This thesis describes tests made on two concrete pavements, five asphaltic type pavements and an untreated gravel macadam to determine their light reflecting characteristics. Tests were made with light from a fixed source and with angles of incidence with the pavement surfaces of forty-five degrees and of seventeen degrees. The reflection from the pavement surfaces was measured with a photometer. The tests were made on dry pavement surfaces and repeated on the same surfaces when wet. Comparisons between the same pavements when dry and when wet and between the different pavement types under both conditions are made. These tests simulate the conditions of fixed highway lighting.

A second series of tests was made on these pavement surfaces in which the headlights of an automobile were used as the light source. The percentage of the light reaching an approaching vehicle due to reflection from the pavement surface was determined. These tests were made on both dry and wet pavement surfaces.

From the results of these tests it is concluded that: The grooved, irregular and matte like surfaces give a greater diffusion of the light both when dry and when wet. Specular reflection or glare increases as the angle of the light with the pavement surface decreases. Glare is increased when the pavement is wet due to reflection from the film of water which covers the pavement surface. Glare can be largely prevented by a surface designed to drain the water off before the entire surface is flooded.
LIGHT REFLECTING CHARACTERISTICS
OF VARIOUS PAVEMENT SURFACES

by

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Head of Department of Civil Engineering

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INTRODUCTION

The science of highway design has made great progress in the last decade. Standards of alignment, grade, and superelevation have been raised to heights unthought of ten years ago. But with all these advances the toll of death, injury, and economic loss from traffic accidents steadily mounts. The phenomenal growth of motor vehicle traffic has exceeded the efforts of public bodies in providing adequate highway facilities. Traffic congestion during daylight hours is forcing steadily increasing night use of highways.

The high accident rate of night driving is a matter of serious concern to all engineers and officials responsible for the construction and operation of highways. Many studies have been made of accident frequency data, and the relationship between accident frequency and visibility. The conclusions reached in these studies are in substantial accord, and clearly show the increased hazard attendant upon night driving. Motor vehicle statistics in (1) the State of California, for the year 1934, show that the

ratio of accidents to total traffic was approximately five times greater during the hour between two and three in the morning than it was between noon and one o'clock. The same study shows that the average ratio of accidents to total traffic was two and one-half times as great at night as in daylight. Another indication of the increased hazard of night driving is the comparison of frequency of fatalities in traffic accidents in summer and winter months. In the State of California, in 1935, the death rate, per ten million gallons of gasoline consumed, was 19.1 during the five summer months, as against 24.3 during the five winter months. Some of this increase is chargeable to weather, but, in the main, it is due to the increased time of poor visibility. Many other compilations of data are available pointing in the same direction. An estimate of an increase of 50 per cent in the traffic accident rate in the hours of darkness over that in daylight is conservative.

The essential difference between daytime and nighttime driving lies in the difference in visibility. It is possible, by properly designed fixed lighting systems, to give visibility at night that approaches the minimum

necessary for safe driving. A considerable number of experimental highway lighting projects have been installed, and on these highways the accident rate has dropped. On some few of these the lighting has been discontinued, and invariably the accident rate has increased. Fixed highway lighting is at least a partial answer to the problem.

Fixed highway lighting is expensive, both in first cost and in operation. On four lane highways the installation cost is approximately $5,500 per mile, and the annual operation and maintenance cost is approximately $900. Present highway revenues can provide such installations only on highways carrying the heaviest traffic and which, for one reason or another, have proved abnormally hazardous.

For many years to come the automobile must carry its own light. Headlights have been improved, and carefully studied regulations for automobile lighting have been put into effect, without appreciably affecting the accident rate. Any further increase in the power of the headlights results in the blinding of approaching traffic, and defeats its own purpose.

With these limitations on the use of fixed lightings, and with the improbability of material improvement in automobile headlights, attention is directed to the
characteristics of the roadway surfaces themselves. The property of the pavement itself to reflect or to diffuse light is a major factor in the problem. Very few data bearing on this phase of highway construction are available. An interesting experiment on a model road is described by C. A. B. Halvorson. The surfacing consisted of truncated conical cups which projected above the water film of the wetted model. These projecting cups broke up the specular reflection or glare and produced a diffuse reflection or luminosity of the surface. He concludes that the glare from wet pavements occurs, "Because usually a film of water submerges the pavement particles and changes the character of reflection, i.e., causes the pavement to become specular without regard to its color, texture or light-reflection factor." Surface particles such as used in Halvorsen's tests can not be used in actual road building, but the tests described hereinafter show that certain types of surfacing, now in use, have this property of breaking up the specular reflection to a marked degree.

DESCRIPTION OF PAVEMENTS TESTED

The great majority of highway pavements are either cement concrete or some form of asphaltic concrete. In the investigation of light reflecting characteristics an attempt was made to select pavement surfaces that were representative of these kinds of pavements. Seven kinds of pavements were examined:

1. A new concrete pavement completed and cured but not yet opened to travel. This pavement is broom finished resulting in small grooves, between one-sixteenth and one-eighth inch in depth, transverse to the center line of the pavement. The surface was clean and unstained. The grooves from the brooming were sharp and unworn. A photograph illustrating the texture is shown on page 9. Duplicate tests were made on this pavement; first with the incident light across the grooves, as would be the case with ordinary illumination; and second with the light parallel with the grooves, as would be the case with a pavement broomed longitudinally.

2. A concrete pavement that had been in use eighteen years. This pavement was originally built with a smooth surface and the years of wear had smoothed down any irregularities that it might originally have had. The
surface had been considerably stained and discolored by oil during its service. A photograph entitled "Old Concrete Pavement" is shown on page 9.

3. An asphalt patch on an old asphaltic concrete pavement. This patch resembles sheet asphalt pavement in its surface characteristics. No aggregates show in the surface and such few irregularities as are present are inconsequential. A photograph entitled "Plain Asphalt" is shown on page 10.

4. An asphaltic concrete pavement that had been in service fifteen years. The surface is quite smooth. Approximately thirty per cent of the surface is made up of aggregate particles. The aggregate particles show considerable discoloration from oil. The irregularities in the surface are inconsequential. A photograph entitled "Worn Asphalt" is shown on page 10.

5. A bituminous macadam, in service about one year. The surface of this pavement is composed of broken stone ranging from one-quarter inch to three-quarter inch in size. The surface is very irregular, with depressions between particles up to as much as one-half inch in depth. Each particle is held by the asphaltic binder, but very little asphalt shows on the exposed surfaces. The broken
stone is a dense, dark colored basalt. A photograph entitled "Bituminous Macadam" is shown on page 11.

6. An asphaltic concrete pavement of the "closed type", which had been in service about two years. This surface showed aggregate up to one and one-quarter inch in size, but with a considerable portion of the surface made up of fine particles and asphalt. The surface contained many pits and depressions. The proportions of aggregate and asphaltic binder were as follows:

<table>
<thead>
<tr>
<th>Size of screen which all aggregates must pass</th>
<th>Percentage of aggregate, 1$\frac{1}{4}$ inch to $3/4$ inch</th>
<th>Percentage of aggregate, $3/4$ inch to $\frac{1}{2}$ inch</th>
<th>Percentage of aggregate, $\frac{1}{2}$ inch to 10 mesh</th>
<th>Percentage of aggregate, 10 mesh to 200 mesh</th>
<th>Percentage of asphalt, passing 200 mesh</th>
<th>Percentage of asphalt, 50-60 penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1$\frac{1}{4}$ inch</td>
<td>15 to 24</td>
<td>24 to 36</td>
<td>12 to 20</td>
<td>20 to 28</td>
<td>3 to 6</td>
<td>4.5 to 6.5</td>
</tr>
<tr>
<td>$1\frac{1}{4}$ inch to $3/4$ inch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$3/4$ inch to $1/2$ inch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$1/2$ inch to 10 mesh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 mesh to 200 mesh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200 mesh to 300 mesh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>300 mesh to 600 mesh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>600 mesh to 2000 mesh</td>
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<td></td>
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<tr>
<td>2000 mesh to 10,000 mesh</td>
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<td></td>
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</table>

The pavement was laid at a temperature of 325 degrees Fahrenheit. The seal coat is eliminated and $\frac{1}{4}$ inch screenings, coated by a two per cent asphaltic content binder, are rolled into the surface mixture, while it is still warm, at the rate of five pounds per square yard. A photograph entitled "Closed Type Asphaltic Concrete" is shown on page 11.

7. An asphaltic concrete wearing surface of the "open type", which had been in service about one year. This surface showed aggregates from three-quarter inch to
one-quarter inch in size. The aggregate particles stand out separately, giving an open surface, which, while true to line, consists entirely of minor irregularities. The proportions of aggregate and asphaltic binder were as follows:

<table>
<thead>
<tr>
<th>Size of screen which all aggregate must pass</th>
<th>3/4 inch</th>
<th>3/4 inch to 1/4 inch</th>
<th>1/4 inch to 10 mesh</th>
<th>10 mesh to 200 mesh</th>
<th>passing 200 mesh</th>
<th>Percentage of asphalt, cutback RC-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of aggregate, 3/4 inch to 1/4 inch</td>
<td>45 to 65</td>
<td>Percentage of aggregate, 1/4 inch to 10 mesh</td>
<td>30 to 35</td>
<td>Percentage of aggregate, 10 mesh to 200 mesh</td>
<td>8 to 14</td>
<td>Percentage of aggregate, passing 200 mesh</td>
</tr>
<tr>
<td>Percentage of aggregate, passing 200 mesh</td>
<td>4 to 6</td>
<td>Percentage of asphalt, cutback RC-4</td>
<td>4 to 6</td>
<td>This is used as a wearing surface only, and is placed on an impervious, closed mix base. The asphalt is of 80-120 penetration cut back with a maximum of 15 per cent naptha. The surface is laid at a temperature ranging from 175 degrees Fahrenheit to 250 degrees Fahrenheit. A photograph entitled &quot;Open Type Asphaltic Concrete&quot; is shown on page 12.</td>
<td></td>
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</table>
NEW CONCRETE PAVEMENT

OLD CONCRETE PAVEMENT
PLAIN ASPHALT

WORN ASPHALT
BITUMINOUS MACADAM

CLOSED TYPE ASPHALTIC CONCRETE
OPEN TYPE ASPHALTIC CONCRETE

UNTREATED GRAVEL MACADAM
DESCRIPTION OF TESTS

The object of the tests on these pavements is to determine their light reflecting characteristics; and to connect these characteristics with their physical properties such as color, texture and materials. The tests were divided into two parts:

1. A narrow beam of light was directed on the pavement to be tested. A rectangular frame was centered around the area illuminated. At the transverse center line of the frame an arm supporting a photometer was attached. This arm rotated across a semi-circular dial, which was graduated in degrees, so that the angle between the axis of the photometer and the pavement surface was read directly. The photometer was kept one foot from the center of the illuminated surface for all readings. Readings were taken at each fifteen degrees around the semi-circular arc. The light source was a spot light focused to give a narrow beam. Readings were taken with the incident light beam at an angle of forty-five degrees with the pavement surface, both in a plane parallel with the light beam, and in a vertical plane perpendicular to the plane of the incident light. Readings were first taken on dry pavement. The pavement surfaces were then wetted to simulate conditions
during a rain. The light source was then changed to give a beam at an angle of seventeen degrees with the pavement surface, and the tests repeated, except for the readings in a plane perpendicular to the plane of incident light. During all the tests the light source was kept constant with a voltmeter and rheostat. The drawing on page 16 shows the set-up of equipment for the test.

2. In this part of the investigation, a 1937 model automobile with the headlight beam in the depressed position was used as the light source. In this position, the center of the light beam struck the pavement surface approximately 65 feet from the headlight. Readings of the intensity of the light at double this distance, or 130 feet, and at the same elevation as the headlights, were taken with a photometer. These recorded the total light both direct from the headlights and reflected from the pavement. A screen was then placed in a position such that only the reflected light reached the photometer. The difference in these two values is the specular reflection, or glare from the pavement surface. The drawing on page 17 shows the equipment set-up for this test. Pavement surfaces were tested both dry and wet. The same pavements previously described were tested, except that the plain
asphalt was eliminated, and an untreated gravel macadam added. This gravel macadam was representative of well maintained surfaces of this type. The greater part of the surface was held by the filler, but with a sprinkling of loose gravel on top. A photograph entitled "Untreated Gravel Macadam" is shown on page 12.

The first series of tests simulate fixed lighting from a source well above the pavement, and with the light striking the surface at a relatively large angle. The second series shows the action of headlights and their affect on the driver of an approaching vehicle. The results of the tests are recorded as light intensity measured in foot-candles at the photometer. Since, in all the tests, the light intensity of the source, and the distance from the source to the reflecting surface and from the reflecting surface to the photometer, were kept constant, the results give a qualitative measurement of the light reflecting characteristics of the pavements tested.
STANDARD 50 CANDLEPOWER CAR SPOT LIGHT FOCUSED TO SPOT ON PAVEMENT

SKETCH OF METHOD USED IN TEST FOR COMPARISON OF PAVEMENT REFLECTION WITH FIXED LIGHT SOURCE

NOTE: LIGHT SOURCE IS KEPT UNIFORM WITH RHEOSTAT AND VOLTOMETER

SCREEN TO SHADE LIGHT METER FROM ALL LIGHT DIRECT FROM LAMP SOURCE
LIGHT METER MOVABLE THRU 180° IN VERTICAL PLANE OF INCIDENT LIGHT

PAVEMENT SPECIMEN

$3'1\frac{1}{2}''$ FOR $45^\circ$
$10'0''$ FOR $17^\circ$

$R=1'0''$
SKETCH OF METHOD USED IN TEST FOR COMPARISON OF PAVEMENT GLARES

STANDARD 32 CANDLEPOWER CAR HEAD LAMPS OPERATING DEPRESSED BEAM FOR PASSING

REMOVEABLE SCREEN FOR SHADING METER FROM ALL LIGHT DIRECT FROM LAMPS

LIGHT METER WESTON MODEL 603-6 SET PERPENDICULAR TO REFLECTED RAYS

NOT TO SCALE
TESTS UNDER CONDITIONS SIMULATING FIXED LIGHTING

In the first series of tests the results obtained on dry pavements, with light at an incident angle of forty-five degrees, and readings taken in the plane of incident light, are shown in Figure 1. It is interesting to note the regularity of the curves for the concrete pavements, and for the bituminous macadam, open type asphaltic concrete, and worn asphalt. These surfaces are almost entirely without glare when dry. Practically as much light is reflected back toward the source as is reflected along the line of specular reflection. There is a slight bulge in the curve for old concrete which is probably due to oil stains on the surface. Due to the rough texture of clean stone chips in the bituminous macadam surface, slightly more of the light is reflected back toward the source than away from it. On the other hand the closed type asphaltic concrete and the plain asphalt show noticeable bulges away from the beam of incident light. On both these types the light impinges on asphalt coated surfaces, which, even when dry, possess mirror like qualities. It is also interesting to note the comparison between the concrete pavements and the asphaltic types. The new concrete pavements show about four times the luminosity of the asphaltic types,
while even the worn and discolored concrete shows twice the luminosity. The direction of the grooves in the concrete seem to make no difference with dry pavement and incident light at this angle.

The results on these same pavements, with the same angle of incident light, but with wetted surfaces is shown in Figure 3. The characteristics of the pavement have entirely changed, and a great amount of specular reflection or glare is apparent. Except for the new concrete pavements very little luminosity is produced, except in the line of specular reflection. Since vision is a function of contracting light values, a comparison of light intensities normal to the pavement with that in the line of specular reflection is of interest. If the light intensity normal to the pavement is taken as one in each case, the intensity in the line of specular reflection has the following values:

- New concrete across grooves: 2.5
- Open type asphaltic concrete: 2.7
- New concrete parallel with grooves: 3.8
- Bituminous macadam: 4.3
- Closed type asphaltic concrete: 10.0
- Worn asphalt: 16.0
- Plain asphalt: 20.0
- Old concrete: 24.0

The irregular surfaces of the new concrete, the bituminous macadam, and the open type asphaltic concrete reduce the glare, even with wet pavements. The luminosity
of the new and clean concrete pavement shows that, at large angles of incidence, light penetrates the water film, and is affected by the color of the surface.

A comparison of Figure 1 and Figure 3 shows that the luminosity, except on the line of specular reflection, is one-half or less when wet than when dry. The high ratio between glare and diffusion, in the last four pavements listed, is supported by driving experience. These pavements appear very bright, directly in line with the light, but practically black at any other angle.

Figure 2 shows the results on dry pavements, with the incident light at forty-five degrees and the reflection measured in a vertical plane perpendicular to the incident light. As would be expected the curves are quite regular. It should be noted that at angles up to thirty degrees with the vertical, the luminosity remains practically constant. Here again new concrete pavements show four to five times the luminosity of any of the asphalt types.

Figure 4 shows the results under the same conditions but with the pavement wet. The luminosity is reduced one-half or more, and the new concrete shows four or more times the luminosity of the asphalt types. The greatest percentage decrease in luminosity occurs with the plain asphalt
and worn asphalt, both of which are smooth, black surfaces. Again it will be noted that at angles within thirty degrees of the vertical the luminosity is practically constant.

A comparison of Figure 1 and Figure 2 brings out the uniform diffuse reflection from dry pavements, at all angles except the line of specular reflection, where bulges in the curves for the smooth pavements occur. A comparison of Figures 1 and 2 and Figures 3 and 4 shows the great change in reflecting characteristics due to wetting. While the diffuse reflection is quite constant in all directions, except along the line of specular reflection, its comparative intensity is reduced to the point where the glare almost completely masks it, and the pavements appear black, except in the direction of the light.

Figure 5 shows the reflection readings on dry pavements with the angle of incident light at seventeen degrees with the pavement surface, and readings taken in the plane of the incident light. It should be noted that as the angle of incidence decreases, the glare increases with all types of pavements, except the bituminous macadam, where the rough surfaces of the stone chips reflect considerable light back toward the source. The superiority of the cross grooved concrete pavement over the
parallel grooved pavement is apparent. The ratio between diffusion and glare being 1.3 for the cross grooved, and 5.0 for the parallel grooved. As in the preceding figures the luminosity of the new concrete pavements is approximately four times that of the asphalitic types. The glare from all the asphalitic type pavements, except the bituminous macadam, is three to four times the diffusion.

Figure 6 shows the results under the same conditions as Figure 5, except that the pavement is wet. With this angle of incident light all the pavements, except the open type asphalitic concrete, show greatly increased glare. Very little diffusion of light is had on any of the surfaces. The concrete pavement has lost its advantage over the other types. It is interesting to note the increased glare from the parallel grooved concrete pavement.
FIGURE 1
LIGHT SOURCE AT 45° TO PAVEMENT SURFACE
REFLECTION IN PLANE OF INCIDENT LIGHT
DRY PAVEMENT SURFACES
FIGURE 2
LIGHT SOURCE AT 45° TO PAVEMENT SURFACE
REFLECTION IN VERTICAL PLANE AT 90°
TO PLANE OF INCIDENT LIGHT
DRY PAVEMENT SURFACES
FIGURE 3
LIGHT SOURCE AT 45° TO PAVEMENT SURFACE
REFLECTION IN PLANE OF INCIDENT LIGHT
WET PAVEMENT SURFACES
FIGURE 4
LIGHT SOURCE AT 45° TO PAVEMENT SURFACE
REFLECTION IN VERTICAL PLANE AT 90°
TO PLANE OF INCIDENT LIGHT BEAM
WET PAVEMENT SURFACES
Figure 5
Light source at 17° to pavement surface reflection in plane of incident light dry pavement surfaces
FIGURE 6
LIGHT SOURCE AT 17° TO PAVEMENT SURFACE
REFLECTION IN PLANE OF INCIDENT LIGHT
WET PAVEMENT SURFACES
TESTS OF LIGHTING BY HEADLIGHTS

In the second part of the investigation, using automobile headlights as a light source, an attempt was made to determine the glare, both from wet and dry surfaces, as a percentage of the total light which the driver of an approaching vehicle would have to face. The results of these tests are shown in Figure 7. It is known from actual driving experience that the glare, from any dry pavement, can be faced without particular danger. It is then logical to assume that those surfaces, whose characteristics change the least when wet, will be the safest to drive, when wet. Attention is called to the fact that the wetting of the surface of untreated gravel macadam, bituminous macadam, and open type asphaltic concrete, has little affect upon glare. This is borne out by driving experience over these types of surfaces. On the contrary, smooth textured surfaces, and surfaces with small irregularities show greatly increased glare when wet. Any smooth and comparatively level surface will hold a film of water which acts as a mirror in reflecting the length. Irregular surfaces, having pits or indentations one-quarter inch or more in depth, especially if these connect so as to provide a channel to the edge of the pavement, break up the water film. The glare from wet surfaces is, in the main,
a function of the texture of the surface, and the least glare is given by those surfaces which are so deeply indented that the water will drain off with sufficient rapidity to prevent flooding the entire surface. Experiments are now in progress in which concrete pavements are given deep, transverse grooves. It is hoped that by adequately draining the surface the light reflecting qualities may be greatly improved, without sacrificing durability or skid resistance.

No attempt at a quantitative evaluation of the various pavement surfaces is attempted; however, the studies do point to certain conclusions which compare the pavements qualitatively.
PERCENTAGE OF INTENSITY OF ILLUMINATION DUE TO SURFACE REFLECTION

FIGURE 7
CONCLUSIONS

1. Concrete pavements can be effectively lighted with installations of lower intensity than are necessary for the asphaltic types. Concrete pavements are from two to four times as luminous as asphaltic types, under the same intensity and conditions of lighting. This is undoubtedly due to the light color of the concrete, as contrasted with the dark color of the asphaltic type pavements.

2. The grooved surface of the new concrete pavements, and the irregular or matte like surfaces of the bituminous macadam and open type asphaltic concrete pavements give a more even diffusion of light than the smooth pavements.

3. The longitudinal grooving of concrete pavements would tend to increase the glare, and would not appreciably improve the diffusion of light, from the pavement surface.

4. Glare is greater from all types of pavement when the angle of incidence is small. Better results can probably be obtained with smaller luminaires more closely spaced, than with more powerful luminaires spaced widely apart. The luminaires should be designed to throw their
light down on the pavement, and to cut off flat rays which
would make a small angle of incidence with the pavement.

5. Wetting of pavements of all types decreases the
luminosity and increases the glare. The smooth surfaces
are more affected than the irregular or matte type sur-
faces. It is probable that at small angles of incidence
the water film acts as a mirror, and that the pavement sur-
face plays little part in the reflection until the irregu-
larities of the surface become great enough to project
through the water.

6. Glare from wet pavements is in the main a func-
tion of the surface texture. Glare can be largely pre-
vented by building water channels into the surface, which
drain the water off before the entire surface is flooded.
This is accomplished by the natural irregularities of
bituminous macadam and open type asphaltic concrete. It
is hoped that the same results can be accomplished by a
change in the finishing procedure on concrete pavements.

The author wishes to acknowledge his indebtedness
to Mr. R. H. Baldock, State Highway Engineer, for his en-
couragement and advice, and to Mr. J. D. Everson for his
help in making the experiments.