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Pavement Slipperiness Factors And Their Measurement

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Pavement Slipperiness Factors And Their Measurement

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In two places—the "Contents" page, and page 48—the title of the paper by H. F. Clemmer and Norman G. Smith should read "Supplemental Tests of Pavement Skidding Resistance With a 2-Wheel Trailer."

Also, the following committee should be added as co-sponsor of the papers in this bulletin:

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Contents

A DEVICE FOR DETERMINING RELATIVE POTENTIAL SLIPPERINESS OF PAVEMENT MIXTURES
E. A. Whitehurst and W. A. Goodwin 1

LOCKED WHEEL SKID PERFORMANCE OF VARIOUS TIRES ON CLEAN, DRY ROAD SURFACES
Samuel Mercer, Jr. 8
Appendix A 22
Appendix B, Tire Tread Designs 22
Appendix C, Test Surfaces. 23
Appendix D, Vehicles Used in Tests 24
Appendix E, Drag Trailer Dynamometer 25
Appendix F, Chronopousometer 25

TEST FOR COEFFICIENTS OF FRICTION BY THE SKIDDING CAR METHOD ON WET AND DRY SURFACES
A. M. White and H. O. Thompson 26

MEASUREMENT OF PAVEMENT SKIDDING RESISTANCE BY MEANS OF A SIMPLE 2-WHEEL TRAILER
P. C. Skeels 35

SUPPLEMENTAL PAVEMENT SKIDDING RESISTANCE TESTS IN VIRGINIA
J. H. Dillard. 46

SUPPLEMENTAL TESTS OF PAVEMENT SKIDDING RESISTANCE WITH A 3-WHEEL TRAILER
H. F. Clemmer and Norman G. Smith. 48

MICHIGAN'S SKID TESTING PROGRAM
M. G. Brown and E. A. Finney 54

A STUDY OF THE POLISHING CHARACTERISTICS OF LIMESTONE AND SANDSTONE AGGREGATES IN REGARD TO PAVEMENT SLIPPERINESS
William J. Stutzenberger and James H. Havens 58
Appendix, Descriptions of Specimens. 74

A Device for Determining Relative Potential Slipperiness of Pavement Mixtures

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As a result of a 5-year study of pavement slipperiness in Tennessee it was concluded that the type of aggregate used in the surface played a major role in determining the eventual slipperiness, or lack thereof. The results of this study have been previously reported. Present investigations are being made to determine what aggregates or combinations of aggregate may be used benefically.

To minimize expensive and time-consuming field experiments, a devise has been constructed to permit the testing of various surface mixtures in the laboratory. The device consists of an automobile wheel, driven by a variable speed motor, which spins against the test specimen. The specimen, either portland cement or asphaltic concrete, is 38 in. square and 6 in. thick. The speed of rotation of the wheel may be varied from below 10 to above 40 mph and the load of the wheel against the specimen may range from about 100 to 1,200 lb.

Tests may be made at one point on the specimen or the specimen may be moved in both directions while the wheel is spinning, thus producing a planing action across any desired portion of the specimen. A test on a single location usually requires from 30 min to 2 hrs.

The measured parameter is the wattage required to drive the motor at the selected speed; as the pavement becomes slippery less power is required. A graph of wattage versus time is taken through use of a recording wattmeter, the relative decrease in power demand being indicative of the relative potential slipperiness of various mixtures. Typical power demand curves for several paving mixtures are presented.

● THE measurement of "skid or non-skid" characteristics of Tennessee pavements began early in 1952 as one of the first investigations to be undertaken by the Tennessee Highway Research Program. Since that time over one thousand measurements have been made on both bituminous and concrete highway surfaces. The majority of these tests have been conducted with a two-wheel trailer, although many tests have been made with an automobile using a stopping-distance as well as a decelerometer method of test. Parameters which have been investigated include pavement temperature, surface type, age and cleanliness under both wet and dry condition, tire pressure, tire tread, and, in the case of the trailer test, wheel loads.

In conducting the trailer test two procedures have been employed, which are referred to as the standard and the running test. The standard test is performed on a representative, relatively level section of highway approximately 200 ft long, and consists of tests made at 10, 20, 30, and 40 mph on both sides of the centerline. Its major advantage is that the surface remains the same throughout the test; its disadvantage lies in the large turn-around areas which must be found beyond both ends of the section.

The running test is performed by towing the trailer over several miles of road and testing a large number of random spots at each desired speed. For any pavement constructed of a uniform combination of materials and subjected to uniform traffic and exposure, the results of standard and running tests are in close agreement.

Stopping-distance tests have been widely employed for many years. They consist simply of measuring the distance which an automobile slides in a locked-wheel skid in coming to a stop from some selected initial speed. In the decelerometer test, the brakes of the vehicle are locked briefly and then released and the deceleration of the vehicle during the braking measured and recorded.

All three of these test methods have been used with varying degrees of success by a number of organizations throughout the country. It is recognized, however, that all have the disadvantage of being adaptable only to "post testing" of the highway surface rather than to "pretesting" of the pavement materials. They also require expensive, time consuming field measurements. The desirability has long been recognized of a method of testing paving mixtures prior to use to evaluate their potential performance with respect to slipperiness. If unsatisfactory materials or combinations thereof may be eliminated prior to use, material savings in maintenance and reconstruction costs will result.

The device described below has been developed in the laboratories of

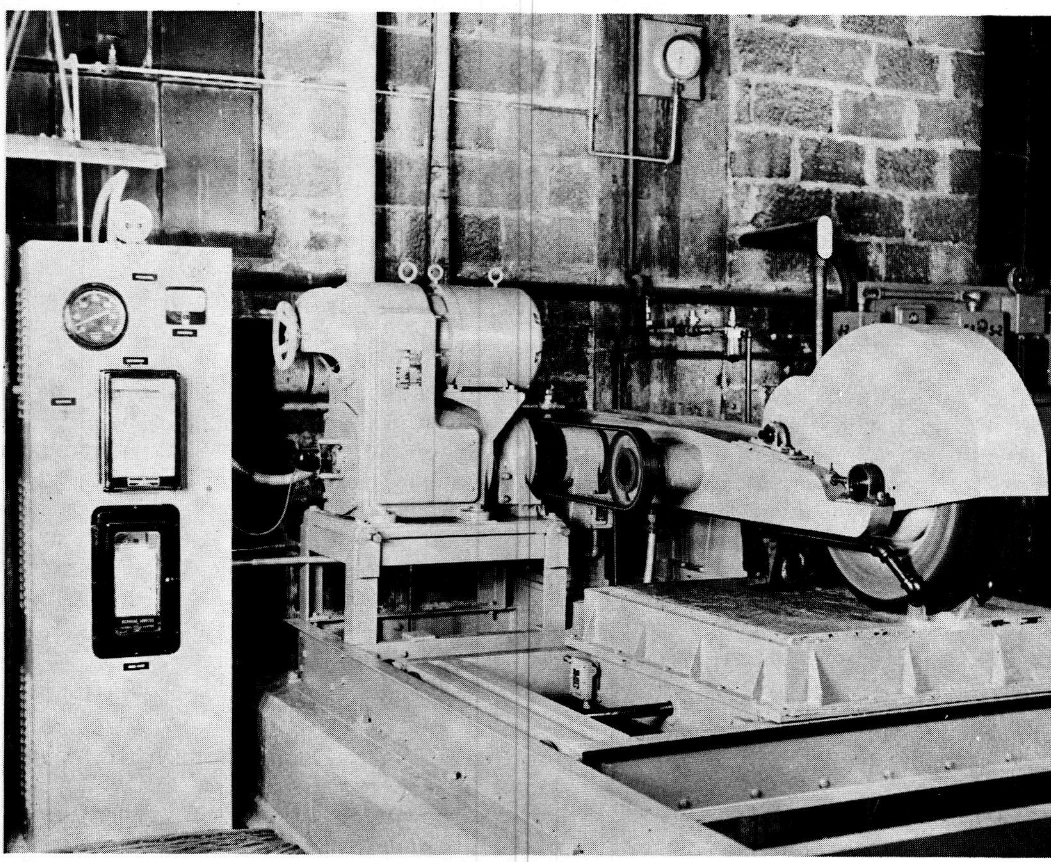

Figure 1.

the Tennessee Highway Research Program to permit the pretesting of paving mixtures with respect to potential slipperiness, and to facilitate the selection of the best available materials for use in pavement surfaces.

APPARATUS

In general, the laboratory device consists of an automobile wheel, driven by a variable speed drive unit, which spins against a test specimen. The power demand of the driven wheel is considered to be a measure of the specimen surface resistance. As the surface becomes more slippery, less power is consumed. A graph of power versus time is obtained through the use of a recording wattmeter. The relative decrease in power demand is indicative of the relative potential slipperiness of various mixtures.

A general view of the test apparatus is shown in Figure 1. The test specimen shown is 36- by 36-in. and 6-in. thick. In this case, it is a portland cement concrete mixture, but bituminous concrete mixtures can also be tested. Specimen size can be varied from 6- by 10-in. to the maximum size shown in the figure. The largest size is preferred as 25 different test locations may be attained on its surface.

At the present time, only specimens fabricated in the laboratory have been tested; however, the device can accommodate specimens placed directly in the field or cut from existing roadway surfaces. In the case of concrete specimens, various surface finishes such as broomed or burlap-dragged can

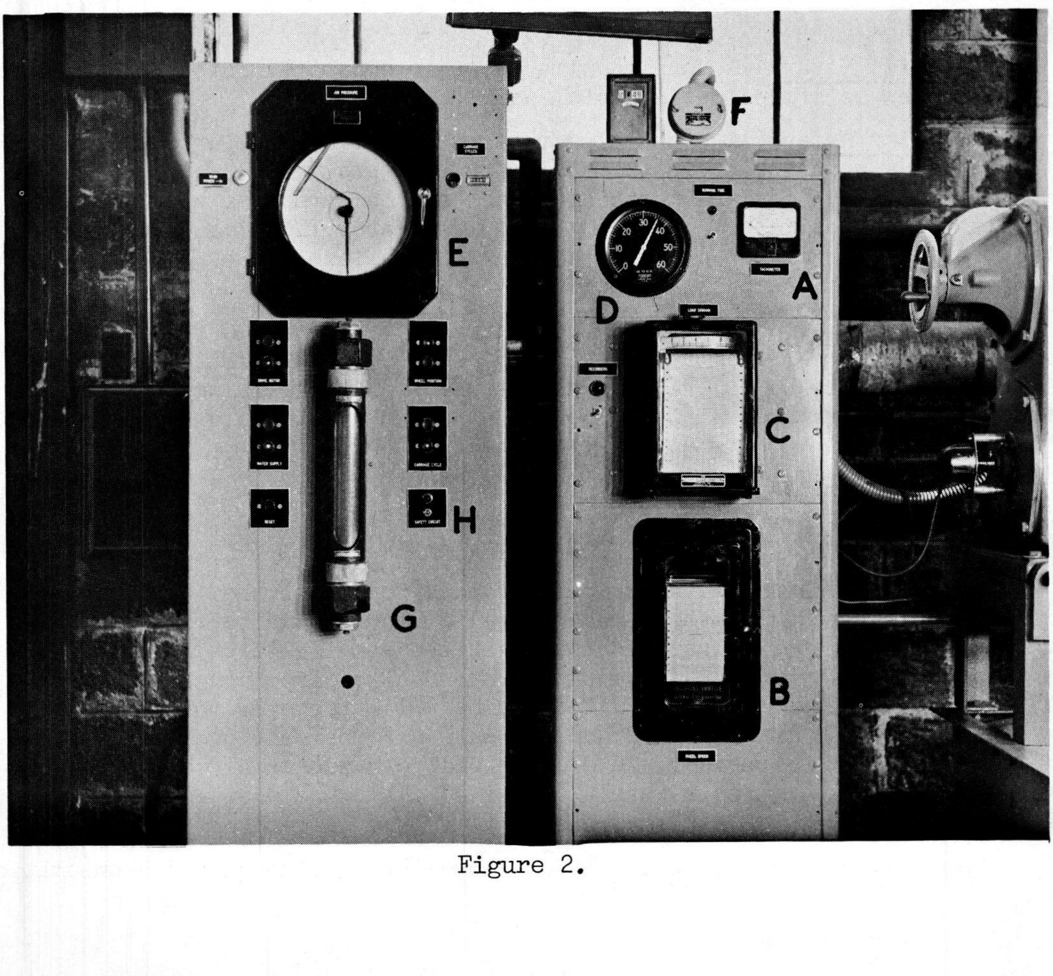

Figure 2.

be evaluated. Presently, several thin surface treatments, sometimes referred to as overlays, are being studied for the purpose of improving existing concrete surfaces.

The relative position of the most important control components located on the control board and panel are shown in Figure 2. A brief description of these components follows:

(A), (B) Tachometer. A tachometer, for visual control of speed, has been calibrated to show rpm and equivalent mph rotation of the wheel. It is actuated by an AC generator which is connected to the output side of the variable speed drive. A DC recording ammeter (B), which records the wheel speed on a chart, is connected through a rectifying bridge circuit to the AC generator. Any variation in the speed of rotation during a test may be observed from this chart.

(C) Recording Wattmeter. An AC recording wattmeter with a range of 1 kw at full scale deflection is used for the purpose of recording power demand of the variable speed drive motor. The range of this meter can be varied by changing taps on two current transformers.

(D), (E) Pressure Recorder. A pressure gage (D) is provided for visual control, however, since the load on the wheel is partly determined from the pressure applied by a pneumatic cylinder, a permanent record of pressure is made while each test is conducted. This record is obtained through a pressure recorder which has a range of 0 to 50 psi and records directly onto a motor driver chart. Any pressure variation during a test may be observed on the chart.

(F) Time Meter. A running time meter is connected into the circuit for the purpose of indicating total hours of operation.

(G) Flow Meter. A water flow meter is used for the purpose of controlling the quantity of water flowing to the specimen. On the outlet side, two 1-in. water lines are positioned such that a stream of water is caused to flow on both sides of the test tire. The water flows continuously during the test and serves not only for wetting the surface but as a coolant for keeping the tire temperature down.

(H) Safety Circuit. Since the equipment was designed for unattended operation, a rather intricate control circuit was installed. The purpose of the circuit is to secure the machine whenever there is any operational failure. For example, if the tire "blows" or the water pressure fails, the machine will be automatically secured.

A schematic diagram of the device is shown in Figure 3. The relative size and location of the various components may be obtained from this diagram.

The units designated as numbers 3 and 4 represent the variable speed drive and gear reduction box, respectively. The two units make up the variable speed motor drive which supplies the driving force for the automotile wheel. It has a maximum output speed of 346 rpm and a minimum of 6.9 rpm. At the present time, it contains a 5 horsepower motor which has a maximum current load of 13.2 amperes with a 20 percent overload factor during the starting period. This drive unit can adequately maintain a wheel speed of 10 mph at a wheel load of 270 lb. The position of the drive is such that it can be replaced at any time by a larger horsepower unit.

The load on the test wheel is obtained through the use of a pneumatic

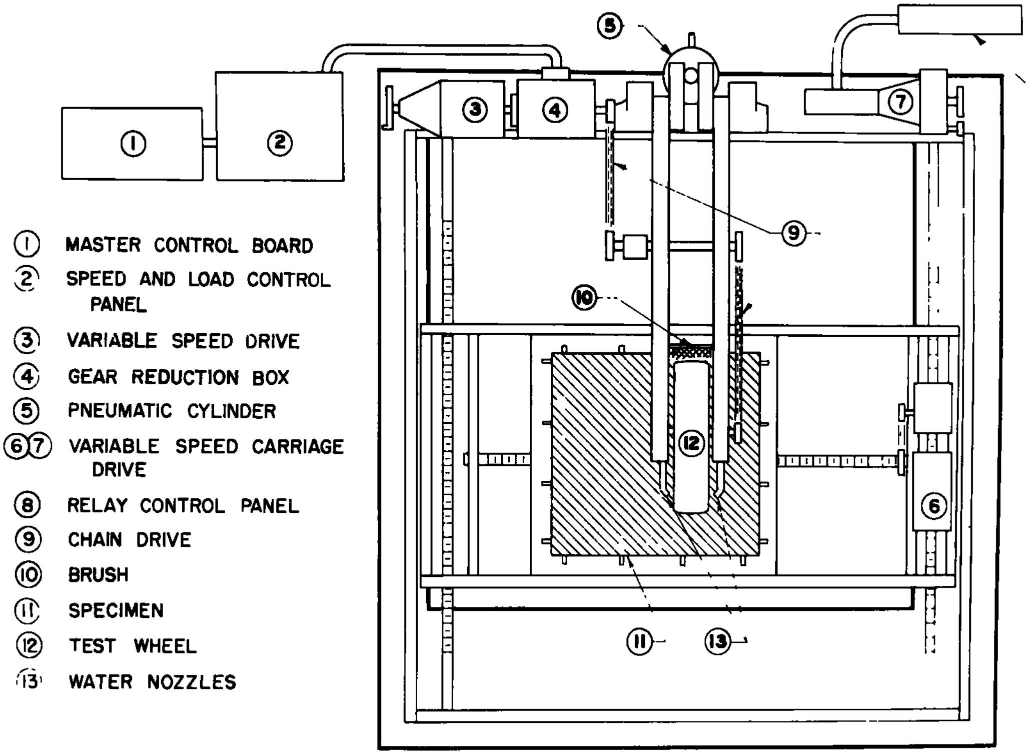

Figure 3. Laboratory Skid Test Device.

cylinder which is connected to the wheel by a loading yoke. Wheel loads can be varied from the dead load up to 1,200 lb by changing air pressure in the pneumatic cylinder.

In order to restrict tire wear and undue overload on the variable speed motor, tests are conducted at a wheel load of 270 lb. This load is obtained, in part, by an air pressure of 5 psi and in part by the dead load weight of the wheel and loading yoke.

Specimens can be tested while they are stationary or moving. In the stationary test, the specimen is locked in one position while the moving test is one in which the specimen continually moves at a slow pace in two directions. This test produces, in effect, a planing action across a small area of the larger specimen. The wheel load and tire speed are kept constant during the test. As a rule, four 1-hr tests and two 24-hr tests are conducted on each specimen under stationary conditions. However, twenty-five different places may be tested on the largest specimen.

RESULTS

A graphical representation of the results of two tests on concrete specimens prepared from two different aggregates are shown in Figure 4. The ordinate of the graph represents power consumption and is the recorded power demand for the variable speed drive when spinning the wheel against the specimen. In order for the ordinate to show only the power consumed for driving the wheel against the specimen, the wheel is started in a raised position and permitted to run without load until the power is constant. The recorder is then adjusted to zero and all subsequent power demand above this constant is recorded as the power required to drive the wheel against the

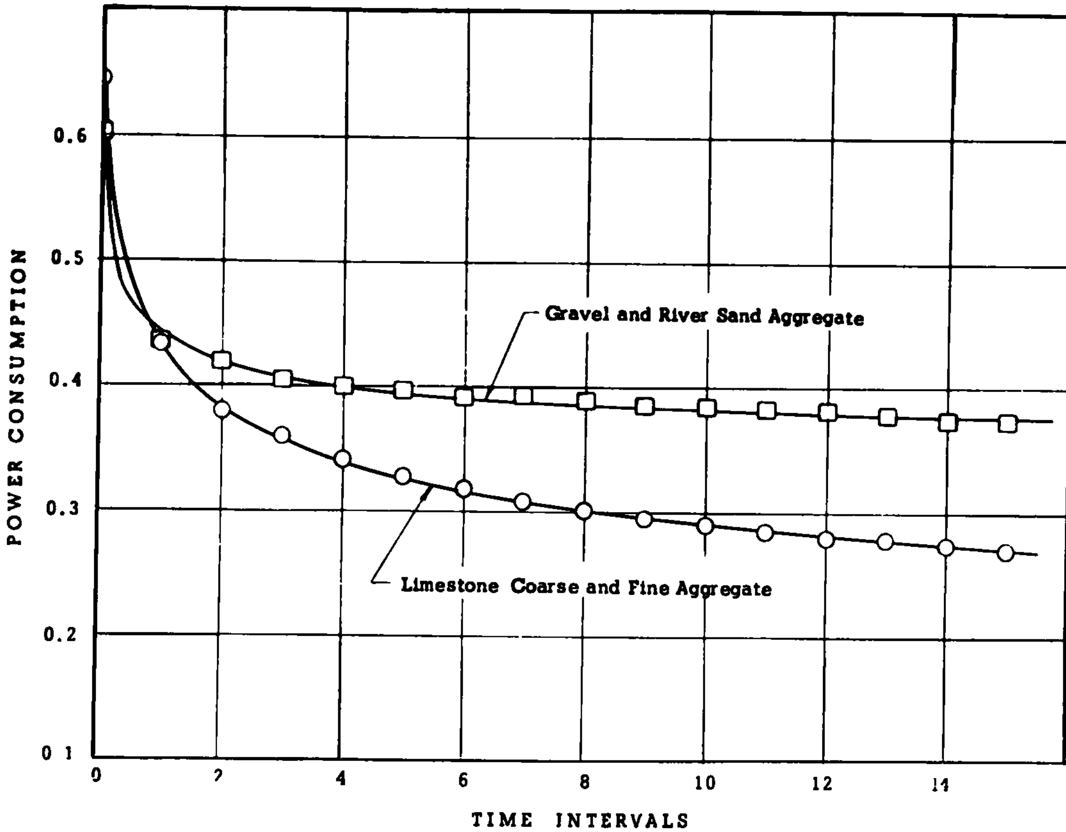

Figure 4. Results on Two Concrete Specimens Prepared from Two Different Aggregates

pavement surface. The units on the ordinate, in kilowatts, express only the power consumed in the test. The abscissa for the graph is shown in time intervals. Each is the distance between lines on the recording chart, and represents a period of approximately four minutes.

The decay in the curve during the first few time intervals indicates the rate of development of pavement slipperiness. In the figure shown, both the limestone and the river sand and gravel concrete specimens show a rather rapid decrease during this period, with the limestone aggregate apparently polishing the faster. After about the first five intervals, the rate of decrease is much slower and becomes almost asymptotic, with the gravel aggregate concrete approximately 38 percent more resistant to sliding than the limestone aggregate concrete.

SUMMARY

Preliminary data indicate that not only can the relative potential slipperiness of mixtures be measured, but that some correlation may be developed concerning the rate at which this slipperiness develops. A study will be made to determine whether or not a pavement surface in service will reach the point of minimum slipperiness. It is also expected that a correlation program will be conducted for the purpose of evaluating laboratory mixtures on the basis of their field performance.

Testing with this apparatus has only begun. Results to date show that remarkably similar results are obtained in repeated runs on the same specimen and that known differences between different specimens are clearly indicated. It is believed that the device will prove to be a most valuable tool in evaluating the relative potential slipperiness of paving materials.

Locked Wheel Skid Performance of Various Tires on Clean, Dry Road Surfaces

SAMUEL MERCER, JR., Associate Professor, Applied Mechanics Department, Michigan State University

Although engineering, legal and educational groups are concerned with the skid performance of tires on dry roadways, most skid investigations have been conducted on wet surfaces. Because of the paucity of data, it was considered desirable to investigate the skid performance of several makes of tires on clean, dry, level road surfaces. Factors investigated included skidding velocity, tire make, wheel loading, and type of road surface.

Data were obtained from trailer drag tests and panic stops of passenger vehicles. Tests were performed using tires of four different makes, three different road surfaces, and several different wheel loadings. For the drag tests, skidding speeds were from 10 mph to 50 mph. Panic stops with passenger vehicles were made from speeds of 30, 40, 50, and 70 mph.

It was found that among different makes of tires of comparable quality there existed differences in stopping ability. Differences in the length of skid and braking distance for a given initial speed and road surface type were found to be about ten percent for the four makes of tires tested. Similar differences were found on other road surfaces.

One of the most significant findings was that the coefficient of friction developed between a given tire and road was found to be greater at the higher speeds. This trend has not been reported by other investigators to the author's knowledge. The implication of this finding is that existing methods of estimating prior speed from length of skid marks laid down in an accident invariably gives a conservative estimate of speed. For a carefully executed experiment, speed estimates will be accurate to within five percent.

● It has been commonly assumed that no significant difference in stopping ability existed among different tires on a clean, dry, level road surface when the brakes of the vehicle have locked the wheels. Engineering, legal, and educational groups have generally accepted this assumption.

The interaction between tire and road surface during a locked wheel stop is a complex phenomenon. Many factors probably influence this interaction and the retarding force associated with it. In a recent publication, A. J. White (1) discussed some of these factors and implied that wide variations in stopping ability do exist among different tires. Since there is little recent experimental data for locked wheel stops on dry pavements, the test program reported here was undertaken.

The specific purpose of the research was to observe the performance of tires on a clean, dry, level road surface under locked wheel skid conditions with the objective of (a) determining the variation, if any, in the coefficient of sliding friction and the variation, if any, in the length of skid required to bring a vehicle to a stop as affected by different speeds, different tires, different vehicles and wheel loadings, and different types of road surfaces; (b) determining the reliability of the square law formula for estimating the speed prior to skidding from the length of skid marks laid down; (c) obtaining motion pictures to be used to educate the public concerning the distances involved in slowing down and stopping from various initial speeds.

EXPERIMENTAL PROCEDURE

Tires

Four different tire manufactures each contributed 12 new tires for the test program. One hundred level, size 6.70 x 15, synthetic compound, blackwall, tubeless tires were used. These were selected at random from warehouse stocks by a representative of the Michigan State Highway Traffic Safety Center. Appendix A identifies the test tires by company and serial number. For this report, a group number and letter is used to distinguish between tires. All tires of the same make have the same group number; letters from A through L were used to differentiate tires in the same group. A photograph of the tires showing the tread designs represented is given in Appendix B. All test tires were run at least two hundred miles under normal operating conditions before being used in the experiments.

Road Surfaces

Three different road surfaces were used in the experiment. All were in the vicinity of Milford, Michigan. All testing done on these road surfaces was completed between August 28 and September 9, 1957.

Most of the tests were run on the General Motors Proving Grounds north-south straightaway, which is a straight, level, bituminous asphalt surface. This will be referred to as Road Surface A throughout the paper. Tests were also made on the east-west straightaway on the General Motors Proving Grounds. This surface is a level, portland cement concrete surface and will be referred to as Road Surface B. The third test surface was a 500 ft section of US 16 approximately 200 yd west of the Kensington Road intersection, subsequently referred to as Road Surface C. This was a heavily used bituminous asphalt highway. Checks using a surveyor's level indicated that the maximum grade was less than three-tenths percent and that the surface was level to within one ft over the entire test length. Photographs are given in Appendix C to further identify the type and texture of the test surfaces.

Passenger Vehicles

Panic stop tests were performed with two different vehicles. A 1956 Chevrolet station wagon belonging to Michigan State University was used for the majority of these tests; the second vehicle was a 1956 Chevrolet 4-door sedan. Use of a third vehicle was contemplated but it was not convenient to obtain a suitable model. Therefore, the Chevrolet sedan was sandbagged to produce a wheel loading equivalent to one of the Pontiac lines of cars. Photographs of the vehicles are given in Appendix D.

Drag Dynamometer

The General Motors Proving Grounds' trailer dynamometer was used for obtaining the drag test data. A photograph of the drag trailer is given in Appendix E. It is a two-wheel trailer unit pulled by a light truck. The trailer is equipped with a pneumatic braking system which locks the trailer wheels during the test. An arrangement of bonded resistance wire strain gauges mounted on the torque tube assembly of the trailer is used as the drag force transducer. A servo instrument mounted in the tow truck cab continuously indicates the average drag friction between the road surface and the trailer tires. The truck speedometer is used for measuring the speed at which the drag is made. A more complete description of the dynamometer and its calibration is contained in a paper by Paul C. Skeels (2).

Trailer Drag Test Procedure

Test tires were mounted in pairs on the drag trailer. Wheel loading was measured on platform scales. For the majority of the drag tests the load per wheel was 1,000 lb. At the test site the road surface temperature was measured and the tire pressure adjusted to 28 psi. For each different test condition, four drags were made. The cycle time for each drag was approximately four to five seconds. About one second was required for the trailer wheels to become fully locked; one to two seconds was required for the indicator reading to stabilize and for the observer to make a reading; the remaining time was for release of the trailer brakes. Depending on the speed of the preceding drag, successive drags were made after one-half to two miles of free running. This permitted the tire temperatures and pressures to stabilize between drags.

One pair of tires was reserved as control tires during the entire program of experimentation. These were dragged periodically to check for unaccountable differences in the friction characteristics of the various road surfaces used.

Panic Stop Test Procedure

Data for most of the panic stop tests were obtained using the station wagon. The remainder was obtained using the sedan. Prior to the experimentation the brakes of both vehicles were carefully inspected and adjusted to give rapid and uniform response to brake pedal movement. No difficulty in locking the wheels was encountered during any of the tests. Observations indicated that there was no tendency for the wheel to lock at the same angular orientation each time.

Tires were mounted on vehicles in groups of four. Where a tire was tested on different vehicles and different road surfaces, it was always used at the same wheel location on the vehicle.

The basic measurements made were speed and distance. On the station wagon, a Wagner fifth wheel was used to actuate a Standard Time, Inc. chronopousometer. A photograph of this indicating device is shown in Appendix F. A motion picture camera was used to make a permanent record of the chronopousometer dials during each test run. The chronopousometer continuously indicated vehicle speed and was triggered by a plunger-type switch to give braking distance and time. The switch was mounted on the steering column in such a position that one-half in. of brake pedal travel closed the switch. In addition to actuating the braking distance indicator and timer, closure of the switch actuated a mechanical detonator which deposited a chalkmark on the pavement at the point of brake application.

Braking distances determined by the chronopousometer and the detonator deposited chalkmark agreed to a fraction of a foot consistently.

The speed indication of the chronopousometer was checked over the entire range of test speeds. Two verification procedures were used. The first method was to time a constant speed run over a measured course. The second consisted of comparing the indication with that of a carefully calibrated fifth wheel. For both check procedures the speed indication of the chronopousometer was found correct to within a fraction of one percent consistently. The maximum observed deviation during all of these checks was six-tenths of a mile per hour, which corresponded to a difference of approximately one and one-half percent. Since an independent fifth wheel actuated speed indicator was used by the test driver for controlling the speed from which each stop was made, further evidence was obtained indicating that the chronopousometer was accurate and stable throughout the entire test program.

Several different devices were used for making distance measurements. Each was verified by comparison with a tape measure. Where there was some question whether the texture of the road surface would affect the reading, the device was checked on the test surface in question. In every instance the indication from the distance measuring device was within one-quarter of one percent of that given by the tape.

During the panic stops two persons were in the vehicle, a test driver and an observer. After preparing the vehicle and instruments for a test run, the vehicle was driven toward the test area. A sufficiently long approach was used so that the test driver had ample opportunity to make speed corrections and enter the test area at a constant speed. Several seconds prior to applying the brakes and on signal from the test driver, the observer would start the camera trained on the chronopousometer dials. When the car was in the test area the driver removed his foot from the accelerator and struck the brake pedal as quickly and as forcibly as possible. A full skid was developed within 10 ft for 70 mph skids and in proportionately shorter distances at the lower speeds. After the vehicle came to rest, the timer and camera were turned off, the skid tracks were marked for measurement, and the detonator was reloaded. The test vehicle was driven to the side of the road and readied for the next test run while measurements were being made on the road surface. Stops were made in alternate directions along the test surface with a minimum of approximately five minutes between successive skids.

Calculations

In calculating coefficients of friction from the drag test observations, the average indication of four drags was used. This was converted to an average friction or drag force by multiplying by the calibration factor as follows:

$$F = kr \tag{1}$$

where

F = friction or drag force in pounds
k = calibration factor in pounds per dial unit
r = instrument reading in dial units

the coefficient of friction was then found from equation 2.

$$f = \frac{F}{W - \frac{b}{L} F} \qquad (2)$$

where

f = coefficient of friction
F = friction drag force in lb
W = wheel loading in lb
b = height of trailer hitch from road surface in in.
L = horizontal distance from hitch to trailer wheels in in.

the factor $\frac{b}{L}$ F in equation 2 accounts for the weight transfer off the trailer wheels when the drag force F is acting.

For calculating the average coefficient of friction during the panic stops, the well known work-energy relation was used to obtain equation 3.

$$f = \frac{v^2}{2\ gs} \qquad (3)$$

where

v = the initial speed in ft per sec.
g = the gravitational acceleration 32.2 ft per sec. squared
s = the length of skid in ft or the braking distance in ft

TEST RESULTS

Trailer Drag Tests

The effect of drag or skidding speed is indicated in Figures 1, 2, 3, and 4 for each of the four pairs of tires tested. The trend was for the friction coefficient to increase with higher speeds. The degree of dependency between average friction coefficient and drag speed varied from slight in the case of the tires in group 1 to very marked for the tires in group 3. In the latter case, the friction coefficient at 50 mph was about 13

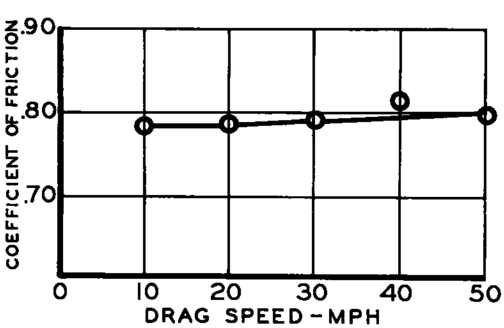

Figure 1. The effect of speed on the skid resistance of a pair of tires from Group 1. Each point represents the average obtained from four drags on Road Surface A.

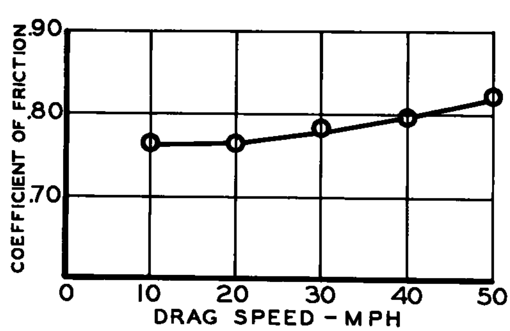

Figure 2. The effect of speed on the skid resistance of a pair of tires from Group 2. Each point represents the average obtained from four drags on Road Surface A.

percent higher than at 10 mph. This same tendency was observed for other tires and on other road surfaces.

To check whether different tires of the same make exhibit differences in stopping ability, a second pair of tires of each make was tested. Table 1 indicates the comparison obtained. For a given speed and road surface, the average coefficient of friction computed for two different pairs of tires of the same make varied as much as 9 percent.

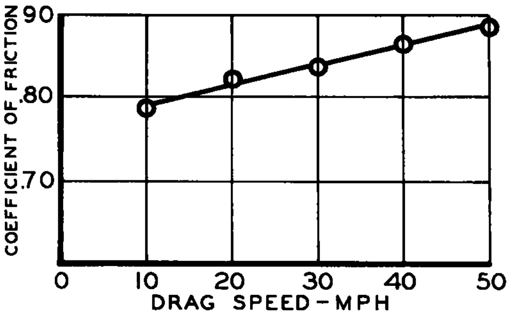

Figure 3. The effect of speed on the skid resistance of a pair of tires from Group 3. Each point represents the average obtained from four drags on Road Surface A.

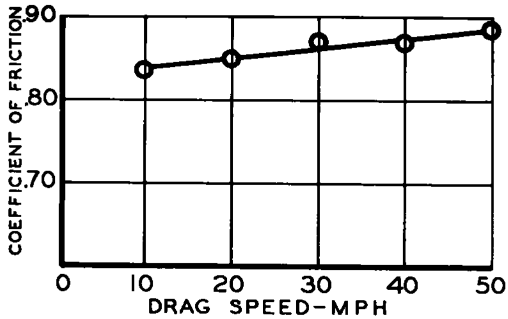

Figure 4. The effect of speed on the skid resistance of a pair of tires from Group 4. Each point represents the average obtained from four drags on Road Surface A.

TABLE 1

RESULTS OF DRAG TESTS COMPARING DIFFERENT PAIRS OF TIRES OF THE SAME MAKE*

Tire Pair Identification	Coefficient of Friction for Drag Speeds of 20 MPH	40 MPH
1A-1B	.79	.82
1C-1D	.83	.87
2A-2B	.77	.80
2C-2D	.83	.87
3A-3B	.82	.87
3C-3D	.87	.92
4A-4B	.85	.86
4C-4D	.82	.88

*All tests performed on Road Surface A.

TABLE 2

RESULTS OF DRAG TESTS AT DIFFERENT WHEEL LOADINGS FOR THE SAME PAIR OF TIRES*

Wheel Load Pounds per Wheel	Coefficient of Friction for Drag Speeds of 20 MPH	40 MPH
770	.84	.87
1000	.77	.80
1500	.77	.78

*Tire pair 1A - 1B used in this test.

Wheel loadings on the drag trailer were varied within the limits of practicability to obtain an indication of the effect of load on the friction developed between tire and road surface. Only one pair of tires was used. The results are given in Table 2. These limited observations were in agreement with those previously reported by Moyer (3). A decrease in the friction coefficient was observed with increased wheel loading. Over the range of loads checked the greatest variation was at the higher drag speed of 40 mph for which the friction coefficient decreased about 9 percent as the wheel loading was increased from 770 to 1,500 lb per wheel.

To compare the friction properties of different road surfaces, four pairs of tires were dragged over three different road surfaces at speeds of 20 and 40 mph. The results of these tests are summarized in Table 3. This table indicates that road surfaces B and C are about comparable in gripping power and that road surface A is somewhat superior to the other two.

Drag tests made with the control tires produced non-uniform results. At first it was thought that road surface temperature might have been the

TABLE 3

RESULTS OF DRAG TESTS USING SAME PAIRS OF TIRES ON DIFFERENT ROAD SURFACE

Tire Pair Identification	Coefficient of Friction on		
	Surface A	Surface B	Surface C
		(20 MPH Drag Speed)	
1C-1D	.83	.76	.80
2C-2D	.83	.78	.78
3C-3D	.87	.89	.86
4C-4D	.82	.78	.72
		(40 MPH Drag Speed)	
1C-1D	.87	.79	.78
2C-2D	.87	.78	.77
3C-3D	.92	.84	.86
4C-4D	.88	.79	.81

cause. A plot of friction coefficient versus temperature is shown for the control tires in Figure 5. No consistent trend is in evidence. In Figure 6 a plot of control test results is shown against date. This figure suggests several possibilities: that there were great differences in the friction characteristics of the road surface from one location to another, that the drag trailer instrumentation was unstable, or that the drag force indication was appreciably affected by tire wear.

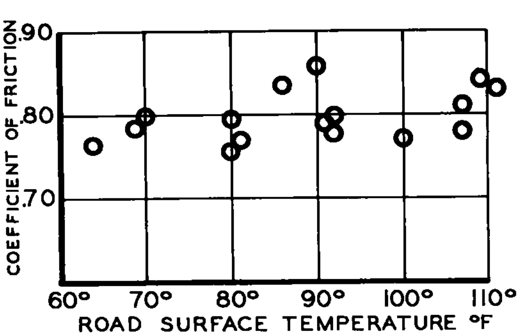

Figure 5. The results of control tests plotted against road surface temperature. Each point represents the average obtained from four drags on Road Surface A.

Subsequent checks of the drag trailer instrumentation were made. The results indicated that the instrument was stable over long periods of time. Therefore, the stability of the instrumentation during the drag experiments cannot be questioned.

Each point plotted in Figures 5 and 6 is the average value computed on four consecutive drags under identical conditions. These drags were made at different locations along the road surface and should, therefore, reflect any inherent differences in road surface characteristics from location to location. Throughout the entire test program the variation

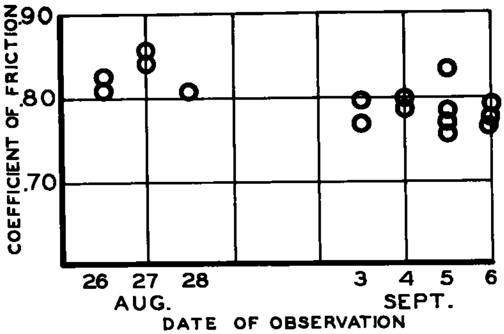

Figure 6. The results of control tests plotted against date of observation. Each point represents the average obtained from four drags on Road Surface A.

in the four consecutive drag readings was of the order of one to two percent whenever the test tires had not been previously dragged. This would indicate that the road surface characteristics do not vary materially from one location to another.

During a drag test, the instrument reading tended to stabilize for a fraction of a second immediately following the development of a full locked-wheel skid condition. As the drag continued, the indication would decrease. This is thought to be caused by a softening of the rubber due to heat generation. The reading recorded was the value at which the indicator stabilized immediately after the wheels locked. It was not easy to assign a definite value for the reading.

It was noted that as the tires accumulated wear, the consistency of four consecutive drag force observations decreased. For example, the first four drags of the control tires produced readings that agreed to within one percent; the eighth set of four drags with the same tires produced readings that agreed to within seven percent; subsequent sets of four readings exhibited spreads that varied from two percent to as high as 15 percent. It is felt, therefore, that the flat spots and roughened areas that were produced on the tires as the tests progressed and the possibility of human error in reading the instrument are the major causes of variability in the drag test results.

Conclusions based on the drag tests are somewhat speculative in view of the variability in the test results. However, since the test tires were each subjected to only a fraction of the number of skids that the control tires experienced and since the data for the test tires were more consistent than for the control tires, it is very probable that valid

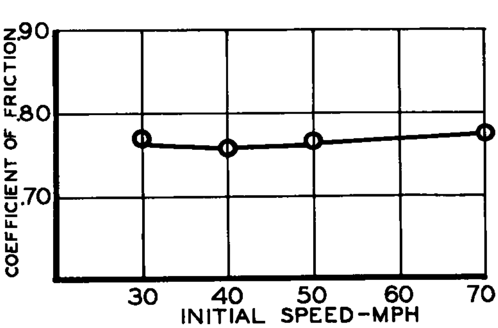

Figure 7. The effect of speed on the skid resistance of a set of tires from Group 1. Each point represents the average obtained from four panic stops on Road Surface A excepting at the 70 mph speed, which is the average of two stops.

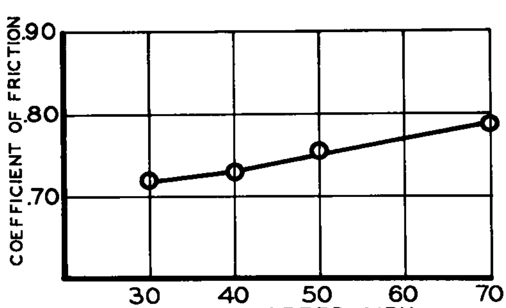

Figure 8. The effect of speed on the skid resistance of a set of tires from Group 2. Each point represents the average obtained from four panic stops on Road Surface A excepting at the 70 mph speed, which is the average of two stops.

indications of the effects of some of the test variables were obtained. For example, the tires of group 3 stood out by yielding the highest coefficient of friction under practically every test condition where comparison of tire makes was possible. For these reasons, it is held that the drag tests provided reliable qualitative indications of the effect of speed, wheel loading, and tire make on stopping ability.

Panic Stop Tests

Results of the panic stop tests were much more consistent than those of the drag tests. The spread of individual coefficients of friction which were averaged to obtain the numerical values reported was less than 0.04 in every case. In more than two-thirds of the tests a spread of 0.03 or less was observed.

In order to assess the effects of speed, one set of tires of each of the four different makes was subjected to panic stops on road surface A from speeds of 30, 40, 50, and 70 mph. The results of these tests are shown in Figures 7, 8, 9, and 10. The friction coefficients plotted are

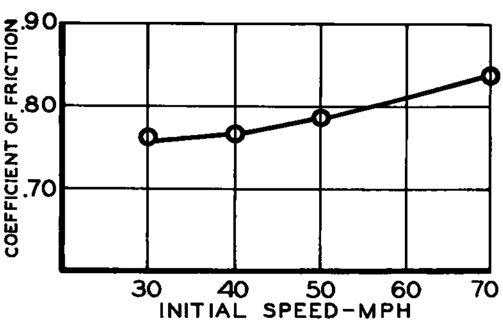

Figure 9. The effect of speed on the skid resistance of a set of tires from Group 3. Each point represents the average obtained from four panic stops on Road Surface A excepting at the 50 mph speed, which is the average of three stops, and at the 70 mph speed, which is the average of two stops.

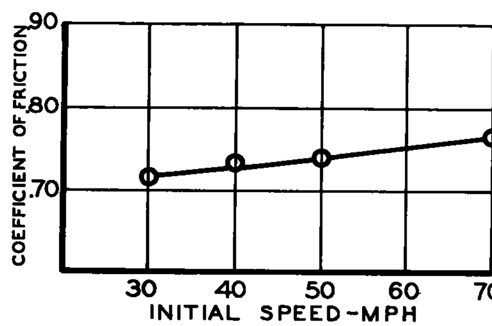

Figure 10. The effect of speed on the skid resistance of a set of tires from Group 4. Each point represents the average obtained from four panic stops on Road Surface A excepting at the 70 mph speed, which is the average of two stops.

based on the average of four skids from speeds of 30, 40, and 50 mph and the average of two skids from 70 mph. Results indicate that for the tires tested the coefficient of friction developed is either reasonably constant or increases as the skid speed increases. This finding is in agreement with the results obtained from the trailer drag tests. In addition it is interesting to note that the tires of group 1 exhibit the least change in friction coefficient with speed in both the panic stop and drag tests and that the tires of group 3 show the greatest increase in friction coefficient with speed in both tests. Since the findings on the effects of speed differ from results previously reported, the fact that the skid test results corroborate the drag test results is considered to be very significant.

These same graphs indicate that there are differences in stopping ability among different makes of tires. The greatest difference in the

TABLE 4

RESULTS OF PANIC STOP TESTS COMPARING DIFFERENT SETS OF TIRES OF THE SAME MAKE*

Tire Set Identification	Coefficient of Friction
1E-1F-1G-1H	.76
1I-1J-1K-1L	.76
3E-3F-3G-3H	.77
3I-3J-3K-3L	.77
4E-4F-4G-4H	.73
4I-4J-4K-4L	.74

*Based on length of skidmarks using average of 40 mph with station wagon on road surface A.

TABLE 5

RESULTS OF PANIC STOP TESTS COMPARING DIFFERENT VEHICLES WITH A GIVEN SET OF TIRES*

Vehicle	Gross Wt. pounds	Coefficient of Friction
1956 Chevrolet Station Wagon	4126	.76
1956 Chevrolet 4 Door Sedan	3576	.79
1956 Chevrolet Loaded to Simulate Pontiac	3926	.76

*Based on length of skidmarks using average of four panic stops from 40 mph on road surface A with tire set 1I-1J-1K-1L.

TABLE 6

RESULTS OF PANIC STOP TESTS COMPARING DIFFERENT ROAD SURFACES*

Road Surface	Coef. of Fric. for Tire Set 3I-3J-3K-3L	4I-4J-4K-4L
A	.77	.74
B	.79	.76
C	.80	.77

*Based on length of skidmarks using average of four panic stops from 40 mph with station wagon.

TABLE 7

RESULTS OF PANIC STOP TEST SHOWING EFFECT OF SPEED*

Tire Set Identification	Coefficient of Friction of Speed of 30 mph	70 mph
1E-1F-1G-1H	.72	.75
2E-2F-2G-2H	.68	.76
3E-3F-3G-3H	.71	.81
4E-4F-4G-4H	.66	.75

*Based on braking distance using average of four panic stops at 30 mph and two panic stops at 70 mph. Tests made using station wagon on road surface A.

average friction coefficient and skidding distance was about 10 percent at the 70 mph speed. Smaller variations were observed at lower speeds.

Runs at 40 mph were made to determine whether variations in stopping ability existed among tires of the same make. Table 4 gives the results of this comparison. For the sets of tires tested, the results were remarkably uniform indicating that there was little significant difference among tires of the same make. This does not agree with the drag test results. Lack of agreement may be attributed to two possible factors, the variability in the drag test data and the greater averaging effect in the panic stop tests due to the use of four tires at a time as compared to the drag tests for which the tires were taken two at a time.

To examine the effect of load on stopping ability, tests were performed using one set of tires and the same road surface but with different

TABLE 8

RESULTS OF PANIC STOP TESTS COMPARING DIFFERENT SETS OF TIRES OF THE SAME MAKE*

Tire Set Identification	Coefficient of Friction
1E-1F-1G-1H	.72
1I-1J-1K-1L	.71
3E-3F-3G-3H	.73
3I-3J-3K-3L	.73
4E-4F-4G-4H	.70
4I-4J-4K-4L	.70

*Based on braking distance using average of four panic stops from 40 mph with station wagon on road surface A.

vehicles and wheel loadings. The results are shown in Table 5. The panic stop test findings were in qualitative agreement with the drag test findings indicating that stopping ability decreases as load increases. The fact that the results using the station wagon compared with those using the sandbagged sedan suggest that vehicle characteristics also play some part. The panic stop tests produced a difference of 4 percent in the friction coefficient as compared to a difference of 9 percent for the drag tests. This is attributed to a wider range of wheel loadings used in the drag tests.

Small differences in the performance of a given set of tires at a given speed were also observed from one road surface to another. Table 6 shows these differences for skids from a 40 mph speed. These results do not agree well with the drag test results. However, it is felt that the panic stop test data are more reliable and more correctly represent the differences in the friction or gripping characteristics of the three test surfaces.

All of the previously discussed results were based on a measured length of skid. Since the different road surfaces exhibited different marking characteristics, calculations on the basis of braking distance were made. The results of calculations based on braking distance are independent of the inherent ease with which a given test surface is marked up during a skid. Results are shown in Tables 7, 8, and 9. In connection with the effects of different skid speeds, different tire makes, different tires of the same make, and different test surfaces, the results based on braking distances are in very close agreement with the results based on skidding distance.

RELIABILITY OF THE SPEED SQUARED FORMULA

In accident investigation, speed estimates are frequently made from skidmark lengths (4, 5). One procedure is to determine the drag factor (average coefficient of friction) of the pavement by making experimental skids from a low speed. Equation 3 is used for the calculation of a friction coefficient or drag factor. Substitution of the experimentally determined value of drag factor and the distance that the car involved in the accident skidded into Equation 3 yields a

TABLE 9

RESULTS OF PANIC STOP TESTS COMPARING DIFFERENT ROAD SURFACES*

Road Surface	Coefficient of Friction for Tire Set 3I-3J-3K-3L	Coefficient of Friction for Tire Set 4I-4J-4K-4L
A	.73	.70
B	.73	.69
C	.75	.72

*Based on braking distance using average of four panic stops from 40 mph with station wagon.

solution for the estimated speed of the accident vehicle prior to skidding.

To check the reliability of this method, the data for a set of tires of each of the four different makes was used. All data were observed during test runs on road surface A. For each set of tires the four 30 mph panic stops were used to calculate a coefficient of friction. This value and the measured length of skid for each panic stop at the other speeds were used to make an estimate of the speed from which each stop was made. The estimated speed and the observed speed were compared. Table 10 gives the results of this comparison. Estimates of speed were in error a maximum of +0.7 and -3.5 mph and were predominantly lower than the observed car speed.

In the above comparisons the same tires were used for the experimental determination of friction coefficient as were used in the skids from which prior speed was estimated. In an investigation, it might happen that the drag factor is determined using a different set of tires. In

TABLE 10

COMPARISON OF OBSERVED SPEED AND SPEED

ESTIMATED USING VELOCITY SQUARED FORMULA WHERE AVERAGE FRICTION COEFFICIENT WAS DETERMINED FOR SAME TIRE SET AT LOWER SPEED

Avg. Lgth. Skidmark ft	Estimated Speed mph	Observed Speed mph	Avg. Lgth. Skidmark ft	Estimated Speed mph	Observed Speed mph
Tire Set 1A-B-C-D f = .77*			Tire Set 2A-B-C-D f = .72*		
72.8	40.9	40.2	74.7	40.1	40.2
69.4	40.0	39.8	73.0	40.0	40.0
67.4	39.5	39.0	76.5	40.7	41.0
65.7	38.9	39.0	73.3	39.8	40.4
109.9	50.3	50.0	112.6	49.3	50.2
110.8	50.6	50.4	112.5	49.3	50.0
111.8	50.8	50.2	112.9	49.4	50.4
111.7	50.7	50.8	108.0	48.3	49.8
215.6	70.5	70.4	205.0	66.4	69.2
212.8	70.0	70.4	208.2	67.0	70.0
Tire Set 3A-B-C-D f = .76*			Tire Set 4A-B-C-D f = .715*		
73.4	41.1	41.0	74.0	39.8	40.2
71.2	40.4	40.2	72.3	39.4	40.2
72.2	40.7	40.6	75.8	40.3	40.8
72.6	40.8	41.0	73.3	39.6	40.0
104.7	49.1	49.4	113.7	49.4	50.4
104.5	48.9	50.0	114.9	49.7	50.4
108.4	49.9	50.4	114.7	49.7	50.0
101.7	48.2	50.0	115.5	49.8	50.6
193.4	66.5	70.0	209.8	67.2	69.4
192.5	66.4	69.4	212.6	67.5	69.8

*Based on skidmarks using average of four panic stops from 30 mph with station wagon on road surface A.

TABLE 11

COMPARISON OF OBSERVED SPEED AND SPEED

ESTIMATED USING VELOCITY SQUARED FORMULA WHERE AVERAGE FRICTION COEFFICIENTS WERE EXTREME VALUES FOUND AT LOWER SPEED

Tire Set	Avg. Lgth. Skidmark ft	Estimated Speed Using f = .715* mph	Estimated Speed Using f = .77* mph	Observed Speed mph
1A-B-C-D	215.6	68.0	70.5	70.4
1A-B-C-D	212.8	67.6	70.0	70.4
2A-B-C-D	205.0	66.2	68.6	69.2
2A-B-C-D	208.2	66.9	69.3	70.0
3A-B-C-D	193.4	64.4	66.7	70.0
3A-B-C-D	192.5	64.3	66.6	69.4
4A-B-C-D	209.8	67.2	69.5	69.4
4A-B-C-D	212.6	67.5	70.0	69.8

*Based on skidmarks using average of four panic stops from 30 mph with station wagon on road surface A.

Table 11 the speeds were estimated based on the lowest and highest average coefficient of friction obtained from the 30 mph panic stops. The comparisons are indicative of the errors that might be made in speed estimates where the drag factor is not determined using the same tires as were involved in the accident skid. The 70 mph panic stops were used for this comparison. The range of error in the estimated speeds was found to be +0.2 to -5.6 mph. In the majority of cases the estimated speed was lower than the measured speed.

CONCLUSIONS

The ability to stop by skidding on a clean, dry, level road surface is dependent on speed, vehicle characteristics, road surface type, and tire characteristics. In the research reported here, skidding speed and tire characteristics were the most influential factors.

The most important result of this research was the consistent trend for friction coefficient to increase as the speed of skidding is increased. This has not been reported previously to the author's knowledge . In most publications the friction coefficient is shown to decrease with speed. This indicates that further research should be done on dry skidding. In addition to resolving this point of difference concerning the effect of speed, it would be desirable to have additional data for comparing tires of the same make, for evaluating the effects of wheel load, and for assessing the effects of vehicle characteristics.

Of the two basically different testing methods, the drag test is less expensive, quicker, and less dangerous than a panic stop test. However, the observed data are less uniform in the case of the drag test. This indicates that further development of drag test equipment is both necessary and desirable. Specific recommendations are to use a recorder in place of an indicator to reduce the factor of human error, to devise a rapid calibration procedure that would permit more frequent calibration checks to be made, and to find some means of reducing localized tire wear. The latter might be accomplished by reducing the time duration of the locked wheel skid or by using a differential slipping device similar to the one reported by Kullberg (6) to distribute the wear more uniformly over the test tire.

Because of the variations found in tires, care must be exercised when making tests for road surface characteristics. The development of standardized equipment for this purpose will necessarily include the development of standard specifications for test tires. Comparable and reproducible results will not otherwise be obtained.

In spite of the many factors that will influence the distance in which a vehicle can be skidded to a stop on a clean, dry pavement, the recommended method of estimating speeds in accident investigations involving the use of the speed squared law is reliable. Under carefully controlled conditions, using the same tires, vehicle, and road surface, estimates are within 5 percent of the true speed. Even where different makes of tires of comparable condition and quality are involved, estimated speeds within 10 percent of actual speed are highly probable. Even more significant is the fact that speed estimates are predominantly conservative. This occurs because tires tend to develop more tractive effort skidding at higher speeds than at lower speeds.

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5. "Use of Skidmarks in Calculating Motor Vehicle Speeds," Public Safety Memo No. 28, National Safety Council, Inc., Chicago, Ill., 15 pp. (1940).

6. Kullberg, G., "Skiddometer," Mimeographed Report, The Swedish State Road Institute, Stockholm, 6 pp. (1957).

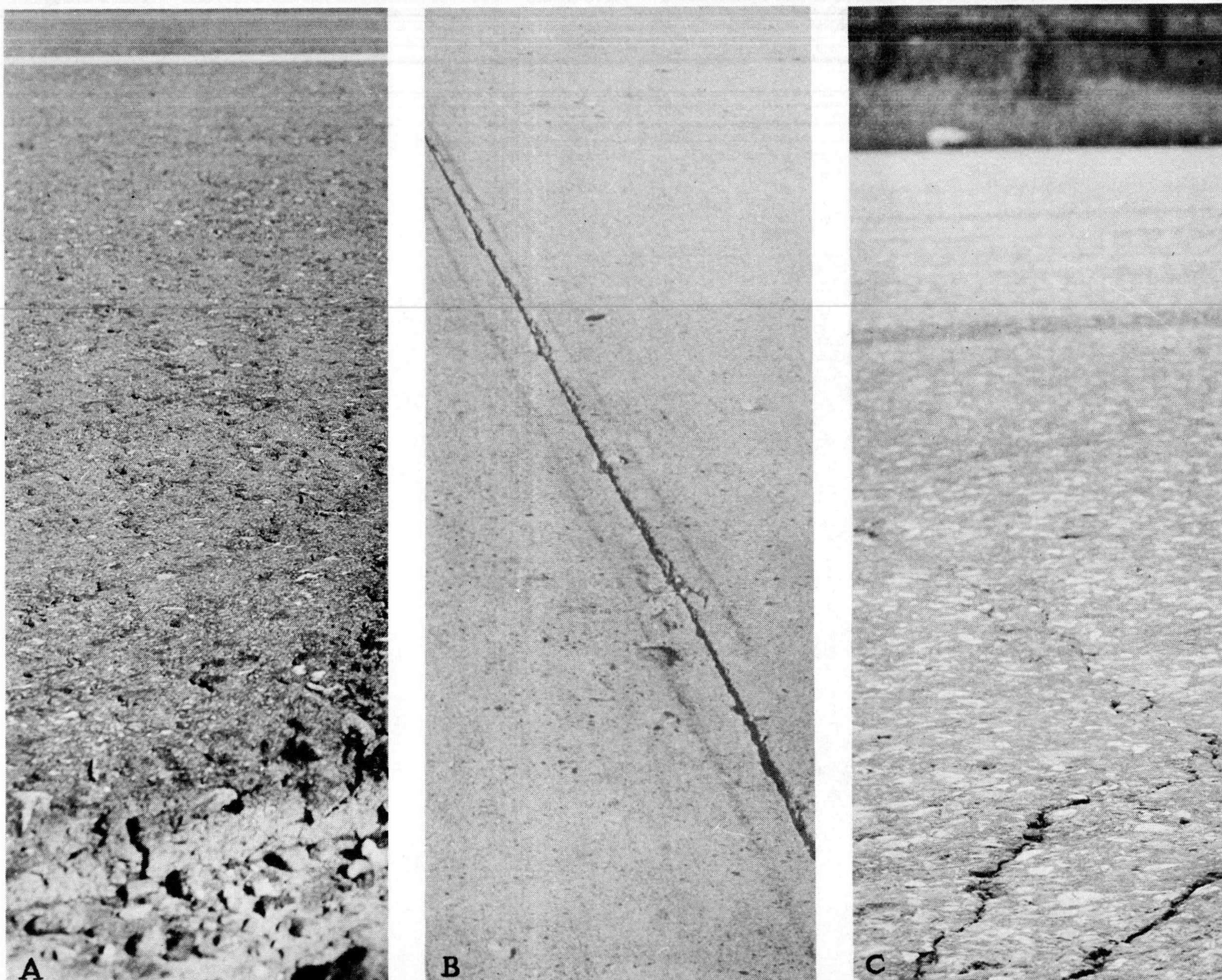
Appendix A

Tires used in research listed by company and serial number.

B.F. Goodrich	U.S. Royal	Firestone	Goodyear
74116 YNL	CT 471197	000177J2EM	E2ES0858
11932 YNL 1	CT 462639	WJ004416C2	E23SH360
11841 YNL 1	CT 437192	WJ003497J2	E23SH262
11878 YNL 1	CT 478138	000178J2EM	E23SH293
11872 YNL 1	CT 414639	000182J2EM	E23SH261
11232 YNL 1	CT 471368	WJ003498J2	E21563G9
11231 YNL 1	CT 437139	WJ000981J2	E23SH221
70186 YNL	CT 461621	WJ003476J2	E2ES0852
70773 YNL	CT 471484	WJ004422C2	E21541G6
11268 YNL 1	CT 471509	WJ001043J2	E2ES085
70613 YNL	CT 461545	000180J2EM	E2ES0845
11372 YNL 1	CT 404668	WJ000975J2	E23SH218

Appendix B - Tire Tread Designs

Appendix C - Test Surfaces



Appendix D - Vehicles Used in Tests

Appendix E - Drag Trailer Dynamometer

Appendix F - Chronopousometer

Test for Coefficients of Friction by the Skidding Car Method on Wet and Dry Surfaces

A. M. WHITE, Traffic Control and Safety Engineer, and H. O. THOMPSON, Testing Engineer, Mississippi State Highway Department

● THE Mississippi State Highway Department being concerned over the problem of pavement slipperiness directed that a comprehensive study be made to determine the skid-resistant characteristic of the various pavements within the state. Accident reports submitted to the Mississippi Highway Safety Patrol indicated that there were 8,572 rural accidents in 1953 and 8,910 in 1954. Reliable information is not available regarding any direct relation between the number of accidents and the texture of the pavements; however, in many cases the cause of the accident was reported as being that of "slippery" pavement. It was the desire to investigate the validity of these reports as well as that of determining what factors constitute high "skid resistant" pavements which instigated this study.

There are certain fundamental differences in the several types of pavement surfaces (concrete and bituminous) constructed by the State Highway Department. The most important difference insofar as the braking distance or stopping distance after brakes are applied is their surface characteristics.

The coefficient of friction is usually high on all dry surfaces and dry surfaces free of loose sand or gravel presents no skidding hazard, the difference occurs when the surface is wet.

TESTS AND EQUIPMENT

Several individuals and organizations in the past have conducted skid-resistance tests, and it has been found that skidding is a function of tire and pavement texture. It is influenced by tire balance, brake adjustment, pavement irregularities, crown of pavement, and transverse dips. A review of the reports of other skid tests indicated several methods have been used to determine stopping distance including: The stopping-distance method which involves locking the brakes of an automobile and measuring the skidding distance, and the utilization of trailers or towed vehicles as skidding units in which the pull following locking the brakes of the towing vehicle is measured on a dynamometer. A study by Moyer (1) revealed that uniform and accurate results may be obtained by use of the stopping-distance method. In comparing results utilizing both methods, he found that either system yielded practically identical ratings. A similar study made by the Virginia Highway Department (2) in which the stopping-distance method was used, produced results closely checking those found in skid tests conducted by other organizations. Based on this information, it was decided to use the stopping-distance method for this study. Moyer (1) also found that wind velocity and air temperature at the time of the tests were of no practical significance and they were not considered in these tests. Equipment used in the tests included two new four-door sedans, electric detonator, water wagon, and measuring chain. Both automobiles were 1954 Chevrolets, each weighing 3,670 lb and equipped with 6.70 x 15 four-ply Firestone Deluxe Champion Super Balloon Tires. The tires were replaced with identical types at the first sign of tread wear. Prior to each series of tests the air pressure was adjusted to 30 psi.

In each test run the vehicle was driven at an initial uniform speed of 40 mph. It was generally agreed that it would be unsafe to conduct tests on wet surfaces at speeds in excess of 40 mph. At the instant the brakes were applied locking all four wheels an electric detonator loaded with 0.22-cal chalk cartridges was simultaneously fired. The gun was attached to the front bumper and was actuated electrically through the brake-stop light system. The distance from the chalk mark on the pavement to the point the car stopped following the skid represented the actual stopping distance (excluding reaction and perception time) which was measured with a metallic tape to the nearest 0.1 ft.

Three or more runs and measurements were made at each location on dry pavement. The road surface was then thoroughly covered with water prior to each wet run and three runs were made on the wet surface. The results shown are average figures for each series of runs. Where it was noted that there was a malfunction of equipment or an unusual skid occurred, the results were not considered and additional runs were made to secure at least three satisfactory skids.

As nearly as possible, test locations were selected on the basis of desiring to achieve results from all types of surfacing of all ages and conditions, in each of six highway districts. Also any section listed by the district as being reported unduly slick was included in the tests. All tests were conducted on straight level sections of road with the car stopping in the travel lanes. Test runs were made using two drivers throughout the series. These drivers were twenty years old, skillful operators, in good physical condition, and full-time employees of the department. Since the tests were rather severe on the cars, a mechanic accompanied the crew to replace brakes, tires, check steering, and to keep the cars in excellent operating condition.

DISCUSSION OF TEST DATA

Usually there were two sites selected in each location of roadway. At each site there were usually three dry and three wet test runs made. The stopping distances of the test runs at each site were averaged for that site. Then the average was obtained for the location or project from the site averages if there were more than one site. All averages were obtained from the original subtotals and the number of locations or projects. Average coefficients were obtained by applying the formula (3):

$$\text{Coeff. of friction} = f = \frac{V^2}{30S}$$

in which V = initial speed in mph at the time of brake application; and S = stopping distance in ft. In each case average distances were used. The average coefficient was not obtained by adding series of coefficients.

In order to properly evaluate the reported "slick" surfaces as to their being excessively slippery when wet, it was evident some criterion was required. Moyer (1) found that a coefficient of 0.30 at speeds above 30 mph were safe for ordinary driving conditions. However, for emergency braking a coefficient of 0.40 to 0.60 was required; therefore, a coefficient of 0.40 was selected as the minimum from a safety viewpoint, and this coefficient was adopted as the criterion. Surfaces having a factor of less than 0.40 are considered to be sub-standard and undesirable.

During the initial portions of the study, it became evident that the age of the road and the volume of traffic had a direct bearing on the condition of the surface, and consequently, on the coefficient of friction and stopping distance. These factors were taken into consideration with the adoption of the "traffic Index", (4) a composite figure derived from the age of the road and the average daily traffic as reflected on the 1954 traffic flow map. This index is calculated as follows:

$$\text{Traffic index} - \frac{\text{Age (In Months)} \quad \text{X Avg. daily traffic}}{100}$$

The Mississippi State Highway Department set out in 1955 to measure the dry and wet stopping distances on all major types of surface on the state-maintained system. This study also included different finishes on concrete pavement, as well as the effect of percentage of crushed particles in gravel seal aggregate used as the final course in a double bituminous surface treatment. Tests completed during 1957 are included in this report.

Sections included in this study were scattered throughout the state, and their surface characteristics were most varied. For example, in double bituminous surface treatments, the following are included: slag on slag, slag on gravel, gravel on gravel (both courses being of uncrushed material), gravel on gravel (50 percent crushed particles in seal), and gravel on gravel (85 percent minimum crushed particles in seal).

Cold mix surfaces tested are: slag mixtures, asphaltic limestone mixtures without quartz sand, asphaltic limestone mixtures with quartz sand, and crushed reef shell with quartz sand.

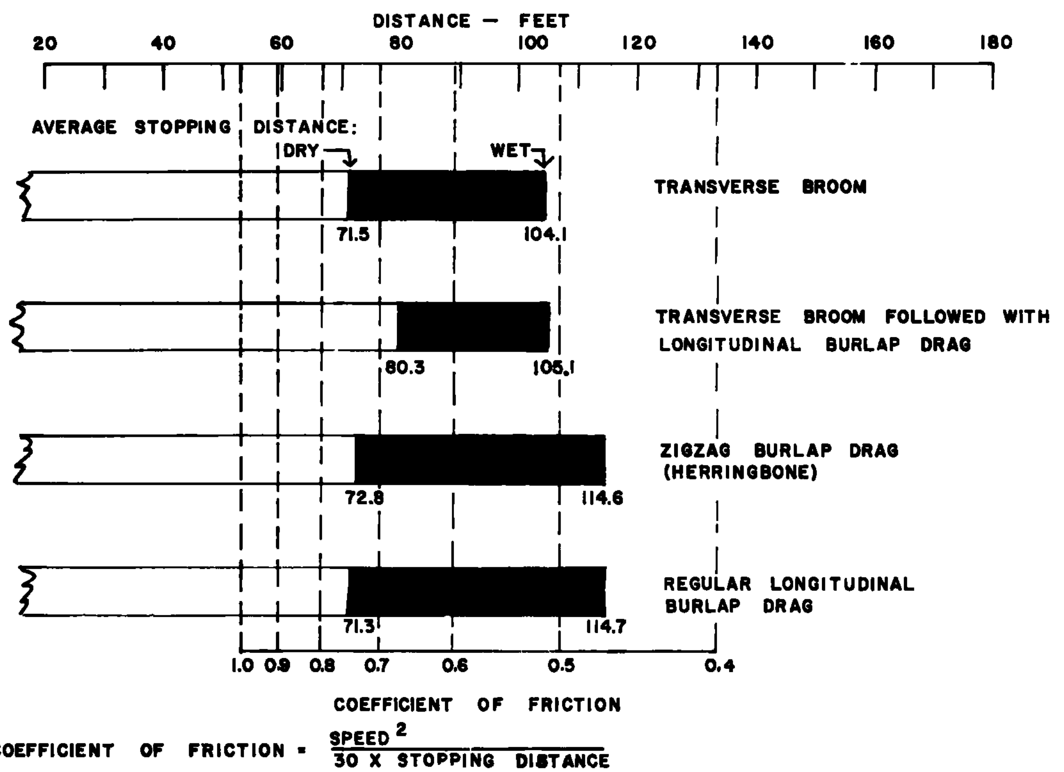


Figure 1. Relative stopping distances on cement concrete pavement with various types of finish; age, 264 days; testing speed, 40 mph; US 51 south of Jackson.

Hot mix pavements tested are: sand asphalts, modified sand asphalts, and asphaltic concrete. Concrete pavements tested consisted of new and old pavements.

Tests were made on about 200 projects, and data from approximately 2,000 skid measurements are included in this report.

DEVELOPMENT OF DATA

(Concrete Pavement - Four Types of Surface Finish)

Surface Finish	Stopping Distance (in ft) Dry	Stopping Distance (in ft) Wet	Coefficient of Friction - Wet
Transverse broom	71.5	104.1	0.52
Transverse Broom (followed with longitudinal burlap drag)	80.3	105.1	0.51
Herringbone (zigzag burlap drag)	72.8	114.6	0.47
Burlap drag (conventional finish)	71.3	114.7	0.47

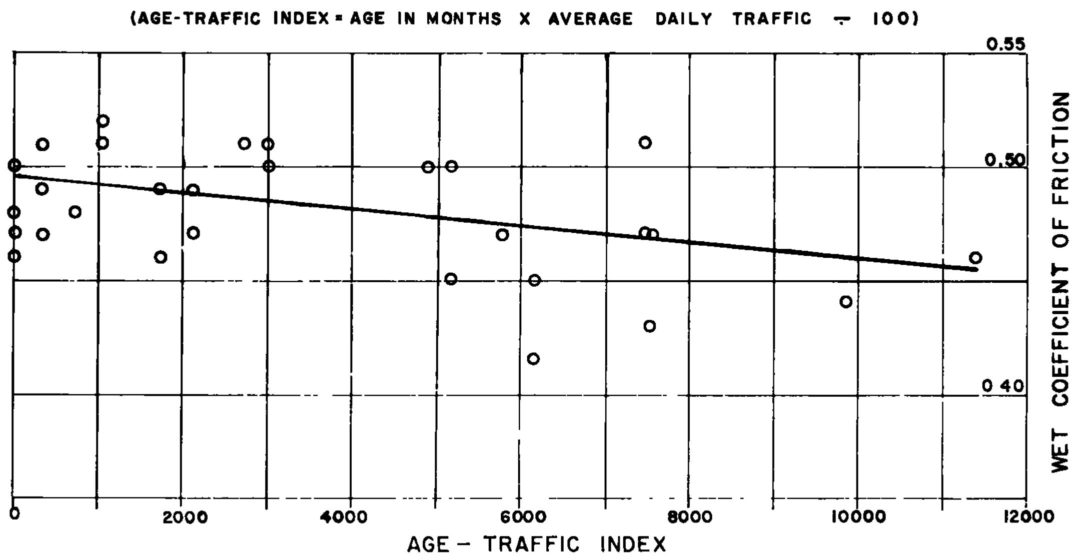


Figure 2. Wet coefficient of friction versus age-traffic index; portland cement concrete; testing speed, 40 mph.

The above pavement is a section of US 51 south of Jackson, Mississippi. Traffic count is 7,260, and the pavement was 264 days old at time of tests. Since the pavement was cured with liquid membrane curing compound (white pigmented type), sufficient time was allowed for traffic to wear the curing compound from the pavement.

All concrete pavements tested and included in Figure 2 were made of gravel aggregate. Twenty-nine different locations were tested, and the age varied from new pavement to pavement over twenty-five years old. Age-Traffic Index ranged from 0 up to more than 11,500.

The curve on this chart is not all-conclusive, but, generally, the trend appears to be downward. As the traffic wears the sand-cement mortar finish from the top of the surface of the pavement, and exposes the gravel aggregates (which, in many cases, take on a high polish, when exposed to heavy rubber-tired traffic), the wet stopping distance increases.

Another contributing factor towards reduction of coefficient of friction on some pavements is the accumulation of oil drippings.

Figure 3 was prepared to show the decrease in wet coefficient of friction as the percentage of uncrushed gravel increased in bituminous hot mix pavements.

You will note that mixtures containing all fine material (nothing retained on No. 10 sieve) had wet coefficient of friction ranging from 0.5 to above 0.60. On the other hand, sections having 40 percent or more uncrushed gravel material retained on No. 10 sieve had wet coefficient of friction ranging from 0.42 to 0.51. The sand in all these mixtures is natural quartz sand. These data appear to support Shelburne and Sheppe in their statement that sandpaper-like textured pavements, properly constructed, yielded excellent stopping distances.

In the testing of stopping distances on sand asphalt pavements, it was

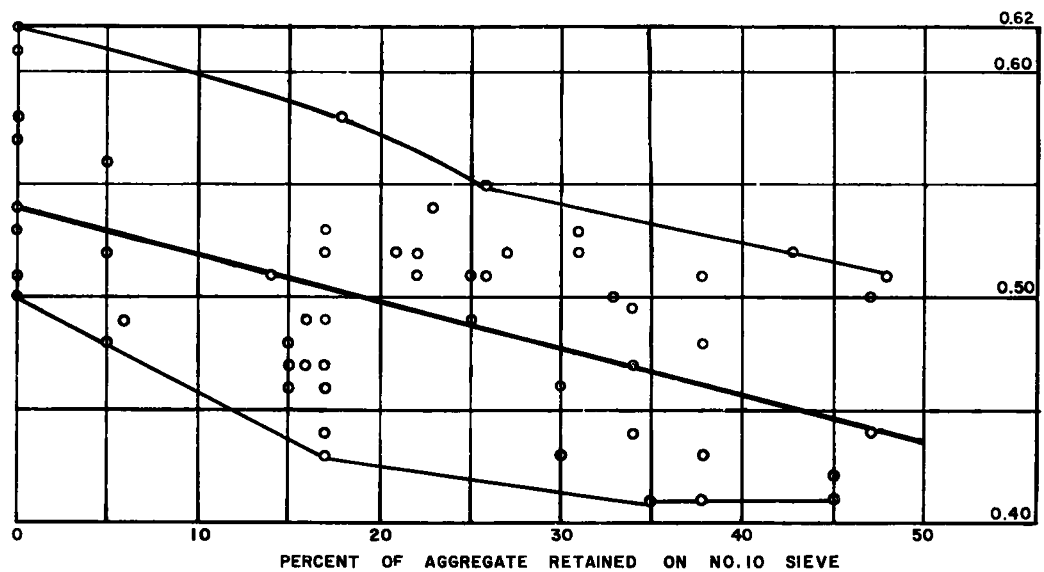


Figure 3. Wet coefficients of friction versus percentage of aggregate retained on No. 10 sieve; testing speed, 40 mph; bituminous hot mix-uncrushed gravel.

noticed that there was very little tendency for the vehicle to skid sidewise—instead the vehicle moved forward in a straight skid.

Figure 4 was prepared to show the effect of wet coefficient of friction of double bituminous surface treatment when the amount of crushed gravel particles used in the seal is varied. The Age-Traffic Index of these projects has been plotted against the wet coefficient of friction.

The top curve represents projects where the gravel seal aggregate contained more than 90 percent crushed particles. Shortly after the projects were constructed, the wet coefficient of friction measured 0.58 or better. On the other hand, projocts containing 50 to 70 percent crushed gravel particles in the seal, gave a wet coefficient of friction of 0.45 to 0.48, a much lower value than the "90 percent crushed" jobs.

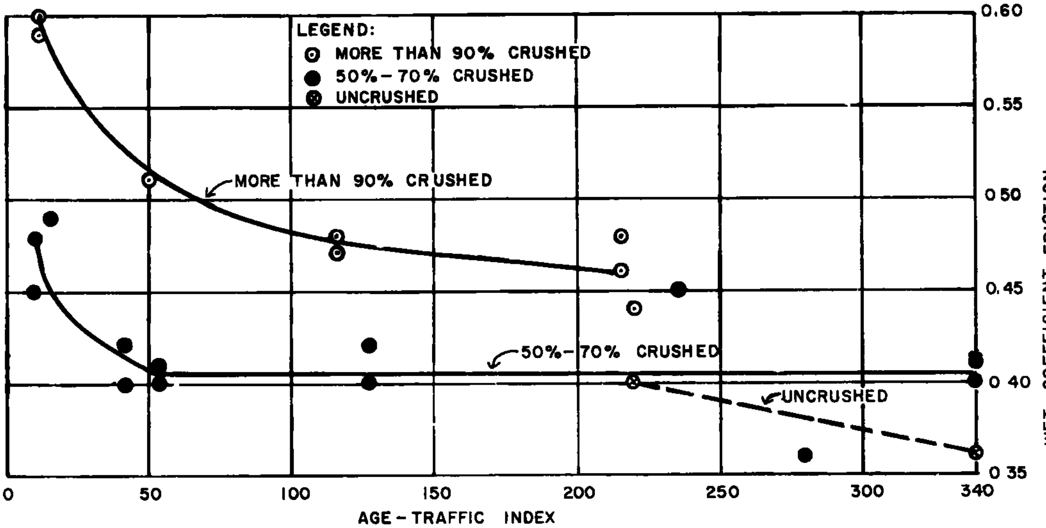


Figure 4. Wet coefficient of friction versus age-traffic index to show the effect of crushed particles in gravel aggregate seal; testing speed 40 mph; double bituminous surface treatment, gravel/gravel. (Age-traffic index = age in months x average daily traffic ÷ 100. In general, wet coefficients of friction below 0.40 are caused by excess bitumen and/or polished aggregate.)

It is noticed that at an age-traffic index of 50 (or, say, 500 vehicles per day for 10 months) the wet coefficient of friction for both the "90 percent crushed" jobs and the "50 to 70 percent crushed" jobs dropped considerably. This is probably caused by the embedment or seating of the seal aggregate particles in the mat. You will note that it takes approximately three years for a traffic count of 500 vehicles per day to reduce the wet coefficient of friction on the "90 percent crushed" jobs to a value equal to that of the "50 to 70 percent crushed" jobs when first constructed.

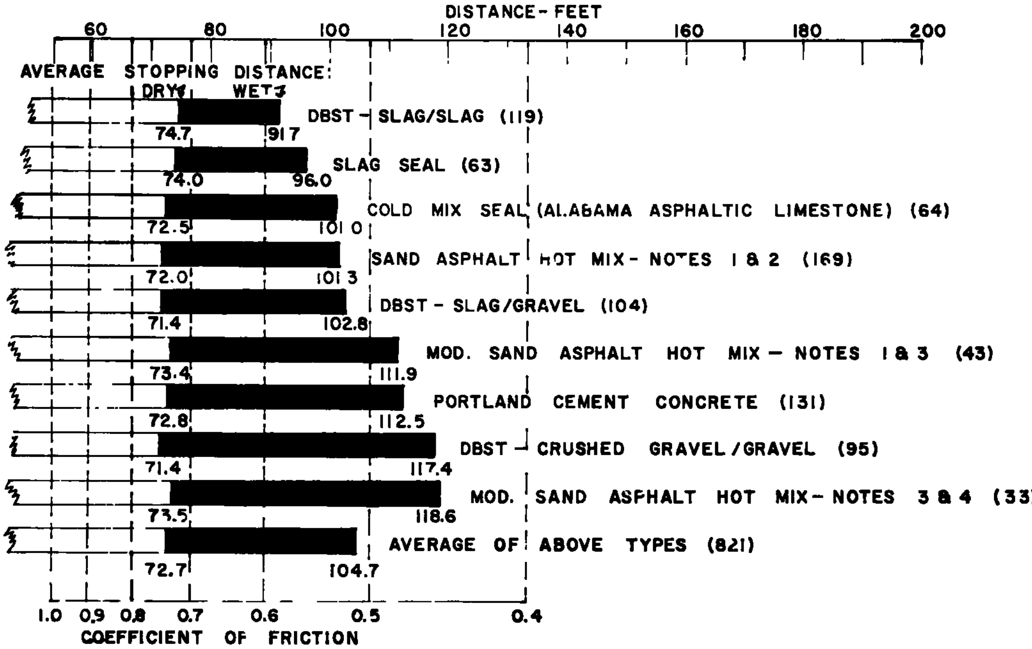
It is noted that the friction value, both in dry and wet tests, follows the same pattern, the highest values being obtained on the more angular aggregate.

Only two projects using uncrushed gravel in the primary and seal courses were available for tests. One of these projects had a wet coeficient of friction of 0.40, and the other project 0.36.

Previous investigators have found a considerable decrease in the friction value of rounded aggregates, particularly in the wet test. It follows that considerable improvement could be effected by using sharp sand or angular chips instead of rounded gravel in small sizes for the seal course.

Generally, a wet coefficient of friction below 0.40 on this type of construction was caused by excess bitumen (bleeding) and/or polished aggregates, or both. Excess asphalt has a pronounced effect in reducing friction values.

Figure 5 records the average stopping distances for several of the various types of surfaces tested, which had wet coefficient of friction of 0.40 or higher.



NOTE 1 : UNCRUSHED GRAVEL AGGREGATE
2 : LESS THAN 25% PLUS NO. 10
3 : MORE THAN 25% PLUS NO. 10
4 : 25%—35% OF GRAVEL AGGREGATE IS CRUSHED.
NUMBER IN (-) INDICATES NUMBER OF TESTS INCLUDED IN AVERAGE.

Figure 5. Average stopping distances for various types of surface having coefficient of friction of 0.40 or more; testing speed, 40 mph.

Data developed and shown on Figure 5 follow:

Surface Type	No. of Tests	Stopping Distance (ft) Dry	Stopping Distance (ft) Wet	Coefficient of Friction Dry	Coefficient of Friction Wet
D.B.S.T. - slag slag	119	74.7	91.7	.71	.58
Slag seal	63	74.0	96.0	.72	.56
Cold mix - Ala. Asp. L.S.	64	72.5	101.0	.74	.53
Sand Asphalt Hot Mix	169	72.0	101.3	.74	.53
D.B.S.T. - Slag/Gravel	104	71.4	102.8	.75	.52
Mod. Sand Asphalt Hot Mix	43	73.4	111.9	.73	.48
Portland Cement Concrete	131	72.8	112.5	.73	.47
D.B.S.T. - Cr. Gvl./Gvl.	95	71.4	117.4	.75	.45
Mod. Sand Asphalt Hot Mix	33	73.5	118.6	.73	.45
Average	84	72.7	104.7	.74	.51

Twenty-eight of approximately 200 projects tested were found to have sections having coefficients of friction (wet pavement) under 0.40. The average data for the group that tested below 0.40 are, in part, as follows:

	Dry (Ft.)	Wet (Ft.)	Coefficient of Friction Dry	Wet
Average Stopping Distance	77.1	152.7	0.69	0.35
Minimum Stopping Distance		135.2		0.39
Maximum Stopping Distance		219.6		0.24*

Most of the sections in this group which fell below the value of 0.40 could be attributed to excess bitumen or polished aggregates.

The Maintenance Division was notified of the sections falling below a value of 0.40 and these sections have been resealed to improve the friction value.

Figure 5 records the average values established for types of pavement listed. The present finish of portland cement concrete pavement is the burlap drag finish.

Surfaces can be constructed with extremely high frictional values; however, as the coefficient of friction increases, the tire wear also increases. Dr. Moyer found that tire wear for a coefficient of friction in the range of 0.50 to 0.60 at a 40-mile speed averaged from one-half to one-third of the tire wear on sharp stone and gravel, yielding coefficients of 0.70 to 1.10.

Tire wear at a speed of 60 mph on highly abrasive surfaces (values above 0.70) was found to be eleven times greater than at 35 mph on surfaces with lower coefficients of friction.

A recent article by George Giles of the Road Research Laboratory of England and abstracted by J. E. Gray, Engineering Director of National Crushed Stone Association, appeared in the Crushed Stone Journal of June, 1957. The suggested standards for skidding resistance converted to 40 mph speed follow:

1. Coefficient 0.66 and greater—A good resistance to skidding, fulfilling requirements even for fast traffic.
2. Coefficient 0.56 to 0.66—Generally satisfactory, meeting most requirements except for curves on a road under fast traffic.
3. Coefficient 0.46 to 0.56—Satisfactory, except for conditions at critical sites such as junctions and curves.

In conclusion, if good resistance to skidding is to be obtained in a pavement surface when the pavement is wet, the composition of the mix must be all right and the aggregates must be of the kind that will remain harsh and resist severe polishing under traffic.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance of the many individuals and agencies who helped to make this report possible. All districts and many Divisions of the Highway Department, as well as the Highway Safety

*A double bituminous surface treatment project sealed in late fall; a large portion of the seal aggregate did not stick in some sections. These sections were resealed the following spring, and the result was excess bitumen. These sections were bleeding badly at time of tests and "Slippery When Wet" signs were found on the project.

Patrol, willingly furnished personnel and equipment wherever needed. The Equipment Division furnished and maintained the test cars in excellent operating condition.

The study was authorized by T. C. Robbins, Director, and was conducted under the general supervision of H. O. Thompson, A. M. White and Jack W. Chambliss. S. A. Tomlinson, Fay Lossing and R. M. Genthon assisted in the analysis and interpretation of the data. Field crews were under the supervision of Oris Gary.

Special acknowledgment should be extended to Dale Y. Holloway and Billy Todd for their skillful and careful driving throughout the tests.

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Measurement of Pavement Skidding Resistance By Means of a Simple 2-Wheel Trailer

P.C. SKEELS, General Motors Proving Ground

There has been an increasing awareness of the seriousness of low friction wet pavements during the past several years. With the increase in interest, there have been developed numerous techniques for measuring the wet skid resistance. The increase in traffic volume on public highways has made it increasingly difficult to apply the simplest sliding brake stop techniques; on many of our most important highways, it is almost impossible to measure skid resistance by older methods because of the hazards involved and the interruptions of the flow of the traffic stream. This paper describes the design and construction of a simple 2-wheel trailer, using passenger car components readily available in any part of the country. This trailer can be towed in the traffic stream so that tests can be made in rapid succession without changing speed and without any interference with other vehicles.

The paper includes samples of data on numerous types of road surfaces.

● About four years ago the General Motors Proving Ground desired to evaluate the coefficient of friction of the various road surfaces used on testing operations in order to correlate braking results obtained on these various surfaces. To obtain this information a car was equipped with instruments for measuring the reaction of the rear wheel brakes; the front wheel brakes were disconnected and the car towed behind a sprinkler truck as shown in Figure 1. The rear wheel brake reaction was read on a servo type of direct reading indicator calibrated to read pounds of force at the road surface.

With this instrumentation it was possible to wet the road and tow the car over the wet area with the rear wheels sliding. The torque developed by the sliding rear wheels was observed and the coefficient of friction of the surface could then be calculated knowing the weight on the wheels, the wheel base of the car, and the height of the tow cable attachment. It is necessary that the last two items be observed in order that the weight transfer from the rear to the front wheels may be taken into account.

This equipment was entirely satisfactory for our immediate purpose and, when its existance became known, several highway agencies requested that we make measurements of selected portions of highway to obtain information on their coefficient of friction. A description of this equipment was given to the Association of Asphalt Paving Technologists at their February meeting in 1956 (5). From our contacts with the highway people, it was quite apparent that there was a great amount of interest in road coefficient particularly when wet and its relationship to accidents; however, the road agencies were hampered by lack of suitable measuring equipment.

The General Motors Proving Ground decided that it could make a worthwhile contribution to highway safety by designing equipment specifically intended to measure road coefficient of friction. This equipment should require a minimum of man power; it should be capable of operation in a completely safe manner at speeds which would provide a minimum of interference with the regular flow of traffic in order to make it useful in cities and on heavily traveled roads; it should also provide accurate information in either indicated or recorded form; and, it should be constructed of parts which are readily available with a very minimum of specially machined parts.

Figure 2 shows the equipment which was developed to fulfill this purpose. The trailer is constructed from a 1950 Buick chassis purchased from

Figure 1.

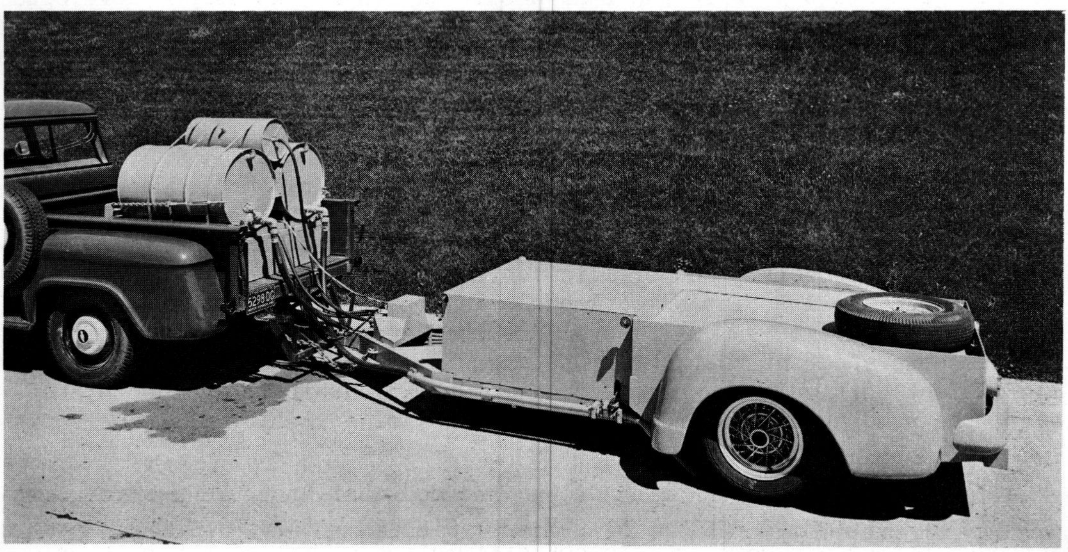


Figure 2.

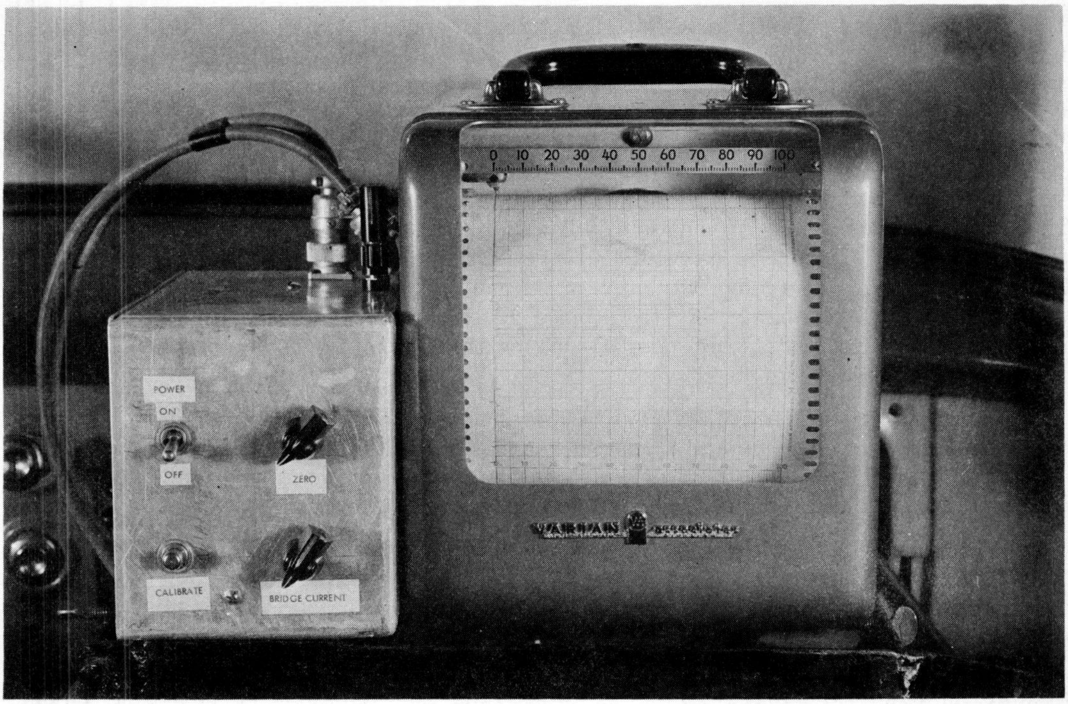


Figure 3.

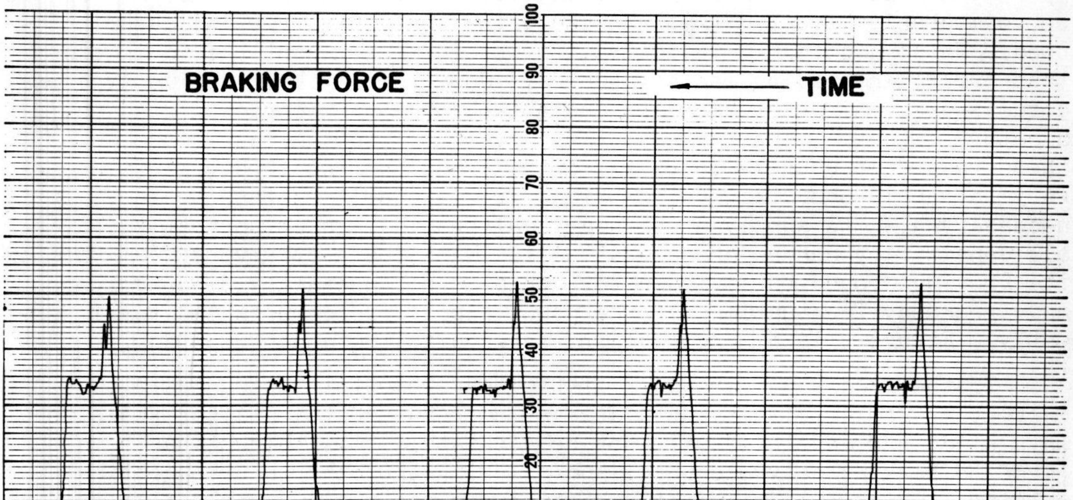


Figure 4.

a junk yard. Practically any Buick chassis built since the war could be used. The Buick is specified since it uses a torque tube drive with coil springs which lends itself well to the installation of strain gages for measuring brake reaction. The complete rear running gear of the original car is retained, the only modifications being in the method of applying the rear brakes. These are applied by a standard truck type power brake unit available at any automotive supply house. The remainder of the construction is mainly a body to supply the necessary weight on the rear wheels and a system for wetting the road surface. This system uses two 50-gal drums located on the back of a pickup truck. Each drum feeds one rear wheel through a large diameter plastic hose. The water flow is controlled by a gate valve in each line located near the center of the trailer. These gate valves are operated by inexpensive windshield wiper motors which are controlled from the cab of the truck. All water flow is by gravity. This system allows a maximum number of runs to be obtained with the limited water supply available. A small pump is carried on the truck running board for use in refilling the 50-gal drums where it is necessary to refill them from a stream or pond.

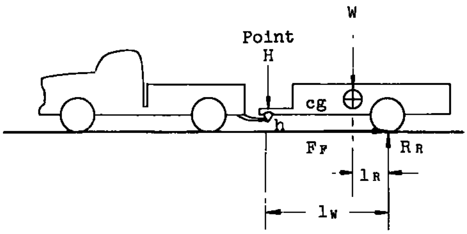
On this installation a single lever operated by the observer controls a timer which opens the water valves and applies the brakes a few seconds later; however, this is not necessary for the successful operation of the system if the complication of the timer is undesirable.

For most Proving Ground work a direct reading indicator is used. This indicator operates on the self-balancing potentiometer principle and is highly accurate and very rugged. It does not produce a permanent record and is not suitable for measuring the transient force involved in the incipient slide condition; however, it has proven highly satisfactory for measuring sliding coefficient. The reading is taken the first 1 or 2 seconds following the start of wheel slide. During this period the reading is relatively stable if the surface is uniform.

As mentioned previously, the indicator used on this trailer is of the servo mechanism type. It is not necessary that this type indicator be used. In some cases it is desired to obtain a permanent record in order that errors in reading can be checked. Commercially built servo type recorders are available which are suitable both as a recorder and as an indicator. Figure 3 shows one of these recorders installed. Inasmuch as these recorders usually operate from a direct current input, it is necessary to supply the strain gage bridge from a stable voltage source. It is necessary also to supply a secondary calibrating system so that the overall sensitivity can be checked at will. With the a-c servo system used on the Proving Ground built indicator, this is not necessary since voltage and frequency fluctuations in the power supply are compensated for inherently. Figure 4 is a sample record taken with the above recorder.

If the road has a crown or if the measurement is being taken on a curve the trailer will slide sideways and readings taken after the sideways slide has developed will not be accurate. Some thought has been given to braking only one wheel and allowing the other one to continue rolling. This would eliminate the sideways sliding and would also conserve water. The original configuration of braking both wheels was chosen because the reading is the result of the average coefficient of the two wheel paths and this was thought to be desirable.

Calibration of this equipment is rather straight forward; however, it is necessary to take into account the weight transfer from the trailer wheels to the trailer hitch as braking force is applied to the trailer wheels. It can readily be seen that when braking torque is developed the rear axle tends to rotate in the direction the wheels are rotating. This torque results in a downward pressure on the trailer hitch. Inasmuch as the weight of the trailer is a constant, any downward force on the trailer hitch must result in a lessening of the weight on the rear wheels. This is a greatly simplified explanation of the weight transfer problem. A more detailed explanation is provided by the following diagram and formulas:



1 $M = \frac{F_f}{R_R}$

2 $\Sigma M_N = W(l_w - l_R) - R_R l_w - hF_f = 0$

3 $R_R = \frac{W(l_w - l_R)}{l_w} - \frac{h}{l_w} F_f$

4 $M = \frac{F_f}{W(1 - \frac{l_R}{l_w}) - \frac{h}{l_w} F_f}$

With no braking,

5 $F_f = 0$ AND THE TOTAL TRAILER WHEEL REACTION FORCE, R_R, BECOMES,

6 $R_R = W(1 - \frac{l_R}{l_w})$ = static weight on the trailer wheels

Therefore,

7 $M = \frac{F_f}{W_s - \frac{h}{l_w} F_f}$

Where

M = Coefficient of Friction

F_f = Friction Force

W_s = Static Weight on Trailer Wheels

h = Trailer Hitch Height

l_w = Trailer Hitch to Axle Distance

Inasmuch as the friction force F_f is the value measured on the indicating equipment in the cab, the coefficient of friction for any friction force can be calculated where values are known for the static weight on the trailer wheels, the height of the hitch above ground, and the distance from the axle center line to the trailer hitch. In this trailer design the hitch height is 10 in. and the distance from the trailer hitch to the axle centerline is 120 in. The static weight on the wheels is 2,000 lb; hence, for this particular trailer, the coefficient of friction equals the friction force in pounds divided by the quantity 2,000 minus 1/12 of the friction force in pounds. In actual practice, a table is prepared showing the coefficient of friction for each increment of indicator reading.

In calibrating the equipment so that the indicator indicates friction force, it is necessary to have a drawbar or its equivalent inserted as a connecting link between the towing truck and the trailer. The trailer wheels are then locked by applying the brakes and force applied to the trailer using the truck engine. The drawbar and the trailer indicator are then read simultaneously at several points from a low drawbar reading up to the maximum obtainable before sliding the trailer wheels. From these readings a table can be made showing the actual drawbar force represented by various indicator readings. Inasmuch as these drawbar readings are the F_f force in Equation 7 and the other factors are known, the coefficient of friction can be calculated and a curve or table reading directly in coefficient of friction can be prepared.

Figure 5 shows the drawbar which we use in our calibration work. This is a special drawbar made in the form of a trailer hitch ball. It contains strain gages on the shank arranged in such a manner that the point of application of force at the ball end is immaterial to the reading obtained. This drawbar is calibrated in a testing mechanism as shown in Figure 6.

Inasmuch as the standing height of the rear axle affects the torque developed in the axle housing for a given F_f it also affects the trailer

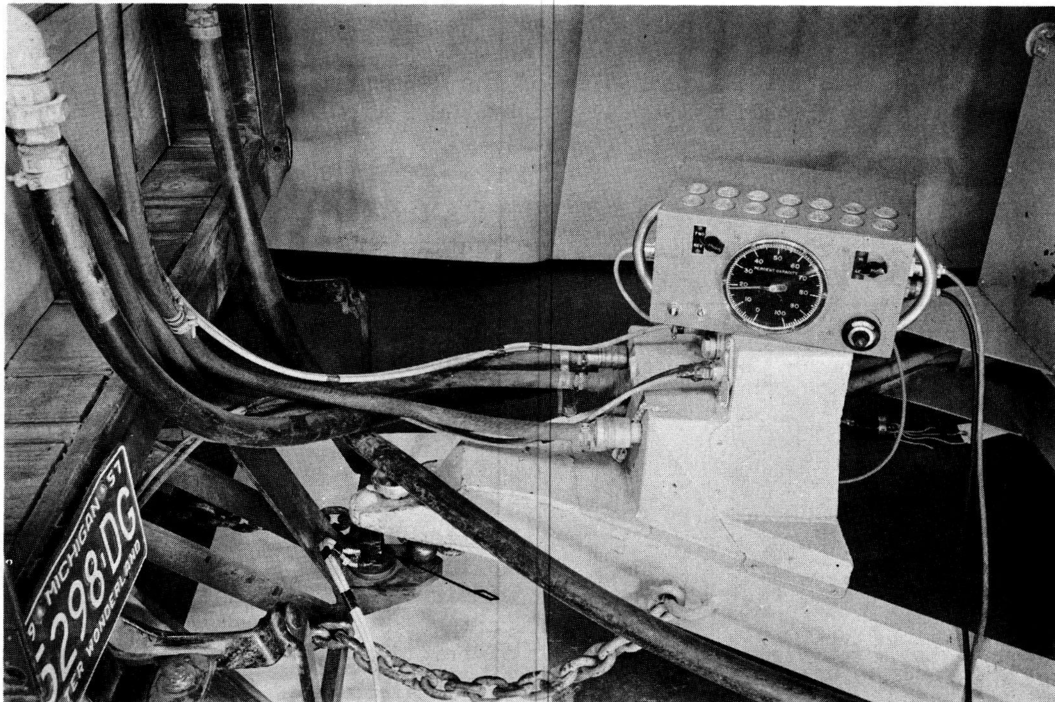


Figure 5.

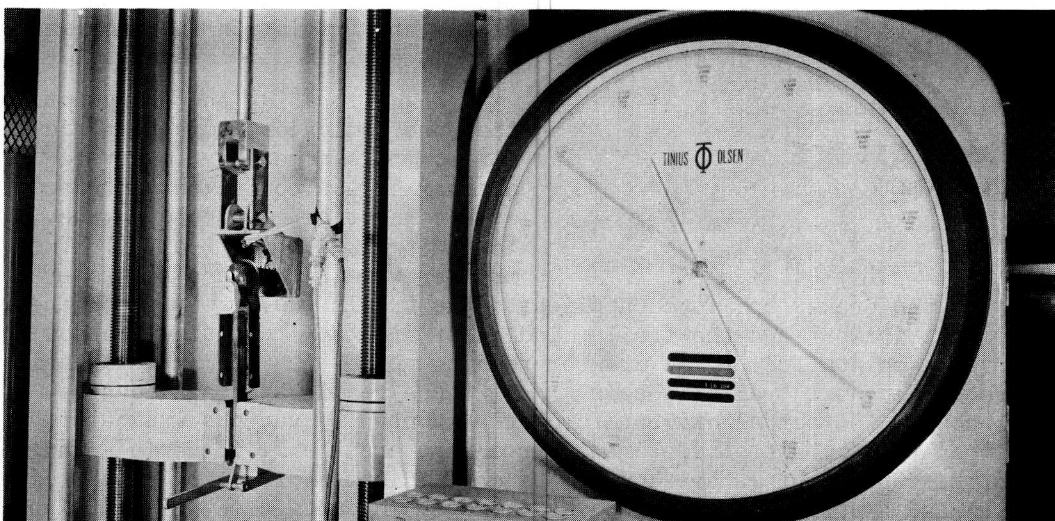


Figure 6.

calibration; hence, a new calibration must be run whenever tires of a different size are used. Generally it is not safe to assume that tires of different makes have the same standing height even though they are of the same size. To be on the safe side we recalibrate each time tires are changed unless these tires are from the same batch.

This equipment was put into service in June of 1957 and approximately 7,000 individual measurements were made during the summer and early fall. These measurements were made on the Proving Ground road system and for various road agencies. During the shakedown runs some improvements were made including a sight glass on the water drums and an improved method for filling the drums; however, the basic design of the trailer was apparently sound since no bugs developed and continuous all-day running is perfectly feasible. As many as 500 individual checks have been made during one day's operation. The trailer will track satisfactorily up to at least 70 mph; however, it is difficult to maintain a constant speed with the trailer wheels sliding at speeds over 40 to 50 mph. The measuring system is designed so that it is virtually unaffected by gravity components; hence, it can be readily used on hills or curves and a small change in velocity of the vehicle during the time a run is being taken does not affect the accuracy of the reading except as the actual coefficient of friction changes with speed. This change in velocity is rarely over 1 or 2 mph even for a 50-mph run.

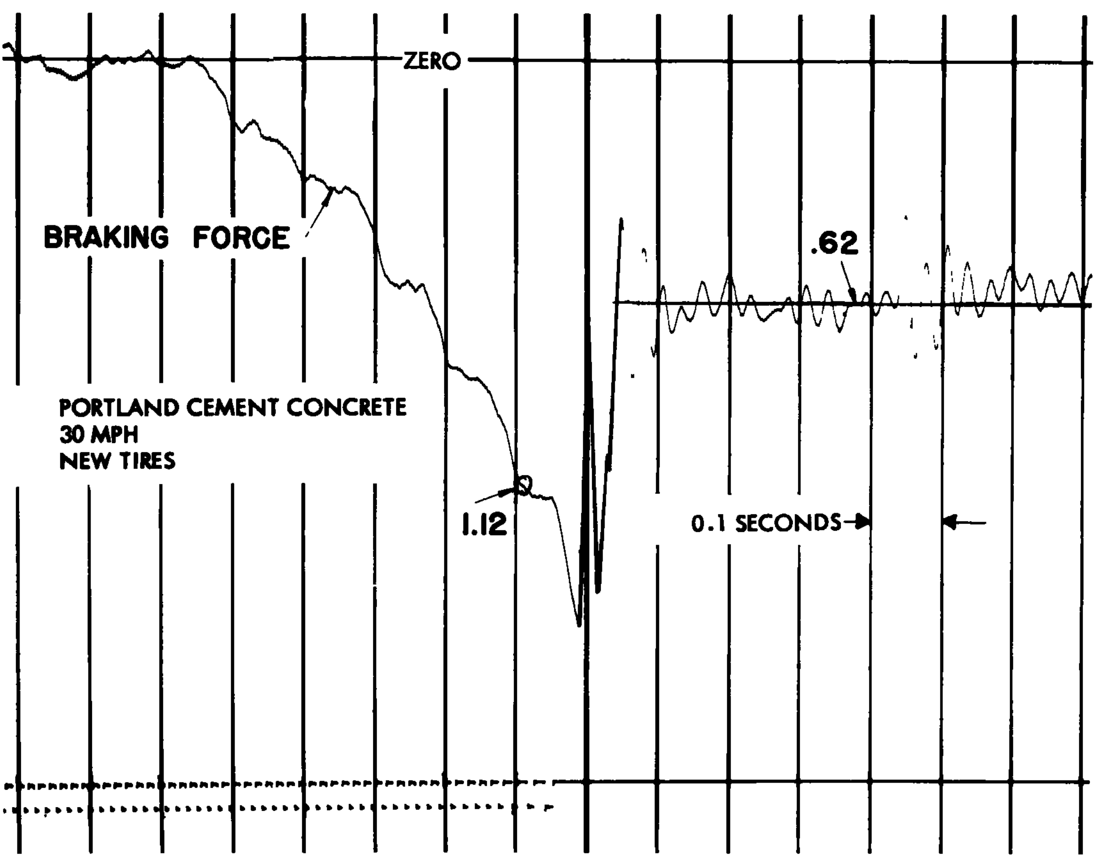


Figure 7.

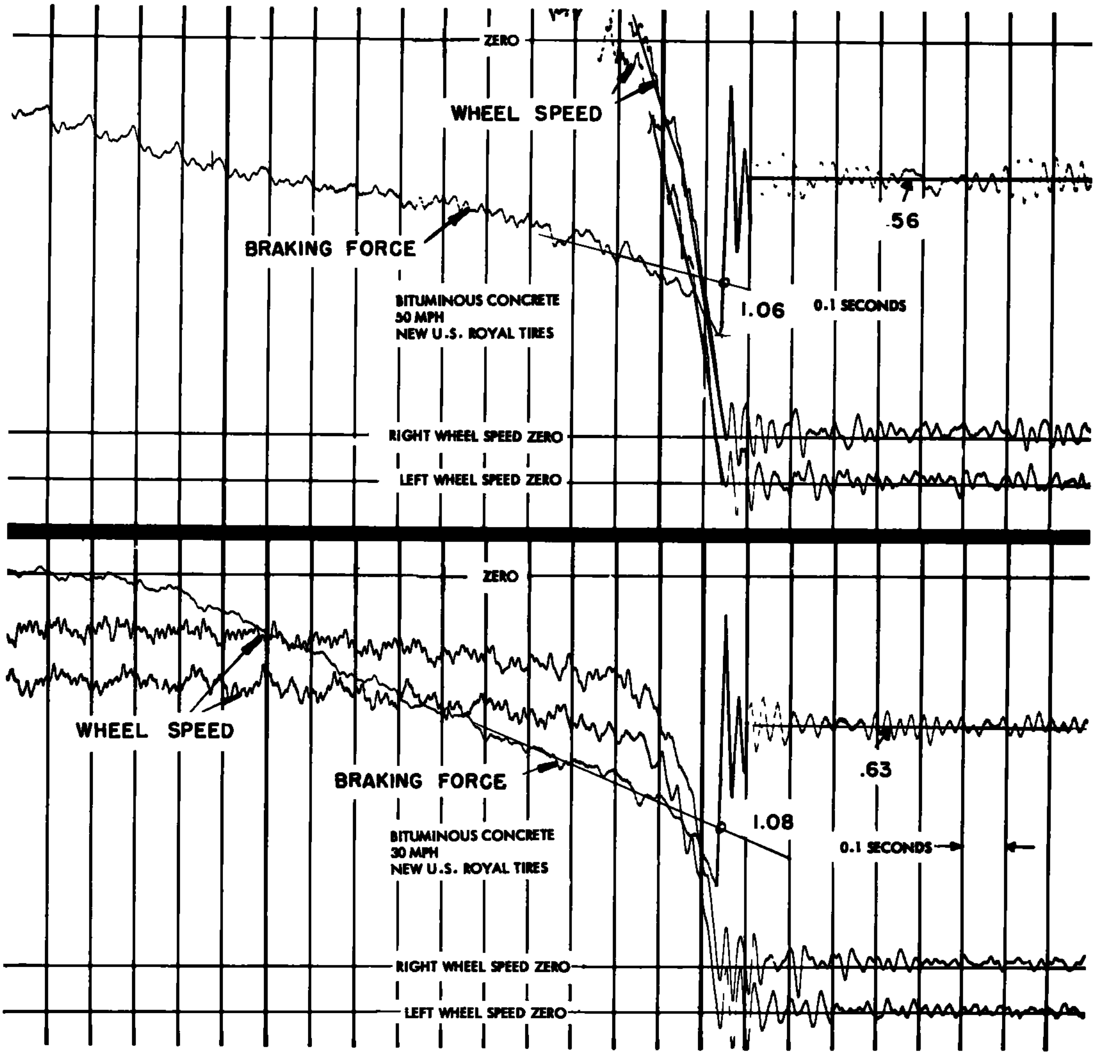


Figure 8.

While the primary purpose of this paper is to describe the measuring equipment, a few results of tests made on the Proving Ground road system are in order. For this series of tests the indicating instrument previously described was not used; instead, a recording oscillograph was connected to record the braking forces in order that a study of incipient coefficient values might be made.

Figure 7 is a reproduction of a record obtained from the recording oscillograph. The horizontal line at the top represents zero braking force on the trailer wheels; as braking force develops the line moves downward. The pips at the bottom of the record each represent 1/10 of a wheel revolution on one wheel. As these pips broaden, decreasing wheel speed is indicated and as they disappear, wheel slide is indicated. The braking force can be seen to increase at a nearly linear rate until just before wheel slide at which time the slope increases. As the wheels start to slide an abrupt drop in braking force is noted and a 35-cycle per second oscillation

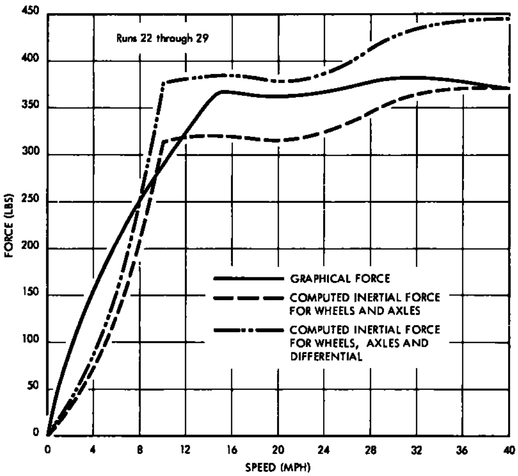


Figure 9. Tire to road force variation versus run speeds.

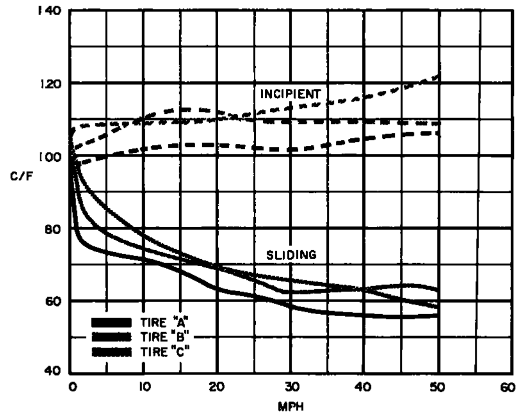


Figure 10. Coefficient of friction, Road Surface A, wet.

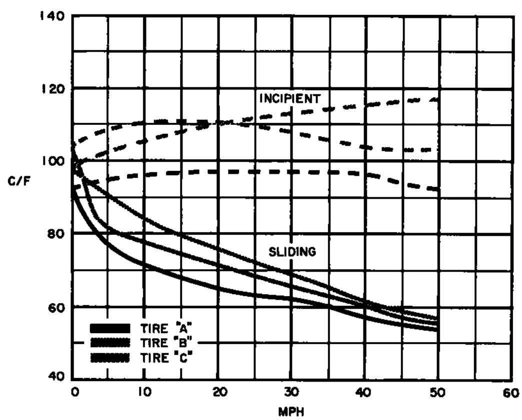


Figure 11. Coefficient of friction, Road Surface B, wet.

develops. The sliding coefficient is derived from the average force immediately after the wheels begin to slide and is represented by the straight horizontal line drawn through the oscillating trace indicated by the arrow and the number 0.62. The incipient coefficient is harder to pinpoint inasmuch as the brake force trace is the result of two distinct force input systems; first, the force developed at the tire road contact point, and second, the force due to the kinetic energy withdrawn from the wheels as their velocity is reduced to zero. At the time this record was taken it was our practice to arbitrarily read the low point immediately preceding the spike which occurs just prior to wheel slide. This point was indicated also by the pips at the bottom of the record; these pips indicate nearly normal wheel velocity at this time. This point is indicated by the 1.12 number on Figure 7.

We realized that this method of reading incipient coefficient was not accurate. Improved instrumentation was installed and records obtained as shown in Figure 8, which shows records taken at two speeds, the upper one at 50 mph and the lower one at 30 mph, all other factors being equal. In taking these records, tachometer generators were installed on each trailer wheel and the output of these generators recorded along with the braking force. Since it was desired to observe the instant each wheel reached the sliding condition, the zeros were offset and are indicated by the two bottom horizontal lines. The wheel speed traces are somewhat irregular because of rotational oscillation of the generators. The top record shows that both wheels slid at nearly the same instant and that the drop in brake force occurs at the very instant the wheel speed reaches zero. In order to evaluate the effect of wheel inertias on these records properly, a comprehensive mathematical analysis was made based on these wheel speed data. Inasmuch as this mathematical treatment is rather unwieldy and therefore difficult to apply to each individual reading, a graphical method was devised which duplicates the mathematical method to a satisfactory degree of accuracy. In the graphical method it is assumed that the rate of rise of the brake force curves is essentially linear and that this linear trend would continue to the moment of wheel slide. The incipient coefficient is derived from the value the extrapolated curve would have at the instant the slide occurs. This is illustrated by the small circle on both records. Figure 9 shows the relationship of calculated to graphically determined points and is our justification for using the graphical method.

In order to obtain experience with this equipment and to evaluate variations between different makes of tires, a series of runs were conducted on three different makes of tires at various speeds. The incipient and sliding coefficients were measured by the above method and the information shown in Figure 10 obtained. This indicates a very rapid drop in coefficient between 0 and 5 mph with a less rapid drop as speed increases. It will be noted that in the 40- to 50-mph region the curve appeared to flatten out. It will be necessary to do additional work at higher speeds to verify this trend. On a different road this tendency is not demonstrated.

It will be noted that the incipient coefficient seems to have a rising tendency with speed, Figure 11. This tendency is not great; however, it is evidenced on all tires run to date. At least it can be said that incipient coefficients do not fall off with speed as the sliding coefficients do.

Inasmuch as the most serious skidding problems occur on wet roads, most of our experience is with measurements taken under these conditions. With wet roads tire wear seems to be no problem unless the trailer brakes cause the wheels to slide before the water is applied or hold the wheels in a sliding condition after the water is shut off. With the brakes properly adjusted a thousand or more tests may be made on one set of tires with good consistency.

Some work has been done on dry pavements. Under this condition results are not nearly as consistent, because the indicated coefficient of friction usually drops rapidly during the period of wheel slide. This makes it difficult to assign a single figure. The cause of this force drop is not thoroughly understood but it could be the result of temperature build-up at the contacting surfaces or a lubrication of the area by soft or torn-up rubber. This condition does not seem to prevail on wet slides. It is also obvious that dry sliding will result in very low tire life since each slide will mark the pavement and produce a flat spot on the tire. The surface of the tire also becomes rough and its coefficient characteristics change rapidly. These conditions might not be so severe on polished pavement; however, it can be stated safely that dry coefficient measurements are not as easy to make as are measurements on wet pavements.

The work that we have done on dry pavements indicates that the coefficients obtained during the early portion of each slide do not drop off drastically with speed as they do on wet pavements.

All of our work to date has been done with commercially available tires made of GRS rubber. It is realized that tires will probably have a significant effect on the values of friction obtained; however, our work has usually involved a survey of a certain road system with the object of pinpointing slippery sections. On this type of survey the absolute value is not of prime importance. If many agencies are making friction measurements it will be very desirable to be able to compare all measurements on a common basis; hence, it is recommended strongly that some type of standard tire be developed for this type of work. The Proving Ground has made some inquiries along this line but has not enough information to make any definite recommendations at this time.

As previously stated, the purpose of building this equipment is to create a simple design which can be readily duplicated. We believe that we have accomplished this and the General Motors Proving Ground has a report and drawings which it will make available upon request to anyone interested in the construction of similar equipment (7).

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Supplemental Pavement Skidding Resistance Tests in Virginia

J. H. DILLARD, Associate Research Engineer, Virginia Department of Highways

● THE stopping distance method of determining skid resistance of pavement surfaces has been used for approximately ten years in Virginia. During that time Virginia has made great progress in providing skid resistant roads despite the fact that one of the major aggregates used in the state is susceptible to polishing. The experience accumulated with the stopping distance method during this period of time indicates that the method has many advantages as well as many disadvantages. The advantages are outlined below:

1. The test is realistic—a standard vehicle is involved in an emergency skid and the consequence observed.
2. Since late model cars are used for the test, the test results reflect the modifications in vehicular and tire design that take place in the automotive industry.
3. The coefficient of friction is an integrated value obtained from a vehicle beginning a skid at 40 mph and ending at 0 mph.

The disadvantages are:

1. Many uncontrolled variables are operating and it is difficult to analyze the data precisely.
2. The old vehicles are replaced with newer models and it becomes difficult to compare the new data with the old.
3. It is difficult to utilize data obtained by other states that use stopping distance test vehicles of a different model.
4. Tests are time consuming and fairly costly.
5. The number of sites that can be tested are limited—both grades and dangerous curves must be avoided. Also, only sites can be tested, it is not practical to test a section over its entire length.

In general it is our belief that the advantages of a stopping distance method can be made available in other test procedures that can also overcome the disadvantages. The General Motors trailer method shows considerable promise in being able to accomplish this.

Experiences With The General Motors Test Trailer

In August 1957 approximately 2,500 measurements were made on over 150 sections of road in just two weeks using the General Motors' test trailer. Since the trailer was available for only two weeks, time was an important factor and under normal conditions we would not anticipate being able to match this performance. However, the potential of the equipment to make tests quickly is certainly an important aspect. We can summarize our experiences with the General Motors trailer as follows:

1. The method is very rapid.
2. The method permits a testing of an entire section throughout its length rather than localized testing.
3. The reproducibility seems to be excellent.
4. The cost of conducting the test is very low; we estimate that testing will cost about $\frac{1}{4}$ as much with the GM test trailer as with our conventional stopping distance equipment.
5. The side sway is rather severe and might be dangerous; this was brought out in Skeel's paper and it has been observed by others also.

Correlation With The Stopping Distance Method

Since there are several significant differences, namely, speed of test, water application, and tire design, between the stopping distance method and the trailer method, we were interested in seeing what correlation existed between the two. After making the General Motors trailer test, stopping distance measurements were made on some of the same sections. Only a limited amount of time was available for the tests and therefore the correlation is very incomplete but it is interesting. The correlation data is shown in Figure 1. Unfortunately few measurements were made where the coefficient of friction was above 0.5. The data suggest that in the critical range (approximately 0.4) coefficients obtained by the GM results are lower than those obtained by the stopping distance method. The significance of this should be noted. If, as is done in Virginia, any pavement where the coefficient of friction is lower than 0.4 is considered unsafe then the two methods would disagree on many miles of pavement in Virginia.

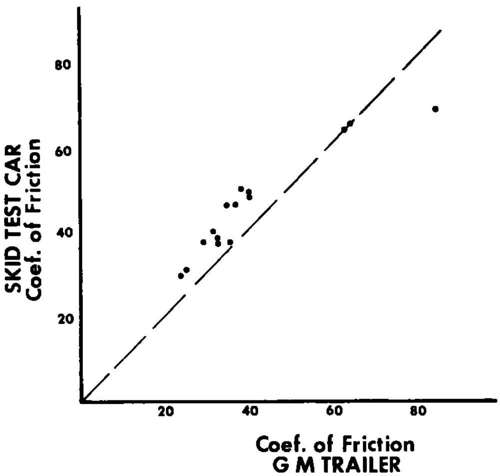


Figure 1. Comparison-Coefficient of Friction, GM Trailer and Skid Car.

These differences, while not extreme, do point out the need for the standardization of equipment. It is becoming apparent that great confusion will follow in the next ten years unless a standard method of measuring road surface slipperiness is adopted.

In summary, then, experience with the GM trailer showed that it is an excellent method of measuring road surface friction, possessing many advantages over existing methods, and further, it is essential that a move to standardize testing equipment for measuring road surface slipperiness be initiated immediately.

Supplemental Tests of Pavement Skidding Resistance With a 3-Wheel Trailer

H. F. CLEMMER, Engineer of Materials and NORMAN G. SMITH, Assistant Engineer of Materials, Materials Development and Testing Division, District of Columbia Highway Department.

● HIGHWAY engineers, automotive engineers, traffic safety engineers, tire manufacturers, aggregate producers and numerous others including the riding public, have had considerable interest in the relative skid resistance of various paving surfaces used on highway systems. A great deal of research has been conducted on the problem of slipperiness of roads and in determining the causes and effects of directly related problems. Ingenious devices have been developed to measure coefficient of friction of pavements and extensive efforts have been directed toward minimizing or reducing potentially hazardous conditions.

Accident information, as correlated by police departments and traffic investigation authorities, have pinpointed certain stretches of highways as having an unduly high rate of automobile accidents where skidding of the vehicle has been a contributing factor. In many cases, investigations by highway engineers have indicated relative low skid resistance on pavement surfaces where considerable polishing or wearing of the surface has occurred. Such investigations have led directly to modifications in design of portland cement concretes or asphaltic concretes.

Automotive engineers and tire manufacturers have made major contributions in developing rubber, tire tread patterns and proper inflation pressures to provide maximum economy in tires and incorporate satisfactory traction characteristics. Highway engineers are making a special effort to determine the friction characteristics of various types of pavements and to improve these surfaces to offer maximum traction.

The District of Columbia Highway Department has previously made some limited coefficient of friction determinations in connection with bituminous surfacing of Michigan Avenue, N. W., in which rubber was used as an additive. These skid resistance tests were run on the pavement in the wet and dry condition at three speeds. The method employed was that used by Moyer and Shelburne and utilized a pickup truck with carefully adjusted brakes, new tires and a calibrated speedometer. An electrically actuated detonator fired a chalk bullet into the pavement at the point of brake application. In this manner, stopping distances from given speeds were measured and coefficient of frictions computed from the formula $f = \frac{V^2}{30S}$. This method of coefficient of friction determination of the pavement presented interesting results but had several undesirable features. It was particularly time consuming and dangerous on heavily trafficked streets; citizens were often startled by the report of the bullet being fired on the city streets, a relatively large crew of men was required; and the street had to be barricaded in the test area. It was necessary to employ a street sprinkler to run the "wet" tests. Results were in terms of an average coefficient of friction, since speed was not constant. Actually, this approach gave usable skid resistance values for comparative purposes; however, measurements also included incipient or impending friction which has been reported by Moyer, Skeels, Stonex, and Finney as being higher than sliding friction.

The equipment developed at the General Motors Proving Ground and described in Skeel's paper resolves most of the undesirable features of the method of determining skid resistance previously used in the District of Columbia. The concept of the use of a towed trailer or automobile in measuring pavement coefficient of friction is not new and many extensive and complete investigations have been reported by Moyer, Agg, Norman, Stinson, Beakey, Klein, Brown, Whitehurst, Goodwin, Shelburne, and others, involving some variation of the general principle. Too, excellent treatises of the skidding resistance of roads have been reported in British technical journals.

The opportunity was presented to make coefficient of friction determinations with the General Motor's equipment on the principal types of pavement surfaces in the District of Columbia. Data was collected from finished portland cement concrete, bituminous concrete, sheet asphalt, and various other types of surface treatments. The information obtained is too limited to draw any definite conclusions; however, the data is believed sufficient to make general observations on a comparative basis, which are pertinent to the Department. It is appreciated that there are numerous complex variables which directly affect test results and have a bearing on the actual skid resistance of any given pavement surface. Some of the more important of these variables include: age, type and conditions of pavement, number and weight of vehicles making up the traffic, degree of wearing or polishing of the surface, temperature and weather conditions, cleanliness of the surface, and type of aggregates used. There are, of course, numerous variables as regards the test vehicle itself including such items as tire pressures, tread patterns, imposed loads, types of rubber, conditions of vehicle brakes, alignment of wheels, driver's reaction, etc., thus the method employed to make coefficient of friction determinations will have a bearing on the value obtained. A number of terms have been developed in research studies which differentiate between types of coefficients such as incipient, average, sideway-force, straight forward, sliding, dry, wet, etc. The General Motors equipment used measured sliding friction at constant speeds. All tests made in the District of Columbia were run in the "wet" condition at a constant speed of 20 mph.

It is desired to report results of the coefficient of friction determinations obtained in the District of Columbia since it is believed that the data obtained is pertinent and will be of interest to those studying this problem. Careful records were kept as to the location of each determination, and photographs made of the surfaces involved. The testing was performed on the high type pavement surfaces of varying ages most frequently used on the arterial highway system. Some data was obtained of the surface treatments using various materials combinations.

A brief description of each type of surface is as follows:

The finished portland cement concrete pavements were constructed of a seven bag mix using natural sands and gravels with maximum size aggregate of 2 in. and with a broomed surface.

The sheet asphalt pavements are constructed with 60-70 penetration AC, bituminous sand and mineral filler. The AC content averages approximately 10 percent with 12.5 percent of the aggregate passing the No. 200 mesh sieve.

The asphaltic concrete surfaces (sand asphalt) are a combination of concrete sand, crushed stone screenings, and 85-100 penetration asphalt cement. This hot mix contains approximately 40 percent crushed materials, 7.2 percent asphalt, and a top sized aggregate of 3/8 in.

Surface treatments generally consisted of approximately 20 lb of cover materials per sq yd (crushed stone, crushed slag, or washed gravel) with binders of RC-3 or RT-9 applied at a rate of approximately 0.3 to 0.5 gal per sq yd. Double surface treatments were of No. 67 and No. 8 "Simplified Practice" sizes and single treatments were the No. 8 size only.

In Figure 1, the results obtained on portland cement concrete surfaces of varying ages ranged from a high of 0.70 to a low of 0.46 with a mean value of 0.57. Photographs of the typical surface conditions for the high, low, and mean results are shown by the photographed surfaces for test Nos. 6, 4, and 3. Figure 2 (test No. 6) shows the parking lane of a pavement constructed in 1955 with a well broomed surface practically unaffected by traffic abrasion. Figure 3 (test No. 4) shows the driving lane of a pavement constructed in 1951 with a heavy accumulation of oil droppings on the surface, probably accounting for the relatively low coefficient of 0.46. Figure 4 (test No. 3) is the passing lane of a concrete pavement constructed in 1951 with a lesser accumulation of oil droppings and represents an average condition.

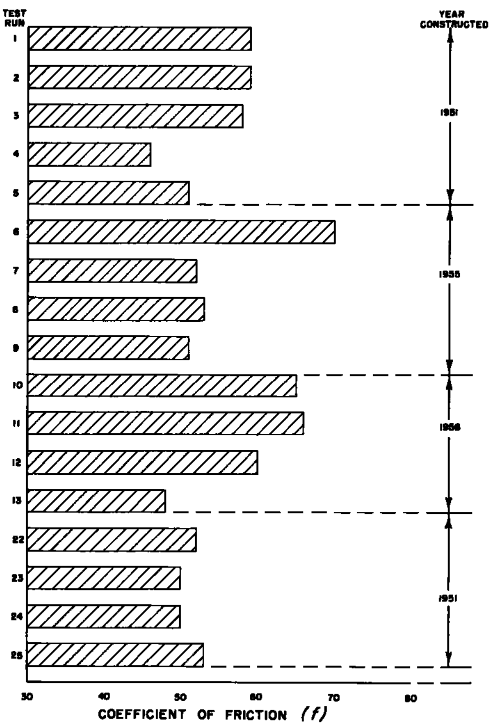


Figure 1. Individual coefficient of friction determinations on portland cement concrete surfaces.

Figure 2. Parking lane of a well broomed concrete surface constructed in 1955.

Figure 5 shows the results of coefficient of friction determinations on sheet asphalt surfaces. The sheet asphalt had a high coefficient of 0.60, a low of 0.50 and an average value of 0.55.

Figure 6 shows the coefficient of friction determinations made on asphaltic concrete surfaces. These surfaces varied between a high of 0.58 and a low of 0.44 with an average value of 0.53.

Figure 7 shows the test determinations made on surface treatment surfaces. Mean coefficient values for the few determinations made were 0.59 for the slag; 0.52 for the crushed

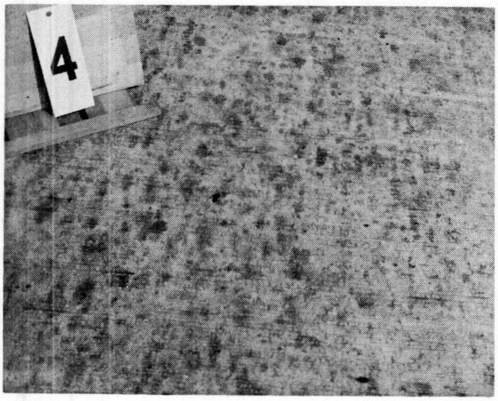


Figure 3. Driving lane of a concrete pavement constructed in 1951 with heavy accumulation of oil droppings on surface.

Figure 4. Passing lane of a concrete pavement constructed in 1951 with relatively little accumulation of oil droppings.

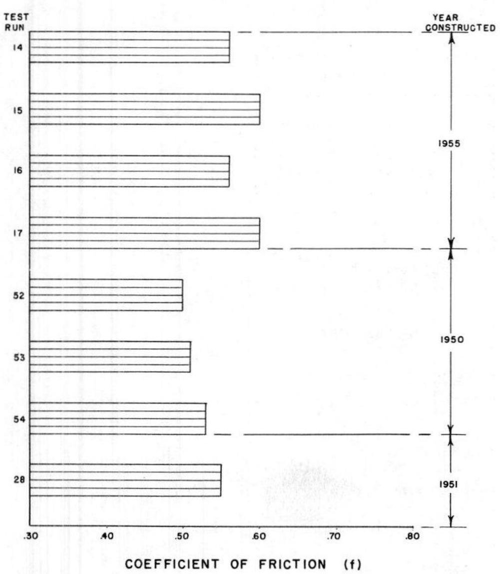


Figure 5. Individual coefficient of friction determinations on sheet asphalt surfaces.

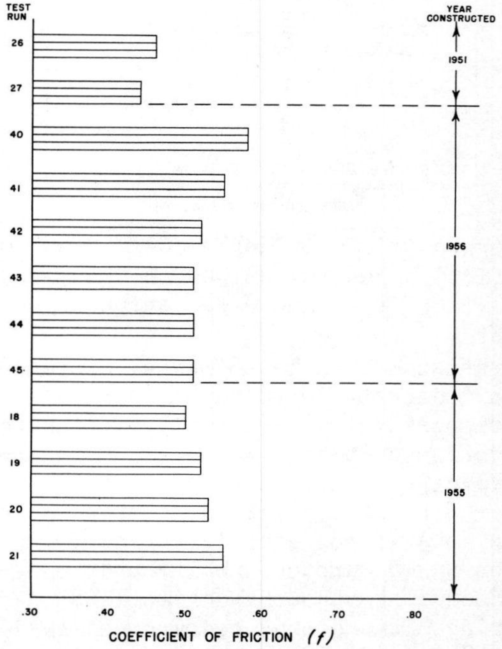


Figure 6. Individual coefficient of friction determinations on asphaltic concrete surfaces (sand asphalt).

stone; and 0.39 for the washed gravel. Results of determinations made on surface treated streets with various types of cover aggregates were more erratic as might be expected because of the nonuniformity of the surfaces as compared with the uniformity of higher type pavements. This nonuniformity of surface texture was due not only to the inherent nature of this type of construction, but to other variables which have an effect on any surface type such as of age, traffic volume and oil droppings, etc.

Figure 8 is a resume of the mean values for the surfaces tested. It is of interest that the sheet asphalt surface containing rubber as an additive has no apparent effect on the skid resistance of the pavement approximately six years after construction.

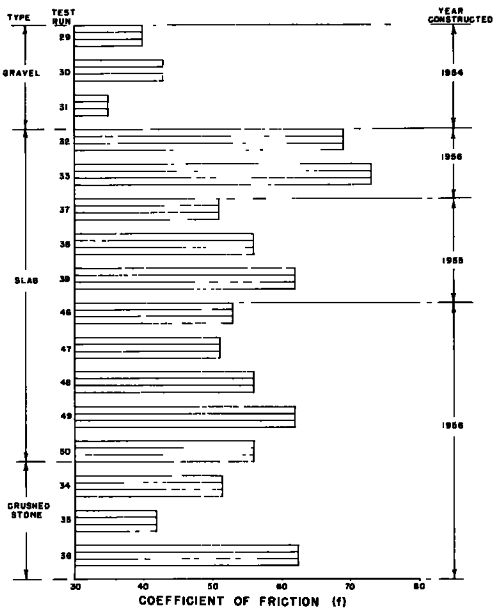
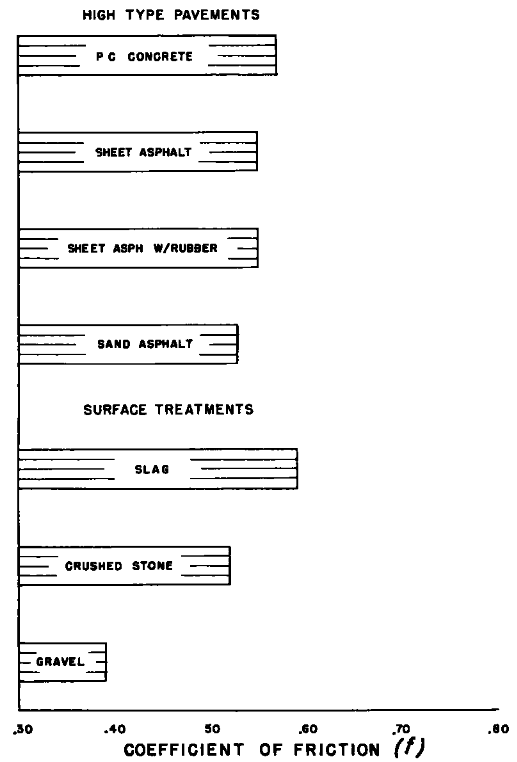


Figure 7. Individual coefficient of friction determinations on bituminous surface treatments of various types.

The data obtained on representative surfaces in the District of Columbia indicates that the higher type surfaces of sheet asphalt, asphaltic concrete (sand asphalt) and finished portland cement concrete have satisfactory skid resistance characteristics when compared with the data presented by the Committee on Road Surface Properties in HRB Bulletin No. 27, 1950.

A research of literature on skid resistance fails to reveal a standard acceptable value for coefficients of friction with relation to design criteria. A very comprehensive report by Giles suggested standards of skid resistance based on a sideway-force coefficient at 30 mph on a wet surface. Whitehurst and Goodwin have used a criteria stopping distances as recommended by AASHO. ("A Policy on Sight Distance for Highways," AASHO, 1947.) It has been well established that coefficient of friction is a function of speed and that it increases as speed decreases. Further, the coefficient of friction is less on a wet pavement than on a dry pavement. It would be most desirable to establish a recommended standard procedure for making coefficient of friction determinations so that a vast amount of data could be collected by various agencies and design criteria established.



Friction 8. Average coefficients of friction on various types of surfaces.

The equipment developed by General Motors appears to have considerable merit. It is probable that the HRB Committee on Road Surface Properties could obtain reasonable agreement on procedures to follow and equipment to be used in order to provide sufficient information to evaluate. The drawn trailer approach as used by General Motors and numerous other investigators, is relatively simple and does provide definite advantages. Some of these advantages include: simplicity of equipment design, a relatively small capital outlay, ease of making numerous determinations without interference to traffic, a minimum number of individuals involved in obtaining data, ease of applying water so that tests can be made on wet surface, and ease of making determinations over a wide range of speeds.

An apparent disadvantage is that it sometimes measures both a sideway coefficient and straight sliding friction since the trailer goes into a sideway skid when taking readings on a relatively high crowned pavement. Whether this is significant is questioned.

The District of Columbia is indebted to Louis C. Lundstrom, of the General Motors Proving Grounds, for his cooperation in making the equipment available for test determinations, and to Paul C. Skeels of that organization who actually made the tests.

It is believed that the data obtained will be of interest to the Committee on Road Surface Properties and others. Too, it was fortunate in that a number of highway officials, engineers, and other interested persons had the opportunity to see this equipment in operation and are therefore aware of its availability as a research tool.

Michigan's Skid Testing Program

M. G. BROWN, Michigan State Highway Department, and E. A. FINNEY, Michigan State University

● THE Michigan State Highway Department began its research on the skidding properties of pavement surfaces with an investigation in 1947-48. This study concerned a number of portland cement concrete projects in Michigan's upper peninsula on US 2 between St. Ignace and Escanaba. With the increase in postwar traffic, a rash of skidding accidents developed on this trunkline, especially when wet. The wet sliding coefficients of friction were measured on these projects, using the stopping distance method from an initial velocity of 20 mph. The average coefficient for the projects in question was only 0.28, and was caused by the highly polished condition of the concrete surface which contained fine and coarse limestone aggregates from a local quarry. As a result of this investigation, use of manufactured limestone sand in portland cement concrete was banned in 1948, and these slippery projects have since been resurfaced with bituminous concrete.

Because of the mutual interest of the automotive industry and highway builders in the performance of pavement surfaces and the vehicles using them, a cooperative skid testing program was undertaken in September, 1954 with General Motors Proving Ground and the Michigan State Highway Department as participants.

About 160 skid tests were performed using a 1954 Buick Special sedan and a tow truck, as described in Skeels' paper. The vehicles and instrumentation were developed and assembled by the General Motors Proving Ground. The Michigan State Highway Department cooperated by furnishing data on mix design, age, traffic, and materials for the specific pavements tested. Most of the projects in this program were bituminous concrete, but several portland cement concrete pavements were included for comparison. Results of this cooperative venture indicated the need for a comprehensive skid resistance survey of Michigan highways.

Actual testing on this statewide program started in May, 1957. This investigation was initiated with three main objectives: (a) to determine the skid resistance level of all highway surface types now existing in Michigan, (b) from this information to develop methods for increasing the friction level on future pavement surfaces, and (c) to study ways and means of de-slicking existing pavement surfaces found to be below a safe standard.

Michigan's skid testing equipment was designed and built concurrently with that of the General Motors Proving Ground, in close cooperation with Skeels. The two skid testing machines are basically the same, with differences in axle weight, manner of recording skidding drag force, and control of the skid cycle.

The Highway Department's skid trailer was made from a junked 1949 Buick frame, altered at the front end to connect with a tow truck by means of a regular trailer hitch, as shown in Figures 1 and 2. A concrete weight was cast and attached above and behind the axle to give an axle weight of 1,550 lb. The two trailer tires are of a standard brand, size 7.60 x 15 which can be easily duplicated, and are mounted on rims with wire spokes to allow for better brake cooling. The hydraulic brakes are air actuated at 40 psig by an electric valve, delivering a total force of about 1,100 lb to the master cylinder.

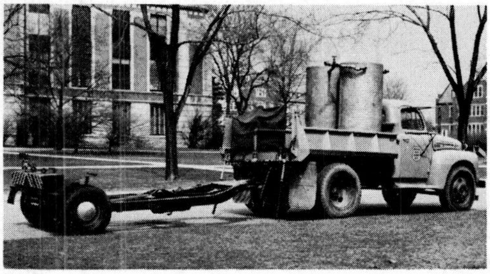


Figure 1. MSHD skid testing equipment.

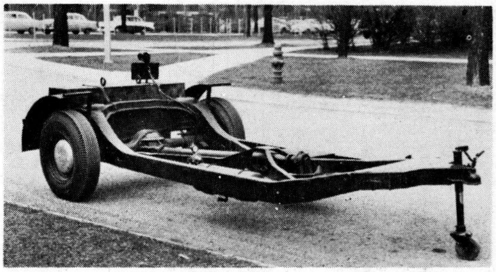


Figure 2. Skid testing trailer.

The tow truck is a two-ton, 1950 Ford dump with two 200 gal water tanks, air pressurized at 40 psig. Approximately six gal of water are used for each test and 50 to 55 tests can be run with one loading of the water tanks.

A typical skidding trace is shown in Figure 3. The trace paper speed is 25 mm per sec. The recording instruments in the right side of the truck cab are a Brush strain analyzer and recording oscillograph as shown in Figure 4. Electrical power for the recording and operating mechanism is furnished by a 3.5 kw, 110 v. AC generator mounted on the truck. Strain is measured by two SR-4, type A-1, strain gages mounted on the top and bottom of the torque tube just ahead of the differential housing and connected for temperature compensated double output. When running the field skidding tests, the strain analyzer is left on constantly and calibration is checked about every hour. The recorder is turned on and off manually for each test cycle.

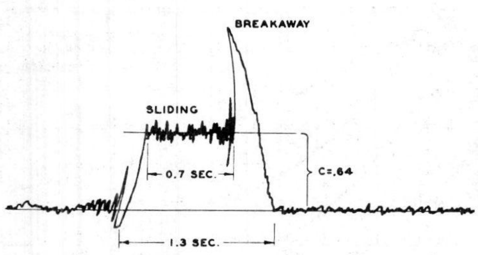


Figure 3. Typical skidding trace on wet bituminous concrete. 40 MPH

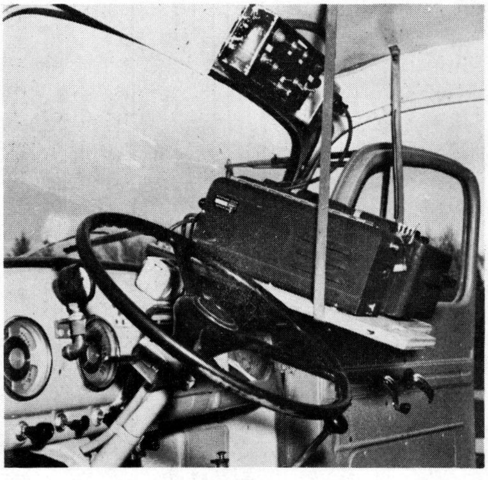


Figure 4. Skid cycle control panel, oscillograph, and strain analyzer.

The skid cycle, which lasts about 4 sec, is completely automatic, controlled by electrically powered cams and micro-switches as shown in Figure 5. When a single starter button is pushed, the following sequence of events takes place:

1. Two electric valves open, flooding the pavement in each wheel track

from water outlets located 10 ft ahead of the trailer wheels.

2. About 1.5 sec later, the trailer brakes are locked by means of an electric valve and air cylinder linkage on the master cylinder.

3. The brakes are released 1.3 sec later.

4. About 1 sec later, the water valves close and the cam drive motor shuts off.

Individual sliding strain measurements are converted to a coefficient value, corrected for weight shift using the method described by Skeels. The average coefficients from each project are summarized for evaluation along with the age, total and commercial traffic volumes, materials and mix details. It is planned that these data will be coded on standard IBM cards to facilitate correlation.

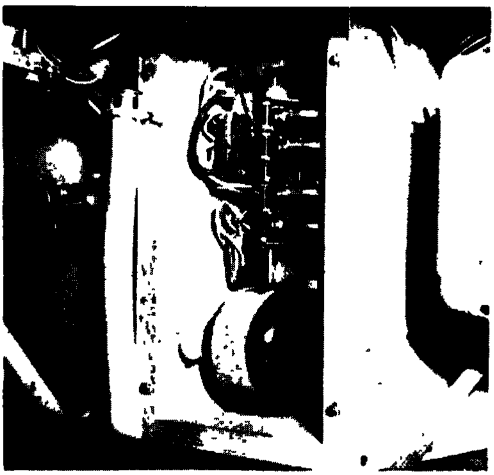


Figure 5. Cycle control cams and motor drive.

Interrelation of skid resistance with project age and traffic volume is accomplished by means of a wear factor, which enables comparison of the projects on a common basis. The wear factor is the product of the average daily traffic volume per traffic lane since construction, weighted for percent of commercial traffic, divided by 1,000 and multiplied by the age of the project in years. Characteristics of pavement materials or mix design will be sought which produce the most gradual decrease in skid resistance as the wear factor increases. This relationship was observed in the 1954 survey and is shown graphically in Figure 6.

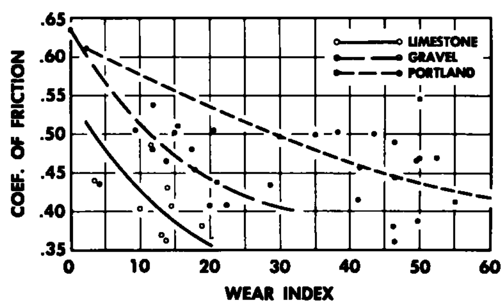


Figure 6. Relation of sliding friction to wear index for three types of pavement surface. (Based on 1954 study.)

Approximately 2,400 skid tests were performed between June and November, 1957, including about 135 portland cement concrete projects, 240 bituminous aggregate and bituminous concrete, and 37 bituminous surface treatments. The wet sliding coefficients run at 40 mph, ranged from a low of 0.10 on a bleeding bituminous surface treatment to about 0.65 on new portland cement concrete. Usually, about six tests are made on each trunkline project at representative locations selected according to the project's length.

Dynamic and static comparative tests of the two agencies' skid equipment were made in and around the General Motors Proving Ground. In general, the Department's equipment gives sliding coefficients about 20 percent higher than General Motors' at 30 mph in the same test areas. This difference is being investigated, since the static calibrations of the two trailers have been found to be the same. The Highway Department's static calibration has not changed after four months of use.

The Department's Traffic Division has requested from time to time that certain projects be tested, due to the frequency of skidding accidents on wet surfaces. These critical areas are tested for skid resistance during the regular field test periods, and the measured coefficients are reported. In most cases, this information has substantiated the need for corrective measures.

As a first step in starting corrective measures, two high-accident intersection areas in Detroit were given anti-skid treatments in the Fall of 1957 utilizing aluminum oxide grain with asphalt and latex emulsions or epoxy resin bond coats. These areas will be retested periodically to determine the effectiveness and permanence of each coating under natural weathering and traffic.

ACKNOWLEDGMENT

The adaptation of the tow truck, skid trailer and control instrumentation were the work of Paul Milliman and Gale Otto of the Electronic Instrumentation Section of the Research Laboratory.

A Study of the Polishing Characteristics of Limestone and Sandstone Aggregates in Regard to Pavement Slipperiness

WILLIAM J. STUTZENBERGER, Research Engineer, and JAMES H. HAVENS, Assistant Director of Research, Kentucky Department of Highways

The coefficient of friction on dry highway surfaces regardless of stone composition and texture has in most cases been at least 0.4 or above. However, some of these same surfaces when lubricated by a small amount of water have given test results dangerously lower. Some interesting theoretical aspects of this situation are presented here along with results from a laboratory study of the fundamental factors affecting tractive friction.

A machine is described for measuring the coefficient of friction between the plane surfaces of 4 in. diameter stone specimens and a rubber annulus of slightly smaller diameter. Measurements were made both wet and dry on finely polished surfaces and on surfaces ground with 80 and 150 grit Carborundum. Tests were conducted under varying loads and speeds. A 60 degree reflectometer was used to evaluate texture and roughness of the plane surfaces. Reflectivity (gloss) values correlated significantly with wet friction values in the highly polished ranges. Tests were conducted on representative samples of four limestones and two sandstones.

Coefficient of friction values of 0.01 and above were measured on finely polished wet limestone surfaces. Sandstones subjected to the same polishing action averaged about 0.22 when wet. In another series of testing, the specimens were abraded with a coarse Carborundum grit, and the wet friction values were consistently between 0.6 and 0.7 for both limestones and sandstones. For further comparison a piece of plate glass was abraded with this same material, and it too measured within the above limits. Dry friction values remained fairly constant regardless of type of stone or texture.

Test results reveal the tendency for fine grained particles bound in a matrix of similar hardness to polish more readily and to a greater extent than hard particles such as quartz bound in a soft matrix. Limestones, being typical of the former condition, polished easier than sandstones.

● PAVEMENT slipperiness is an intrinsic hazard often associated with wet-weather driving. Even the most skilled drivers are not immune to its dangers. Highway departments, generally alert to the problem, erect emergency warning signs at critical locations once they are discovered, or may even begin de-slicking treatment. While Kentucky, at present, has no specific program for measuring and monitoring the slickness of highways, de-slicking operations using natural sandstone rock asphalt or chip seals have been normal practice for many years. Actually, in many cases only slight distinction can be drawn between de-slicking and some maintenance resurfacing. Oftentimes slickness has been one of the principal reasons for resurfacing.

For the past few years, Kentucky has required 50 percent natural silica sand in high-type bituminous concrete surface courses. This is in response to a desire to "build in" skid-resistance and recognizes the susceptibility of surfaces composed entirely of limestone aggregates to polish and become slick. It may be also a reaction from the ideas that high density and high bitumen contents were requisites for durability. While this reaction was not necessarily in repudiation of those ideas, it was an expedient recourse from the slipperiness that they fostered.

The use of 50 percent sand is attributed to the work in Tennessee (24) and Virginia (29). The work in Virginia has demonstrated that 25 to 30 percent sand gives slight although inadequate improvement in skid-resistance, and the work in Tennessee has indicated further improvement as the percentage of sand is increased. However, with 50 percent sand, additional problems arise in the design of the mixtures. The percentage voids in these mixes may be a high as 10 percent; and while these combined circumstances have apparently alleviated the slickness problem to some degree, the possibility remains that this approach may not make the most advantageous use of the sand and limestone aggregates.

Since test data from various sources prove rather conclusively that limestone surface courses are inherently responsible for slickness, this does not present a very favorable outlook for a state where limestones are abundantly used for highway construction, unless skid-resistance can be artifically induced in the limestone or else achieved by some other means.

Elementary physics points out that the coefficient of friction is a property between two materials and that it is thereby largely independent of surface textures, areas of contact, velocities and normal loading (weight). All of this seems to be fairly true for non-lubricated surfaces, and it is not surprising that clean dry pavements regardless of compositions always have high resistance to skidding. Likewise, and as this report later confirms, it has been the general belief that friction between lubricated surfaces is largely dependent upon the texture of the surfaces and on film-strength and viscosity of the lubricant. Thus, from an academic point of view, wet-slickness of a pavement is attributed to texture and not categorically to the identity of the material comprising it. Susceptibility to polishing, however, appropriately classifies such materials.

To further understand the mechanism of wet-slickness, it must be realized that stress at a point-contact is infinitely large and is capable of rupturing or penetrating through a lubricating film. In other words, it is capable of squeezing the lubricant from the contact point. On the other hand, a tire riding on a wet, polished surface tends to trap water within the contact area; and since there are no points of high stress, the escape velocity of the water is very low. The result is that at high speeds the tire tends to ride up on the water film, and the tire is, at least in part, out of actual contact with the surface. Thus a porous surface, or one comprised of sharp angular particles, would tend to relieve these excess hydraulic pressures and thereby produce greater skid-resistance.

Briefly, the present approach to the problem involves a laboratory study of the polishing characteristics of limestones and sandstones in regard to their petrology, resulting textures, and corresponding coefficients of friction, wet and dry. The results, in general, confirm the susceptibility of limestones to polishing as reported elsewhere, but only slight differences were apparent among the various limestones in comparison to the wide difference between the limestones and sandstones. Such differences are attributed to the relative hardness of the grains and cementing materials.

SOME BASIC ASPECTS OF PAVEMENT FRICTION

An automobile or truck is accelerated by an engine, and decelerated, normally, by brakes. But, regardless of the power of its engine or the size and efficiency of its brakes, the maximum rate at which it can vary its speed is ultimately controlled by the coefficient of friction—or traction—between its tires and the pavement. This coefficient, in turn, depends primarily upon the condition of the pavement surface—whether it is wet or dry. To some extent wet friction is affected by speed and by qualities of the tire, such as the hardness and compliance of the tread rubber, the design and condition of the tread, and the inflation pressure. Most dry pavements, regardless of type, provide enough traction to prevent skidding under normal driving conditions; but when they are wet considerable differences in traction may appear dramatically—often dramatically enough to result in death.

When the brakes of a vehicle are locked and all wheels are sliding, the skid resistance of the pavement can be expressed by the formula

$$F = fW$$

where F is the maximum force of friction and denotes the tangential force in the direction of motion; W the normal force or weight of the vehicle; and f the effective coefficient of friction between tires and pavement.

The acceleration of the vehicle due to the force F is expressed as

$$F = Ma = \frac{Wa}{g}$$

where a denotes the acceleration, and W the weight of the vehicle. Combining these two equations gives

$$f = a/g.$$

Thus when a vehicle is moving in any given direction with all its wheels sliding or spinning, its maximum acceleration or deceleration expressed in g's is equal to the coefficient of friction between the tires and pavement.

The most familiar equation applied to this problem is derived by equating frictional energy, F.E. $= fWS$, with kinetic energy, K.E. $= \frac{1}{2}\, mV^2$, from which $fWS = WV^2/2g$ and $f = V^2/2gS$, where V is the maximum velocity and S is the sliding stopping distance. Actually, in this equation f represents a theoretical value of the maximum possible traction during stopping. When V is expressed in miles per hour and S in feet the equation becomes

$$f = \frac{V^2}{30S}.$$

Differentiating either frictional or kinetic energy with respect to time (work/time) gives an equation for power in which f appears as a limiting factor, and $P = \frac{1}{2}\, fWV$. Expressing P in horsepower, V in miles per hour, and assuming W to be 3,850 lb, the equation becomes

$$H.P. = 5.18\, fV.$$

This equation describes the time rate of the work done while skidding to a stop.

These expressions assume that all four wheels of the automobile are in traction and skidding. Except for the fact that during maximum acceleration—"scratching off"—only the rear wheels are normally in traction, the equations would apply equally well to decelerations and accelerations. However, by assuming the weight of the vehicle to be equally distributed over the front and rear wheels, the maximum tractive force that can be developed during acceleration can be expressed approximately as $\frac{1}{2}$ fW. Or, in other words, the maximum horsepower that can be utilized in acceleration is approximately half the amount used in a skidding stop on any particular pavement.

For example, from the stopping distance equation, if f = 0.14 and V = 60 mph, S = 857 ft and H.P. = 42; if f = 0.6 and V = 60 mph, S = 200 ft, and H.P. = 187; then if f = 1 and V = 60 mph, S = 120 ft and H.P. = 310. Here it is seen that the maximum horsepower that could be utilized in accelerating to 60 mph on a pavement where f = 0.14 would be 21. Similarly, when f = 0.6, H.P. = 94; when f = 1, H.P. = 155. Finally, considering f = 1 and V = 100 mph, H.P. = 259.

As f approaches unity, the direction of least resistance becomes inclined upward and tends to limit the maximum force of friction to F = W. Therefore, it is not surprising that pavement friction values may approach but never exceed unity. From above then, if f = 1, the stopping distance equation becomes equivalent to $V^2 = 2gh$ and it is seen that 310 H.P. if fully utilized would produce the same velocity in either a horizontal or vertical direction. At this velocity, 60 mph, regardless of weight, a vehicle has enough stored kinetic energy to cause it to hurtle 121 ft in a vertical direction.

It is understood, of course, that these calculations have not considered the intangible factors of driver reaction time and safe stopping distances. It is obvious, however, that even the highest coefficient of friction can not guarantee safety or even prevent sliding; but it may be reasonably assumed that there would be a greater likelihood of a skidding accident as the coefficient decreases.

Giles (32) has presented an excellent treatise on the physical and statistical aspects of the problem. He points out a likelihood and hazard of unseating unwary passengers if a vehicle is decelerated at greater than 0.5 g and places the comfortable limit of cornering at about 0.3 g. He observed that most drivers occasionally require decelerations of 0.4 g and higher. When $f < 0.4$ g, the risk and frequency of accidents due to skidding increased rapidly, but when $f > 0.5$ g the risk and frequency decreased rapidly. Vectoral additions of the simultaneous effects of cornering and braking indicated an occasional need for $f > 0.5$ g.

Most road surfaces when dry provide coefficients of 0.4 or greater. While the minimum value of 0.4 is not necessarily accepted as a criterion of safety, it is being used by some states as a criterion for de-slicking. If $f < 0.4$ when tested wet, de-slicking treatments are recommended.

EQUIPMENT, MATERIALS AND PROCEDURE

For the comparisons intended, it was necessary to devise a means evaluating the degree to which the stone specimens were polished, and to determine as accurately as possible the coefficient of friction between a prepared specimen of stone and a piece of rubber similar to that used in tires. The use of controlled polishing agents and a 60 degree reflectometer—a gloss meter—was found sufficient to deal with the first problem; but the second required the designing and building of new equipment.

Friction Measuring Device

The device, shown in Figure 1, is designed simply to rotate a rubber ring, or annulus, against the surface of a stone of known composition and

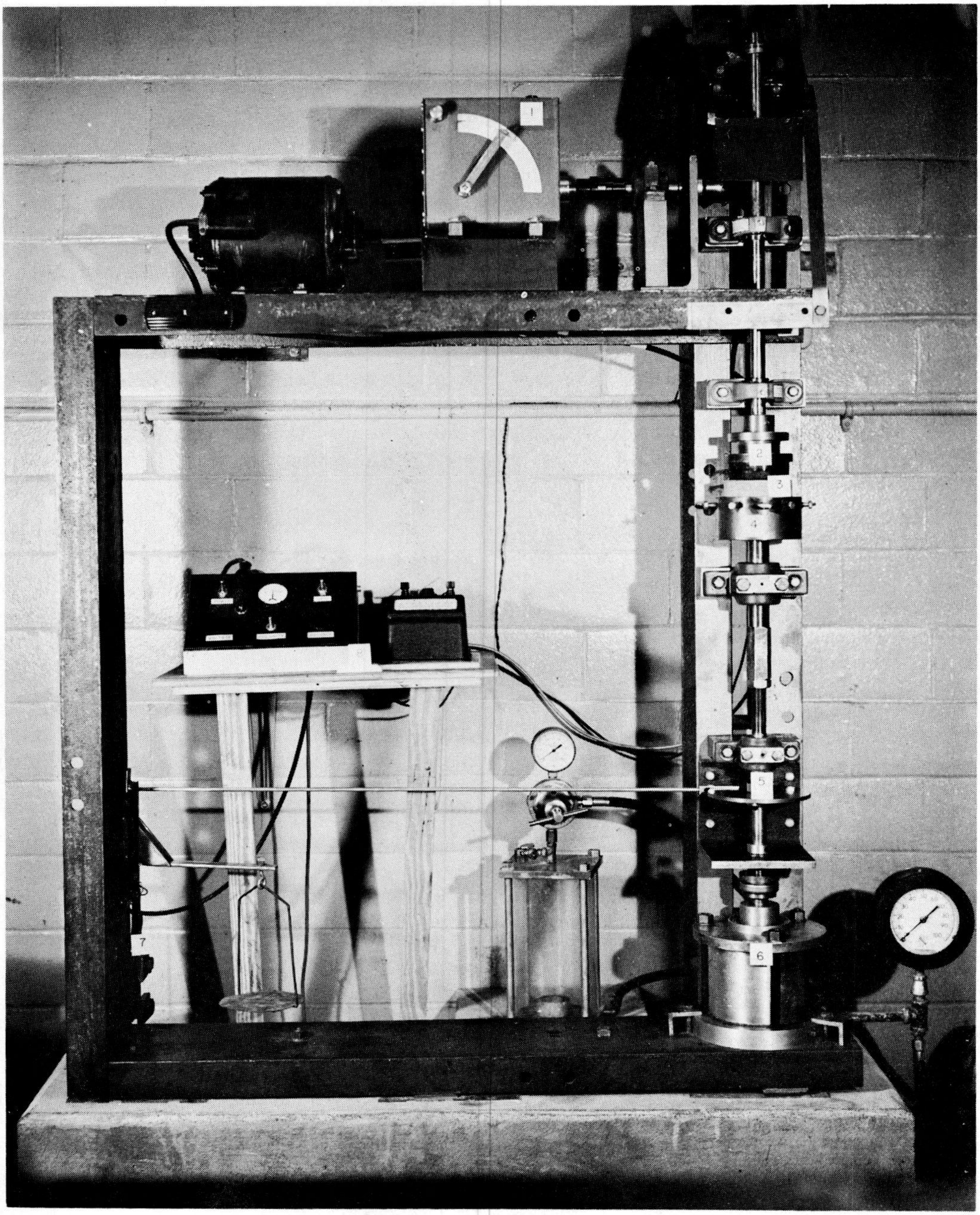


Figure 1. Friction measuring device.

degree of polish and to measure the amount of torque transferred to the stone. In the description which follows, the numbers in parentheses refer to the corresponding numbers of the parts in the illustration.

The shell of the device consists of a framework of 2- by 8-in. channel beams bolted together to provide a rigid support. A 1/3 h.p., 1750 rpm electric motor furnishes the driving power through a hydraulic torque converter (1) which permits the rotation of the upper shaft to be controlled within a range of 0 to 300 rpm. A face plate (2), threaded so it can be detached from the upper shaft, supports the annulus rigidly. A cup-shaped container (4) with three curved metal clamps holds the specimen securely with its face parallel to the surface of the annulus. The cup and the supporting shaft below are designed for use with specimens varying in length from one to five inches, and the clamps can accommodate a 4-in. diameter specimen with a tolerance of $\pm \frac{1}{4}$ in.

A steel disk (5) transfers the torque of the lower shaft through a steel rod to a strain gauge bar (7). The rod can be attached by a pin through either of three holes at different distances from the shaft—1, 1-3/4, or 2-$\frac{1}{2}$ in.—depending on the intensity of torque developed.

The loading mechanism (6) consists of a pneumatic cylinder fitted with a plunger at the top in order to transfer a given load—from 0 to 32 psi—to the lower shaft, and thence to the specimen. The pressure cell gauge was calibrated by loading the shaft with dead weights, opening the air valve, and then recording the reading of the gauge at the instant the shaft began to move upward. This procedure was carried out for several known weights, as well as for the unweighted shaft itself, and from the data a curve was plotted of pressure readings versus the effective load.

The strain gauge bar (7) is attached to the side frame by two clamps, leaving an unsupported free length of ten inches to the point where the rod is attached. On each side of the bar, just above the top clamp, are fastened two type A-1, SR-4 strain gauges. When the machine is in operation the torque of the lower shaft, which holds the specimen, is transferred to the gauge bar, causing it to deflect. This deflection is measured by the changes in resistance within the strain gauges, which are connected in a Wheatstone Bridge circuit, with readings taken from a connected galvanometer. By varying the voltage on the bridge, curves were established for 5, 10, 15, 20, 30 and 50 lb of load, at full scale on the galvanometer. By changing the voltage to correspond with one of these curves, an appropriate scale of the galvanometer could be slected for each test condition. The annuluses were made from a sheet of camelback cold retread rubber and vulcanized in the specially designed mold shown in Figure 2. Each annulus had an outside diameter of 3-3/8 in. and a contact rim width of $\frac{1}{2}$ in.

Reflectometer

A 60 deg specular reflectometer was built for use in determining the degree of fine polish of the stones' surfaces. This device, illustrated in Figures 3 and 4, works simply by directing a beam of light onto a plane surface at an angle of 60 deg from the vertical, and then measuring the intensity of the beam reflected at 60 deg in the opposite direction. Thus, if the surface had "perfect" smoothness—no ridges or peaks whatever—all of the light incident at 60 deg would be reflected at 60 deg, except for that portion absorbed. But the more irregularities in the surface, the more the projected beam will be scattered, and the less the intensity of the 60 deg specular reflection. A measurement of this specularly reflected

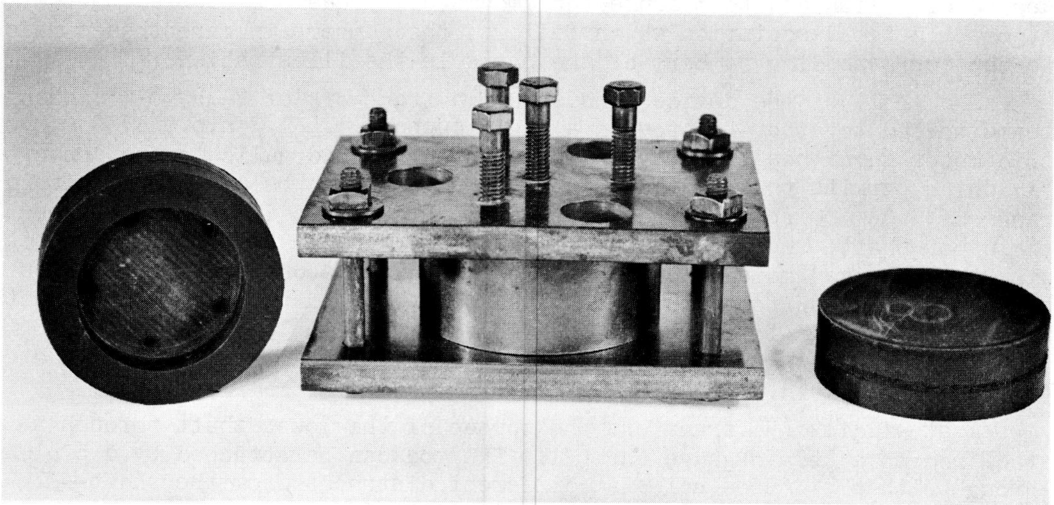


Figure 2. Two of the annuluses used for testing, shown with the vulcanizing mold used in their preparation.

light indicates comparatively the degree of irregularity of the surface, and consequently its smoothness or degree of polish.

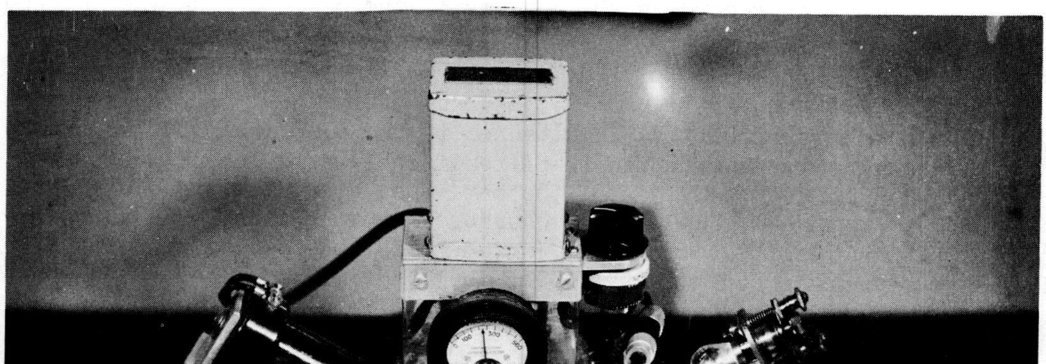


Figure 3. Sixty degree reflectometer in position for measuring surface gloss of specimen.

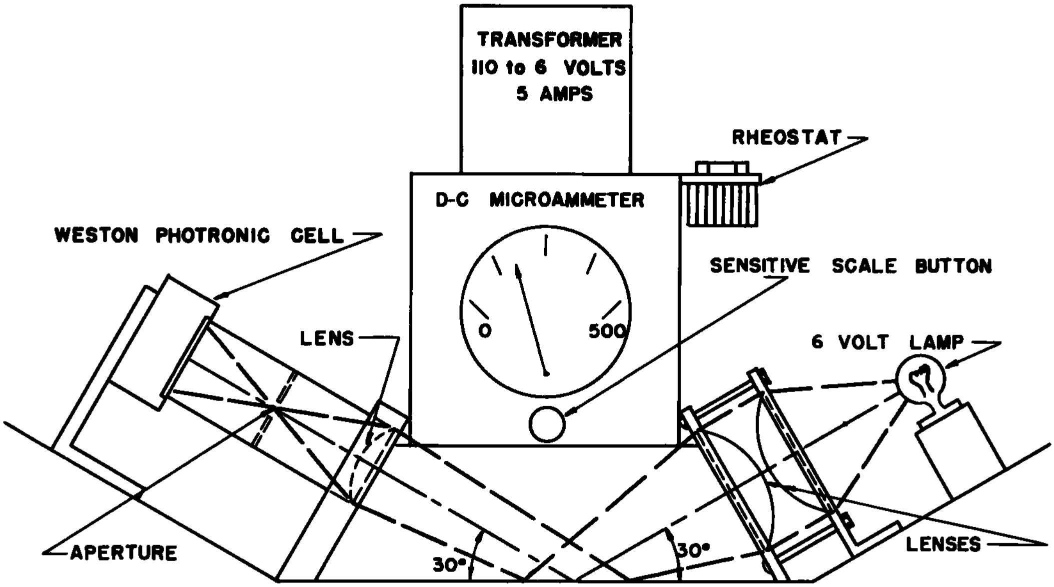


Figure 4. Schematic drawing of sixty degree reflectometer.

The reflectivity readings presented in Table 3, are referred to and based on an assumed 100 percent reflection of a first surface mirror, and are not corrected for the minor differences in absorption of the samples.

Materials

Twenty-four specimens of stone were selected from six quarries throughout the state—four limestone and two sandstone. These were chosen to include the various limestone formations and the varied physical properties of these formations. The limestone quarries supply the stone used on many of the highway projects within their areas, and pass all the requirements of Kentucky highway material specifications. Most sandstones, however, will not meet the state's requirements and therefore are little used in highway construction at present. Considerable experimental work has been done with sandstones and it is anticipated that in the future it may be possible to use more of them. For this reason it was considered important to include sandstone specimens in this project for practical application as well as for comparative purposes.

Samples were secured from both open face and underground quarries. Several chunks were taken at each location in an attempt to choose a representative sample from each quarry. Pieces of stone whose faces were fairly parallel were selected, for ease in coring. A 4-in. core-drill was used to cut the necessary specimens from the chunks.

After the cores were cut, a masonry saw was used to cut the end faces perpendicular to the axis. Cores ranged from 2 to 4 in. in length and when sawed they were ready to be polished.

The specimens were designated as A, B, C, W, S and F, depending on the quarry from which they were obtained. Four or more specimens in each classification were prepared, with the exception of the Oregon limestone and calcareous sandstone groups, which had 1 and 2 stones respectively.

The four limestone classifications were Camp Nelson, Tyrone, Oregon, and Oölitic*; the sandstones were graywacke and calcareous. (Camp Nelson, Tyrone and Oregon are names of Kentucky limestone formations, while Oölitic, graywacke, and calcareous are merely identifying adjectives, used since no definite formation names have been assigned to these types.)

A petrographic examination was made of each specimen to determine the stone's classification. For descriptive purposes, some two or three stones were grouped as one when they were geologically alike. However, each stone was tested independently in measuring the coefficient of friction. A thin section was prepared from a small chip of each and studied to determine the size and kind of mineral particles composing the stone. Photomicrographs taken of the thin sections are presented in the appendix, along with photographs of the polished and roughened surfaces. From the photomicrographs the fine matrix grains can be easily distinguished from the coarser grains. Stones containing large areas of fossil debris or limestone fragments show plainly on these photographs.

Preparation of Specimens

After considerable experimentation a method of polishing was set up and followed. The sawed faces of the specimens were first ground on a wheel faced with a No. 40 aluminum oxide abrasive paper. This was done to smooth off any rough places left after the faces were sawed. The specimens were then ground on a glass plate in a slurry of coarse Carborundum, and this process was repeated with a fine grit Carborundum. There was no set length of time for grinding the specimens; each was ground until the surface was uniform and smooth. Grinding was then continued further on another glass plate with a slurry of levigated Alumina No. 1. For the final polish, an 8-in. buffing wheel was used. This was faced with a heavy gauge duck material saturated with a No. 3 Alumina slurry. The stones were polished on this wheel and periodically measurements were taken of the reflectance of their surfaces. Polishing was continued until three consecutive readings on the reflectometer remained unchanged. The stones were then considered ready for measuring the frictional resistance. They could, of course, have been polished to a higher degree, but for the purpose of this work and within the limits of the methods used this was considered the end point.

After testing, the faces of the stones were prepared for two other conditions—roughening with a No. 80 and then a No. 150 Carborundum. In each case a slurry was made with the designated grit size and using this the stone was ground on a glass plate until the surface was uniform. Here again the amount of surface reflectance was determined with the reflectometer. Final reflectometer readings were taken of all specimens after the polishing or roughening was completed.

Method of Testing

Tests were conducted on all three types of surfaces under both wet and dry conditions. Although the principal interest was in slipperiness, or that condition developed from pavement wetness, consideration of the stones when dry was necessary to provide a clearer picture of the problem involved.

*These were actually bio-clastic limestones, but are referred to in this text under the general classification of Oölitic.

Preliminary testing led to the conclusion that tests could be conducted best at speeds of 180 and 240 rpm and at pressures of 10, 15 and 20 psi. This would provide a range such that sufficient data could be collected and dependence would not be merely on a few specific tests. Also, the speeds and pressures were well within the limits of the machine.

The testing operation itself was relatively simple. The specimen was placed in the holder, leveled, and locked tightly into place by the thumb screw clamps. The motor switch was opened and the lever on the converter box was set to provide the desired rpm. The air valve was opened to the desired pressure. With everything now in operation the galvanometer was read as soon as it reached a steady position and held it. This completed the testing operation. For running the wet tests a large rubber band was clamped around the top of the specimen. An amount of water sufficient to keep the surface well covered was placed within this band. If the water became hot during the testing period the test was halted, water changed, and the test begun again. Three runs were performed for each setting of pressure and speed, and from these the average was calculated.

RESULTS AND ANALYSIS

The coefficient of friction values for all stones were calculated by the following method. The readings taken from the galvanometer were converted into pounds, using the calibration graphs for each respective bridge voltage. Since the frictional resistance was taken in pounds, it was necessary to multiply the tangential force in pounds by the distance from its line of action to the center of the shaft. All readings were taken when the rod was fastened at either 1-3/4 or 2-1/2 in. from the shaft center.

The basic friction formula is stated as $f = F/N$. The normal load, N, in this case becomes moment of normal force (applied pressure in pounds times the mean radius of the annulus) and F, becomes moment of the tangential force, or by formula,

$$f = \frac{M}{P\left(\frac{r_2 + r_1}{2}\right)}$$

This formula was used in computing all coefficients of friction values.

Each specimen was tested wet and dry for three different surface conditions at various loads and speeds. The values determined for each classification group and test condition were averaged. There being but one specimen in the Oregon classification its value in comparison was limited. The results of all friction tests are given in Tables 1 and 2. Reflectivity data for all specimens and conditions reported in Tables 1 and 2 are given in Table 3.

Figure 5 gives a comparison of the average coefficient of friction for each classification at each loading for the polished wet and dry surfaces. For the wet surfaces the variation between the four limestones was slight. At a normal load of 15 psi the range was from 0.019 to 0.033, with an average of 0.027. The value for the two sandstones was somewhat greater, approximately 0.1, or more than three times the average of the limestones. For the 20 psi load the average of the limestones was about 0.06, with the sandstones averaging 0.223, approximately four times the limestone value. (As a note of comparison and interest, it was found that the coefficient of friction for ball bearings was in the range of 0.0011 to 0.0015.)

TABLE 1

COEFFICIENT OF FRICTION VALUES FOR WET SURFACES

Specimen No.	Surface / Load / R.P.M.	Polished 20psi 180	Polished 20psi 240	Polished 15psi 180	Polished 15psi 240	150 Grit 20psi 180	150 Grit 20psi 240	150 Grit 15psi 180	150 Grit 15psi 240	150 Grit 10psi 180	150 Grit 10psi 240	80 Grit 20psi 180	80 Grit 20psi 240	80 Grit 15psi 180	80 Grit 15psi 240	80 Grit 10psi 180	80 Grit 10psi 240
								Camp Nelson									
C_1		0.095	0.090	0.044	0.032	0.69	0.63	0.70	0.60	0.49	0.38	0.68	0.66	0.66	0.63	0.47	0.48
C_2		0.034	0.030	0.023	0.025	0.69	0.65	0.70	0.67	0.46	0.20	0.67	0.66	0.68	0.65	0.46	0.45
C_3		0.083	0.080	0.032	0.030	0.69	0.61	0.73	0.65	0.47	0.21	0.67	0.69	0.67	0.65	0.49	0.49
A_1		0.056	0.053	0.034	0.030	0.66	0.61	0.67	0.68	0.34	0.26	0.63	0.66	0.64	0.62	0.56	0.42
A_2		0.039	0.034	0.029	0.026	0.66	0.60	0.67	0.65	0.42	0.25	0.65	0.66	0.64	0.65	0.42	0.46
A_4		0.051	0.047	0.027	0.025	0.66	0.62	0.75	0.66	0.53	0.44	0.59	0.59	0.66	0.60	0.52	0.48
B_4		0.053	0.052	0.024	0.023	0.73	0.69	0.68	0.64	0.22*	0.47	0.67	0.71	0.69	0.65	0.55	0.48
B_5		0.047	0.045	0.023	0.022	0.66	0.62	0.67	0.63	0.50	0.43	0.70	0.72	0.67	0.66	0.48	0.49
Avg.		0.057	0.054	0.030	0.027	0.68	0.63	0.70	0.65	0.46	0.33	0.66	0.67	0.66	0.64	0.49	0.47
								Tyrone									
A_3		0.053	0.049	0.027	0.023	0.68*	0.61*	0.69*	0.61*	0.43*	0.38*	0.66	0.67	0.66	0.63	0.55	0.51
B_1		0.019	0.016	0.011	0.008	0.37	0.36	0.29	0.27	0.19	0.15	0.79	0.77	0.72	0.65	0.55	0.39
B_2		0.020	0.016	0.013	0.010	0.32	0.31	0.29	0.27	0.13	0.14	0.75	0.73	0.70	0.65	0.49	0.39
B_3		0.095	0.083	0.034	0.030	0.35	0.34	0.28	0.26	0.15	0.15	0.75	0.77	0.67	0.65	0.46	0.44
C_4		0.059	0.052	0.030	0.024	0.23	0.22	0.24	0.23	0.12	0.14	0.68	0.68	0.66	0.63	0.44	0.46
Avg.		0.049	0.043	0.023	0.019	0.32	0.31	0.28	0.26	0.15	0.15	0.73	0.72	0.68	0.64	0.50	0.44
								Oregon									
C_5		0.102	0.093	0.036	0.033	0.70	0.68	0.73	0.66	0.28	0.22	0.68	0.66	0.66	0.63	0.48	0.43
								Oölitic									
W_1		0.060	0.052	0.040	0.037	0.61	0.59	0.65	0.59	0.51	0.44	0.70	0.69	0.67	0.63	0.44	0.45
W_2		0.052	0.048	0.021	0.020	0.72	0.63	0.65	0.61	0.36	0.42	0.74	0.73	0.66	0.65	0.38	0.46
W_3		0.061	0.052	0.037	0.032	0.65	0.63	0.66	0.59	0.50	0.43	0.69	0.71	0.64	0.67	0.49	0.49
W_4		0.057	0.044	0.032	0.028	0.69	0.61	0.62	0.58	0.41	0.37	0.72	0.70	0.64	0.66	0.49	0.46
Avg.		0.058	0.049	0.033	0.029	0.67	0.61	0.65	0.59	0.45	0.42	0.71	0.71	0.65	0.65	0.45	0.47
								Graywacke									
S_1		0.099	0.090	0.053	0.050	0.70	0.64	0.66	0.62	0.49	0.49	0.72	0.72	0.65	0.62	0.51	0.46
S_2		0.325	0.295	0.143	0.130	0.72	0.71	0.70	0.67	0.53	0.51	0.71	0.70	0.73	0.66	0.54	0.51
S_3		0.337	0.316	0.096	0.079	0.73	0.66	0.67	0.64	0.51	0.50	0.66	0.69	0.72	0.65	0.54	0.50
S_4		0.350	0.334	0.240	0.227	0.66	0.65	0.64	0.61	0.52	0.48	0.73	0.72	0.68	0.65	0.52	0.51
Avg.		0.278	0.257	0.133	0.122	0.70	0.67	0.67	0.64	0.51	0.50	0.71	0.71	0.70	0.65	0.53	0.50
								Calcareous									
F_1		0.189	0.172	0.115	0.096	0.70	0.67	0.71	0.61	0.50	0.43	0.67	0.69	0.64	0.65	0.49	0.49
F_2		0.234	0.206	0.121	0.097	0.73	0.73	0.63	0.62	0.51	0.47	0.73	0.73	0.63	0.62	0.51	0.47
Avg.		0.212	0.189	0.118	0.097	0.72	0.70	0.67	0.62	0.51	0.45	0.70	0.71	0.64	0.64	0.50	0.48
								Plate Glass									
		0.013	0.014	0.010	0.011	0.64	0.60	0.60	0.61	0.46	0.49	0.72	0.69	0.66	0.61	0.63	0.56

* Not included in average

TABLE 2

COEFFICIENT OF FRICTION VALUES FOR DRY SURFACES

Specimen No.	Surface / Load / R.P.M.	Polished 15psi Incipient	Polished 10psi Incipient	150 Grit 20psi 180	150 Grit 20psi 240	150 Grit 15psi 180	150 Grit 15psi 240	150 Grit 10psi 180	150 Grit 10psi 240	80 Grit 20psi 180	80 Grit 20psi 240	80 Grit 15psi 180	80 Grit 15psi 240	80 Grit 10psi 180	80 Grit 10psi 240
Camp Nelson															
C_1		0.89	0.45	0.96	0.89	0.97	0.87	0.84	0.63	0.98	0.95	0.99	0.89	0.68	0.55
C_2		0.88	0.59	0.96	0.92	0.98	0.98	0.82	0.77	0.96	0.94	0.98	0.91	0.87	0.69
C_3		0.82	0.50	0.99	0.95	0.97	0.96	0.80	0.69	0.97	0.94	0.99	0.86	0.82	0.64
A_1		0.63	0.39	0.99	0.94	0.98	0.93	0.83	0.75	——	0.93	0.97	0.90	0.81	0.82
A_2		0.69	0.37	0.96	0.92	0.98	0.95	0.80	0.74	0.93	0.88	0.94	0.92	0.72	0.74
A_4		0.75	0.44	0.87	0.87	0.98	0.91	0.91	0.76	0.90	0.84	0.99	0.85	0.78	0.66
B_4		0.87	0.58	0.85	0.83	0.96	0.94	0.78	0.71	0.97	0.92	0.97	0.90	0.74	0.72
B_5		0.94	0.60	0.84	0.81	0.94	0.89	0.72	0.68	0.91	0.83	0.93	0.80	0.73	0.61
Avg.		0.81	0.49	0.93	0.89	0.97	0.93	0.81	0.72	0.95	0.90	0.97	0.88	0.77	0.68
Tyrone															
A_3		0.72	0.45	0.99	0.98	0.90	0.92	0.74	0.66	0.94	0.89	0.96	0.86	0.75	0.70
B_1		0.79	0.44	0.93	0.94	0.99	0.98	0.92	0.79	——	0.94	0.99	0.95	0.82	0.73
B_2		0.89	0.47	——	0.98	0.99	0.99	0.76	0.71	0.95	0.90	0.94	0.87	0.73	0.66
B_3		0.81	0.62	——	0.99	0.91	0.95	0.69	0.71	——	0.95	0.97	0.81	0.78	0.61
C_4		0.93	0.49	——	——	0.95	0.88	0.76	0.65	——	0.95	0.98	0.87	0.74	0.63
Avg.		0.83	0.49	0.96	0.97	0.95	0.94	0.78	0.70	0.95	0.93	0.97	0.87	0.76	0.67
Oregon															
C_5		0.67	0.37	0.89	0.86	0.99	0.95	0.86	0.68	0.96	0.92	0.96	0.87	0.70	0.61
Oölitic															
W_1		0.69	0.41	0.94	0.91	0.92	0.87	0.69	0.64	0.91	0.88	0.89	0.85	0.65	0.62
W_2		0.89	0.43	0.95	0.89	0.98	0.74	0.94	0.71	0.87	0.83	0.98	0.77	0.77	0.55
W_3		0.72	0.41	0.81	0.79	0.97	0.79	0.71	0.63	0.83	0.76	0.86	0.80	0.66	0.59
W_4		0.82	0.51	0.93	0.87	0.99	0.94	0.75	0.73	0.91	0.86	0.91	0.87	0.71	0.67
Avg.		0.78	0.44	0.91	0.87	0.97	0.84	0.77	0.69	0.88	0.83	0.91	0.82	0.70	0.61
Graywacke															
S_1		0.84	0.44	0.83	0.78	0.90	0.86	0.68	0.68	0.84	0.79	0.84	0.79	0.67	0.62
S_2		0.92	0.53	0.89	0.86	0.89	0.88	0.68	0.67	0.86	0.80	0.81	0.76	0.65	0.59
S_3		0.77	0.49	0.82	0.77	0.90	0.84	0.67	0.63	0.85	0.79	0.75	0.70	0.53	0.49
S_4		0.59	0.58	0.84	0.77	0.86	0.81	0.65	0.63	0.83	0.78	0.74	0.71	0.65	0.59
Avg.		0.78	0.51	0.85	0.80	0.89	0.85	0.67	0.65	0.85	0.79	0.79	0.75	0.63	0.57
Calcareous															
F_1		0.78	0.39	0.87	0.84	0.87	0.84	0.66	0.62	0.90	0.83	0.82	0.78	0.65	0.57
F_2		0.78	0.34	0.81	0.75	0.86	0.87	0.64	0.66	0.84	0.78	0.81	0.78	0.63	0.58
Avg.		0.78	0.37	0.84	0.80	0.87	0.86	0.65	0.64	0.87	0.81	0.82	0.78	0.64	0.58
Plate Glass															
		0.99	0.77	0.88	0.82	0.96	0.90	0.80	0.68	0.96	0.90	0.92	0.81	0.73	0.72

TABLE 3

REFLECTOMETER READINGS IN PERCENT*

Sample	Polished Surface	150 Grit Surface	80 Grit Surface
A_1	6.5	0.7	0.7
A_2	7.8	0.7	0.7
A_3	7.0	0.7	0.7
A_4	7.0	0.7	0.7
B_1	10.4	0.9	0.9
B_2	8.7	0.9	0.9
B_3	5.7	0.9	0.7
B_4	7.4	0.7	0.7
B_5	7.2	0.4	0.4
C_1	4.3	0.7	0.7
C_2	7.8	0.7	0.7
C_3	5.9	0.7	0.7
C_4	7.0	0.9	0.9
C_5	5.2	0.7	0.7
W_1	3.7	0.7	0.7
W_2	5.7	0.7	0.7
W_3	3.9	0.4	0.4
W_4	4.6	0.7	0.7
S_1	4.3	0.5	0.5
S_2	2.6	0.4	0.4
S_3	2.2	0.4	0.4
S_4	2.2	0.4	0.4
F_1	1.7	0.4	0.4
F_2	1.1	0.4	0.4

*Based on an assumed 100 percent reflectance value as taken from a first surface mirror.

The Tyrone formation was found to have the lowest average of all classifications at both loadings. The petrology indicates the average grain size of the Tyrone stones to be approximately 0.0043 mm, or the smallest of any of the groups. Another interesting fact is that the stones in this group reflected a larger percentage of light when the surface gloss was measured than any other group. The variation in the two sandstones might be due to the large areas of fossil debris present in the calcareous stones compared with the little or none present in the graywackes. This debris, evident in the photographs of the polished stone surfaces, polished easily and seemed much smoother than the base material.

Figures 6 and 7 present a wet and dry surface comparison of the No. 80 and 150 grit surfaces respectively. The graphs showing coefficients for the 15 and 20 psi loadings indicate that the coefficients are virtually the same for the wet surfaces, with one exception: the 150 grit surface of the Tyrone classification is consistently lower at each testing load. It is

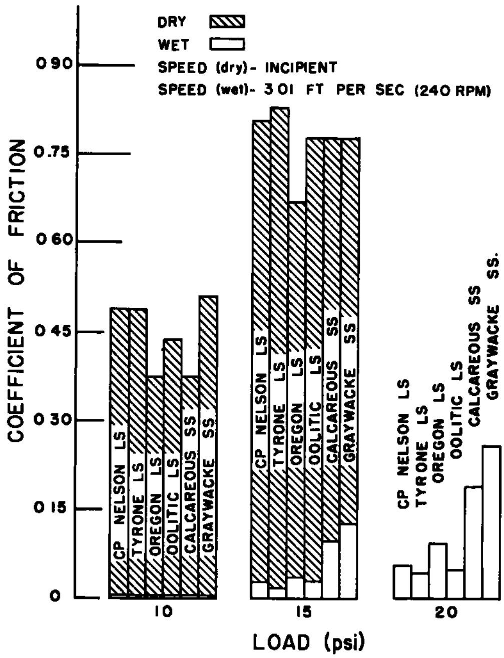


Figure 5. Relationship between coefficient of friction and load for all polished specimens, wet and dry.

known that the Tyrone specimens are more dense and fine grained than any other stones tested. It is probable, then, that when the specimens are roughened with the 150 grit a certain amount of the surface area remains unaltered or is altered to such a small degree that the area as a whole remains polished and, compared with the other classifications, only a few small, rounded asperities are formed. Since the stones are so dense, it is difficult to tear the grains apart or loose; and moreover, when a grain is torn loose its area compared to the entire surface area is so minute that its effect on the surface as a whole is slight. There was positive evidence in polishing the sandstones that a certain number of surface grains were broken from the loose cementing material, while little or no evidence of this was found among the limestones.

It was found that for all classifications other than the Tyrone the wet coefficient of friction values are within a close range. In no case is there more than 0.1 difference between the specimens for any corresponding load. For the 150 grit wet surface the over-all average values are 0.66, 0.63 and 0.38 for 20, 15 and 10 psi loadings respectively. For the 80 grit wet surface the averages are 0.70, 0.64, and 0.47 for like loadings. The 80 grit specimens were less variable than the 150. Figure 6 shows that at the 15 psi loading the variation on the 80 grit roughened surface for all specimens is less than 0.03.

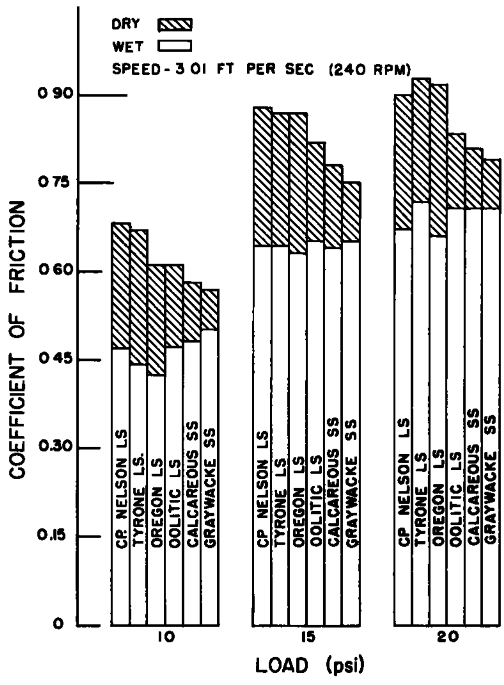


Figure 6. Relationship between coefficient of friction and load for all specimens roughened with No. 80 grit, wet and dry.

When the coefficient of friction reaches an equal, constant value for the various stones this would indicate the coefficient to be independent of the type of stone, grain size, and chemical or petrological composition, and dependent principally upon the surface texture and condition. This is believed to be the case for all stones roughened with the 80 grit. There was

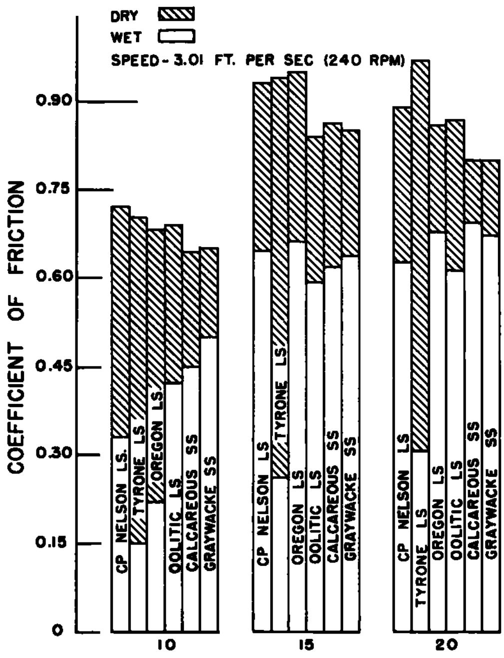


Figure 7. Relationship between coefficient of friction and load for all specimens roughened with No. 150 grit, wet and dry.

little fluctuation for some stones even when roughened with the 150 grit. However, to determine that point where the coefficient of friction is dependent upon the surface condition rather than independent of it, it would be necessary to roughen the specimens with varying grit sizes smaller than 80 until the coefficient of friction measurements responded with a definite decrease in value.

The 80 and 150 Carborundum grits were used to grind a piece of plate glass. This glass was tested and its value of friction was well within the range of the stones tested under like conditions. The reflectometer readings for all stones roughened with the 80 to 150 grit showed less than one percent reflectance, which would indicate little polished surface area remaining. In this case, however, the values are so small the applicability of the reflectometer for determining minor differences within this range would be impractical.

Reviewing Figures 6 and 7 for the coefficient of friction for 80 and 150 grit roughened dry surfaces a much wider variation is found than for the wet surfaces. Values range from approximately 0.75 to 0.97 for the 15 and 20 psi loadings. Here, too, there appears to be a differentiation between the Camp Nelson, Tyrone and Oregon limestone group and the sandstones and Oölitic limestone group. The average for the first group—both 80 and 150 grit at 15 and 20 psi loading—being 0.90 and 0.82 for the sandstones and Oölitics. Problems encountered in conducting the dry tests were those of the heat generated and of the rubber's shearing. These were held to a minimum but could not be eliminated entirely; it was realized that their effect was present but the degree by which they altered the results could not be directly ascertained. During the progress of the tests it was noted that the fine grained stones—Camp Nelson, Tyrone and Oregon—generated heat and burned rubber more rapidly than the other stones. It is likewise true that sheared rubber shreds tended to contaminate the interface. These facts may account for some variations in the stones and possibly explain why the finer grained stones had coefficients higher than the others when tested dry.

The problem of heat, shredding and adhesion of rubber from the annulus was of such magnitude that it was impossible to measure the coefficient of friction of the polished dry surface at the same speeds used in the other tests. The results given in Figure 5 are those of tests performed at incipient motion and at loads of 10 and 15 psi only. At the 15 psi loading all classifications averaged near 0.78 while the 10 psi loading was less, averaging about 0.44. Because of the complex effects of velocity on frictional forces these measurements made at incipient motion can not be directly compared with those conducted at other speeds. The coefficient values do follow the laws governing friction in that kinetic friction was found to be less than static friction. It is generally accepted that frictional resistance will vary with speed, but no established relationship has been formulated.

The discussion of the friction values determined in this project was restricted to those data taken with an annulus rotation of 240 rpm. Throughout the testing procedure it was found that the operation of the friction measuring device was smoother and more consistent at 240 rpm. The difference between the values at 240 and 180 rpm is slight, however; most of them fall within 0.05 of each other for the particular loading conditions. Also, more emphasis is placed upon the values at the 15 and 20 psi load, because here again it is believed these data represent the operation of the friction measuring machine at its best.

CONCLUSIONS

It has been deduced here and elsewhere that the polishing of pavement aggregates is due principally to fine abrasive particles found in "road scum" and imbedded in tire treads. The continual attrition of these materials produced by the movement of traffic may cause coarse wear in some cases without producing slickness; while in others it may cause fine wear, polishing and consequent slickness when wet. This action is analogous to wear on a grinding wheel; it is well known that grinding wheels must undergo a certain amount of coarse wear or else they become dull and clogged. Thus the hardness and cementation of the grains are very important factors in their design. There was an obvious parallel to this in attempting to polish sandstones: oftentimes the quartz particles would be torn loose from the weaker cementing materials, whereas grains more firmly bound eventually polished, and the surrounding cementing material was abraded away. Since this resulted in a surface comprised of polished facets and interspaced cavities, the sandstones always retained a significantly higher wet friction factor than the limestones.

The tendency of sandstones to undergo coarse wear, even when subjected to fine abrasion, is attributed to the differential in hardness between the quartz sand particles and the cementing material. Also, since quartz is ranked seventh in the scale of mineral hardness, the only mineral abundantly present in road scum that would be sufficiently hard to cause its polishing would be quartz itself.

Limestones (calcite) rank third in the hardness scale and are therefore susceptible to polishing or wear by almost any grit that might be present in road scum. However, some differences among limestones are apparent; and these seem inherently related to the size, interlocking, and cementation of the crystals. Fine-grained, dense stone polished more readily than coarse-grained stone and gave consistently lower wet friction coefficients and higher gloss readings. Close attention to the photomicrographs of the polished and roughened surfaces and thin section (see Appendix) of these stones will show the variations in grain size and crystallization. None of the limestones showed any evidence of grains being torn out of their sockets during polishing.

The general conclusions from the study are as follows:

1. The dry friction factors between tread rubber and the limestones, sandstones, and glass seem to be largely independent of the types of materials and their surface textures. Values ranged from about 0.4 upward.
2. The wet friction factors seem to be independent of the types but

inherently dependent upon the textures of the materials. Values ranged from 0.010 upward to 0.73 from the most highly polished to the roughest conditions.

3. Sandstones never exhibited as low a wet-friction value as limestones because they could not be polished to the same degree.

4. The low friction values on wet surfaces are attributed to lubrication of the contact interface. Highly polished dense surfaces are easily lubricated, whereas the asperities of rough surfaces tend to protrude through the water film, and the excess hydraulic pressures within the contact interface tend to dissipate through the valleys or pores of the rough surfaces.

5. These results also suggest that a high friction coefficient might be preserved or even restored in soft pavement aggregates by inducing coarse wear. To accomplish this, it would be necessary to provide periodically a coarse grit such as sharp sand and to rely upon traffic to grind and roughen the pavement surface.

The report deals only with specific aspects of pavement slipperiness related to or influenced by the aggregate. It has been shown that some control over slickness may be exercised by selection of types of aggregate or possibly by inducing sacrificial wear. The authors, of course, recognize that there are many aspects of the problem beyond the scope of the present report. Sand-asphalt surface treatments offer an obvious alternative method of providing skid-resistance, irrespective of the structural aggregate within the pavement; and it is anticipated that future research will be directed along that line, as well as towards the further development of polishing resistant aggregates.

Appendix
Descriptions of Specimens

Limestones

$A_{1,2,4}$

A Camp Nelson brown dolomitic limestone with a mortar texture consisting of a matrix of anhedral calcite crystals ranging from 0.00086 mm to 0.017 mm with average size of 0.0043 mm, fibrous calcite, and zones of dolotomized areas ranging up to 9 mm wide and 35 mm long.

A_3

A light brown Tyrone dolomitic limestone with a mortar texture consisting of anhedral calcite crystals ranging from 0.00086 mm to 0.017 mm with average size of 0.0043 mm, areas of few dispersed dolomite rhombs to areas which are predominately dolomite, sizes of the dolomite rhombs ranging from 0.017 mm to 0.13 mm.

$B_{1,2}$ A light gray lithographic Tyrone limestone with a mortar texture consisting of anhedral and euhedral calcite crystals measuring from 0.00086 mm to 0.017 mm with average size of 0.0034 mm. The stone also contains a few dispersed dolomite rhombs up to 0.05 mm and areas of clear anhedral and euhedral calcite crystals up to 0.58 mm.

B_3

A light brown Tyrone limestone with a mortar texture consisting of anhedral calcite crystals from 0.0017 mm to 0.013 mm with average size of 0.0043 mm, numerous dispersed euhedral dolomite rhombs ranging from 0.017 mm to 0.083 mm, and areas of clear calcite crystals ranging from 0.017 mm to 1 mm. Matrix shows cell structure of fossils.

B_4

A light brown Camp Nelson limestone with a mortar texture consisting of anhedral calcite crystals ranging from 0.0017 mm to 0.015 mm with average size of 0.0061 mm; there are areas of very few dolomite rhombs to areas of numerous dolomite rhombs ranging in size from 0.025 mm to 0.083 mm, and dispersed euhedral calcite crystals up to 0.58 mm.

B_5

A grayish brown Camp Nelson dolomitic limestone with a mortar texture consisting of anhedral crystals of calcite ranging from 0.0016 mm to 0.0103 mm with average size of 0.0043 mm, numerous dolomite rhombs ranging from 0.017 mm, to 0.041 mm and areas of clear anhedral calcite crystals up to 1.58 mm in length with crystal sizes up to 0.33 mm.

C_1

A Camp Nelson formation mortar textured pink calcitic dolomite consisting of anhedral calcite crystals ranging from 0.00086 mm to 0.0103 mm and slightly dispersed dolomite rhombs ranging from 0.017 mm to 0.125 mm. Gray areas are due to disseminated pyrite and carbonaceous matter.

C_2 and C_3

A Camp Nelson formation pink dolomite with euhedral mosaic texture consisting of dolomite rhombs ranging from 0.017 mm to 0.091 mm in cubic packing. The voids are filled with anhedral calcite crystals ranging from 0.0017 mm to 0.017 mm. Portions of the stone are gray in color due to the disseminated pyrite and carbonaceous matter.

C_4

A Tyrone formation light brown limestone with a mortar texture consisting of anhedral calcite crystals ranging from 0.00086 mm to 0.019 mm and numerous dispersed euhedral crystals of dolomite ranging from 0.017 mm to 0.175 mm. There are also numerous precipitated calcite infillings ranging up to 7 mm in size.

C_5

An Oregon formation light pink dolomite with a simple mosaic texture of dolomite rhombs ranging from 0.025 mm to 0.12 mm with average size of 0.083 mm.

W_1 and W_2

A bio-clastic limestone with a crystalline calcite matrix enclosing partly silicified fossils, limestone fragments, chlorite, and disseminated pyrite within the interstices. The gray color of the rock is accredited to the pyrite.

Grain sizes are as follows: fossils - up to 4.6 mm; limestone fragments - up to 6.0 mm; pyrite - up to 0.12 mm.

W_3

A bio-clastic limestone with matrix composed of calcite, quartz, chalcedony, and pyrite. Enclosed within the matrix is detrital carbonate, silicifed fossil debris, chlorite, muscovite, biotite, and angular quartz.

Grain sizes are as follows: detrital carbonate - 1.0 mm to 2.0 mm;

fossil debris - 0.03 mm to 0.5 mm; chlorite - 0.06 mm to 0.2 mm; muscovite - up to 1.0 mm; biotite - up to 0.17 mm; quartz - up to 0.17 mm.

W_4

A bio-clastic limestone composed of matrix of quartz, chlorite, clay and calcite. Enclosed within the matrix are limestone fragments, calcareous and silicified fossil debris, and chlorite aggregates.

Grain sizes are as follows: limestone fragments - up to 1.74 mm; fossil debris - up to 1.2 mm; chlorite - up to 0.24 mm.

Sandstones

S_1

A light gray subgraywacke with matrix composed of calcite, iron oxide, quartz, sericite and chlorite. The disrupted framework is composed of angular to sub-angular quartz, muscovite, chlorite andesine, and microcline.

Grain sizes of disrupted framework are as follows: quartz - up to 0.44 mm; muscovite - up to 1.0 mm; chlorite - up to 0.5 mm; microcline - 0.067 mm to 0.33 mm; andesine - 0.067 mm to 0.33 mm.

S_2

A light gray subgraywacke with framework composed of angular to sub-rounded quartz, chlorite, muscovite, microcline and andesine. The interstices are filled with cement of quartz, limonite, and very little calcite. Some interstices are impregnated with asphalt residue.

Grain sizes of framework are as follows: quartz - 0.008 mm to 0.50 mm; chlorite - 0.07 mm to 0.50 mm; muscovite - up to 0.6 mm; microcline - up to 0.20 mm; andesine - up to 0.20 mm.

S_3

A light gray-green subgraywacke composed of matrix of calcite, iron oxide, quartz, and chlorite. Areas up to 1 mm are impregnated with asphalt. The disrupted framework is composed of angular to sub-rounded quartz grains, muscovite, chlorite, microcline, and andesine.

Grain sizes of disrupted framework are as follows: quartz - up to 0.5 mm, muscovite - up to 1.0 mm; chlorite - up to 1.1 mm; microcline - up to 0.46 mm; andesine - up to 0.46 mm.

S_4

A light gray graywacke composed of a cubic packed framework of angular to sub-rounded quartz grains, plagioclase feldspar, scattered grains of chlorite, and numerous muscovite flakes. The interstices are filled with cement consisting of quartz, calcite, and limonite. Some interstices are impregnated with asphalt.

Grain sizes of framework are as follows: quartz - up to 0.45 mm; muscovite - up to 0.83 mm; chlorite - up to 0.22 mm; feldspar - up to 0.25 mm.

F_1

A light gray calcareous sandstone with matrix of fibrous calcite, euhedral and anhedral calcite, sericite, and quartz. Dispersed within

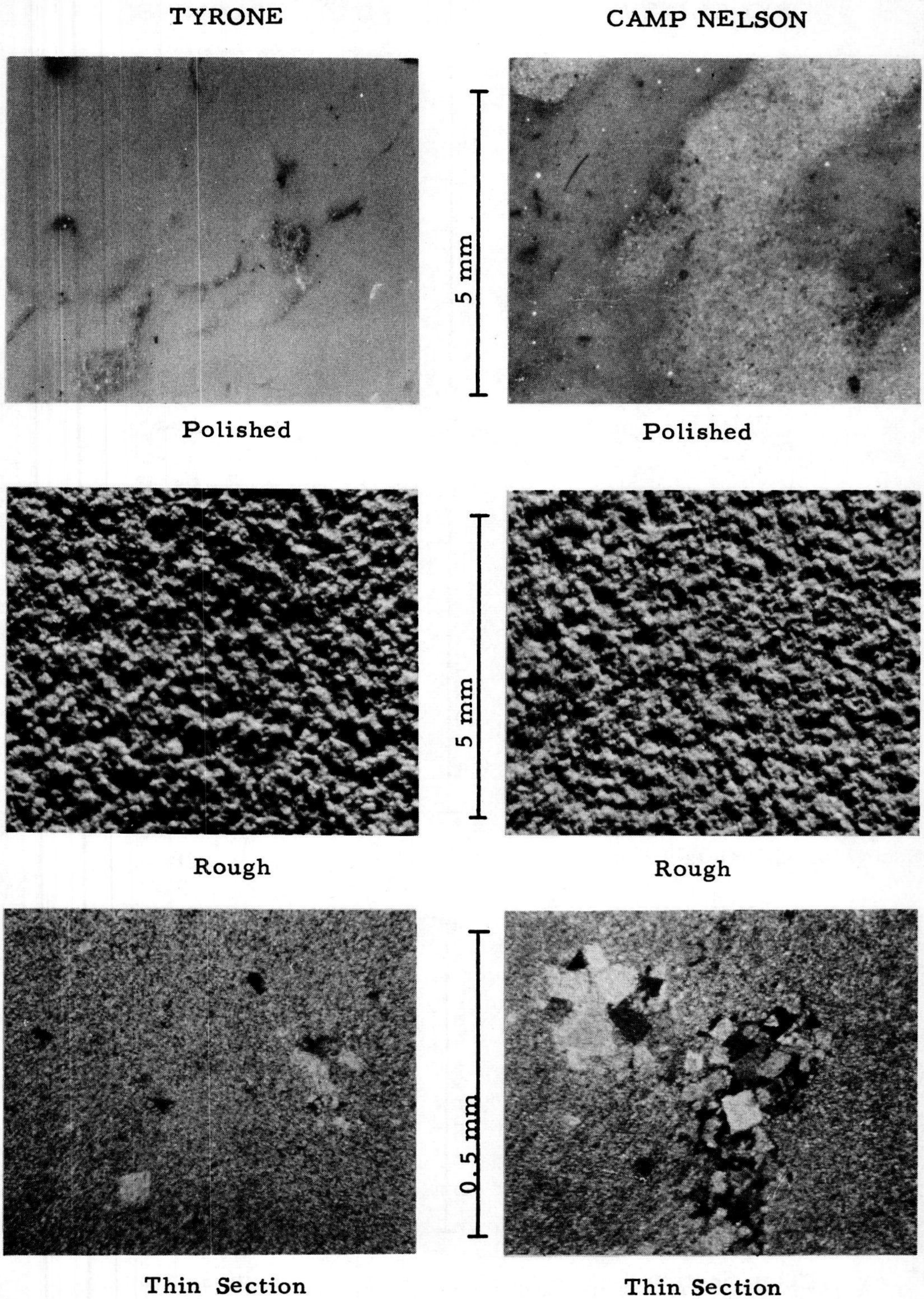


Figure 8. Photomicrographs of prepared specimens of tyrone and Camp Nelson limestones.

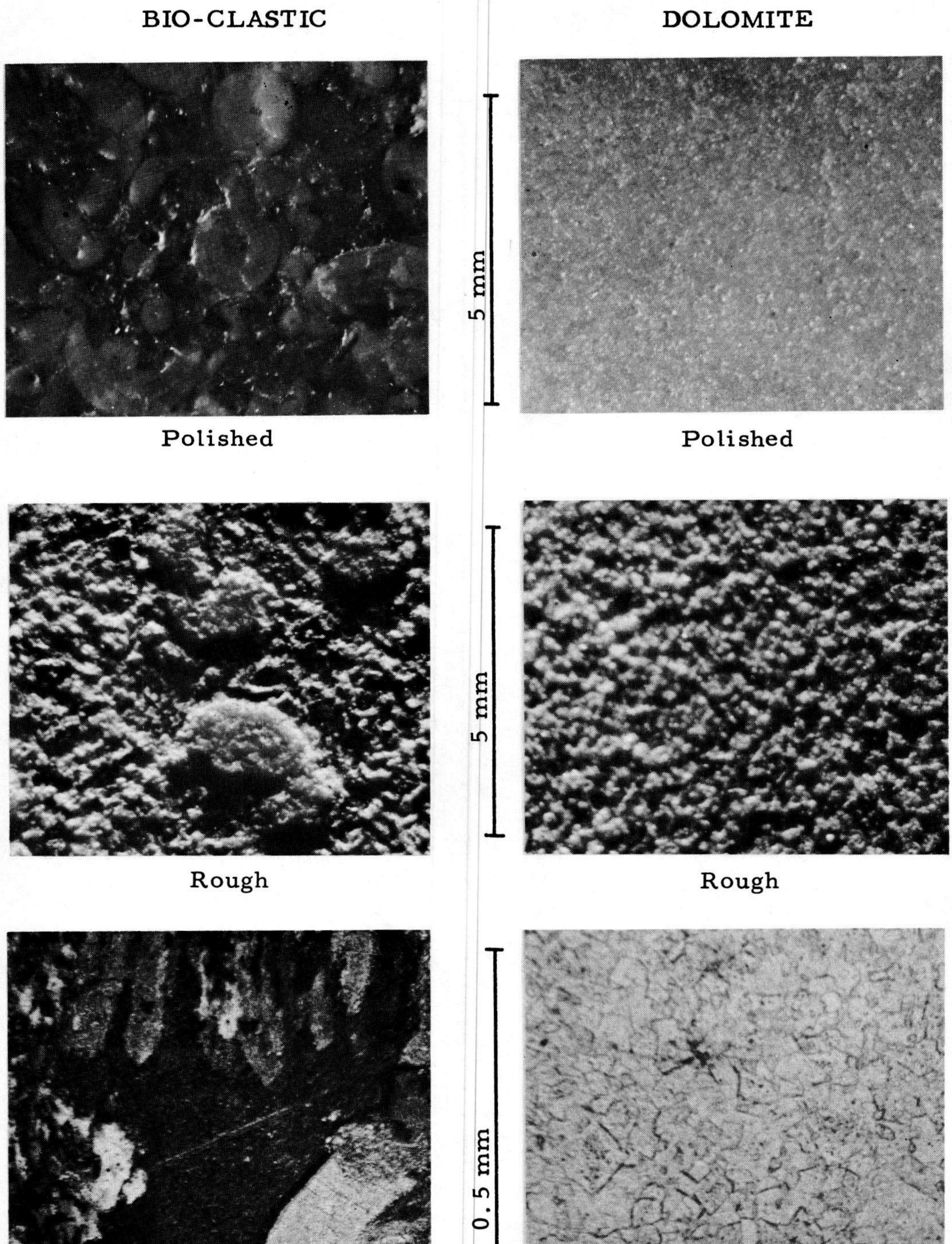


Figure 9. Photomicrographs of prepared specimens of bio-clastic limestone and Oregon dölomite.

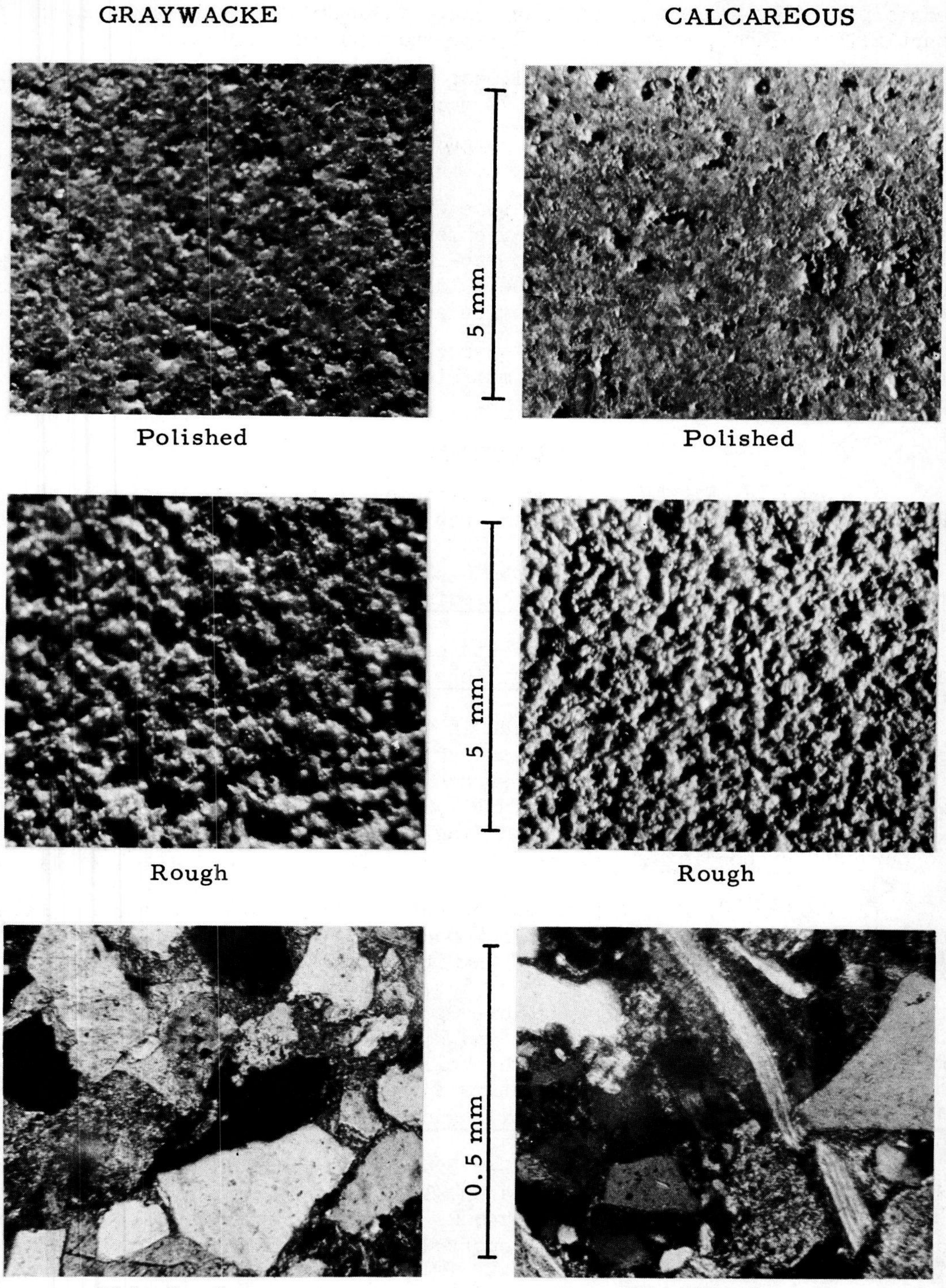


Figure 10. Photomicrographs of prepared specimens of graywacke and calcareous sandstone.

the matrix are debris of angular to sub-rounded quartz grains with the edges partially replaced, few plagioclase feldspar fragments with edges partially replaced, muscovite, chlorite and rounded fossils.

Debris grain sizes are as follows: quartz - up to 0.44 mm; feldspar - up to 0.22 mm; chlorite - up to 0.75 mm; muscovite - up to 1.0 mm; fossil debris - up to 10.0 mm.

F_2

A light gray calcareous sandstone with matrix of fibrous calcite, anhedral calcite, quartz, sericite, chlorite and feldspar. Dispersed within the matrix is debris of angular to sub-rounded quartz grains with the edges partially replaced, few plagioclase feldspar fragments with edges partially replaced, muscovite, biotite, chlorite and rounded calcareous fossils.

Debris sizes are as follows: quartz - up to 0.40 mm; feldspar - up to 0.26 mm; muscovite - up to 2.3 mm; biotite - up to 0.55 mm; chlorite up to 0.9 mm; fossils - up to 9.0 mm.

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