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THE DESIGN OF AN ASPHALT PAVING SURFACE USING A DURABLE SANDSTONE AND AN INVESTIGATION OF THIS AGGREGATE'S RESISTANCE TO POLISHING ACTION

by

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INTRODUCTION

This nation has long been known as a nation on wheels, and, in the more recent years, these wheels have been turning faster and faster. The wheels of automobiles as well as those of industry are turning faster, and the need for adequate structural and surface design of highway pavements is becoming more and more necessary. Since 1941, the average vehicular speed of automobiles has increased 16 mph. This increase represents a 33 per cent increase in average speed and an increase in kinetic energy of each vehicle of 78 per cent (13). The average vehicular speed will probably continue to increase in the coming years. Highway designers have taken this factor somewhat into account by designing highways that have gentler slopes, larger curves, and no at-grade intersections. In these designs the slipperiness of the pavement surface may be given some consideration, but most consider it only a minor factor in the design.

Almost any pavement will provide adequate vehicle stability when the pavement surface is dry, but when the pavement becomes wet it can be very dangerous. The unsuspecting driver who speeds along on a wet pavement at high speeds and suddenly decides he must stop, immediately becomes aware of this fact, and to his dismay, may find himself involved in a costly accident. Should this driver be warned with a "slippery when wet" sign or should the wet pavement surface be designed to provide sufficient skid resistance at the high speeds that the geometrically-designed features permit? It is fast becoming the opinion of most highway engineers that the design of a skid-resistant surface is an important step in the pavement design of modern high-speed highways.

It is one of the purposes of this thesis to develop a simple yet qualitative method of investigating just how well a given surface will retain its non-skidding properties when wet.

The Problem

This thesis will be limited to the investigation of asphalt concrete surfaces. An investigation of portland cement concrete surfaces may be warranted, but in either type of pavement the fundamental skid-resistance properties are dependent, to some extent, upon the type of aggregate used. Therefore any conclusions drawn from one type of pavement investigation may be applied with discretion to other types of pavements.

The coefficient of friction of a pavement surface is dependent on many variables. Perhaps the most well known of these variables is the aggregate that is contained in the paving surface. As a surface is subjected to traffic action, the binder material is eroded slightly, exposing the aggregate particles. The pneumatic tires of passing vehicles are then in direct contact with the aggregates. The initial shape of the aggregates is usually very angular, and their sharp corners provide adequate skid resistance even when the surface is wet. But after many vehicular passages the sharp corners are rounded off; as more and more traffic passes a given point, the aggregates become polished. The same pavement that produces sufficient non-skidding properties in its early life will become less skid-resistant with age, due to this polishing action. Previous studies have shown that some aggregates are more susceptible to polishing action than others.

In a study by Messrs. Shupe and Lounsbury (16) a native Kansas sandstone, Lincoln Quartzite, (a calcareous sandstone in which quartz grains are bound in a matrix of calcite) was used as one of their trial aggregates. They found that this particular sandstone retained its non-skid properties even after repeated polishings. Since this sandstone exhibited excellent skid resistance, it was decided that the aggregate should be used in the design of an asphalt hot-mix paving surface. The problem then is to design a high-quality asphalt paving mix using this sandstone as aggregate, and to develop a method of simulating traffic action to investigate further this aggregate's resistance to polishing.

Approach to the Problem

Dr. John W. Shupe recommended that the recently purchased portable skid-resistance tester, developed in England, be used to evaluate the skid-resistance of Lincoln Quartzite. Although this method of evaluating the coefficient of friction is relatively new, and although little correlation with the stopping-distance method has been demonstrated, its unique size and operation make it readily adaptable to laboratory use.

Before the skidding properties of a given asphaltic concrete mix can be evaluated, a satisfactory mix must be designed. The Asphalt Institute Manual, Series 2, (11) considers the following in asphalt mix design:

> "Regardless of the design method being used, the overall objective for the design of asphalt paving mixes is to determine an economical blend and gradation of aggregates (within the limits of the project specifications) and a corresponding asphalt content that yields a mix having:
>
> (a) Sufficient asphalt to coat thoroughly the aggregate particles and to waterproof and bond them together to insure a durable pavement under suitable compaction;
>
> (b) Sufficient mix stability (as provided under the specific design method being used) to satisfy the service requirement and demands of traffic without distortion or displacement;
>
> (c) Sufficient voids in the total compacted mix to provide a reservoir of space for the expansion of asphalt and for a slight amount of additional compaction under traffic loading;
>
> (d) Sufficient workability to permit the placement of the paving mix as an efficient construction operation."

With these requirements in mind and the fact that the equipment required was readily available, the Marshall method of mix design was chosen. The Immersion-Compression test was also performed on the aggregate to see if it possessed any stripping tendencies.

After the proper mix was designed, equipment was developed to prepare specimens for testing with the portable skid-resistance tester. Specimens were prepared using the desired mix. These specimens were subjected to a wearing process and then tested for a coefficient of friction. Ten identical specimens were prepared to allow a statistical analysis of variance to be computed.

To allow some comparison of results, three other types of typical surface aggregates were also investigated. These included a sand-gravel mix, a chat mix, and a mixed aggregate mix using limestone, sand, and blow sand.

A crusher-run sample of the material used in the design was obtained from the quarry at Lincoln, Kansas, so that a comparison could be made between the gradation used in this investigation and the gradation of the aggregate as it was produced from the crusher. These samples were obtained so that a recommendation could be made to the Kansas State Highway Commission on the design of a highly skid-resistant surface.

Review of Previous Work

The literature reviewed in this thesis will be limited to two main areas, namely, factors affecting the skid resistance of pavements, and methods of evaluating pavement friction in the laboratory.

Factors Affecting the Skid Resistance of Pavements. The variables that cause pavement surfaces to exhibit different coefficients of friction have been reviewed in an article by Ralph A. Moyer (12). From data gathered over the last 30 years, he has defined approximately 15 road surface factors that affect pavement slipperiness. With all these variables in combination, it is doubtful whether the true effect of each variable can be determined. Some of the variables include the following:

"1. Road Surface Factors

Surface type and condition, aggregate type, amount of cement or binder, surface texture, road roughness, surface contamination, water depth or film thickness, age of surface, weathering, temperature, traffic, and geometric highway design factors.

2. Vehicle Operation Factors

Vehicle speed, size, weight distribution braking (sliding stop versus impending skid or rolling stop), accelerating (maximum rolling versus spinning wheel acceleration), cornering and related slide-skid factors when driving on curves.

3. Tire Factors

Tire size, tread pattern, load, contact area, inflation pressure, tread stock composition, plies, cord angle and related tire design factors."

Each of the factors affecting skid resistance are broken down and extensively discussed by Mr. Moyer. A discussion of the basic laws of friction and the theory of skidding are presented in detail.

The State Road Laboratory of the Netherlands has been doing research on the relationship between the non-skid properties of a surface and the number and size of the projections on the surface (18). The Leroux Pendulum Apparatus was used to determine the amount of energy consumed as a rubber slider passes over the surface in question. Tests were run on wet and dry, smooth and ground glass, in order to calibrate the instrument. Tests were made to demonstrate that the basic friction equation, $F = fN$, is not always valid. Granulating hammer heads were used as the trial surface. These surfaces were composed of pyramidal projections. The pyramidal projections were varied in height and size to try to locate an optimum shape. Also, eight different types of rubber tread were investigated, and it was found that the hardest rubber absorbed the least energy from the passing pendulum.

The Road Research Laboratory, Department of Scientific and Industrial Research, United Kingdom, has carried out research related to the polishing of roadstones (7). The aggregate in question is cemented on the outer circumference of a 16-inch wheel. This wheel is free to turn. A smooth treaded pneumatic tire comes in direct contact with the specimen at the outer edge. The load is applied and the large wheel, on which the specimen is mounted, is made to turn and the polishing process is accomplished. It was found that no polishing took place unless some type of abrasive was used between tire and specimen. This abrasive was justified due to the fact that upon close observation of pavement surfaces in use there was a small amount of mineral dust present. This procedure produced polished aggregates very similar to those produced by traffic action. The coefficient of friction was measured with a modified version of the British portable skid-resistance tester.

In order to correlate their polishing procedure with the actual road surface conditions, specimens were prepared that could be placed in areas of heavy traffic. These specimens were placed at a variety of locations, including straight lengths, curves, lightly traveled highways. Very good correlation with laboratory results was obtained. Some other interesting findings were that specimens on curves, under similar traffic conditions, polished seven times faster than straight lengths.

Also, it was found that aggregates polish faster under hot, dry climatic conditions than under cool, wet conditions.

Messrs. Shupe and Lounsbury have reported a study of the Polishing Characteristics of Mineral Aggregates carried out at Purdue University (16). The report includes the following factors:

> "1. The polishing characteristics of different mineral aggregates, in both portland cement and bituminous concrete mixtures, and their relation to basic aggregate properties; 2. The effect of texture, as determined by gradation, on the anti-skid characteristics of bituminous mixtures; and 3. The effect of initial aggregate shape, or degree of harshness, on the skid resistance of bituminous mixtures."

Twenty-two different mineral aggregates from five different states were chosen for the initial part of the study. Included in the group were 12 limestones, 2 gravels, 2 sandstones, and a variety of others. These were all evaluated in bituminous concrete specimens. The machine used to polish and test the specimens will be described in another part of this review of literature. The relative resistance to skidding values (RRV) were based on the RRV of Kentucky Rock Asphalt taken as unity. All specimens were subjected to the same wear treatment cycle, and the RRV value was measured after the conclusion of the cycle. Three conclusions were drawn from this initial investigation,

1. Limestones do not exhibit as good resistance to polishing as do other aggregates. The average of all limestones was 0.45 RRV; the average of all others was 0.63.

2. Different limestones exhibit appreciably different resistance to skidding, ranging from 0.30 to 0.56 RRV.

3. Sandstones, ranging from 0.75 RRV to 0.88 RRV, are far superior to the limestones in this respect.

Four aggregates were chosen for the surface texture investigation. The surface texture was changed by varying the gradation of the mixture. All aggregates investigated showed a higher RRV value for a denser mix. The same four aggregates were used in a study of the effect of the initial shape of the aggregate. A set of specimens was made with freshly crushed aggregate and one with aggregate rounded in a Los Angeles rattler. The freshly crushed aggregate showed a higher RRV value at the end of one wearing cycle, but after three cycles both aggregate types exhibited essentially the same value.

Portland cement concrete specimens were made with a well-graded aggregate, a high cement factor, and a low slump. The specimens were prepared with the idea of simulating new concrete pavement construction. The skid resistance was measured at three points in the wear and polish cycle. The first test was prior to polishing; the second test after a polishing cycle similar to bituminous specimens, and the third test after the top 1/4-inch of specimen was sawed off and this surface subjected to the wear and polishing action. Six aggregates were selected, and a comparison between bituminous and concrete specimens was carried out. Portland cement concrete specimens generally had a higher RRV value than the bituminous specimens. Shupe and Lounsbury concluded that:

1. Dense-graded mixes produce better anti-skid properties than open-graded.

2. There is some justification in requiring all naturally-rounded coarse aggregate being crushed before used in pavement.

3. Polishing characteristics of Portland cement concrete and bituminous surfaces are the same for a given aggregate.

4. Some limestones should not be used in pavement surfaces.

5. On the other hand, some limestones may be used if heavy traffic is not expected.

6. Surfaces consisting of the more abrasive limestones will eventually polish.

7. To retain skid resistance on a pavement surface, a type of coarse particle by particle wear is necessary.

Methods of Evaluating Pavement Friction in The Laboratory. The Tennessee State Highway Department's method of evaluating potential pavement slipperiness is used mainly to pre-test materials that are to be used in highway surfaces (19). The apparatus consists of a rotating automobile wheel that is driven by an electric motor. The wheel is rotated at a given speed, and a given load is applied through the wheel to the pavement surface in question. As the trial surface becomes more slippery, less power is required to drive the wheel. The difference in skid resistance of trial surfaces is then measured by the amount of power required to drive the wheel. Most testing has been done with Portland cement concrete specimens. At the date of this report, no effort has been made to correlate the values measured with those attained under actual field conditions.

Another undertaking at Purdue University concerns a laboratory method of determining the non-skid properties of bituminous paving surfaces (15). In this article, Messrs. Shupe and Goetz describe the development of equipment for use in the study of aggregate behavior in a pavement surface. The apparatus was designed for specimens prepared in the laboratory, and also for specimens that were cored from the roadway.

The specimen to be tested is placed in a special mold that is securely fastened to a high-speed shaft. This shaft rotates at an angular speed of 2500 rpm which gives a relative speed of 30 mph at the mean radius of the 6-inch diameter specimen. The specimen is brought to the desired speed, and a rubber testing shoe is allowed to come in contact with the specimen. The contact pressure is 28 psi. The rubber shoe has an outside diameter of 5 1/2 inches, and an inside diameter of 2 1/2 inches. The area of the shoe is divided into eight segments by 3/8-inch slots. The rubber shoe is firmly glued to a metal backing plate which is attached to a vertical shaft. Near the top of the shaft is attached a small beam. This beam rests on a fulcrum at the opposite end. SR-4 strain gages are attached to the beam near the shaft. During the three-second testing cycle, the specimen is flooded with water. The stresses induced in the small beam through the shaft are a function of the skidding resistance between the rubber shoe and the specimen. Strains induced in the beam are automatically recorded as relative resistance values, based on

Kentucky Rock Asphalt as unity.

The preparation of laboratory specimens consisted of placing the specimen in the mold, vibrating to desired density, and then subjecting the surface to the wearing process. Many different procedures were tried in an effort to reproduce a surface that resembled a traffic-polished surface. Also, abrasives were used in different gradations and composition until a satisfactory surface was obtained. The final wear and polishing procedure was very complicated, but it produced very representative specimens.

A field correlation study was next undertaken to compare the stopping-distance method coefficient of friction with the RRV value of specimens cored from the traffic lanes of selected sites on Indiana highways. On the basis of this correlation study, the laboratory method was considered to be useful in determining the skidding resistance of bituminous paving surfaces. The differences between the two methods seemed to favor the laboratory method for speeds greater than 30 mph.

A method of pavement surface evaluation developed by the National Crushed Stone Association consists of preparing a mix with the aggregate in question and placing this in a 14-foot circular track (3). This track has a rectangular cross section of 18- by 6 inches. After the mix is placed, it is thoroughly compacted with a steel-faced roller and then the surface is subjected to traffic action. A 7.00 X 20 bus tire is used to polish the surface that is first covered with a layer of wet sand. This process is continued until the desired surface is produced and the relative slipperiness is measured by using a vertically mounted bicycle tire that has a counterweight attached to one side.

California's skid tester was developed for both laboratory and field use (5). A 4.80/4.00 - 8 tire that is ground to a smooth surface is mounted on a carriage. The carriage is free to move on ball bearings along two guide bars. The tire and carriage assembly is placed just above the surface and brought to the desired speed. The entire carriage is then dropped. If the surface has a low value, the tire will slip and the carriage will not move very much. A greater movement indicates a larger friction value. The tire is rotated by a 6-volt starter motor. The entire assembly may be hooked to a truck thereby allowing skid-resistance measurements to be taken at any location.

This machine has been used in a wear and polish study of seal coat performance. The field application of aggregate to a freshly primed surface is simulated in the laboratory, and this surface is subjected to a polishing action. The polishing action is performed by a door mat, constructed of old tire materials, rubbing against the protruding aggregates.

The portable skid-resistance tester of the Road Research Laboratory of Great Britain is one of the more recent methods of evaluating pavement slipperiness (2). As its name implies, this instrument is highly portable; it also reproduces values very well. A slider takes the place of a skidding tire. This slider is mounted at the end of a pendulum. As the slider passes over the surface, a certain amount of energy is lost. This energy loss is measured by the angle through which the arm will swing after it passes over the surface. A more descriptive explanation of this skid-resistance tester is given in a later section of this thesis.

The most recent article concerning the portable skid-resistance tester was written by D. C. Mahone of the Virginia Council of Highway Investigation and Research (8). Mr. Mahone was interested in correlating data obtained from the stopping-distance method with data from the British portable tester. Fourteen different pavements with widely varying surface characteristics were selected. Before any tests were run, a statistical analysis was performed to determine the number of repeat trials that must be made on each section. It was decided that seven would be needed for the stopping-distance method and that four would be adequate for the portable tester. Three different slider lengths were used to try to find if there was a direct relationship between slider length and a certain speed.

Before each test, the roadway was completely saturated with water. The test car was skidded on the pavement, and then the portable tester was used. A later stage of the investigation consisted of first using the portable tester and then predicting the value the stopping-distance method would give. Most of the data obtained from the stopping-distance method came within 95 per cent of the predicted values. Some conclusions of this study were:

> 1. Values on the same pavements using both devices were significantly different for at least 50 per cent of the surfaces.

2. The coefficient of friction for the stopping-distance method can be predicted using the portable tester and estimating equations.

3. Fewer measurements are necessary with the portable tester than the stopping-distance method.

4. The repeatability of the British portable tester is not influenced by slider lengths.

5. The repeatability of the stopping-distance method is influenced by test speeds and differs from site to site.

In light of all previous work, it can be said that, generally, the method of pavement evaluation is an expensive and tedious process. The British portable skid-resistance tester is a step in the right direction. The laboratory method of traffic simulation developed for this thesis is an attempt to make it fairly simple for the engineer to evaluate accurately an aggregate's polishing characteristics prior to the placing of this aggregate in a pavement surface.

MATERIALS, EQUIPMENT, AND PROCEDURE

Materials

The aggregate, Lincoln Quartzite, was supplied by the Quartzite Stone Company, Lincoln, Kansas. The aggregate as received from the supplier was stored in open bins to air dry. All material received was to pass the 3/4-inch sieve, and to be retained on the No. 8 sieve. The aggregate was then crushed in a "jaw"-type crusher, and each of the following sizes was screened out and stored in open pans: retained on 3/8 in., No. 4, No. 8, No. 16, No. 30, No. 80, No. 200, and the portion passing No. 200. This was done to enable more exact blending to meet the required specifications.

The specific gravities and absorption capacities of the aggregates are:

Dry bulk specific gravity, ...	2.62
Saturated bulk specific gravity, ...	2.63
Apparent specific gravity, ...	2.66
Absorption, ...	0.63 %

The aggregate was also tested for resistance to abrasion in accordance with AASHO Designation T 96-61, Grading B. The result was 30.4 per cent wear, which meets K.S.H.C. Specifications for aggregate to be used in asphaltic paving surfaces.

The soundness of the aggregate under conditions of freezing and thawing was determined in accordance with AASHO Designation T 103-42. Since the blend of aggregate to be used in the design did not come close to the suggested gradations, the following gradation was used:

Table 1. Soundness gradation.

Sieve Size	Before Freezing		After Freezing	
	% Ret.	% Pass.	% Ret.	% Pass.
3/4"	0	100	0	100
1/2"	45	55	43.3	56.7
3/8"	80	20	71.8	28.2
No. 4	90	10	88.8	11.2
No. 8	100	0	98.7	1.3
total	315		302.6	

$$\text{Loss Ratio} = \frac{302.6}{315} \times 100 = 96.1\%$$

K.S.H.C. Spec. - greater than 85%

A chemical analysis of this aggregate is presented on page 55 of the Appendix.

The asphalt used was an asphalt cement, 85-100 penetration. It was stored in a closed 15-gal. drum. The asphalt originated from the Phillips Petroleum Company Refinery at Kansas City. Since previous research has proved this asphalt to meet K.S.H.C. Specifications, it was felt that the standard tests that qualify an asphalt would not be necessary (10). The only test that was run on this asphalt was the determination of the specific gravity. The specific gravity determination was performed in accordance with AASHO Designation T 43-54 using the Pycnometer method.

Specific Gravity of Asphalt .... 0.993.

Equipment and Procedure

The Design of an Asphalt Paving Mix. The K.S.H.C. Specification for Surface Courses (HM-3), Grading A, was used as the basic gradation. Three different gradations were used with five different asphalt contents. The gra dations were as shown in Table 2. From the table, it can be seen that the two end points and the mid point of the specifications limits were chosen as the trial aggregate blends. The asphaltic cement contents used were: 5.0, 5.5, 6.0, 6.5, and 7.0 per cent by weight of total mix.

Table 2. Gradations for mix design (per cent retained).

Sieve Size	Fine	Medium	Coarse	K.S.H.C. Spec.
1/2"	0	0	0	---
3/8"	15	22.5	30	15-30
No. 4	30	39	48	30-48
No. 8	40	49	58	40-58
No. 16	54	61	68	54-68
No. 30	63	69	75	63-75
No. 80	80	84	88	80-88
No. 200	92	94	96	92-96
- 200	100	100	100	100

The Marshall method of mix design was chosen to evaluate each of the trial mix designs. In preparing the trial mixes, the aggregate was placed in the bowl of a Lancaster Batch Mixer and placed in an electric oven for four hours at 320° F. Two and one-half hours before mixing the asphalt cement and the molds were placed in the oven at the same temperature. After the desired time had elapsed, the batch was mixed in a Lancaster Mixer for exactly two minutes. At the conclusion of this mixing, the batch was divided into three portions of 1200 gms each. These were placed in another oven at 290° F. for twenty minutes, to simulate the travel time between the plant mixer and the paving distributor. Each portion was then placed in the mold and compacted by applying 50 blows on each side with a standard automatic Marshall compacter. The specimens were allowed to cool, at which time their specific gravity was determined and the void analysis performed. Approximately 24 hours after compaction, the specimens were tested for stability and flow in the Marshall apparatus.

Since there is a tendency for aggregates containing a high percentage of quartz to strip, an Immersion-Compression test was performed. Only the general stripping properties of this aggregate were desired; so one set of specimens was prepared. The mix chosen was the one with medium gradation and 6.0 per cent asphalt content. The initial preparation of the test specimen, including mixing, was performed in the same way as for the Marshall specimens. After mixing, the batch was divided into three portions of 1950 gms each. These were placed in an oven for 20 minutes at 290° F. The specimens were then compacted using 3000 psi pressure for two minutes. Each specimen was removed from its mold and allowed to cool for two hours. At this time, the specific gravities were determined. The six specimens were divided into two groups of the nearest alike densities. One group was cured in a 140° F. water bath for 24 hours, and the second group was cured in a 140° F. air bath for the same period of time. After 24 hours the specimens in the water bath were placed in a 77° F. water bath for two hours. The other three specimens were removed from the oven and allowed to come to room temperature. The specimens were then tested in unconfined compression at a rate of 0.05 in. per minute per inch of height of the specimen. The specimens were four inches high; so the rate was 0.2 in. per minute. The results are given as per cent retained strength in Table 7.

$$\text{Per cent Retained Strength} = 100 \times \frac{\text{Strength Immersed Spec., psi}}{\text{Strength Dry Spec., psi}}.$$

Laboratory Skid Resistance Investigation. The development of an apparatus to simulate traffic action will be considered first. The objectives considered in designing the Traffic Simulator were:

1. The apparatus should be simple in operation, yet produce a surface similar to the actual road surface.

2. The apparatus should be rugged in construction to enable a large number of surfaces to be polished.

3. The apparatus should be capable of repeating reproducible data.

4. The apparatus should be able to produce a surface area of a specimen large enough so that the British portable skid-resistance tester can be used to measure the coefficient of friction between the rubber slider and the surface.

Using these objectives as guides, the Traffic Simulator shown in Figs. 1 and 2 was constructed. In the following discussion of the Traffic Simulator, reference will be made to Fig. 1, the schematic diagram of the apparatus. The device consists mainly of a reciprocating carriage, 14, on which is mounted a mold, 11, holding the trial specimen, 8. The mold is made of 3/8-inch steel, and is such that it may be easily fitted and removed from the carriage assembly. The inside dimensions of the mold are 4- by 9 3/4- by 1 5/8-inches high. The carriage is made to move back and forth by an arm connected to an eccentric, 5. Since the British portable tester requires a slider length of 5.0 inches to test a specimen, the eccentric was designed with a 3-inch offset giving a total traveled distance of 6 inches.

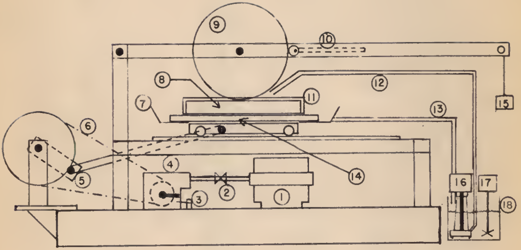

Fig. 1 SCHEMATIC DIAGRAM OF TRAFFIC SIMULATOR

Fig. 2 TRAFFIC SIMULATOR

This allows for any irregularities that might exist at the outer edges of the polished surface. Also, it is known from the mechanics of a flywheel connecting rod assembly that, as the throw of a flywheel approaches a horizontal position, the linear speed of the other end of the connecting rod approaches zero. This slow speed would be at the edges of the polished surface, and would not be tested by the tester while the center of the polished area, where the speed is faster and more uniform, serves as the area to be tested.

The power to drive the eccentric is supplied by a 1/3 hp electric motor, 1. The electric motor is connected to a gear box, 4, with a flexible coupling, 2. The gear box reduces the speed of the input shaft by a ratio of 48:1. The gear box has output shafts on either side. A smaller eccentric is connected to one of these output shafts and this actuates a counter, 3, after each revolution. A chain sprocket is connected on the other output shaft. This sprocket is connected to another larger sprocket by a No. 65 roller chain, 6. These two sprockets further reduce the speed by a ratio of 18:11. A common shaft, connecting the large sprocket to the eccentric, is held in place by two roller bearings. A rectangular rod with a bearing on each end connects the eccentric to the carriage assembly and this completes the driveline. The speed of the eccentric shaft is now reduced to approximately 22 rpm; therefore the specimen makes 44 passes under the rubber tire, 9, each minute.

The rubber tire used to perform the polishing is a standard go-kart tire. The size of the tire is 4.10/3.50 x 6, and it is a smooth tread, standard production line tire. The tire is inflated to 30 psi, and this pressure is maintained throughout the test. A brake, 10, that is pinned off center, is used to prevent the tire from turning as the carriage assembly moves. A constant load is applied to the tire by use of a sealed gallon paint can, 16, filled with water. The geometry of the upper arm holding the tire is such that any load applied at the end of the arm results in three times the load at the contact point of the rubber tire and the surface.

Previous investigations have shown that some type of abrasive must be present in order for polishing to occur. Therefore a small water pump, 16, is provided for the purpose of supplying a solution of water and abrasive to the area being polished. The abrasive is held in suspension by a small mixer, 17. The solution is pumped through a hose, 12, to the specimen. A thin metal shield is placed around the inner edges of the mold to keep as much of the abrasive as possible from being lost. The water and abrasive in solution are collected after passing over the specimen, and are routed back to the pumping chamber, 18, through another rubber hose, 13. The same solution is pumped through again. New abrasive is added periodically because it is impossible to collect and return 100 per cent of the abrasive to the mixing chamber.

The British portable tester was used to evaluate the coefficient of friction after the specimen had been subjected to the wearing procedure. This tester, Fig. 3, is a pendulum type device, and it measures the frictional resistance as a rubber slider passes over a wet

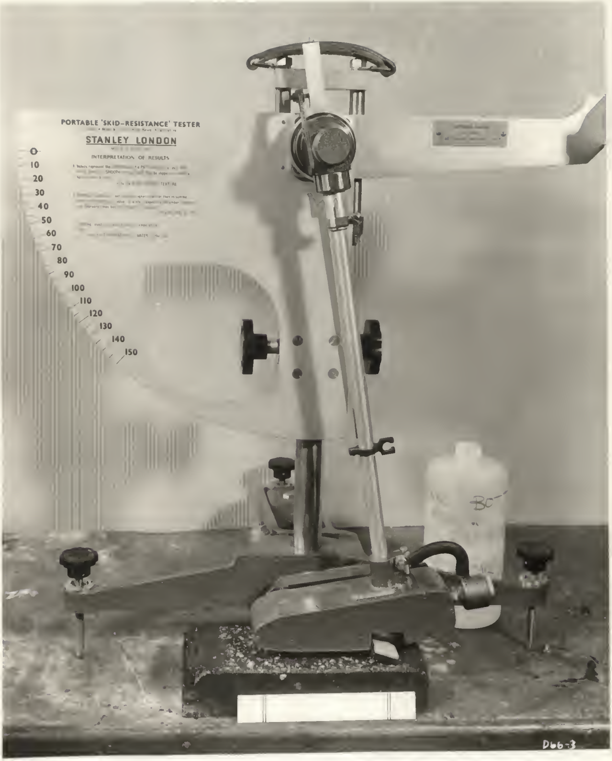

Fig. 3 BRITISH PORTABLE TESTER

surface. This slider is a 3 by 1-inch block of rubber, and is spring loaded so the normal force on the surface in question remains constant. The rubber on the slider was developed to represent a patterned pneumatic tire. The machine can be adjusted vertically; this allows the slider length to be kept at a constant value for different pavement surfaces. After the proper adjustments are made, the pendulum and a pointer (coincides with pendulum and lies in the same axis) are cocked in a right-hand horizontal position. The lock is not quite shown in Fig. 3, but it is just to the right at the upper-right-hand corner. When the pendulum is released, it carries the pointer across the surface, and to the furthest point of the arc traversed. At this point, the direct measurement is recorded. The values range from 0-150 and represent 100 times the effective coefficient of friction.

A free swing of the pendulum would result in 180^{0} of travel, i.e., a reading of zero, but when the slider comes in contact with a surface some energy is lost. This energy lost is equal to the work done against friction by the rubber slider, and is measured by a swing of something less than 180^{0}. The development of the equations for determining the coefficients of friction and the procedure for calibrating the tester are given in a paper by Sabey (14); therefore, they will not be presented here.

The manual (6) that is supplied with the portable tester recommends that a slider length between 5.0 and 4.9 inches be used. A scale, shown underneath the pendulum arm in Fig. 3, is provided to adjust the length of slide properly. Five measurements with the tester are required to obtain a representative value.

The values given in Table 3 were developed as a guide to be used in determining whether or not the pavement in question provides sufficient skid-resistance.

The complete procedure for preparing, polishing, and testing one specimen will now be considered. The aggregate to be tested was placed in the oven in a Lancaster mixing bowl at 320° F. four hours prior to mixing. Two and one-half hours prior to mixing the asphaltic cement and molds were placed in the oven. The materials were then mixed in a Lancaster mechanical mixer for two minutes. At this time a portion of the total mix was placed in another oven at 290° F. for 20 minutes. The mix was then placed in the mold shown in Fig. 4, and a 4 by 3 by 1/2-inch angle was placed on the surface. Between the spacer and the moving head of the compression machine was placed a 3/4-inch Clevland Air Vibrator. A load of 6000 lb was applied to the specimen, and the air valve to the vibrator was opened. The specimen was held in this position for 30 seconds. Then the load was removed and the angle was changed end for end. This was done to obtain a more level surface since it was impossible to apply the load directly in the center of the angle. The load was again applied and held for 90 seconds while the vibrator operated. The specimen and mold were then allowed to cool for 24 hours.

After 24 hours, the sides of the mold were loosened, and a thin metal shield was fitted around the inside dimension to retain the water and the abrasive that was to be used. The sides of the mold were again tightened, and the mold was bolted to the carriage assembly of the

Table 3.** Suggested values of 'skid-resistance' for use with the portable tester.

Category	Type of site	'Skid-resistance' on wet surface	Standard of skidding resistance represented
A	Most difficult sites such as: (i) Roundabouts. (ii) Bends with radiul less than 500 ft on de-restricted roads. (iii) Gradients, 1 in 20 or steeper, of length greater than 100 yd. (iv) Approach to traffic lights on de-restricted roads.	Above 65	'Good:' fulfilling the requirements even of fast traffic, and making it most unlikely that the road will be the scene of repeated skidding accidents
B*	General requirements, i.e., roads and conditions not covered by categories A and C.	Above 55	'Generally satisfactory:' meeting all but the most difficult conditions encountered on the roads
C*	Easy sites, e.g., straight roads, with easy gradients and curves, and without junctions, and free from any features, such as mixed traffic, especially liable to create conditions of emergency	Above 45	"Satisfactory only in favorable circumstances'
D	All sites	Below 45	'Potentially slippery'

* On smooth-looking or fine-textured roads in these categories, vehicles having smooth tires may not find the 'skid-resistance' adequate. For such roads, accident studies should also be made to insure that there are no indications of difficulties due to skidding under wet conditions.

** Reprinted from Road Note No. 27, Department of Scientific and Industrial Research, Road Research Laboratory (1960).

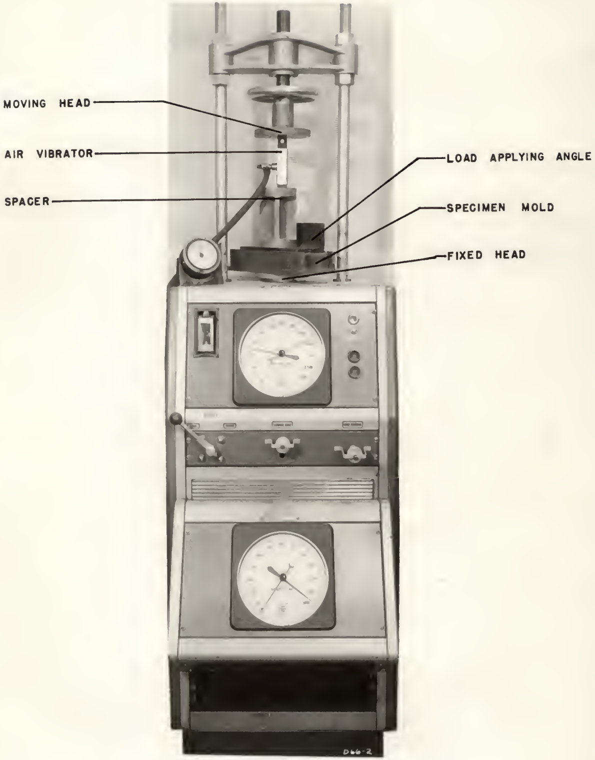

Fig. 4 EQUIPMENT FOR PREPARING SPECIMENS

Traffic Simulator. The rubber tire was locked in position and the load applied. The load between the tire and specimen was equal to 70 lb. The mixing chamber was then filled with water, and the mixer and pump were started. The abrasive used in all wearing cycles was the same durable sandstone that was used in the mix design. Two different sizes were:

1. Coarse abrasive, passing the No. 80 sieve and retained on the No. 200,

2. Fine abrasive, passing the No. 200.

These abrasives were placed in the mixing chamber by first filling a 125 ml beaker and then dumping it in the chamber. To recover as much abrasive as possible, a catch basin was made and fitted at the end of the mold which contains the specimen. From this catch basin the solution of abrasive and water is routed directly back to the mixing chamber. (See Fig. 2 for details.) The water and abrasive that fall outside the metal shield and catch basin are also returned to the mixing chamber through another rubber hose. With this complex recovery system, it is still impossible to recover all of the abrasive so additional abrasive is added from time to time.

As the wearing cycle started, the counter was set at zero, and 60 ml of fine abrasive, and 125 ml of coarse abrasive were added to the water in the mixing chamber. The rubber tire was locked and the load applied. For the first 3000 revolutions recorded on the counter (one revolution of counter equals 1.22 skids of tire on specimen) the position of the wheel was slightly rotated after each 500 revolutions.

This was found necessary due to the fact that some asphaltic cement collected on the tire. Table 4 shows the final procedure that was used to polish one specimen.

Table 4. The polishing cycle.

Counter readings, revolutions	Treatment
0	60 ml fine abrasive, 125 ml coarse abrasive added
500	60 ml coarse abrasive added, tire rotated
1000	tire rotated
1500	60 ml coarse abrasive added, tire rotated
2000	tire rotated
2500	60 ml coarse abrasive added, tire rotated
3500	tire rotated
5000	specimen removed from mold to be tested

At the end of the polishing cycle the specimen was allowed to come to room temperature. The surface was then wetted, and the British portable tester was set in place. One swing of the pendulum was made to wet the slider, and then five trials were made on the specimen. Before each trial, the surface was completely covered with water at room temperature. These five values were recorded, and the specimen was allowed to dry. After the specimen was completely dry, it was divided into two parts and the apparent specific gravity determined. This specific gravity was reported along with the skid-resistance values.

The procedure may sound quite complicated, but it is not very difficult to perform. At times the complete cycle was not carried out due to the pump becoming clogged; however, the specimen's surface closely resembled the others that had been subjected to the complete cycle. The procedure did not demand constant supervision, except at each 500 revolutions when the different treatments were applied. By comparing the specimen to road surfaces that had been subjected to considerable wear, it was concluded that the Traffic Simulator produced a surface very much like actual road surfaces. Figure 6 shows what the finished surface looked like. Number 1 is the sandstone specimen.

Comparison of Four Different Asphalt Mixes. The purpose of this study was to compare the skidding properties of four different aggregates after each had been subjected to the same wear and polish cycle. Four types of possible surface mixes with widely varying characteristics were tried. The four aggregates were:

1. Lincoln Quartzite - The same aggregate as used in the initial study, a calcareous sandstone in which quartz grains are bound in a matrix of calcite.

2. Sand-gravel - Naturally rounded quartz particles formed by the disintegration of rock. The desired gradation was formed by combining Blue River sand and Blue River gravel.

3. Chat - A by-product of the lead and zinc mining process in southeast Kansas.

4. Mixed aggregate - A combination of crushed limestone, sand, and blow sand. The proportions used were 65 per cent limestone, 28 per cent sand, and 7 per cent blow sand.

The gradations and asphalt contents used for the mixes are shown in Table 5. The Lincoln sandstone gradation is not shown because its gradation was the same as that used for the previous investigation. (See Table 2, medium gradation.)

Table 5. Gradations of aggregates used in comparing four mixes.

Sieve size	Per cent retained			K.S.H.C. Spec.
	Sand gravel	Chat	Mixed Agg.	
3/4"	0	0	0	0-5
3/8"	15	3	16	15-30
No. 4	46	29	31	30-48
No. 8	56	48	45	40-48
No. 16	66	60	57	54-68
No. 30	69	71	69	63-75
No. 80	80	85	87	80-88
No. 200	94	93	94	91-95
Asphalt content % by wt. of total mix	5.5	6.0	6.0	----

Two specimens were prepared for each type of mix. The procedure followed for testing and preparing the specimens was the same as already has been described.

PRESENTATION OF DATA

The data presented in this thesis are divided into the following parts:

1. The Marshall test values for mix design.
2. The Immersion-compression test values for the mix design.
3. The skid-resistance values for the initial investigation.
4. The skid-resistance values for the investigation of four different aggregates.

The data are presented in tabular form to enable the reader to compare values more easily.

Table 6. Marshall test values.

		Gradation		
		Fine	Medium	Coarse
5.0% Asphalt Content				
Density	1	2.285	2.317	2.344
	2	2.277	2.317	2.340
	3	2.279	2.317	-----
	Av.	2.280	2.317	2.342
Stability	1	1919	2256	2291
	2	1968	2188	2501
	3	1864	2089	----
	Av.	1917	2178	2396
Flow		8.0	7.6	6.5
% Total Voids		6.94	5.31	4.49
% Voids Filled		61.82	68.14	71.69

Table 6. (cont.)

		Gradation		
		Fine	Medium	Coarse
5.5% Asphalt Content				
Density	1	2.302	2.340	2.362
	2	2.306	2.341	2.374
	3	2.380	2.339	2.379
	Av.	2.305	2.340	2.372
Stability	1	2476	2743	2186
	2	2492	2729	2359
	3	2654	2702	2687
	Av.	2541	2725	2411
Flow		7.6	6.6	5.6
% Total Voids		5.33	4.10	2.87
% Voids Filled		71.33	76.82	83.16
6.0% Asphalt Content				
Density	1	2.373	2.388	2.408
	2	2.369	2.402	2.411
	3	2.379	2.390	2.411
	Av.	2.374	2.393	2.410
Stability	1	2936	2698	2314
	2	2838	2742	2614
	3	3023	3067	2485
	Av.	2932	2836	2471
Flow		8.6	6.0	11.0
% Total Voids		2.07	1.24	0.41
% Voids Filled		88.12	92.92	98.17
6.5% Asphalt Content				
Density	1	2.360	2.368	2.363
	2	2.380	2.392	2.368
	3	2.379	2.392	2.387
	Av.	2.373	2.384	2.373
Stability	1	2352	1733	1775
	2	2450	2088	1931
	3	2526	2406	2592
	Av.	2443	2076	2099
Flow		11.3	16.0	17.3
% Total Voids		1.25	0.83	1.25
% Voids Filled		92.93	95.35	92.93

Table 6. (concl,)

		Gradation		
		Fine	Medium	Coarse
7.0% Asphalt Content				
Density	1	2.365	2.365	2.371
	2	2.356	2.378	2.368
	3	2.350	2.379	2.364
	Av.	2.357	2.374	2.368
Stability	1	2265	1785	1915
	2	2201	1704	2041
	3	2055	1664	1915
	Av.	2174	1718	1957
Flow		14.0	16.3	15.0
% Total Voids		0.84	0.42	0.42
% Voids Filled		95.14	97.49	97.49

Table 7. Immersion-compression test values.

		Initial Test	Check Test
Density of Specimen	1	2.344	2.345
	2	2.331	2.350
	3	2.344	2.351
Density of Immersed Spec.	4	2.347	2.352
	5	2.345	2.355
	6	2.345	2.358
Strength of dry spec., psi	1	373	369
	2	365	414
	3	399	446
	Av.	379	410
Str. of Immersed Spec., psi	4	485	406
	5	479	485
	6	559	532
	Av.	508	474
Per cent Retained Strength		134.0	115.6

Table 8. Skid resistance values for initial investigation.

Specimen	Trial 1	2	3	4	5	Av.	Specific Gravity	Passings of Tire	Remarks
1	61	61	61	61	62	61.2	2.33	6100	
2	67	67	66	67	66	66.6	2.30	6100	
3	64	63	63	62	62	62.8	2.33	6100	
4	62	61	60	60	60	60.6	2.30	6100	
5	62	61	61	60	60	60.8	2.33	4485	pump clogged
6	58	57	57	57	56	57.0	2.32	6100	agg. not prominent
7	60	60	60	59	59	59.6	2.33	6100	
8	62	60	60	59	59	60.0	2.34	6100	agg. not prominent
9	62	61	61	60	61	61.0	2.32	6100	
10	62	62	61	61	60	61.2	2.30	6100	

Table 9. Skid resistance values for comparison study.

Specimen		Trial 1	2	3	4	5	Av.	Specific Gravity	Passings of Tire	Remarks
Sand-Gravel	1	50	49	49	49	48	49.0	2.32	3847	pump clogged; uneven surface
	2	46	46	45	45	45	45.4	2.30	6100	
Chat	1	47	46	46	46	46	46.2	2.13	4496	pump clogged
	2	47	47	47	46	46	46.6	2.12	6100	
Mixed Agg.	1	55	55	54	53	53	54.0	2.33	6100	
	2	54	53	53	52	52	52.8	2.29	6100	
Sand-stone	4	62	61	60	60	60	60.6	2.30	6100	
	8	62	60	60	59	59	60.0	2.34	6100	

INTERPRETATION OF DATA

Mix Design

The Marshall method of mix design is based on five parameters. Four of these parameters are used in selecting the optimum asphalt content while the fifth is used as a limiting value. The mix design considered is mainly for a surface course approximately one inch thick. This makes the problem unique as to aggregate size and asphalt content as will be discussed. Also, if this aggregate is ever chosen to be used as a surface mix, the problem of economics will enter into the situation in two ways. One way would be in the transportation of the material to the construction site, and the other way in the crushing operation. Three gradations were used in order to evaluate any differences that might exist and to see if these differences are significant in considering the optimum asphalt content.

The maximum size of the aggregate in all gradations was limited to 1/2 inch. This limitation would allow a design thickness of 3/4 inch to be used and still maintain a thin layer of matrix between the aggregate and the surface. The coarse gradation would require less crushing and would probably result in a lower unit price if large quantities were ordered. The fine gradation would require more expensive crushing and would result in more wear and tear on the crushing equipment, thereby increasing the unit cost. All of these factors must be considered before this aggregate is used to provide a highly non-skid surface.

For a surface course of this thickness, the stability should be as high as possible to prevent shear failures, yet the surface course should be flexible enough to smooth out any irregularities that might exist in the surface that it overlays. The voids should be such that the asphalt binder will not oxidize; oxidation causes hardening and eventually the formation of pot holes. On the other hand, too few voids result in bleeding of the surface which completely defeats the purpose for which the pavement is designed.

The curves and test values showing the test characteristics of the different asphalt contents and different gradations are given in Fig. 5, and in Table 6. The given characteristic is plotted against the per cent asphalt cement by weight of total mix. The curves concerning the voids are fairly uniform except for a few erratic values. The per cent voids in aggregate filled for the coarse gradation is about ten percentage points above the fine gradation except for the two higher asphalt contents. This may be due to the fact that the fine aggregate gradation has a much larger surface area for a given sample, thus resulting in a lower asphalt cement to surface area ratio. At the higher asphalt contents, when more asphalt cement is available, all aggregate surfaces have a more equal chance to absorb the asphalt cement, and the values approach each other. The Kansas State Highway Commission Specifications call for no specific per cent of voids in aggregate filled, but values often used are from 75-82 per cent (11). The asphalt contents at the midpoint of these values are:

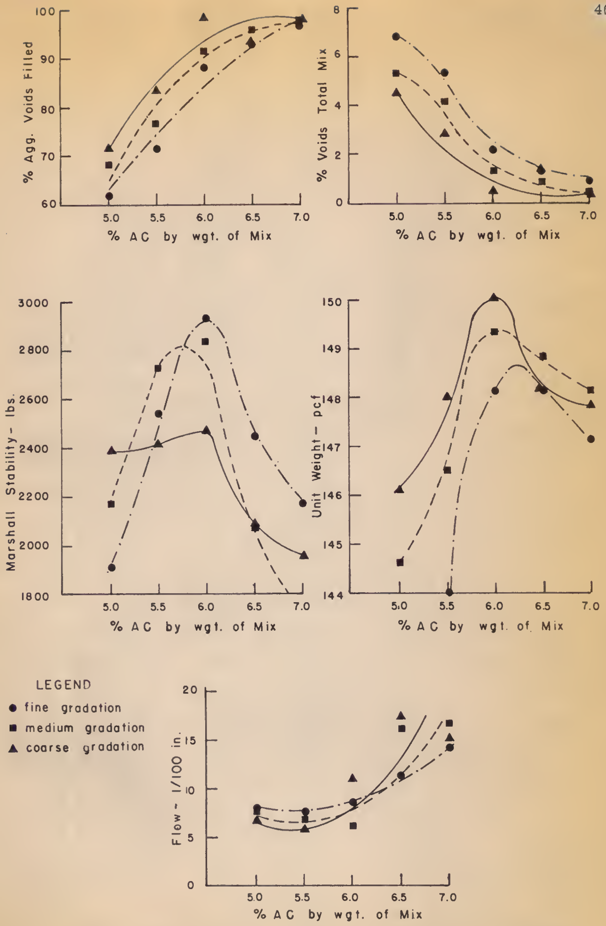

Fig. 5 TEST PROPERTY CURVES FOR MIX DESIGN

Coarse gradation ----------	5.20
Medium gradation ---------	5.40
Fine gradation ------------	5.70

The per cent voids in total mix is also not specified by the K.S.H.C. Specifications. This specification is used mainly to allow for added compaction that may be brought about when the new pavement is subjected to traffic action. A good value for this is 3 - 5 per cent (11). From Fig. 5, using 4 per cent voids total mix, the asphalt contents are:

Coarse gradation ------------	5.10
Medium gradation -----------	5.45
Fine gradation --------------	5.65

The stability of an asphalt concrete is perhaps the most important parameter when considering thin asphaltic concrete layers. Therefore the asphalt content giving the maximum stability for each gradation was selected. The curves for stability vs. asphalt content are very good for the fine and medium gradation, but the coarse gradation curve is flat for the lower asphalt contents. This flat portion of the curve could be caused by the grain-to-grain contact supporting the load when the asphalt content is low. Most designs specify a minimum of 500 lb Marshall stability for 100 psi tires but since all values were above this, the asphalt giving the greatest stability was chosen. These values were:

Coarse gradation -----------	6.00
Medium gradation ----------	5.80
Fine gradation -------------	6.00

The fifth parameter, the flow, is used only to check the optimum asphalt content against a maximum value. The maximum flow value permitted under most specifications is 20. All of the combinations of different mixes are below this value so this will not be considered to affect the design.

The optimum asphalt content can now be found by averaging the four parameters.

Parameter	Gradation		
	Fine	Medium	Coarse
% Voids in aggregate filled	5.70	5.40	5.20
% Voids total mix	5.65	5.45	5.10
Stability	6.00	5.80	6.00
Density	6.25	6.00	6.00
Avg.	5.90	5.66	5.58

From these data it can be seen that the asphalt content is nearly the same for any gradation. Therefore as long as the gradation meets K.S.H.C. Specifications, Grading A, Aggregate for Surface Courses, the asphalt content could be any of the averages shown.

Some aggregates containing a large amount of quartz have a tendency to strip. Therefore the Immersion-compression test was performed on the medium gradation using the 6 per cent asphalt content. The test values are given in Table 7. The initial test was performed, and the per cent retained strength was 134.0. This would mean that the specimens immersed gained strength, instead of losing strength as would be expected. This happens in some cases, but to make the results more convincing, another series of tests was performed. This check test resulted in 115.6 per cent retained strength. This leads one to believe that this aggregate will not have any serious stripping tendency.

The foregoing data do not single out one gradation as being better than another; therefore, selection of the proper or optimum gradation is impossible.

If the material is to be used in large quantities for a surface course, it must meet K.S.H.C. Specifications. The cheapest material available would be that material already in production. The gradation selected for use would then be the one nearest the crusher run material meeting the specifications. To see what gradations might be available at the quarry site, a trip was made to Lincoln, Kansas, to obtain some samples. The material sampled was referred to by the company as 3/4-inch crusher run. The 3/4-inch crusher run material was sampled from stockpiles, and was placed in sacks for transport to the laboratory. All material retained on the 1/2-inch sieve was discarded, and a gradation was run on all other material. The gradation was as shown in Table 10.

Table 10. Gradation of samples.

Sieve Size	Per cent Retained	K.S.H.C. Specifications
3/4"	0	0-5
3/8"	19.6	15-30
No. 4	48.5	30-48
No. 8	62.6	40-58
No. 16	69.1	54-68
No. 30	73.2	63-75
No. 80	88.5	80-88
No. 200	94.8	92-96

From these gradations and a comparison with the specifications it can be seen that a small adjustment in gradation would allow this material to meet the specifications. Then the Kansas State Highway Commission could use this material, when necessary, to produce a highly non-skid asphaltic concrete surface course.

Initial Skid Resistance Investigation

The purpose of this investigation was to develop a traffic simulator that could be used to produce specimens capable of having their surface coefficient of friction evaluated by the British portable tester. Ten specimens were prepared under the same conditions. These were prepared to enable a statistical analysis known as "Analysis of Variance" (17) to be performed on the data. This analysis is shown in Appendix B.

The values were arranged in order starting with the highest mean down to the lowest. Fifty units were subtracted from the original values to simplify the computations. The F-test leads to the rejection of the null hypothesis that the sample means are alike. The within specimen mean square of 0.62 indicates that there is very good repeatability in measuring the coefficient of friction on one specimen. This mean square value is an estimate of the variance that can be expected from trial to trial on one specimen, and this low value indicates that the method of testing each individual specimen was very good.

The mean square value from specimen to specimen was somewhat larger. This large value led to the significant F-test which resulted in the rejection of the null hypothesis. The F-test gave a value of 48.19 while the value of F with (9,40) degrees of freedom at the .05 level is 2.12. As can be seen, the F value is significant. Although the F-test is not required before making comparisons between means, it was used in this case to supplement the comparison test.

The test selected for comparing these means is known as Duncan's New Multiple Range Test. This test has special protection against Type I errors. A type I error is the rejection of the null hypothesis when it actually is true. This test is also shown in Appendix B. The actual difference is shown, and the Duncan NMRT difference is shown beneath the actual value. The values marked with an asterisk are significant with the risk of making five wrong decisions per 100 decisions made. The means were ranked for easy comparison. Concerning the different specimens, the following statement can be made: Specimens 2, 3, and 6 are significantly different from all the rest; Specimens 1 and 10 are significantly different from 7, but none of the other values are significant.

This leads one to believe that this method of laboratory traffic simulation is not consistent from specimen to specimen. Since only relative values are needed in determining whether one specimen of a given aggregate is different from another specimen of another aggregate, the method should serve this purpose fairly well.

Comparison of Four Aggregates

The purpose of this study was to see if these four aggregates reacted differently to the wear and polish cycle by giving a different coefficient of friction for each aggregate type. The four aggregates selected were as previously mentioned, including specimens 4 and 8 of the initial investigation. These were selected by going to a table of random numbers and randomly pointing to a number. This number and the following, reading across, were used as the random sample to represent the sandstone in the comparison. Figure 6 shows a comparison of the surface texture of these different specimens. The test values are given in Table 9. The "Analysis of Variance" was also used to analyze these data.

Since two specimens were prepared with each aggregate type, all the values were put together to perform the comparison test. The computations for the analysis of variance and comparison test are given in Appendix C. The same comparison test that was used in the initial investigation was used for these data. The values indicate that the sandstone specimens are significantly different from all the rest. This shows that the sandstone exhibits the best resistance to polishing when compared with the other three specimens. There is also a slight indication that the mixed aggregate gradation is better than the chat or sand-gravel, but the sand-gravel and chat are nearly the same.

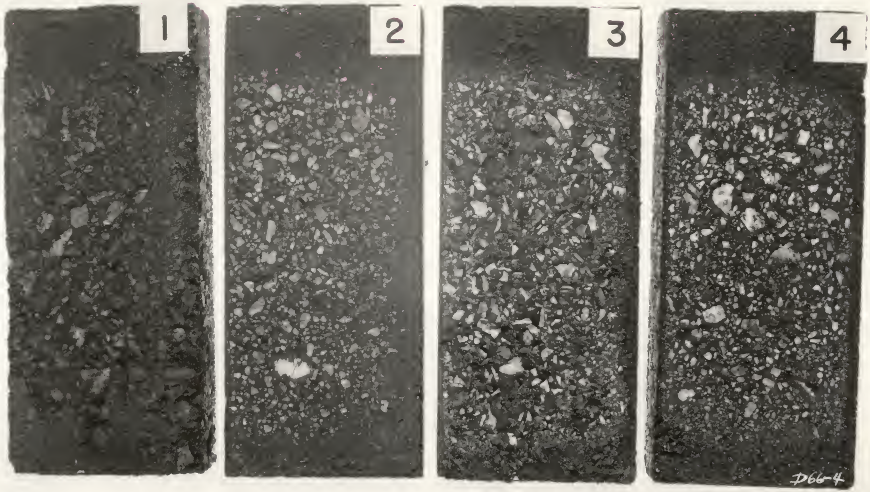

Fig. 6 SURFACE TEXTURE OF FOUR AGGREGATES

DISCUSSION OF RESULTS

The primary objective of this investigation was to design a satisfactory asphalt paving surface and to develop a simple method of simulating traffic action in the laboratory. The aggregate that was used in the mix design and for the initial skid resistance investigation was a durable sandstone. In the initial skid resistance investigation one type of aggregate (Lincoln Quartzite) was used to establish some sort of range of values that might be expected. A comparison study of four types of aggregates was undertaken to evaluate the polishing characteristics of different aggregates. A brief summary of results is given with recommendations for future investigations of this nature.

Summary of Results for Mix Design

1. The Marshall stability values are adequate at the optimum asphalt content for any gradation.
2. The density of the compacted mixture is fairly high due to the specific gravity of the aggregate.
3. An asphalt content, by weight of total mix, in the range of 5.5 to 6.0 per cent is the optimum for this aggregate.
4. No gradation is especially better than another as long as the specifications are met.
5. Economically speaking, the coarse gradation is the cheapest to use due to the cheaper crushing operation.

Summary of Results for Traffic Simulator

1. The procedure developed for the wear and polish procedure is fairly easy to perform.

2. The surface produced is striated but the aggregate protruded slightly and the polished surface closely resembles an aged road surface.

3. The repeatability of the surface from specimen to specimen is not too good as the statistical analysis demonstrated.

Summary of Results for Comparison of Four Aggregates

1. Statistically speaking, the sandstone surface coefficient of friction is significantly higher than all the others.

2. All other surfaces produced by the Traffic Simulator are potentially slippery when the pavement surface is wet.

3. Surface texture of sandstone and others are slightly different in appearance. The sandstone specimen appears to remain darker as if it were holding the asphalt within its void spaces.

Analysis of Results

The results of this investigation show that the aggregate, Lincoln Quartzite, could be used in a pavement surface mixture to produce a highly skid resistant surface. The mix design values show very little change in test characteristics from gradation to gradation. A definite decision cannot be made on which gradation would produce the highest coefficient of friction because only the medium gradation was used in the skid resistance investigation. Future study could be carried out in an effort to determine the gradation that would display the best coefficient of friction.

The investigation to establish a range of values that could be expected with the Traffic Simulator did not prove to be very successful. It is the opinion of this author that although the specimen to specimen variation was significant, the relative skid resistance of different surfaces in comparing different aggregates would be such that the best surface could be chosen. This was brought out in the comparison of four different aggregates.

The Traffic Simulator and procedure discussed in this thesis comprise another step in the right direction that will eventually allow the inclusion of pre-testing of aggregates that are to be used in pavement surfaces in the design of modern-day, high-speed highways.

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APPENDIX A

Chemical analysis of Lincoln Quartzite.*

Chemical Compound	Per cent of total, by wt. %
Silicon dioxide	68.03
Aluminum oxide	1.61
Ferric oxide	0.84
Calcium oxide	15.91
Magnesium oxide	0.26
Sodium oxide	0.26
Potassium oxide	0.10
Carbon dioxide	12.99
Water	0.28

* Courtesy of the Road Materials Laboratory of the Kansas State Highway Commission, Manhattan, Kansas. Lab. No. 97126, March 14, 1957.

APPENDIX B

Analysis of Variance for initial skid-resistance investigation.

	Skid-resistance values - 50										Entire Experiment
	2	3	10	1	9	5	4	8	7	6	
	17	14	12	11	12	12	12	12	10	8	
	17	13	12	11	11	11	11	10	10	7	
	16	13	11	11	11	11	10	10	10	7	
	17	12	11	11	10	10	10	9	9	7	
	16	12	10	12	11	10	10	9	9	6	
ΣX	83	64	56	56	55	54	53	50	48	35	554
ΣX^2	1379	822	630	628	607	586	565	506	462	247	6432.0
$\frac{(\Sigma X)^2}{n}$	1377.8	819.2	627.2	627.2	605.0	583.2	561.8	500.0	460.8	245.0	6138.3
Σx^2	1.2	2.8	2.8	0.8	2.0	2.8	3.2	6.0	1.2	2.0	293.7

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square
Between specimens	9	268.9	29.88
Within specimens	40	24.8	0.62
Total	49	293.7	

Duncan's NMRT

Speci- men	: $\bar{x}$	$\bar{x}$-57.0	$\bar{x}$-59.6	$\bar{x}$-60.0	$\bar{x}$-60.6	$\bar{x}$-60.8	$\bar{x}$-61.0	$\bar{x}$-61.2	$\bar{x}$-61.2	$\bar{x}$-62.8
2	66.6	9.6* (1.67)	7.0* (1.63)	6.6* (1.59)	6.0* (1.54)	5.8* (1.49)	5.6* (1.42)	5.4* (1.33)	5.4* (1.21)	3.8* (1.01)
3	62.8	5.8* (1.63)	3.2* (1.59)	2.8* (1.54)	2.2* (1.49)	2.0* (1.42)	1.8* (1.33)	1.6* (1.21)	1.6* (1.01)	
10	61.2	4.2* (1.59)	1.6* 1.54)	1.2 (1.49)	0.6 (1.42)	0.4 (1.33)	0.2 (1.21)	0.0 (1.01)		
1	61.2	4.2* (1.54)	1.6* (1.49)	1.2 (1.42)	0.6 (1.33)	0.4 (1.21)	0.2 (1.01)			
9	61.0	4.0* (1.49)	1.4 (1.42)	1.0 (1.33)	0.4 (1.21)	0.2 (1.01)				
5	60.8	3.8* (1.42)	1.2 (1.33)	0.8 (1.21)	0.2 (1.01)					
4	60.6	3.4* (1.33)	1.0 (1.21)	0.6 (1.01)						
8	60.0	3.0* (1.21)	0.4 (1.01)							
7	59.6	2.6* (1.01)								
6	57.0									

* Indicates significance.

APPENDIX C

Analysis of Variance for comparison of four aggregates.

	Skid-resistance**								
	SS4	SS8	MA1	MA1	SG1	C-2	C-1	SG2	
	62	62	55	54	50	47	47	46	
	61	60	55	53	49	47	46	46	
	60	60	54	53	49	47	46	45	
	60	59	53	52	49	46	46	45	
	60	59	53	52	48	46	46	45	
ΣX	303	300	270	264	245	233	231	227	2073
ΣX^2	18365	18006	14584	13942	12007	10859	10673	10307	108743
$(\Sigma X)^2$	18362	18000	14580	13939	12005	10858	10672	10306	107433
Σx^2	3	6	4	3	2	1	1	1	1310

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square
Between agg. types	7	1289	184.10
Within	32	21	0.66
Total	39	1310	

Duncan's NMRT

Speci-men	$\bar{x}$	$\bar{x}$-45.4	$\bar{x}$-46.2	$\bar{x}$-46.6	$\bar{x}$-49.0	$\bar{x}$-52.8	$\bar{x}$-54.0	$\bar{x}$-60.0
SS4	60.6	15.2* (1.68)	14.4* (1.62)	14.0* (1.56)	11.6* (1.50)	7.8* (1.40)	6.6* (1.27)	0.6 (1.05)
SS8	60.0	14.6* (1.62)	13.8* (1.56)	13.4* (1.50)	11.0* (1.40)	7.2* (1.27)	6.0* (1.05)	
MA1	54.0	8.6* (1.56)	7.8* (1.50)	7.4* (1.40)	5.0* (1.27)	1.2* (1.05)		
MA2	52.8	7.4* (1.50)	6.6* (1.40)	3.8* (1.27)	(1.05)			
SG1	49.0	3.6* (1.40)	2.8* (1.27)	2.4* (1.05)				
C-2	46.6	1.2 (1.27)	0.4 (1.05)					
C-1	46.2	0.8 (1.05)						
SG2	45.4							

** Abbreviations used for aggregates are as follows: SS-sandstone, MA-mixed aggregate, SG-sand gravel, and C-chat.

* Indicates significance

THE DESIGN OF AN ASPHALT PAVING SURFACE USING A DURABLE SANDSTONE AND AN INVESTIGATION OF THIS AGGREGATE'S RESISTANCE TO POLISHING ACTION

by

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B. S., Kansas State University, 1961

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The purpose of this investigation was to design an asphaltic concrete paving surface and to develop a laboratory method of traffic simulation. The need for a simple method of evaluating how a given aggregate will react to traffic action has become more pronounced in recent years. The vehicles of today require a larger coefficient of friction at the road surface to provide adequate stability at high speeds, and this requires that the engineer be more selective in the aggregate he chooses for a pavement surface.

The aggregate used in the design was a durable sandstone known as Lincoln Quartzite. This aggregate is a calcareous sandstone in which quartz grains are bound in a matrix of calcite. The aggregate is very hard and dense, and has a very low absorption.

The Marshall method of mix design was chosen to evaluate the characteristics of the different mixes. Five different asphalt contents were used with three gradations. These gradations represented the upper, lower, and midpoint of the Kansas State Highway Commission specification for aggregate to be used in surface courses of asphaltic concrete.

After designing the mixture, a device called a Traffic Simulator was constructed and this was used to evaluate the polishing characteristics of the Lincoln sandstone. Ten identical specimens were prepared using the same procedure in order to allow a statistical analysis to be performed. The coefficients of friction of the specimens were determined by the recently developed British portable tester.

To study further the polishing characteristics of different aggregates, four different aggregates were selected consisting of a sand-gravel aggregate, chat aggregate, mixed aggregate, and the sandstone used in the previous investigation. The Traffic Simulator was used to polish each specimen, and the surface coefficient of friction was determined with the British portable skid resistance tester. A statistical analysis was used to interpret these data. A brief summary of results follows:

1. The optimum asphalt content of any gradation within the specifications is from 5.5 to 6.0 per cent by weight of total mix.

2. Procedure for preparing and testing sandstone skid resistance specimens was fairly simple, yet it produced a surface that resembled a heavily travelled road surface.

3. The repeatability from specimen to specimen using the same aggregate was not too satisfactory using the Traffic Simulator to polish the specimens, but the Traffic Simulator was useful in determining the relative susceptibility to polishing of different aggregates.

4. Compared with other aggregates, the sandstone specimens resulted in the highest coefficient of friction on the basis of the method developed in the work described in this thesis.