A STUDY OF THE POLISHING CHARACTERISTICS OF LIMESTONE AND SANDSTONE AGGREGATES IN REGARD TO PAVEMENT SLIPPERINESS

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ABSTRACT

        The coefficient of friction on dry highway surfaces regardless
of stone composition and texture has in most cases been at least 0.6 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 fric-
tion between the plane surfaces of four-inch 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 correlat-
ed 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 lower 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.

I: INTRODUCTION

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 re-surfacing. 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 im-

provement 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 as 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 lime-

stone 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 lime-

stones are abundantly used for highway construction, unless skid-resis-

tance 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 indepen-

dent of surface textures, areas of contact, velocities and normal loading

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* The underscored numbers in parentheses refer to the list of references
at the end of the report.

(weight). All of this seems to be fairly true for non-lubricated surfaces, and it is not surprising that clean dry pavements regardless of composition 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.

II: SOME BASIC ASPECTS OF PAVEMENT FRICTION

An automobile or truck is accelerated by an engine, and decele-
rated, 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 pave-
ment surface -- whether it is wet or dry. To some extent wet fric-
tion is affected by speed and by qualities of the tire, such as the hard-
ness 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. $= 1/2\ mV^2$, 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 $P = 1/2\ fWV$. Expressing P in horsepower, V in miles per hour, and assuming W to be 3850 lbs., 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 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 affects 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.

III: 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-deg. 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 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 $\pm$ 1/4 in.
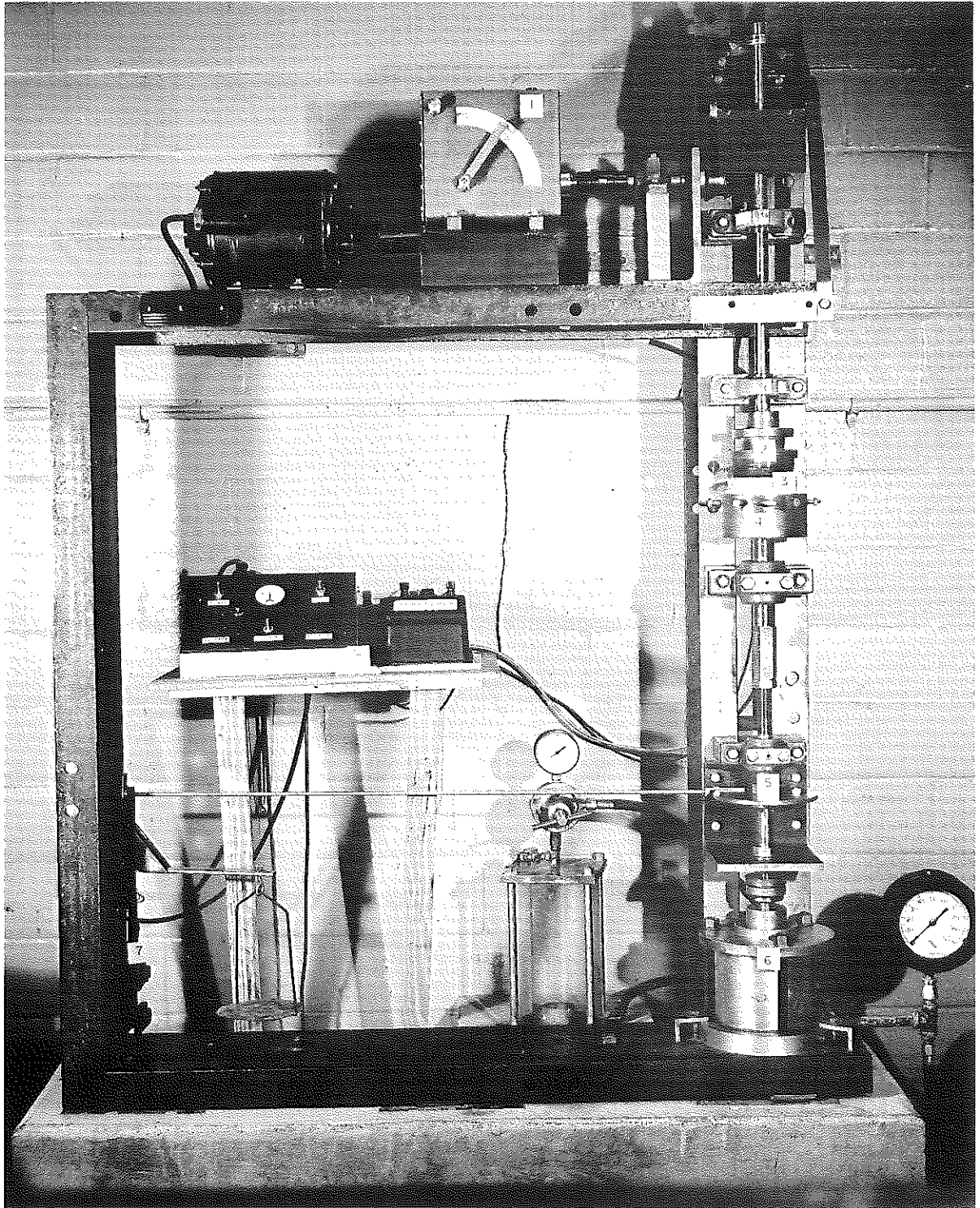
Fig. 1: Friction Measuring Device

A steel disk (5) transfers the torque developed in the lower shaft through a steel rod to a strain gauge bar (7). This torque transfer rod can be attached by a pin through either of three holes at different distances from the shaft -- 1, 1-3/4, or 2-1/2 inches -- 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 hence to the specimen. The pressure cell gauge was calibrated by loading the lower shaft with dead weights, opening the air metering 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 obtained 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 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 pounds 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 selected 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 1/2 in.
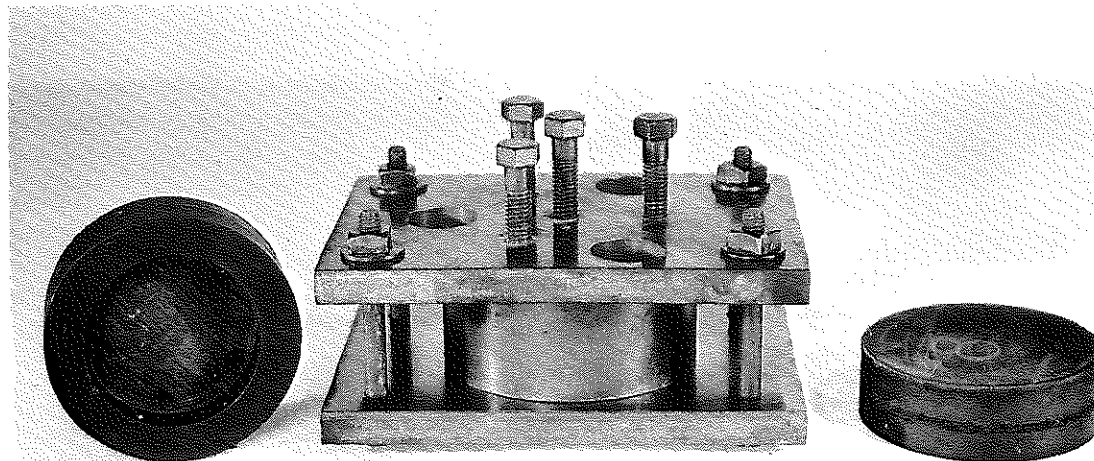
Fig. 2: Two of the Annuluses used for Testing, Shown with the Vulcanizing Mold
         used in their Preparation

Reflectometer

A 60-deg. specular reflectometer was built for use in deter-
mining 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 degrees from the vertical, and then
measuring the intensity of the beam reflected at sixty degrees in the oppo-
site direction. Thus, if the surface had "perfect" smoothness -- no
ridges or peaks whatever -- all of the light incident at 60 degrees would
be reflected at 60 degrees, 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 light indicates comparatively
the degree of irregularity of the surface, and consequently its smoothness
or degree of polish.

The reflectivity readings presented in Table 3, in Section IV
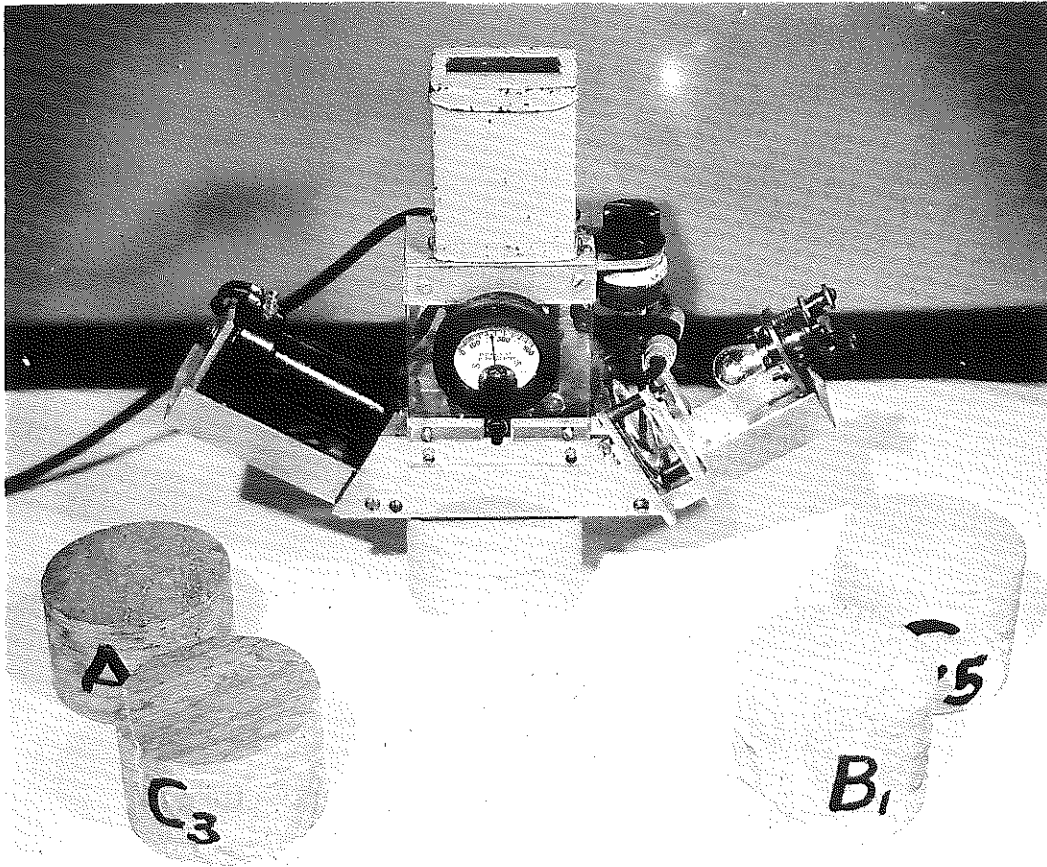of this report, are referred to and based on an assumed 100 percent

Fig. 3: Sixty Degree Reflectometer in Position for Measuring Surface Gloss of Specimen
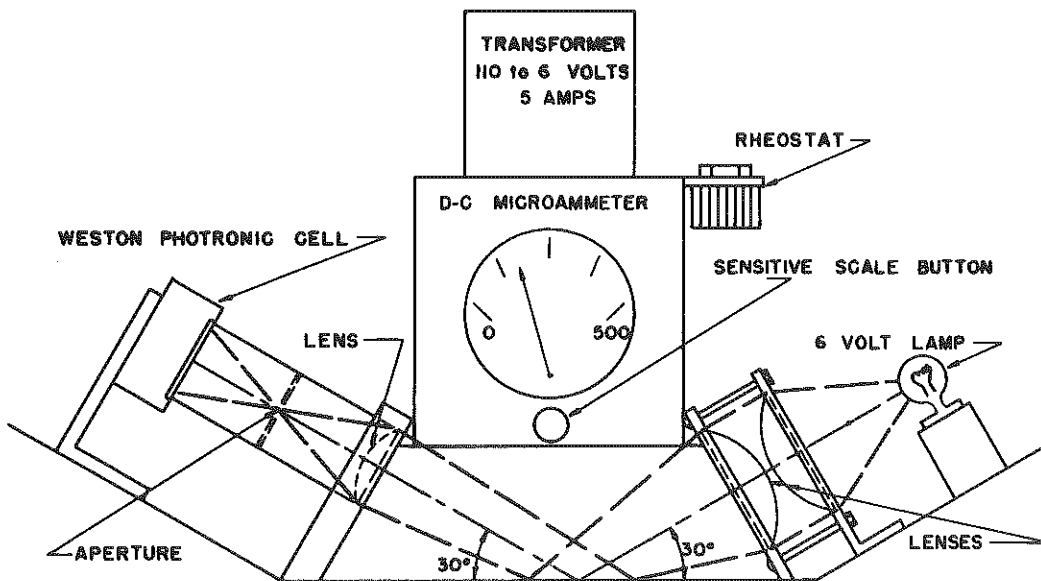

Fig. 4: Schematic Drawing of Sixty Degree Reflectometer

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 four-inch 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 inches 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 standstone groups, which had 1 and 2 stones

respectively.   The four limestone classifications were Camp Nelson,

Tyrone, Oregon, and oölitic*; the sandstones were graywacke and calca-

reous. (Camp Nelson, Tyrone and Oregon are names of Kentucky lime-

stone 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;

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

each was ground until the surface was uniform and smooth. Grinding

was then continued further on another glass plate with a slurry of levi-

gated Alumina No. 1. For the final polish, an eight-inch 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 reflecto-

meter. 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 slipperi-

ness, or that condition developed from pavement wetness, consideration

of the stones when dry was necessary to provide a clearer picture of the

problem involved.

        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.

IV: 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 inches 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,

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

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.

TABLE I
COEFFICIENT OF FRICTION VALUES FOR WET SURFACES

Specimen No.	Surface Load R.P.M.	Polished 20psi		15psi		150 Grit 20psi		15psi		10psi		80 Grit 20psi		15psi		10psi	
		180	240	180	240	180	240	180	240	180	240	180	240	180	240	180	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	10psi	150 Grit 20psi 180	240	15psi 180	240	10psi 180	240	80 Grit 20psi 180	240	15psi 180	240	10psi 180	240
		Incipient													
						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
						Oolitic									
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% reflectance value as taken from a first sur-
face mirror.

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 lime-

stones 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 sand-

stones 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 bear-

ings was in the range of 0.0011 to 0.0015.)

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 sand-

stones might be due to the large areas of fossil debris present in the

calcareous stones compared with the little or none present in the gray-

wackes. This debris, evident in the photographs of the polished stone

surfaces, polished easily and seemed much smoother than the base ma-

terial.

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
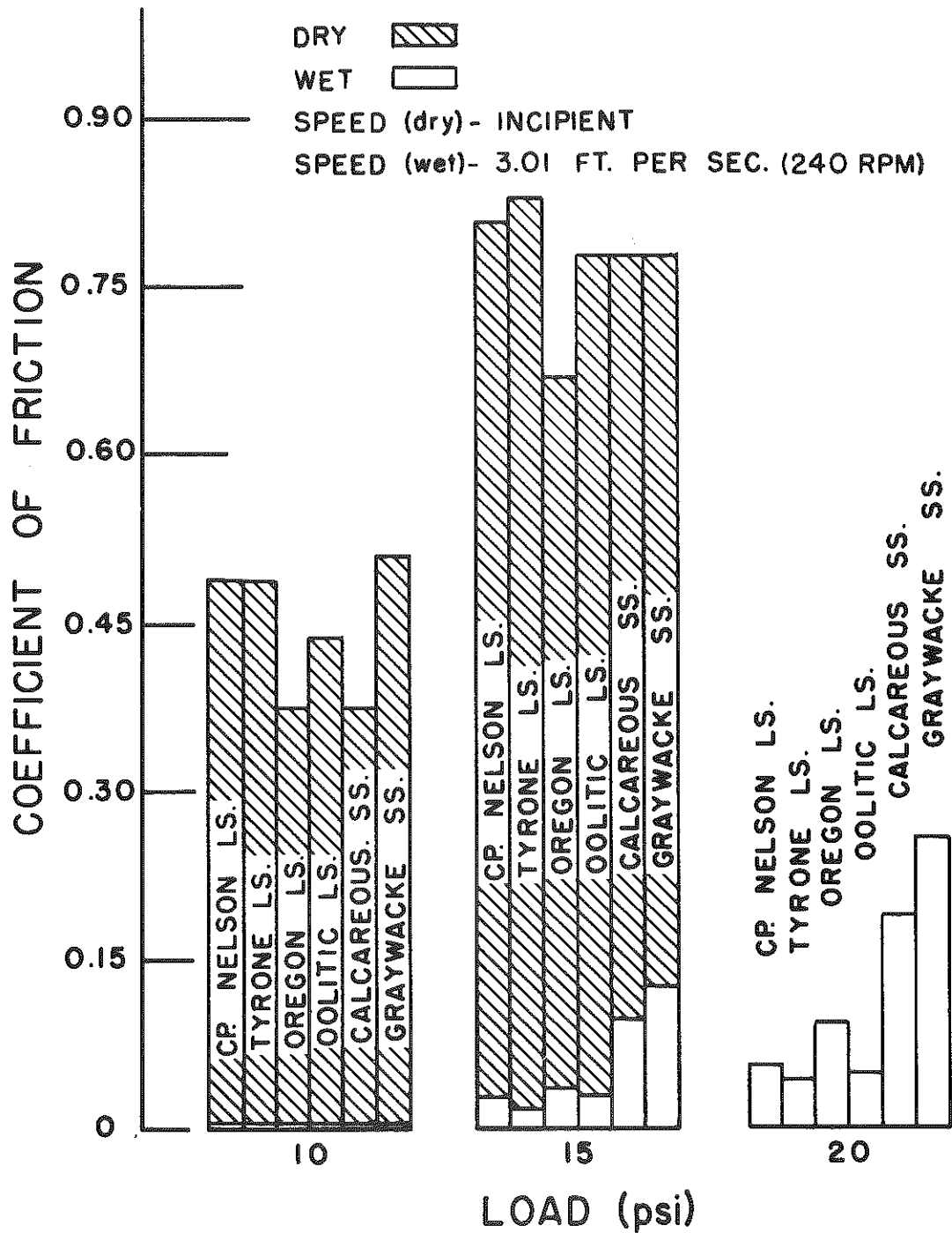
Fig. 5: Relationship Between Coefficient of Friction and Load for all Polished Specimens, Wet and Dry
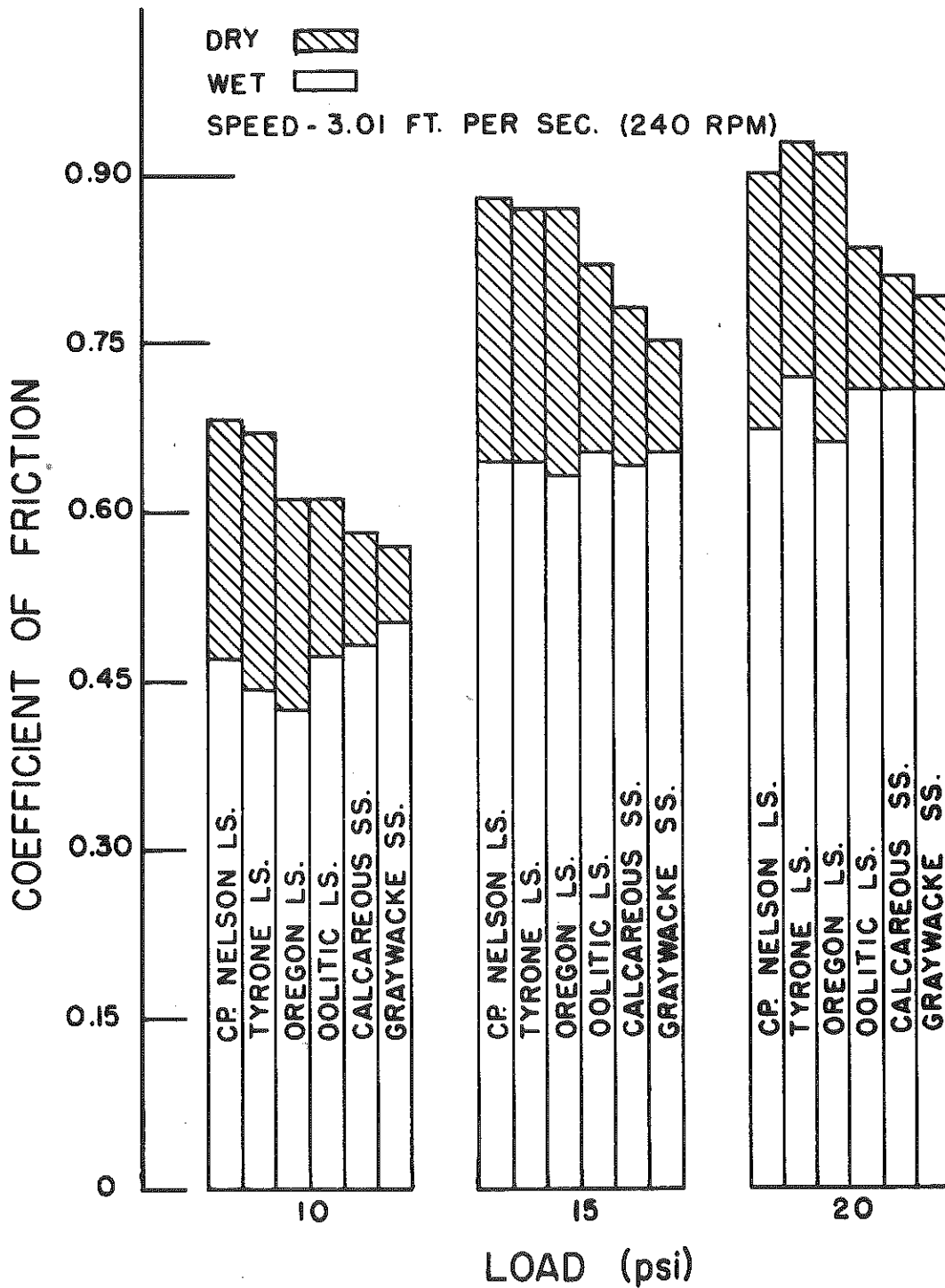
Fig. 6: Relationship Between Coefficient of Friction and Load for all Specimens
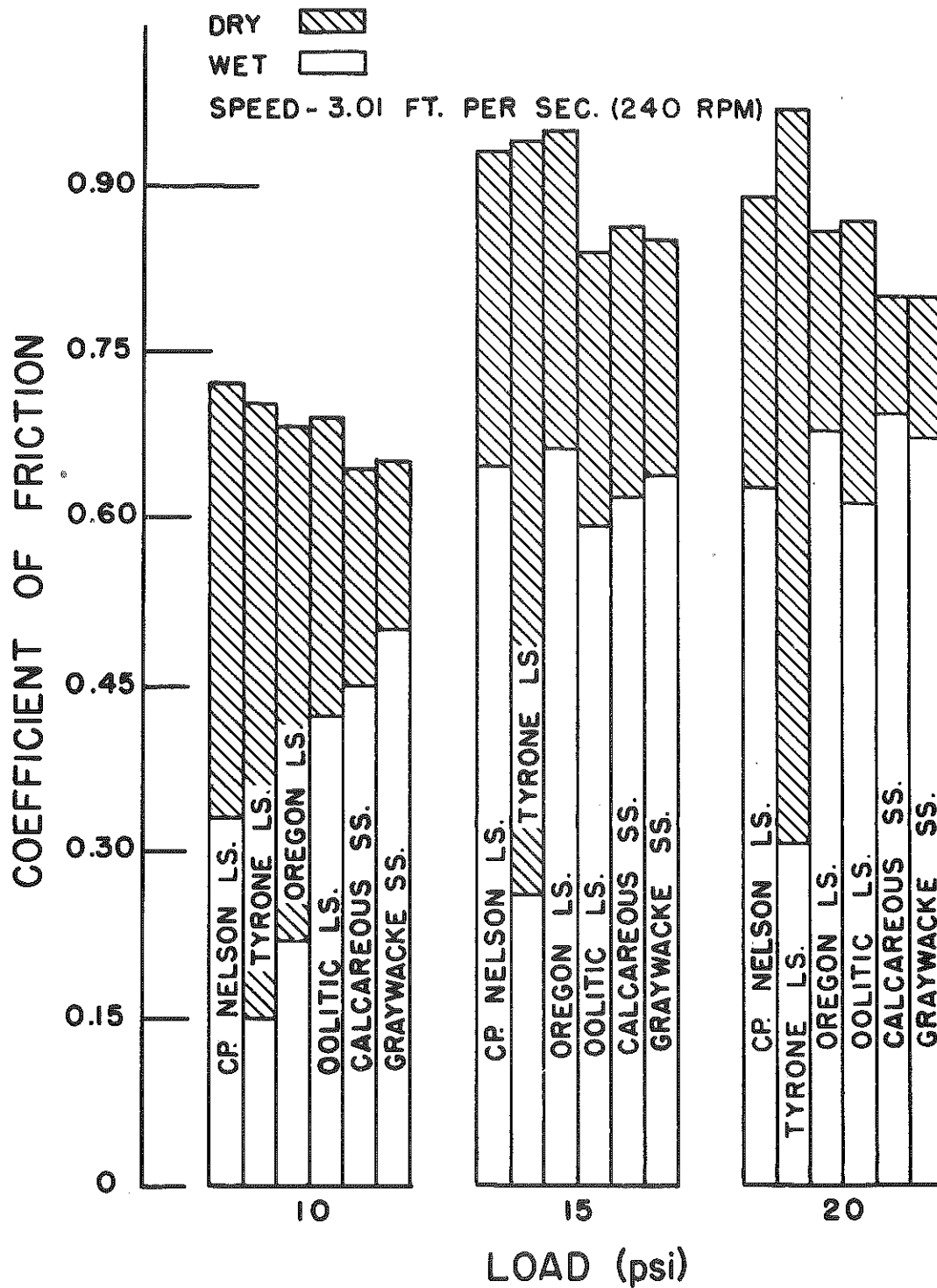Roughened with No. 80 Grit, Wet and Dry

Fig. 7: Relationship Between Coefficient of Friction and Load for all Specimens
Roughened with No. 150 Grit, Wet and Dry

testing load. It is 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 sur-
face area remains unaltered or is altered to such a small degree that the
area as a whole remains polished and, compared with the other classifica-
tions, 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 corres-
ponding 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.

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 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.

V: 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 inter-spaced 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 sections (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 & 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 & 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, silicified 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 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.

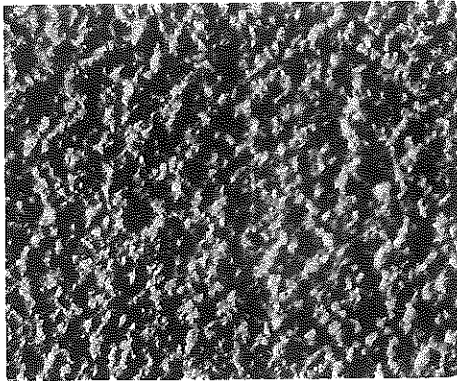muscovite - up to 2.3 mm.

biotite - up to 0.55 mm.

chlorite - up to 0.9 mm.
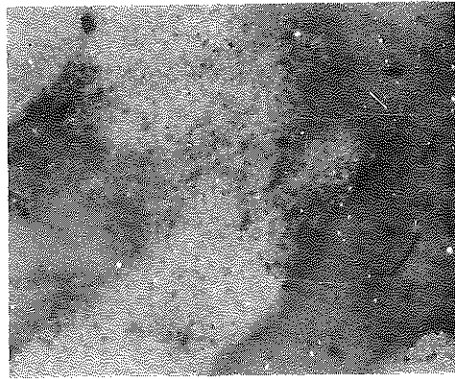
fossils - up to 9.0 mm.
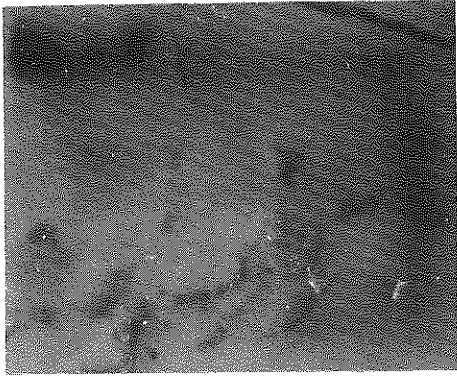
TYRONE   CAMP NELSON

Polished (10 X)   Polished (10 X)

Rough (10 x)   Rough (10 X)

Thin Section (103 X)   Thin Section (103 X)

Fig. 8: Photomicrographs of Prepared Specimens of Tyrone and Camp Nelson Limestones
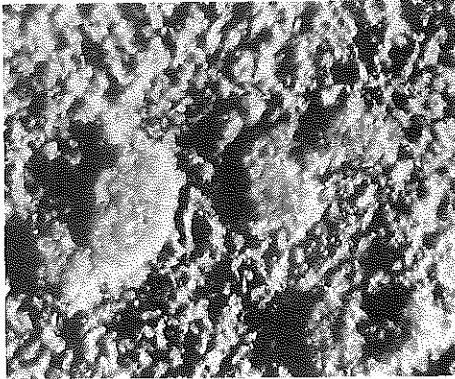
OOLITIC   OREGON

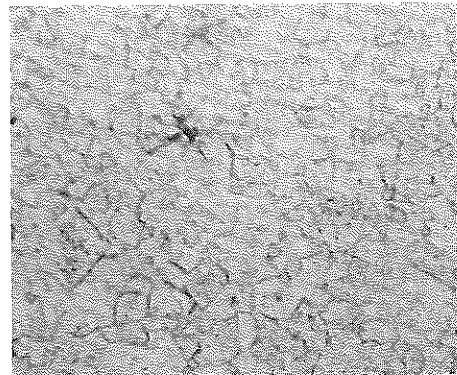Polished (10 X)   Polished (10 X)
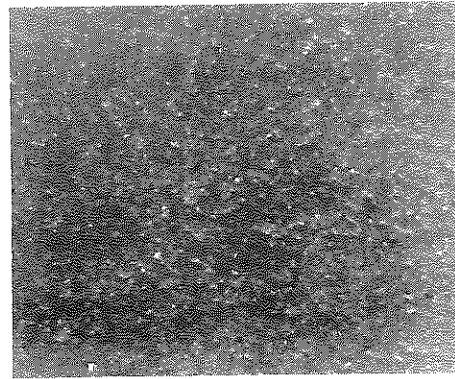
Rough (10 X)   Rough (10 X)
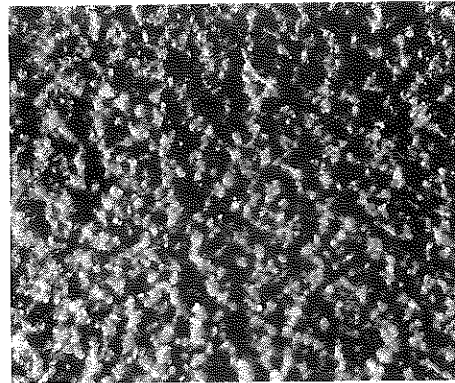
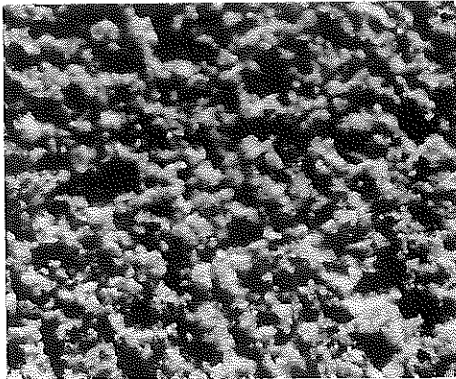Thin Section (103 X)   Thin Section (103 X)

Fig. 9: Photomicrographs of Prepared Specimens of Oölitic and Oregon Limestones
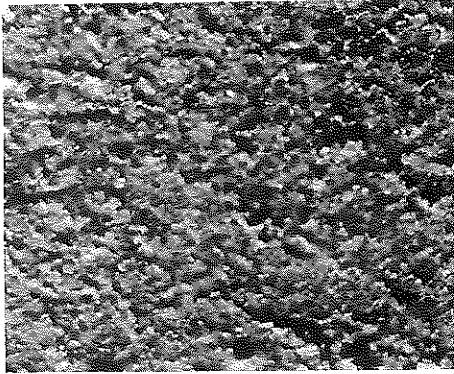
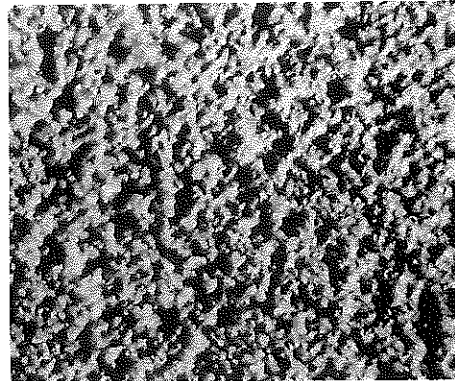GRAYWACKE   CALCAREOUS

Polished (10 X)   Polished (10 X)
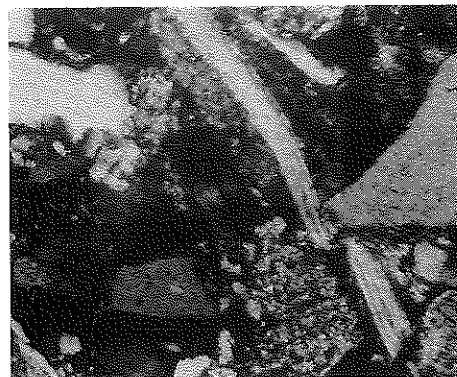
Rough (10 X)   Rough (10 X)

Thin Section (103 X)   Thin Section (103 X)

Fig. 10: Photomicrographs of Prepared Specimens of Graywacke and Calcareous Sandstones

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