 7 - CHOCOLAY QUARTZITE



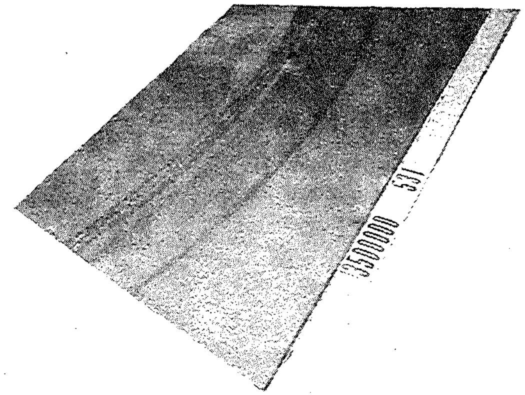

MIX 8 - RHYOLITE

END OF TEST PAVEMENT APPEARANCE

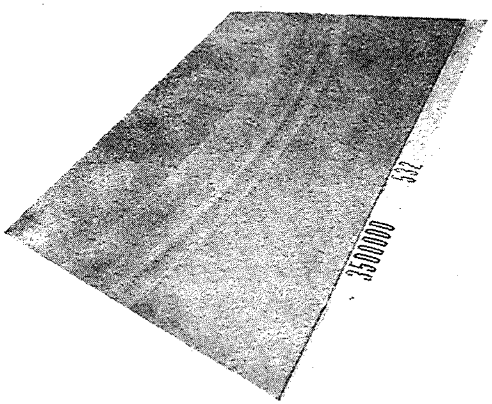
FIGURE 19



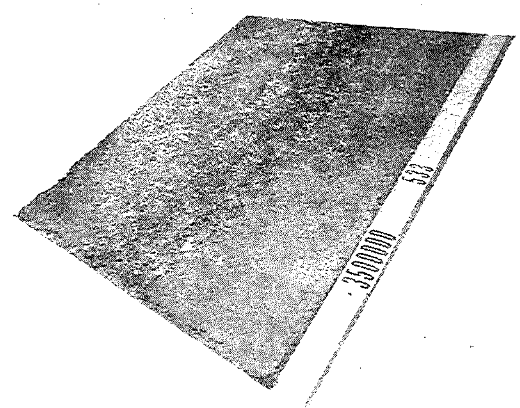

MIX 9 - TRAP ROCK




MIX 10 - DUNE SAND



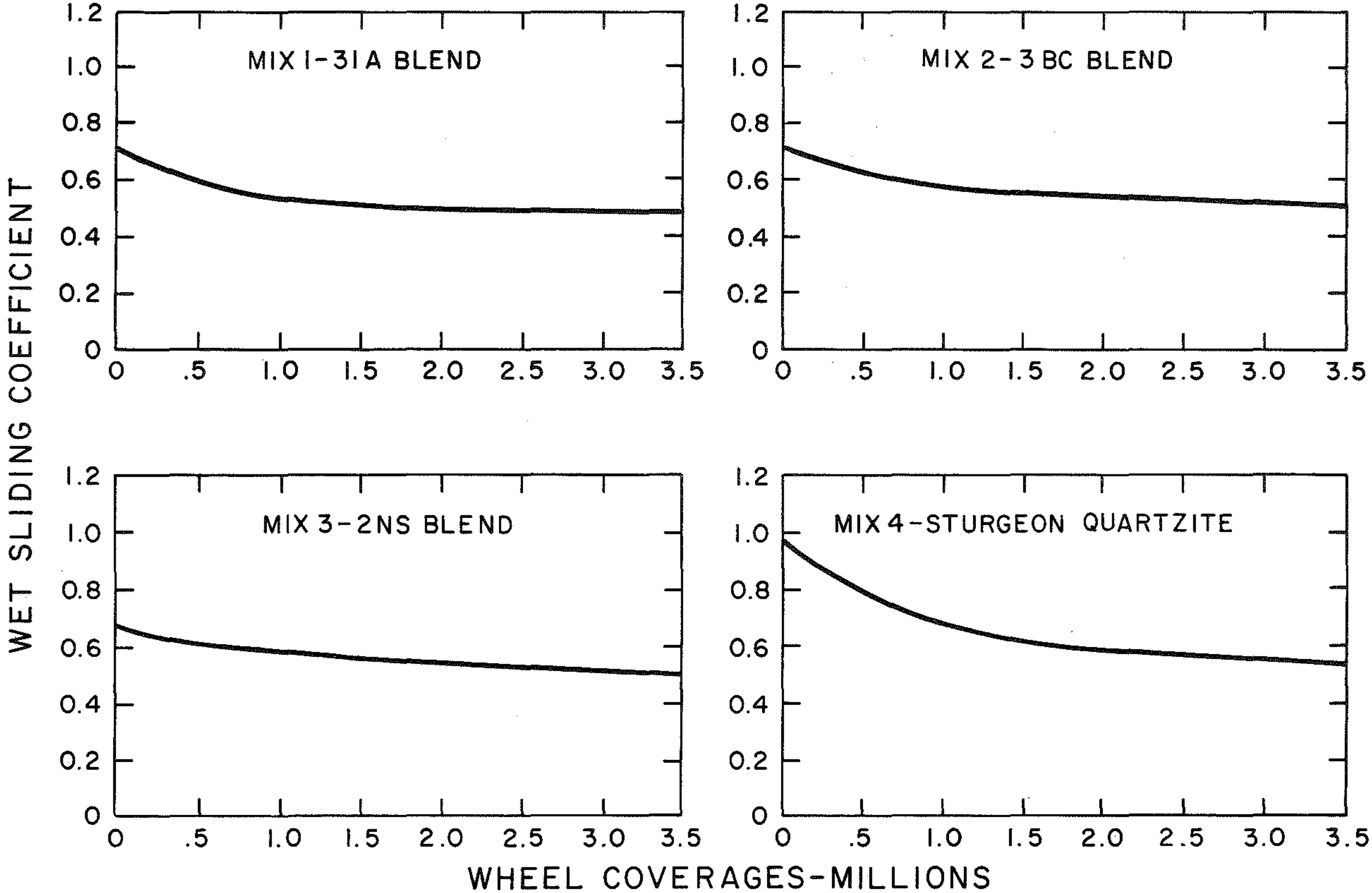

MIX 11 - SLAG SAND




MIX 12 - SANDSTONE

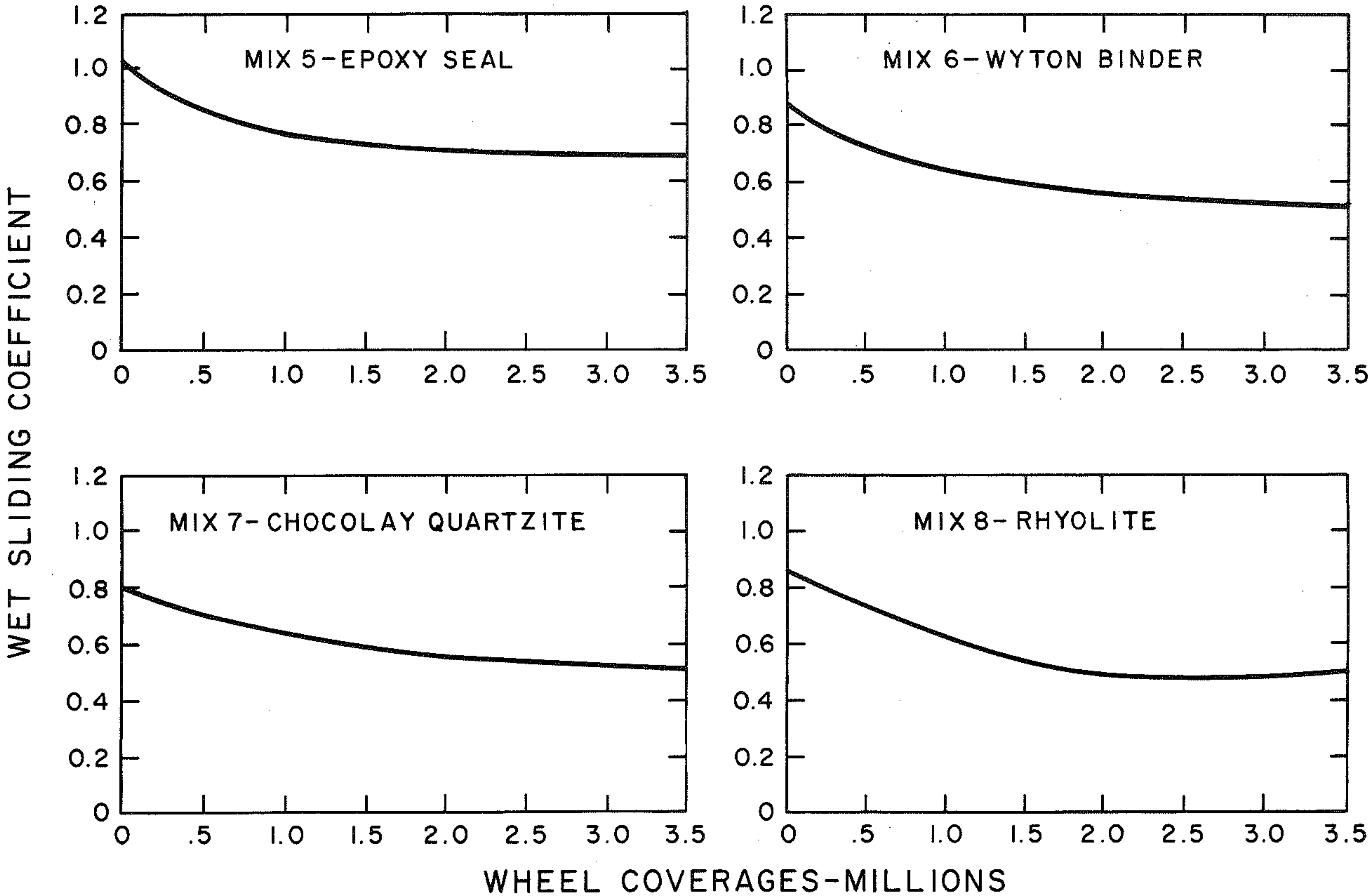
END OF TEST PAVEMENT APPEARANCE

FIGURE 20



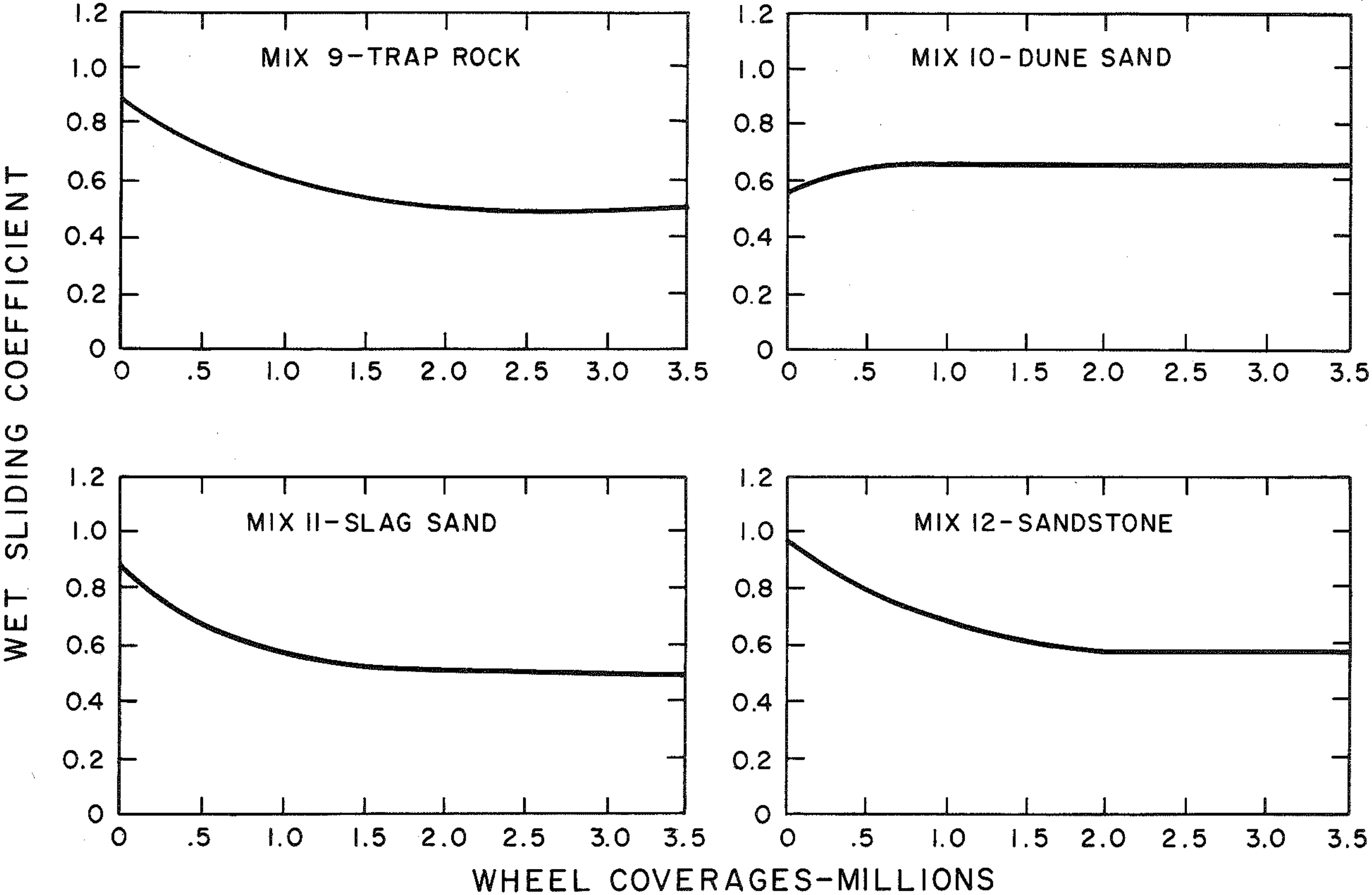

VARIATIONS IN PAVEMENT WHEEL PATH SLIPPERINESS

FIGURE 21



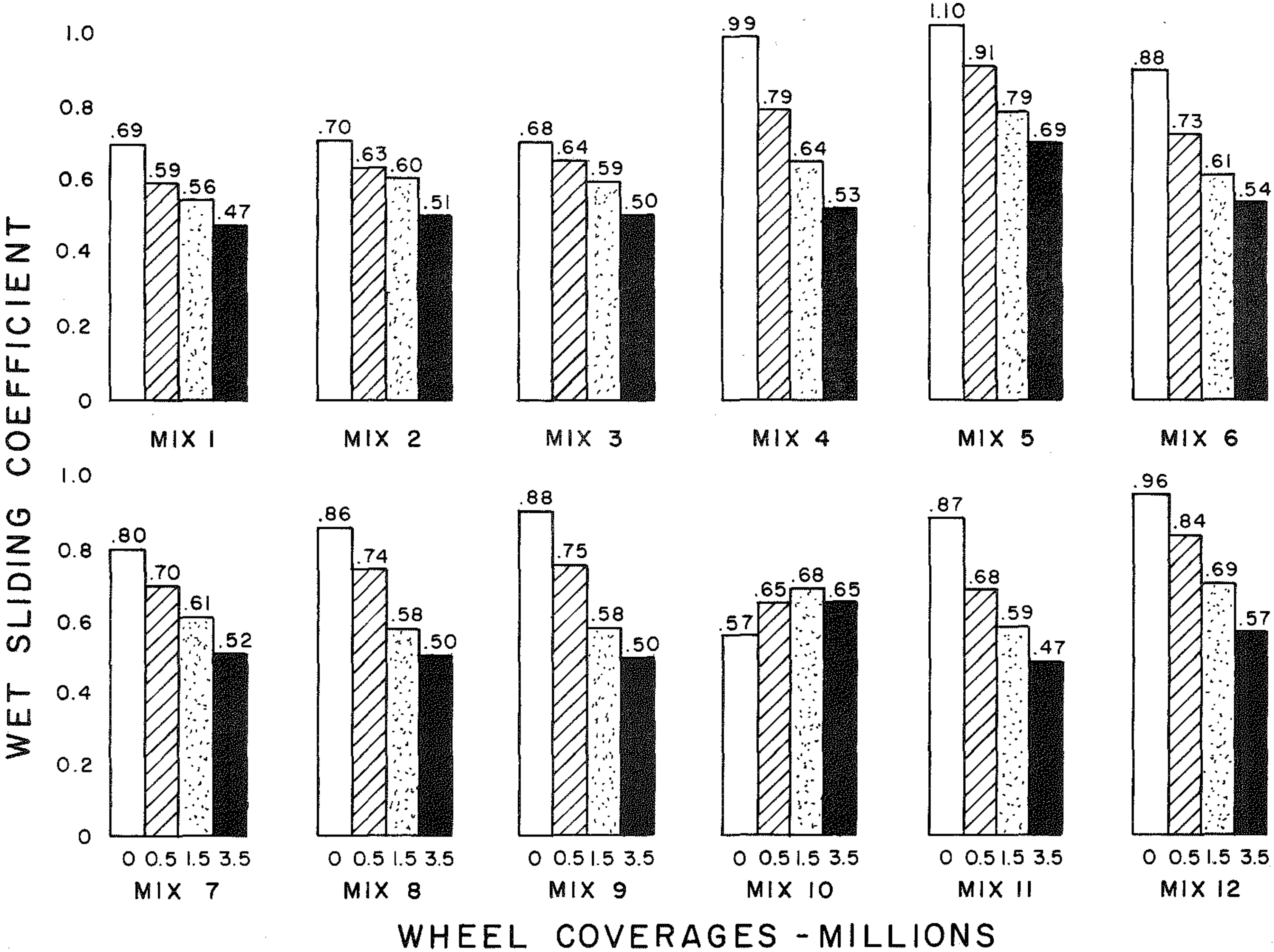

VARIATIONS IN PAVEMENT WHEEL PATH SLIPPERINESS

FIGURE 22




VARIATIONS IN PAVEMENT WHEEL PATH SLIPPERINESS

FIGURE 23




DESLICKING MIXTURE PERFORMANCE

APPENDIX I

LABORATORY ANALYSES OF
BITUMINOUS MIXTURES USED ON AMERICAN OIL COMPANY'S CIRCULAR TRACK SKID RESISTANCE INVESTIGATION

| Mix No. | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | | 9 | | 10 | | 11 | | 12 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MSHD Lab. No. 64A- | 9281 | | 9643 | | 9297 | | 8612 | | 8612 | | 8875 | | 8875 | | 9128 | | 9127 | | 8265 | | 9280 | | 8921 | |
| Mix Type | Amer. Agg. 31AA | | 3 BC | | 2 NS Mod. | | Sturgeon R. Quartzite Asphalt | | Sturgeon R. Quartzite Epoxy Seal | | Chocolay Quartzite Wyton | | Chocolay Quartzite Asphalt | | Bergland Rhyolite | | Wakefield Basalt Trap Rock | | Dune Sand 2.0% Asbestos | | Slag 3 BCS | | Grindstone City Sandstone | |
| | MSHD | CTL | MSHD | CTL | MSHD | CTL | MSHD | CTL | MSHD | CTL | MSHD | CTL | MSHD | CTL | MSHD | CTL | MSHD | CTL | MSHD | CTL | MSHD | CTL | MSHD | CTL |
| Gradation % Passing | | | | | | | | | Base Course | | | | | | | | | | | | | | | |
| 3/8 | 100 | 100 | | | 100 | 100 | | | 99 | 100 | | | | | | | | | | | | | 100 | 100 |
| 4 | 73 | 75 | | | 98 | 99 | | | 61 | 67 | 100 | 100 | 100 | 100 | 100 | | | | | | 100 | 100 | 64 | 65 |
| 8 | 56 | 57 | 100 | 100 | 83 | 84 | 100 | 100 | 44 | 49 | 61 | 65 | 61 | 62 | 99 | 100 | 100 | 100 | | 100 | 82 | 85 | 44 | 46 |
| 16 | 50 | 51 | 96 | 97 | 67 | 67 | 71 | 70 | 33 | 36 | 39 | 41 | 38 | 36 | 60 | 63 | 57 | 58 | | 99 | 60 | 62 | 37 | 37 |
| 30 | 45 | 46 | 89 | 88 | 50 | 49 | 51 | 50 | 26 | 27 | 27 | 27 | 25 | 24 | 38 | 37 | 36 | 36 | 100 | 97 | 43 | 42 | 34 | 34 |
| 50 | 32 | 33 | 65 | 66 | 22 | 22 | 40 | 40 | 17 | 18 | 19 | 19 | 17 | 16 | 24 | 24 | 23 | 22 | 62 | 53 | 27 | 27 | 32 | 32 |
| 100 | 13 | 12 | 19 | 20 | 5.0 | 5.0 | 32 | 31 | 7.0 | 6.3 | 13 | 12 | 12 | 11 | 16 | 15 | 16 | 14 | 2 | 0.9 | 16 | 15 | 28 | 28 |
| 200 | 6.1 | 6.5 | 5.9 | 5.6 | 3.3 | 2.7 | 21 | 20 | 4.8 | 4.4 | 8.0 | 7.5 | 8.0 | 6.9 | 10 | 10 | 11 | 8.6 | 1.3 | 0.4 | 9.0 | 8.4 | 9.8 | 8.5 |
| Bitumen | 5.6 | 5.8 | 6.5 | 6.4 | 6.4 | 6.4 | 6.9 | 6.9 | 5.3 | 5.5 | 5.7 | 5.6 | 5.8 | 5.8 | 5.6 | 5.7 | 5.7 | 5.7 | 6.5 | 6.4 | 7.9 | 8.0 | 7.3 | 7.5 |
| Tests Recov. AC | | | | | | | | | | | | | | | | | | | | | | | | |
| Pen. | 40 | 40 | 39 | 43 | 42 | 47 | 38 | 42 | 38 | 37 | 45 | 58 | 37 | 40 | 45 | 46 | 38 | 38 | 38 | 41 | 48 | 52 | 48 | 43 |
| Duct. | 150+ | 150+ | 150+ | 150+ | 150+ | 150+ | 150+ | 150+ | 150+ | 150+ | 150+ | 150+ | 150+ | 150+ | 150+ | 150+ | 150+ | 139 | 150+ | 150+ | 150+ | 150+ | 150+ | 150+ |
| Ash | 2.08 | 1.47 | 2.17 | 1.50 | 1.71 | 0.30 | 1.07 | 0.70 | 2.12 | 1.09 | 0.81 | 0.71 | 2.32 | 1.64 | 2.79 | 3.34 | 2.97 | 4.05 | 1.32 | 1.74 | 1.07 | 0.70 | 1.94 | 0.41 |
| Marshall Test | | | | | | | | | | | | | | | | | | | | | | | | |
| Act.Spec.Grav. | 2.401 | 2.361 | 2.073 | 2.020 | 2.170 | 2.121 | 2.260 | 2.254 | 2.390 | 2.373 | 2.250 | 2.203 | 2.245 | 2.214 | 2.124 | 2.087 | 2.334 | 2.289 | 1.907 | 1.873 | 2.309 | 2.270 | 2.102 | 2.089 |
| Max.Spec.Grav. | 2.488 | | 2.401 | 2.400 | 2.445 | | 2.385 | | 2.540 | | 2.455 | | 2.434 | | 2.410 | | 2.645 | | 2.385 | | 2.502 | | 2.386 | |
| Air Voids % | 3.5 | | 13.7 | 15.8 | 11.2 | | 5.2 | | 5.9 | | 8.4 | | 7.7 | | 11.9 | | 11.8 | | 20.0 | | 7.7 | | 11.9 | |
| Vf % | 79 | | 49 | 43 | 55 | | 74 | | 68 | | 60 | | 63 | | 49 | | 52 | | 38 | | 70 | - | 56 | |
| VMA,% | 16.7 | | 26.9 | 27.8 | 24.9 | | 20.0 | | 18.4 | | 21.0 | | 20.8 | | 23.3 | | 24.6 | | 32.3 | | 25.7 | | 27.0 | |
| Stab. lbs. | 1850 | 1280 | 260 | 120 | 480 | 90 | 3180 | 2980 | 2730 | 2150 | 1570 | 1680 | 1980 | 1990 | 1890 | 1760 | 1810 | 2080 | 80 | 0 | 2060 | 1830 | 3010 | 2850 |
| Flow | 10 | 12 | 10 | 10 | 8 | 8 | 12 | 12 | 10 | 12 | 10 | 10 | 12 | 11 | 13 | 15 | 11 | 15 | 12 | 0 | 14 | 15 | 17 | 14 |
| Hubbard Fld. | | | | | | | | | | | | | | | | | | | | | | | | |
| Act.Spec.Grav. | 2.315 | | 2.049 | | 2.125 | | 2.177 | | 2.344 | | 2.198 | | 2.220 | | 2.125 | | 2.336 | | 1.804 | | 2.270 | | 2.022 | |
| Air Voids % | 7.0 | | 14.7 | | 13.1 | | 8.7 | | 7.7 | | 10.5 | | 8.8 | | 11.8 | | 11.7 | | 24.4 | | 9.3 | | 15.3 | |
| Vf % | 64 | | 47 | | 50 | | 63 | | 61 | | 54 | | 60 | | 50 | | 53 | | 32 | | 65 | | 48 | |
| VMA,% | 19.4 | | 27.7 | | 26.2 | | 23.5 | | 19.7 | | 22.8 | | 22.0 | | 23.6 | | 24.9 | | 35.9 | | 26.6 | | 29.4 | |
| Stab. lbs. | 2430 | | 330 | | 1300 | | 2920 | | 3370 | | 2600 | | 3420 | | 2530 | | 3110 | | 70 | | 2910 | | 2240 | |

Note: MSHD - Marshall and Hubbard Field Samples prepared by rehating in Ann Arbor Laboratory on balance of bituminous mixture left over from circular track preparation.

CTL - Marshall Samples prepared by American Oil Company while mixtures still hot on left over material. After cooling specimens sent to Chicago Testing Laboratory for testing.

APPENDIX II

LABORATORY ANALYSES OF
BITUMINOUS CORES REMOVED FROM THE AMERICAN OIL COMPANY'S CIRCULAR TRACT SKID RESISTANCE INVESTIGATION UPON COMPLETION OF TESTING

| Mix No. | 1 | 2 | 3 | 4 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Lab. No. 65B- | 639-648 | 649-652 | 672-680 | 701-709 | 692-700 | 664-671 | 653-663 | 681-691 | 720-730 | 710-719 | 731-741 |
| Core No. | 125-134 | 135-138 | 158-166 | 187-195 | 178-186 | 150-157 | 139-149 | 167-177 | 206-216 | 196-205 | 217-227 |
| Mix Type | Amer. Agg. 31AA | 3 BC | 2NS Mod. | Sturgeon R. Quartzite Asphalt | Chocolay Quartzite Wyton | Chocolay Quartzite Asphalt | Bergland Rhyolite | Wakefield Basalt Trap Rock | Dune Sand 2.0% Asbestos | Slag 3 BCS | Grindstone City Sandstone |
| Gradation % Passing | | | | | | | | | | | |
| 3/8 | 100 | | 100 | | 100 | | | | | | 100 |
| 4 | 75 | | 98 | | 99 | 100 | | 100 | | 100 | 65 |
| 8 | 57 | 100 | 84 | 100 | 63 | 64 | 100 | 99 | | 86 | 46 |
| 16 | 51 | 97 | 68 | 72 | 41 | 39 | 65 | 57 | | 62 | 39 |
| 30 | 46 | 89 | 51 | 52 | 28 | 26 | 40 | 35 | 100 | 43 | 36 |
| 50 | 32 | 66 | 23 | 41 | 19 | 18 | 25 | 23 | 75 | 27 | 34 |
| 100 | 13 | 23 | 7 | 33 | 13 | 13 | 17 | 16 | 2 | 17 | 30 |
| 200 | 6.4 | 7.1 | 4.0 | 19.9 | 7.8 | 8.3 | 11.0 | 9.9 | 1.1 | 10.1 | 11.9 |
| Bitumen | 5.7 | 6.4 | 6.4 | 6.7 | 5.7 | 5.9 | 5.8 | 5.4 | 6.5 | 7.9 | 7.0 |
| Orig. Pen. | | | | | | | | | | | |
| Rec. Pen. | 33 | 35 | 34 | 31 | 17 | 31 | 32 | 30 | 34 | 40 | 34 |
| Rec. Duct. | 150+ | 150+ | 150+ | 150+ | 150+ | 150+ | 150+ | 150+ | 150+ | 150+ | 150+ |
| Ash % | 1.07 | 1.07 | 0.34 | 1.87 | 2.41 | 1.95 | 1.68 | 1.70 | 1.20 | 2.28 | 2.31 |
| Core Results: Thickness | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.8 | 0.6 | 0.6 | 0.7 | 0.6 | 0.6 |
| Core Density | | | | | | | | | | | |
| Wheel Track | 2.332 | 1.981 | 2.162 | 2.135 | 2.132 | 2.160 | 2.068 | 2.280 | | 2.282 | 2.022 |
| Outside Wheel Track | 2.236 | 1.978 | 2.044 | 1.882 | 2.040 | 2.038 | 1.948 | 2.018 | 1.775 | 1.949 | 1.852 |
| Max.Theor.Sp.Gr. | 2.488 | 2.401 | 2.445 | 2.385 | 2.455 | 2.434 | 2.410 | 2.645 | 2.385 | 2.502 | 2.386 |

| Core Results | 1 WT | 1 OWT | 2 WT | 2 OWT | 3 WT | 3 OWT | 4 WT | 4 OWT | 6 WT | 6 OWT | 7 WT | 7 OWT | 8 WT | 8 OWT | 9 WT | 9 OWT | 10 OWT | 11 WT | 11 OWT | 12 WT | 12 OWT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Air Voids | 6.3 | 10.1 | 17.5 | 17.6 | 11.6 | 16.4 | 10.5 | 21.1 | 13.2 | 16.9 | 11.3 | 16.3 | 14.2 | 19.2 | 13.8 | 23.7 | 25.6 | 8.8 | 22.1 | 15.3 | 22.4 |
| Voids Filled | 67 | 55 | 42 | 38 | 54 | 44 | 58 | 38 | 47 | 40 | 52 | 41 | 44 | 36 | 52 | 32 | 31 | 67 | 40 | 48 | 37 |
| VMA | 19.1 | 22.4 | 30.2 | 28.4 | 25.2 | 29.3 | 25.0 | 34.0 | 24.9 | 28.2 | 23.5 | 27.6 | 25.4 | 30.0 | 28.8 | 34.9 | 37.1 | 26.7 | 36.8 | 29.4 | 35.6 |
| % Compaction | 97.1 | 93.1 | 95.6 | 95.4 | 99.6 | 94.2 | 94.5 | 83.3 | 94.8 | 90.7 | 96.2 | 90.8 | 97.4 | 91.7 | 97.7 | 86.5 | 93.1 | 98.8 | 84.4 | 95.2 | 88.3 |

5-26-65