Final Report

Reflectivity of Light Emitting Diodes and Incandescent Light on Concrete and Asphalt Pavements

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Ready Mixed Concrete (RMC) Research & Education Foundation

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Young Hoon Kim, Jeremy Rice, Zhihui Sun, and J.P. Mohsen

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ABSTRACT:

The objective of this research was to evaluate the reflectiveness of two most commonly used modern pavement systems in the United States (concrete and asphalt). The R tables, used for roadway lighting design, were established several decades ago as a critical parameter for determining the light reflectivity (luminance) of pavement surfaces. With the existence of modern pavement systems and also the new lighting technologies it is necessary to examine the applicability and representability of the current R tables. A total of 12 different pavement surfaces were evaluated to characterize the light reflectivity of two light sources (incandescent and light emitting diodes [LED]). The reflective properties of the pavements were evaluated considering the influence of angular light (incident lighting angles). The testing program evaluated five different angles (0°, 27°, 45°, 63°, and 79°) between the observation plane and the incident light plane (γ). These five angular measurements were repeated with the combination of four angles (0°, 15°, 30°, and 45°) measured between the incidence light plane and the observation plane (β). A total of 1,200 luminance measurements were performed on 12 pavements, four cast or cored pavement samples together with eight in-situ field tested pavements. Light intensity (illuminance) and pavement reflectivity (luminance) were measured to construct updated R tables. A customized portable goniometer was used to measure the light reflectivity of various pavements.

Research findings concluded that the current R1 table (concrete) values remain representative of modern concrete pavements illuminated by traditional (incandescent) lights. Whereas, modern concrete illuminated by LED lights was found to be statistically different from the current R1 table (as a result of the LED light and not the concrete pavement). Test results also indicated a significant difference between the current R3 table (asphalt) values and the measured asphalt values illuminated by both traditional (incandescent) and LED lights. The LED light measurements appeared to have minimal influence on the generalized data or average reflected light. However, the angular light distribution was different between traditional (incandescent) and LED lights. Therefore, it is recommended that new R tables be constructed for modern asphalt pavements illuminated by traditional lights as well as consider new R tables for all pavements to properly characterize the unique angular light distribution of LED lights.

Keywords: Glare; Light; Reflectivity; Luminance; R-Tables; Incandescent; LED; Concrete; Asphalt; Gonioreflectometer; Portable Goniometer.

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INTRODUCTION

General

"Light" can be quantified by two different forms; illuminance and luminance. Illuminance (E) is defined as the amount of light that is evenly distributed over a given surface area. Luminance (L) is defined as the amount of light reflected from a given surface area in various angular directions (Van Bommel 2015). The visual sensation of light is influenced by the amount of light reflected (luminance) from a road surface into the human eye. The amount of light reaching the road surface (illuminance) gives no indication of how bright a road surface appears to the human eye.

Light reflectivity is affected by the height of the light pole, the intensity of the light, and the distribution of angular light from the pavement surface. These parameters ultimately determine the spacing required between adjacent light poles. To determine these design parameters, the reflectivity of pavement is critical. Minimizing glare and uniform lighting are also critical components in adequate roadway lighting. To ensure the safety of travelers on roadways, glare reduction and uniformly lit roadways are directly influenced by the pavement reflectivity characteristics (Hassan et al. 2008). The Recommended Practice (RP-8) was proposed in 1976 by De Boer and Vermeulen (Van Bommel 2015). This was the first method that incorporated light reflectivity as one of the primary factors of roadway lighting design. The light reflective design parameters vary depending on the type of pavement being used. Pavements were categorized into four separate classification groups (R1, R2, R3, and R4) based on extensive laboratory testing of many different road surface samples measured by Illuminating Engineering Society of North America (IESNA). This system established standard parameters for classifying pavement reflective surfaces considering the two following variables, "lightness" and "specularity", which will be defined in the proceeding section. The road reflection classification system is commonly referred to as the "reduced luminance coefficient tables" or the current R tables.

Van Bommel (2015) states: "The road surface often forms the background to objects on or close to the road. This is why the road surface luminance concept is usually better suited than the (horizontal) illuminance concept for use in defining the visual performance and comfort of the motorized road user." The road surface luminance concept is the most appropriate method for designing uniform lit roadways. Despite this approach being the best suited design method there continues to be debate on the accuracy of the current R tables (FHWA of International Programs 2014). The non-consensus of the R tables is mainly attributed to the fact that the current R tables were constructed from tests performed on pavements several decades ago. Therefore, the current R tables are not well representative of modern pavement systems. The Illuminating Engineering Society of North America (IESNA) and the American National Standards Institute (ANSI) accepted and published RP-8-14 (ANSI/IES 2014). This standard Recommended Practice (RP) recommends luminance design method for high speed roadways, and the horizontal illuminance design method for low speed streets and intersections (Van Bommel 2015).

Problem Statement and Research Motivation

The U.S. Department of Transportation Federal Highway Administration (FHWA) reports that "European roadways are lit to levels more than twice as high as those in the United States, and with better uniformity." This is most likely due to the limited research on this subject. Coincidently, the Office of International Programs also reported that "Pavement reflectance is an important element of lighting design." The (FHWA) international panel closes by recommending that more research must be conducted, including "in-situ" field measurements, to overcome the acknowledged inadequacy of the current R table values.

Illuminance only considers the light source itself in the design calculations. Luminance deals with the interaction between the light source and the reflective surface. A priority of this research was to assess not only modern pavements but also the interaction of newer lighting technologies with those pavements. Traditional lighting can be defined as all lighting technology prior to the advent of light emitting diodes (LED) lights. For example, "traditional" could be referred to compact fluorescent lamps (CFL), high intensity discharge (HID), metal halide (MH), or incandescent lighting technology. Although the light source used to develop the current R tables is unknown, it was developed many decades before the existence of the LED technology. Therefore, more research is needed to understand the applicability of the existing (current) R tables with new lighting technology. In this study, the experimental testing uses incandescent lights as the "traditional" and LED lights as "new".

Van Bommel (2015) states, "LED road lighting luminaires consist of an array of numerous small bright LEDs. The consequence is that these luminaires have a much more pronounced non-uniform luminance over their light-emitting surface as compared to luminaires using more conventional light sources." As LED lights have become more common in recent years there has been an increasing amount of complaints from observers about viewing discomfort due to the glare of the light. The American Medical Association (AMA) has reported, "because LED light is so concentrated, it can cause severe glare, resulting in pupillary constriction in the eyes" (Stevens, 2016).

In summary, the current R tables were constructed by testing outdated pavements using traditional light sources. This study intends to construct equivalent R tables by testing modern pavements using both traditional and LED lights.

Research Objectives

The goal of this research was to evaluate the reflectiveness of the two most commonly used modern pavement systems in the United States (concrete and asphalt). The reflective properties of both pavement systems were evaluated considering the angular light (β and γ) from two varied light sources (incandescent and LED). The uncertainty of the R tables is reasonable due to the lack of research and the complexity of the procedures required to collect this data. Further research is needed to collect data using modern pavements and light sources, which can be used to construct updated R tables. Therefore, the following research objectives are established:

1. Measure pavement reflectivity using traditional (incandescent) and LED lights.
2. Collect luminance measurements of modern pavement systems (concrete and asphalt).
3. Develop an experimental program capable of testing "in-situ" pavements (portable goniometer).
4. Analyze the data to compare measured R values with the current R tables (RP-8-14, ANSI/IES).

Research Significance

This research investigated modern pavements (particularly concrete and asphalt) illuminated by LED lights for the purpose of updating the current R tables. Also, this research demonstrates the feasibility of using a portable goniometer for in-situ field measurements. This can be a practical method for collecting luminance pavement data of various pavements. This research provides the fundamental knowledge for the interactive behavior between illuminated light and surface reflectivity with respect to varied light sources and pavement types. Therefore, this research demonstrates that updated R values are needed to determine the proper light reflectivity (luminance) of new light sources on modern pavements. Any potential change in the current R values will impact the database of the software used in the light design of roadways and parking lots.

BACKGROUND

The following section is intended to fundamentally explain the physics of light reflectivity through both the theoretical and design mathematical approaches.

Reflectivity Characteristics
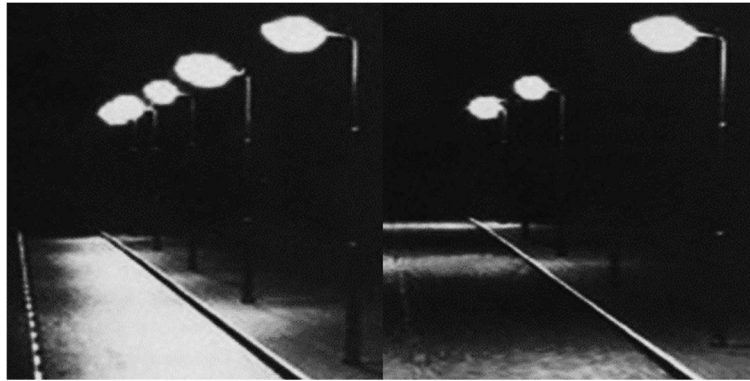
(a)   (b)
Figure 1. Uniform vs. Non-Uniform Lighting
(Source: Van Bommel and De Boer 1980)

Figure 1 (a) represents lights that have a high level of uniformity, and Figure 1 (b) represents lights that have a low level of uniformity, also referred to as non-uniform. When they have the same light sources, the light spacing seems to be a critical factor to determine uniformity of lights. This is also affected by light source such as LED (Van Bommel 2015).

(a)   (b)
Figure 2. Specular vs. Diffused Pavement
(Source: Van Bommel and De Boer 1980)

Figure 2 (a) is a picture of a specular roadway in which the pavement is most likely asphalt. Figure 2 (b) is a picture of a diffused roadway in which the pavement is most likely concrete. The lighting configuration in both Figure 2 (a) and (b) are the same and therefore equal illuminance levels are achieved. Pavement reflectivity characteristics are the critical parameter that makes the lighting appear different in each of these scenarios. When these characteristics are quantified in the engineering parameters of light design, the R tables are used to ensure the proper (e.g., uniform) illumination on the specific pavement types.

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Theoretical Calculations

Illuminance (E) can be calculated by the following equation:

$$E = \left(\frac{I}{D^2}\right)$$ (1)

where E = illuminance (lux), I = light intensity (candelas or cd), and D = light distance to surface (m).

Pavement surfaces are made visible by the light directly reflected from the surface into the human eye. Illuminance can be directly calculated based on exact and measurable variables (light intensity and height). Luminance calculations require empirically derived coefficients which are used to define the reflective characteristics of pavements (concrete and asphalt).

Luminance (L) can be calculated by the following equation:

$$L = [(q)(E)] = \left[(q)\left(\frac{I}{D^2}\right)\right]$$ (2)

where L = luminance (cd/m^2) and q = luminance (empirically derived) coefficient (*Eq.3*).

For example, consider the light design of a parking lot utilizing the illuminance and luminance formulas. To design a parking lot based on minimally required illuminance levels only two factors must be initially assumed, light intensity and light distance or pole height. Since pole heights are typically standardized heights the light intensity can be directly manipulated to provide the required illuminance levels. Whereas, to design the parking lot based on minimally required luminance levels an additional variable (reflectivity) must be incorporated in the design calculations. Since luminance is directly influenced by the reflectivity of a surface, the designer must now also consider the type of pavement in the design.
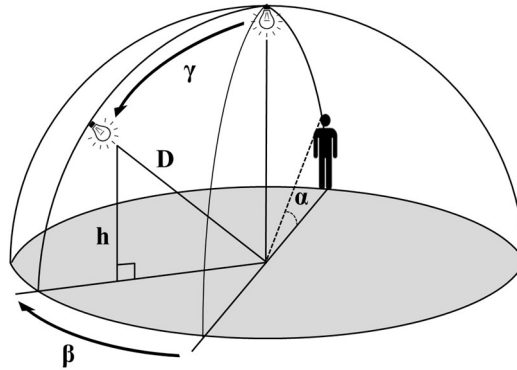
Figure 3. Defining Light Angles

Luminance can be calculated using the luminance coefficient (q) which is a function of the β and γ angles as defined in Figure 3. The γ angle is measured from the top of the vertical arch to the bottom. The β angle is measured from the observer's line of sight rotating left (or right) parallel to the horizontal surface.

Therefore, the luminance coefficient (q) can be defined by the following equation:

$$q = f(\beta, \gamma)$$ (3)

where the luminance coefficient is a function of the β and γ angles.

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The angle between the driver's viewing height and the horizontal (surface) plane is referred to as the observation angle (α) as defined in Figure 3. The current R table values assume a 1° observation angle. This angle assumes that the average driver's viewing height is about 1.5 m (5 ft) above the horizontal (surface) plane and the observer is traveling at relatively high velocities. To provide a 1° observation angle (with a vertical view height of 1.5 m (5 ft)) the horizontal viewing distance must be approximately 120 m (395 ft) in front of the driver. Driving velocities corresponding to a 120 m (395 ft) horizontal viewing distance (correlated with minimum stopping sight distance) is approximately 130 km/h (80 mph). Therefore, the assumption of a 1° observation angle is only accurate for the design of high speed roadways.

There is limited research related to observation angles greater than 5° that would be more applicable to other driving scenarios such as driving through tunnels or in low speed parking lots. Luminance values can be measured utilizing luminance measurement setups capable of collecting data with various combinations of the β and γ angles. Assuming an angle of 1° observation, the current reduced luminance coefficients (derivation of R tables) were empirically derived through extensive experimental laboratory testing performed over 30 years ago.

Design Calculations

The reduced luminance coefficient (R) can be calculated by the following equation:

$$R = \left[\frac{(h^2)(L)}{(I)} \right] \qquad (4)$$

where R = function of the β and γ angles and h = (cos γ) (D) = height (m).

It is important to note that light distance (D) and light height (h) are not the same (unless $\gamma = 0°$) and are visually defined in Figure 3. The reduced luminance coefficient values are tabulated into R values as a function of β and γ angles which is referred to as the R tables. Inversely, the reduced luminance coefficients are used in the design process to calculate luminance. Therefore, the empirically derived R tables can be utilized to calculate corresponding luminance values without actual measurements of pavement reflectiveness.

Luminance (L) can be calculated by the following equation:

$$L = \left[\frac{(R)(I)}{(h^2)} \right] \qquad (5)$$

where R = reduced luminance coefficient (R table value) as defined in the previous equation (*Eq.4*).

Lightness and Specularity

The reflectivity characteristics of pavements are influenced by two variables: lightness and specularity. Lightness is defined as the grey scale color of the surface from white to black. Specularity is defined as the shininess of the surface from specular to diffused.
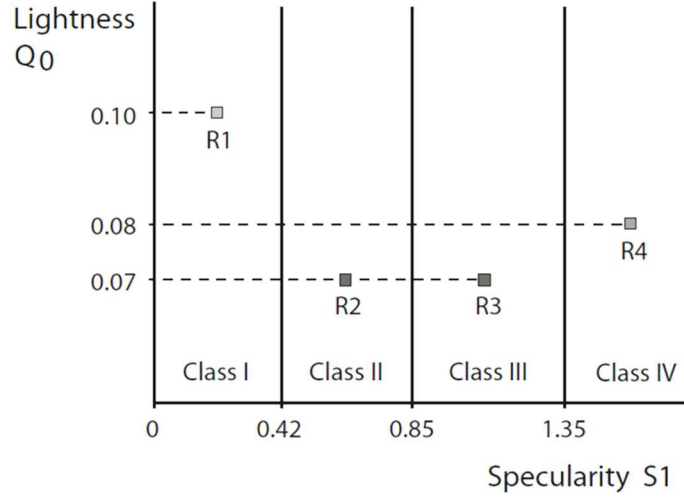
Figure 4. Lightness and Specularity of Current R Tables
(Source: Van Bommel, 2015)

Figure 4 illustrates the lightness and specularity values of the current R tables as defined by the IESNA. The lightness of a surface influences the quantitative values proportionally in the entire R table regardless of the angular incident light (β and γ angles). On the other hand, the specularity of a surface influences values differently with respect to the angular incident light (β and γ angles).

The lightness (Q_0) is calculated from the reduced reflection table as shown in the following equation:

$$Q_0 = \frac{1}{\Omega} \times \iint_{\Omega} q\,(d\beta)(d\gamma) \tag{6}$$

where Ω = solid angle being measured from incidence point on the surface.

The specularity ($S1$) is calculated from two R values as shown in the following equation:

$$S1 = \frac{R(\beta = 0, \tan\gamma = 2)}{R(\beta = 0, \tan\gamma = 0)} \tag{7}$$

where β and γ are previously defined in Figure 3, $\tan^{-1}(2) \approx 63° = \gamma$, and $\tan^{-1}(0) \approx 0° = \gamma$.

While the value scale is influenced by lightness, the general trends or patterns of each R table are directly influenced by the surface specularity with respect to both the β and γ angles. For example, since asphalt is darker than concrete (asphalt pavement absorbs more light) the average R3 values are nearly half as much as the R1 values (with respect to lightness). Whereas, the reflective behavior of both concrete and asphalt (shape of 3D surface plot for both R1 and R3) is unique because each surface distributes angular light differently (with respect to specularity). Adrian and Jobanputra (2005) also reported higher average lightness values for concrete ($Q_0 = 0.1138$) compared to that of asphalt ($Q_0 = 0.0793$).
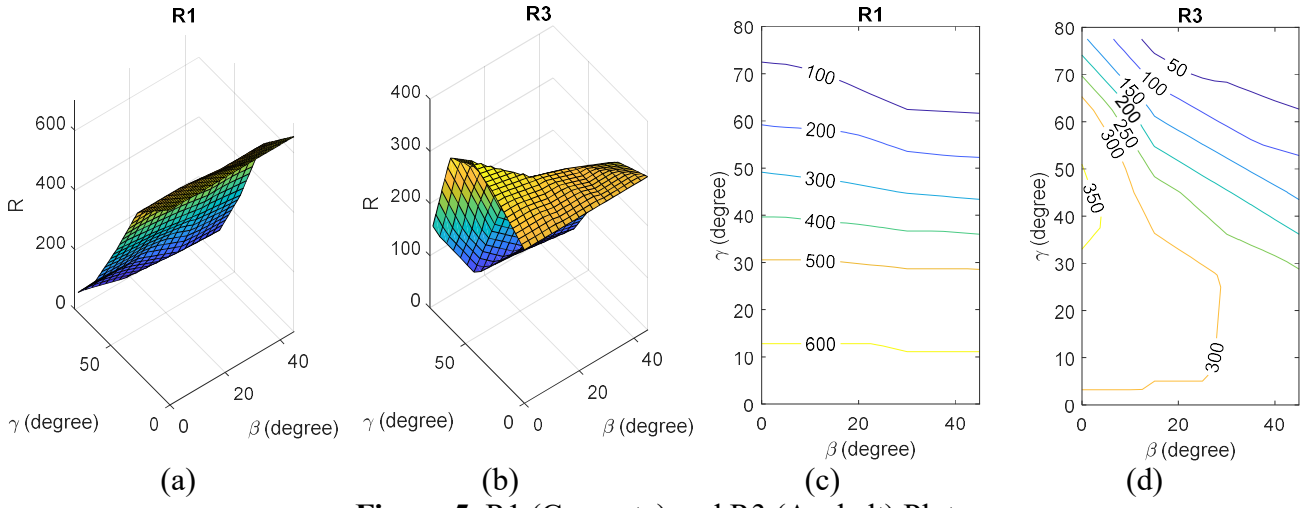
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Figure 5. R1 (Concrete) and R3 (Asphalt) Plots

Figure 5 shows the plots of the current R table values for R1 (concrete) and R3 (asphalt). Figure 5 (a) and (b) are 3D surface plots of R1 and R3 values, respectively, and Figure 5 (c) and (d) are 2D contour plots of R1 and R3, respectively. The side-by-side presentation is intended to allow the visual comparison of the pavement reflectivity characteristics seen in both R1 (concrete) and R3 (asphalt).

The important characteristics to notice are that these two plots have different trends with respect to the angles β and γ. The R1 3D surface plot has R values that are linearly proportional with respect to the γ angle (see Figure 5 (a)). The decrease in R values with respect to the γ angle is indicative of a diffused reflective surface which is seen in the current R1 table (See Figure 5 (a)). Whereas, the decrease in R values with respect to both β and γ angles is indicative of a specular reflective surface which is seen in the current R3 table (see Figure 5 (b)).

The 2D contour of the R3 table indicates that the R value has a peak R value at the angle $\gamma = 45°$ and is also influenced with respect to the β angle, indicated by the right-side sloping (see Figure 5 (d)). Compared to the 2D contour of R1 the non-uniform distribution of R3 values is primarily determined by the specularity (as a function of the β and γ angles) of the pavement's reflective surface (see Figure 5 (c) and (d)). It is important to note that the R4 table is an extreme case intended to represent lightened asphalt and will not be further considered in the proceeding sections. The current R table values for R2 are intended to represent slightly specular (slightly diffused) asphalt pavements. The R2 table represents the reflective characteristics observed in both the R1 and R3 tables. Therefore, the R1 table refers to diffused and specular concrete, the R2 table refers to diffused asphalt, and the R3 table refers to specular asphalt.

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EXPERIMENTAL PROGRAM

Test Matrix and Pavement Samples

There was a total of 12 pavement samples tested in the experimental program. Of the 12 samples, four were "cast" or "cored" samples tested in the laboratory and the other eight samples were "in-situ" pavements tested in the field. All the lab samples had three measurement trials performed on each of the samples, whereas only five of the eight field samples had three measured trials. The other three field samples were only tested once due to unexpected weather conditions on the day of testing. Altogether, there was a total of 30 measurements performed on 12 different pavement systems.

Table 1. Experimental Test Matrix

Test Condition	Pavement Type	Characteristics	Sample Name	Age (years)
Lab (L)		w/c = 0.40 (40)	LC-40	0
		w/c = 0.45 (45)	LC-45	0
Field (F)	Concrete (C)	Specular (SP)	FC-SP	6
		Diffused (DF)	FC-DF	12
		Newest (01)	FC-01	0.5
		New (02)	FC-02	1.5
		Old (03)	FC-03	4
		Oldest (04)	FC-04	16
Lab (L)	Asphalt (A)	Light (LT)	LA-LT	1.5
		Dark (DK)	LA-DK	2
Field (F)		Newest (01)	FA-01	0.5
		Oldest (02)	FA-02	4

*Sample Name = (Test Condition)(Pavement Type)-(Characteristics)

Table 1 defines the sample identification (name) of the 12 different pavement samples tested in the experimental program. Sample names are designated according to the naming rules shown at the bottom of Table 1. The first letter of the sample name describes if the sample was a lab (L) or field (F) sample. The second letter states if the pavement was concrete (C) or asphalt (A). The next two letters following the dash is a description of that specific sample's characteristics. Table 1 also defines the estimated age for each experimental pavement sample. The average estimated age of all the concrete and asphalt samples tested were five years and two years, respectively.
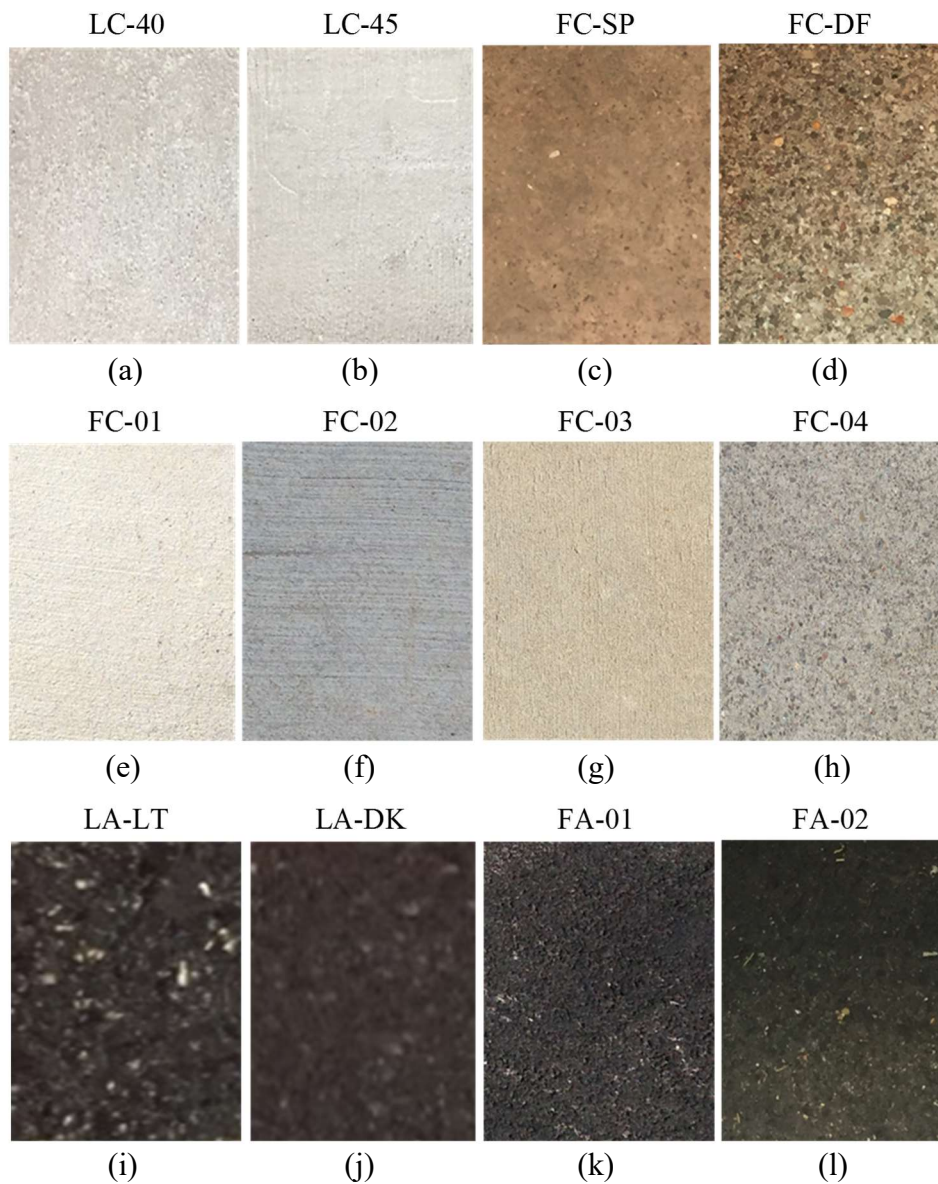
Pavement Samples

Figure 6. Pavement Sample Pictures

Figure 6 shows the pictures of each pavement sample tested in the experimental program. The pictures (left to right) correspond with the pavement sample names defined in Table 1. The surface of each sample is depicted in dry condition.

Measurement Equipment and Light Sources

Two measurement devices were required in the experimental testing program. The illuminance meter (AMPROBE LM-200LED) was used to measure the amount of illuminated light (E) distributed on the reflective surface. The luminance meter (Konica Minolta LS-150) was used to measure the luminance (L) or the amount of light reflected from the surface. Luminance meters are typically designed for field measurements. The particular luminance meter used in this study had no restriction to the maximum measurement distance but the minimum measurement distance was limited to approximately 1m (3 ft). To assist the measurements with shorter distance, a No. 122 close-up lens was used. It allowed measurements to be taken approximately 230 mm (9 in.) away from the target. Data Management Program (CS-S20) was also used for data collection purpose. It allows data to be simultaneously displayed and recorded on an external portable laptop. More detailed information can be found in Rice (2016).
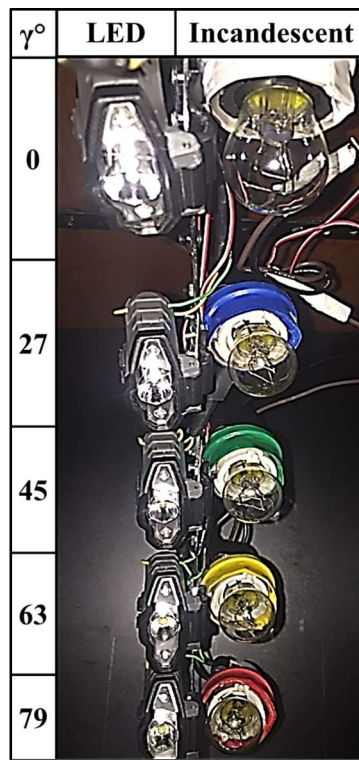
Figure 7. Dual Light Sources

Figure 7 displays the two experimentally evaluated light sources as incandescent (traditional) and light emitting diodes (LED) lights in the customized equipment.

Measurement Set-up and Procedure: Laboratory Testing

One of the primary concerns with the accuracy of the current R tables is that they were developed by testing "cored" samples in a laboratory setting. When the tested samples are removed from their current "in-situ" environment there is possibility of disruption to the reflective surface layer. Therefore, a small proportion (1/3) of the data consisted of lab measurements while the majority (2/3) was "in-situ" field measurements.

Figure 8. Lab Testing Goniometer Design

The configuration of the lab test set-up can be sketched in Figure 8 that visually illustrates the light angle combinations utilized in both (lab and field) experimental test programs (Rice 2016). The combinations of angular light used in both lab and field testing are shown in Table 2.

Table 2. Angular Combinations

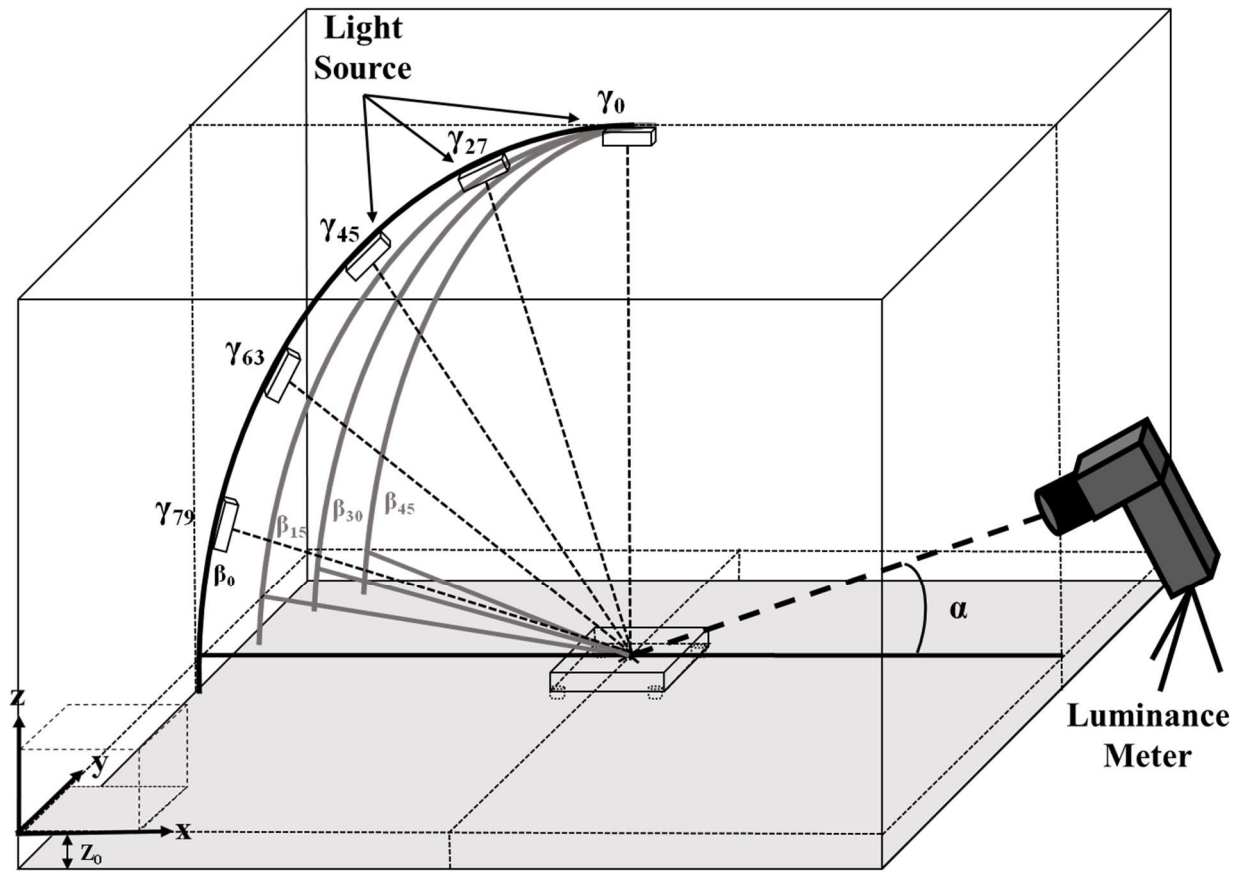| $\alpha°$	$\beta°$	$\gamma°$	P
30	0	0	P_1
		27	P_2
		45	P_3
		63	P_4
		79	P_5
	15	0	P_6
		27	P_7
		45	P_8
		63	P_9
		79	P_{10}
	30	0	P_{11}
		27	P_{12}
		45	P_{13}
		63	P_{14}
		79	P_{15}
	45	0	P_{16}
		27	P_{17}
		45	P_{18}
		63	P_{19}
		79	P_{20}

The corresponding measurement points ($P_{No.}$) used in the experimental program are also listed. The observation angle (α) was held constant throughout experimental testing at an approximated 30° angle. The γ angle was varied by selectively turning on each individual light at five different angles (0°, 27°, 45°, 63°, and 79°) measured from the top light moving downwards along the arch. Each γ angle was repeated for four different β angle (0°, 15°, 30°, and 45°) combinations. There were 20 different angular measurements performed for each trial of tested pavement.

Laboratory testing was performed on "cast" square concrete samples and "cored" circular asphalt samples. Each pavement sample had a different thickness (Z_0) or surface height. The "cast" square concrete samples had a consistent thickness of 20 mm (0.75 in.) because they were all freshly poured into the same casting mold. There were two different asphalt lab samples that were approximately 25.4 and 32 mm (1.0 and 1.25 in.) thick. Each of the varied surface heights were compensated for adjusting each base platform (Z_0) to create equivalent surface heights. This task was achieved by raising or lowering the lighting arch fixture as well as the luminance meter. The same approach was applied in the field by making the datum (Z_0) at the ground level, because the "in-situ" pavement had a 0 in. thickness. Images of samples used can be found in Figure 6.

Measurement Set-up and Procedure: Field Testing

This experimental test required the development of a test program which could be utilized for "in-situ" field measurements. The field testing differed from the lab testing by having a fixed measurement height (Z_0) which was the external ground level at each of the field pavement sample surfaces. This required the lighting arch fixture, lighting power controls, and luminance meter to be encased in a portable housing structure. Developing a method of testing these samples "in-situ" requires a portable goniometer.
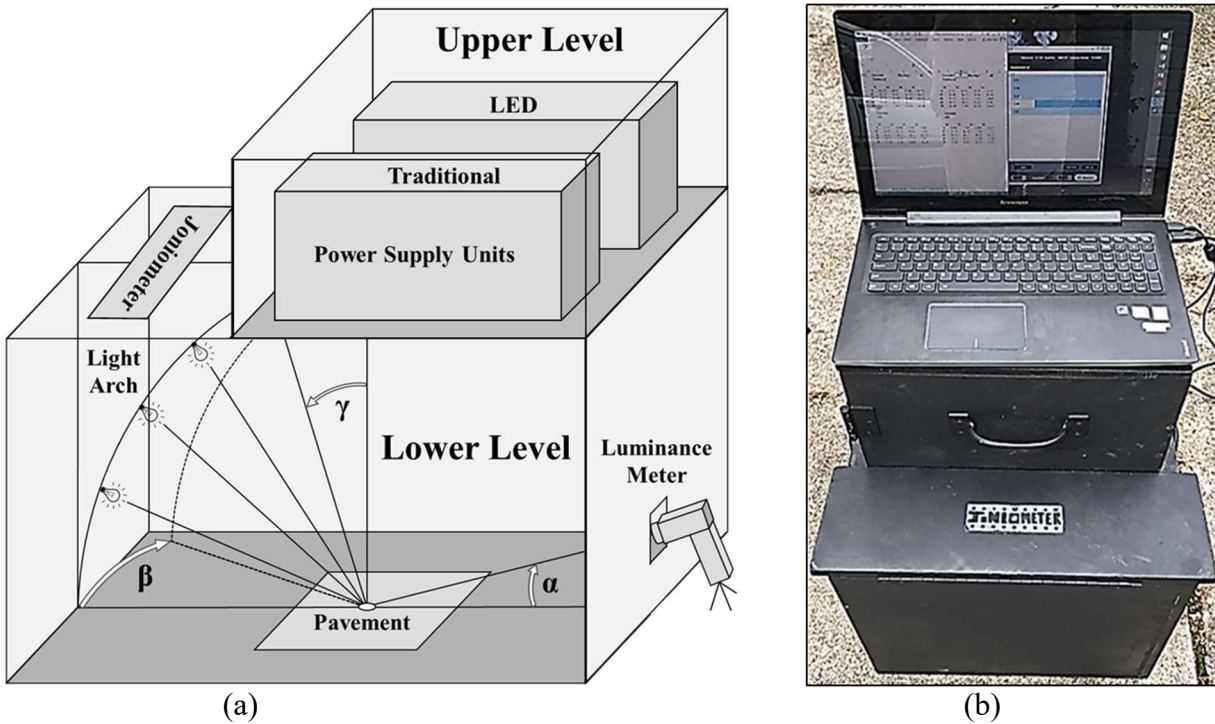
Figure 9. Portable Goniometer Schematic and Picture

The portable goniometer design is shown in Figure 9. The front door flap (with "Joniometer" plate on it) opens to the lower level where the lighting arch fixture is located (depicted in Figure 7). Each individual light source was connected to a power supply unit (Manufacturer: BK Precision) which was utilized to manipulate the power supply and light intensity. For example, the LED lights required much lower levels of supplied power, compared to the incandescent lights, to provide the same equivalent light intensity.

The handle directly above swings open to access the upper level where the light power supply units (one for incandescent and one for LED) were housed, which allowed the light intensity to be manipulated without allowing exterior light leakage into the lower level. A tight-fitting hole in the back allowed the luminance meter (LS-150) to externally record data which could then be directly supplied to the laptop for easy analysis.

Testing Procedure

The following steps were repeated for each sample trial measurement in the experimental program:

1. The top light ($\gamma = 0°$) was turned on separately for each light source (incandescent and LED).

2. The illuminance meter was manually placed directly below the top light ($\gamma = 0°$) and the light intensity of each light source was measured.

3. The measured light intensity was adjusted by manipulating the power supplied to each light source.

4. Initially, the goal was to try to achieve similar illuminance levels by each separate light source. Also, it is important to note that similar illuminance levels were achieved at distinct levels of supplied power. For example, since LED lights are so energy efficient they typically only required 0.55 volts to produce an illumination (9 in. from the light source) of 300 lux. Whereas, the less efficient incandescent light required approximately 12.80 volts to produce 300 lux of illuminance.

5. The only way to measure illuminance produced by the angled lights ($\gamma = 27°$, $45°$, $63°$, and $79°$) was to manually tilt the illuminance meter to be perpendicular to each individual light. Since the exact same lights were used (with respect to each source) the alternative method of matching light intensity levels (illuminance) was to make each lights power supply (volts) equivalent. Therefore, equivalent light intensities (illuminance) of the other four lights ($\gamma = 27°$, $45°$, $63°$, and $79°$) were achieved by using the same voltage (with respect to each light source) as the top light ($\gamma = 0°$).

6. The illuminance level of the top light ($\gamma = 0°$) was recorded and the power supply was constantly monitored throughout the testing to guarantee that the same light intensity levels were produced.

7. The luminance meter was situated in the back and manually aimed at a point on the pavement surface that was located directly underneath the top light ($\gamma = 0°$).

8. Preliminary luminance measurements were performed with none of the lights on to check for any possible external light leakage. For example, with no lights turned on, a luminance measurement greater than 0.005 cd/m^2 indicated excessive external light leakage.

9. Each light was then turned on independently ($\gamma = 0°$, $27°$, $45°$, $63°$, and $79°$) for each light source (incandescent and LED) and the luminance was measured accordingly. This process was repeated for the combination of all four of the β angles as well ($0°$, $15°$, $30°$, and $45°$). There was a total of 40 luminance measurements for each measurement trial (including both light sources).

10. The recorded luminance data can then be easily converted into corresponding R table values utilizing known light intensity and height.

RESULTS AND ANALYSIS

Light Source and Pavement Type Interaction Analysis

All the measurements are reported in the Appendix. The following (box plot) analyses do not consider the variation of angular parameters (β and γ). The range of the R table values are compared with respect to pavement types and light sources. These results represent the overall reflective behavior. General box plots show the distribution of data, where the rectangular spans (the interquartile range or IQR) from the 1st to the 3rd quartile and median is indicated by the line inside the rectangle. The maximum and minimum are shown by the outer whiskers. The median line adequately represents the general behavior of the given parameter. The outliers are represented by crosses which are values that are more than 3×IQR above the third quartile or below the first quartile. In this particular case, the outliers represent R values measured when the β and γ angles are either smaller or larger. Therefore, the outliers are not indicative of error in the experimental data.

(a)   (b)
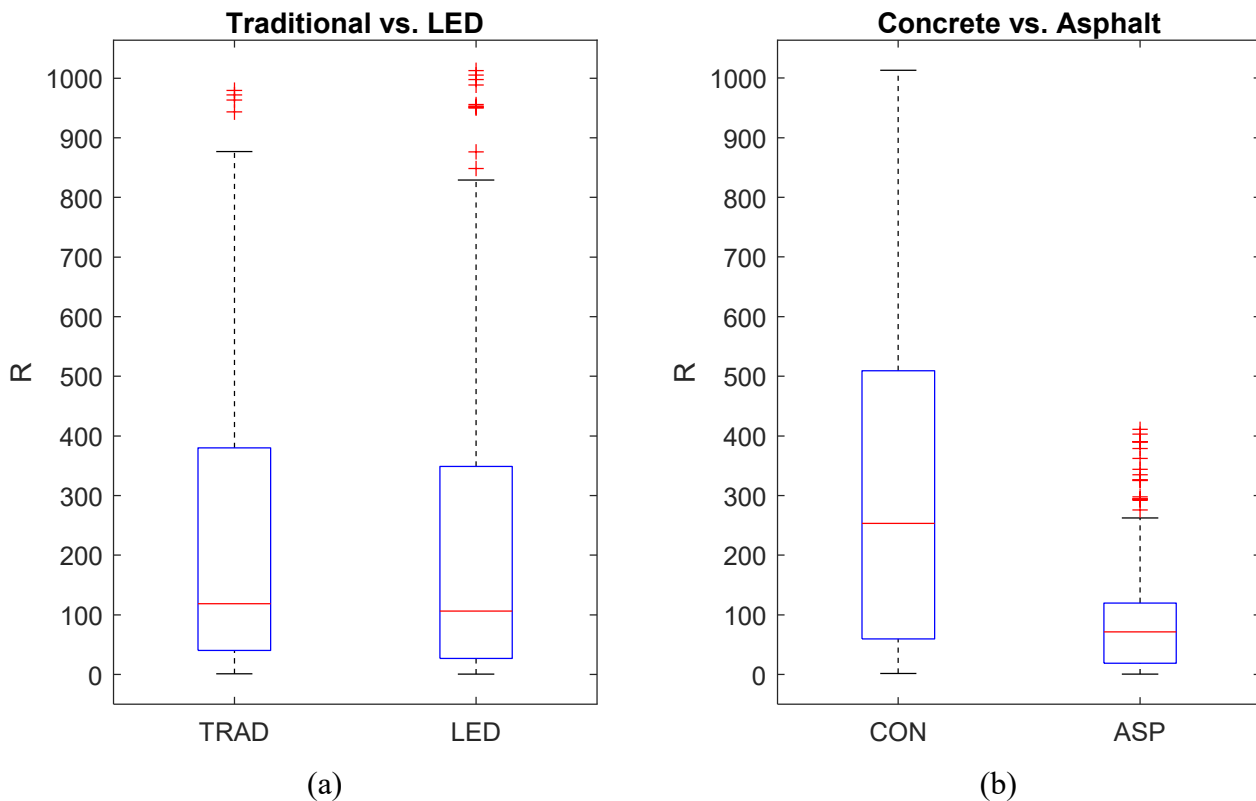
Figure 10. Light Source and Pavement Type

Figure 10 (a) shows the R values measured on all the tested samples with respect to each light source (incandescent and LED). Figure 10 (b) shows the R values measured on all the tested samples with respect to each pavement type (concrete and asphalt). The median R value of concrete (250) is about three times higher than that of asphalt (80). These results indicate that regardless of the angular contributions and type of light, concrete is up to three times more reflective than asphalt pavements.

Table 3. Two-way ANOVA Analysis of Light Source and Pavement Type

Source of Variation (Main Factor)	p-value	Significance Evaluation	Interpretation
Light Source	0.108	0.108 > 0.05	Not Significant
Pavement Type	0.000	0.000 < 0.05	Significant

Note: Secondary factor is 20 angle combinations.

Table 3 shows the two-way Analysis of Variance (ANOVA) statistical analysis which intends to highlight any significant differences between the measured values of traditional (incandescent) and LED lights as well as differences between measured values on concrete and asphalt. This also can capture the interaction between main variables (either light source and pavement type) and the 20 different angle combinations. The full analysis of results is presented in the Appendix. When the p-value is less than 0.05, the difference between two means are significant at a 95% confidence level (denoted by "Significant" in Table 3), while, a p-value greater than 0.05 indicates the difference between the means are not significant (denoted by "Not Significant" in Table 3). The analysis indicated that there was an insignificant difference between the measured R values using traditional (incandescent) and LED lights. When considering the consumption of energy, LED lights (0.55 volts) yield the similar performance as compared to incandescent lights (12.80 volts). Therefore, a significant reduction of energy can be achieved (up to 96%) using LED lights with comparable performance to traditional (incandescent) lights. Whereas, there was a significant difference between the measured R values on concrete and asphalt pavements. Therefore, when angular light distribution is not considered, traditional (incandescent) and LED lights produce the same amount of overall reflected light. Whereas, concrete and asphalt do not reflect the same amount of light. Statistically, the concrete exhibits higher reflectiveness than asphalt regardless the light source.

In addition, there are no interactions between the light sources and the 20 angle combinations. This can be confirmed from the interaction p-value which is 0.108 (Not Significant). This indicates the LED and incandescent lights have equivalent R value trends with respect to the angular light. However, this trend turns out to be opposite in the interaction between pavement types and the angles. The angles are considered as a significant factor that vary the R value in different proportional manners. This indicates the angle effect on R values are potentially different depending on pavement types. This behavior is indicative by the p-value of interaction that is close to 0 (Significant).
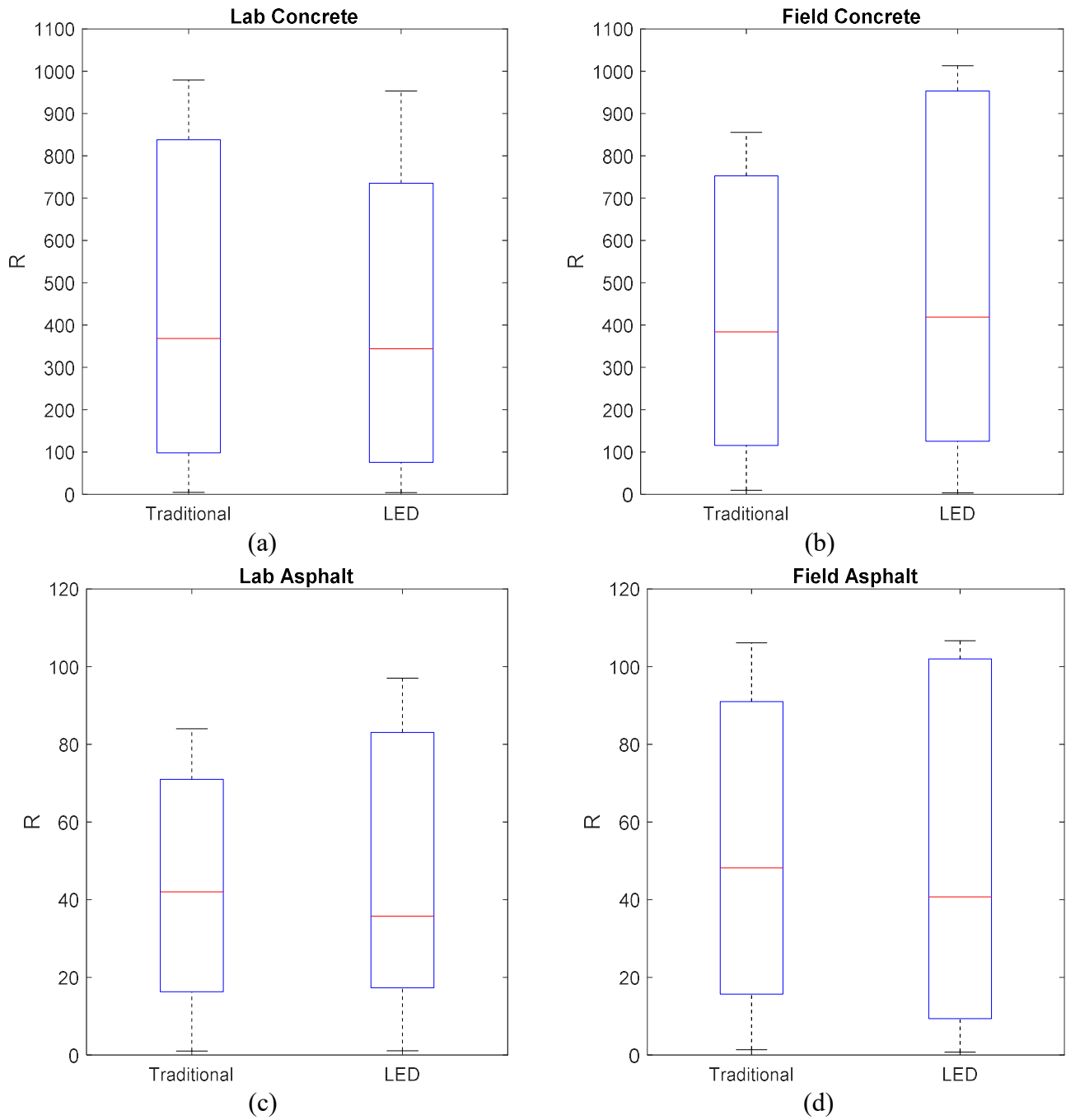
Figure 11. Lab vs. Field

Figure 11 shows the lab and field results of two comparable concrete samples, where Figure 11 (a) shows the results of LC-45 and Figure 11 (b) shows the results of FC-02, respectively. Likewise, the results of two comparable asphalt samples are displayed, where Figure 11 (c) shows the results of LA-DK and Figure 11 (d) shows the results of FA-02. Comparing R values of lab with R values of field, each sample had relatively close median values which were assumed to be equal, with respect to each light source.

Table 4. Two-way ANOVA Analysis of Lab vs. Field

Source of Variation (Main Factor)	p-value	Significance Evaluation	Interpretation
Lab and Field Concrete	0.875	0.875 > 0.05	Not Significant
Lab and Field Asphalt	0.359	0.359 > 0.05	Not Significant

Table 4 shows the two-way ANOVA statistical analysis which intends to highlight any significant differences between the concrete and asphalt R values measured in the lab and field. The secondary factor is the 20 combinations of angles. The entire analysis is reported in the Appendix. The analysis indicated that there was an insignificant difference between the concrete and asphalt samples measured in the lab and the concrete and asphalt "in-situ" pavements measured in the field. The p-value of interaction between lab and field concrete was 0.875 which is greater than 0.05 (Not Significant). The p-value of interaction between lab and field asphalt was 0.359 which is greater than 0.05 (Not Significant). Also, there was no interaction between the angle combinations and the main considerations (lab and field measurements). These results indicate that the R values are statistically not different between laboratory and field measurements with respect to angles. Therefore, the lab and field samples can be assumed equivalent and are not further mentioned in the proceeding sections.

Pavement Age Effects

One of the crucial issues when trying to define pavement systems into generalized categories is that their properties tend to change over time. As time passes, pavements will be deteriorated and weathered from vehicular travel and exposure to the natural environment. For example, as asphalt ages it tends to become lighter in color whereas concrete tends to get darker in color.
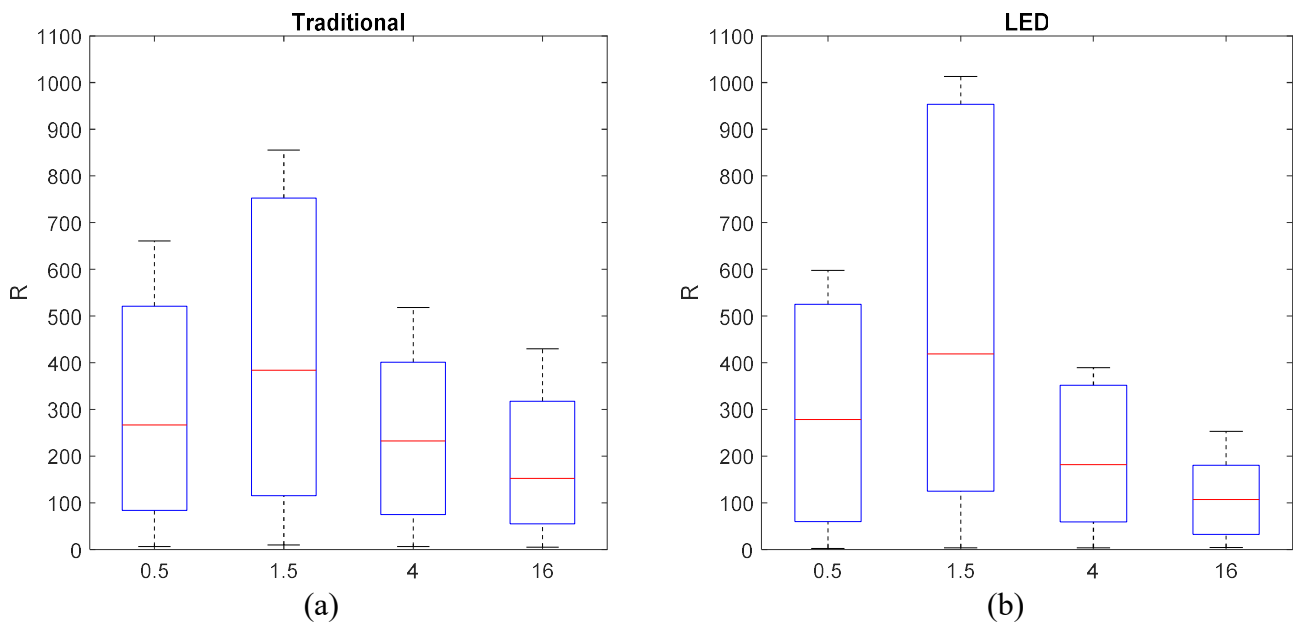

Figure 12. Pavement Age and Light Source Interaction

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Figure 12 shows the R values of the tested field concrete pavements as a function of ages illuminated by (a) traditional and (b) LED lights. Where the concrete ages (years) 0.5, 1.5, 4, and 16 correspond to the pavement samples FC-01, FC-02, FC-03, and FC-04 respectively. The analysis indicated that R values correlate with pavement age. Concrete tends to get darker over time while asphalt tends to get lighter. Therefore, the trend of decreasing R values with respect to age is to be expected. It should be noted that the medians of the oldest concrete (FC-04) still range from 100 to 200 (See Figure 12) which are still much greater than the peak R values seen in any of the tested asphalt pavements.

Table 5. Two-way ANOVA Analysis: Pavement Age and Light Source Interaction

Source of Variation	p-value	Significance Evaluation	Interpretation
Light Source (Main)	0.404	$0.404 > 0.05$	Not Significant
Age (Secondary)	0.000	$0.000 < 0.05$	Significant
Light Source and Age	0.120	$0.120 > 0.05$	Not Significant

Table 5 shows the two-way ANOVA statistical analysis which intends to highlight any difference between the R values of each light source while considering age effect of the pavements. The analysis indicated that there was an insignificant difference between each light source's R values with respect to pavement age (e.g., comparing the data in Figure 11 (a) and Figure 11 (b) with the same age). Therefore, there is no significant interaction between the light source and the age of pavement with regards to the influence of R values (See Table 5). However, age is a significant factor for influencing the R value over time.

Table 6. Concrete Age Comparisons (A Pair Comparison Amongst Four Ages)

Age "A"	Age "B"	p-value	Significance Evaluation	Interpretation
0.5	1.5	0.0000	$0.0000 < 0.05$	Significant
0.5	4	0.1013	$0.1013 > 0.05$	Not Significant
0.5	16	0.0002	$0.0002 < 0.05$	Significant
1.5	4	0.0000	$0.0000 < 0.05$	Significant
1.5	16	0.0000	$0.0000 < 0.05$	Significant
4	16	0.2185	$0.2185 > 0.05$	Not Significant

As shown in Table 6, the R values of year 4 have no significant difference from those of year 16. R values of year 1.5 are different from any R values of 0.5, 4, and 16 years. Therefore, the year 1.5 are generally statistically different from all the R values. In summary, for concrete tested pavements, the exposure of 4 years begins to behave differently from the 0.5-year exposure. However, beyond 4 years, the change is not significant compared with the R value of 16-year exposure.

In general, the measured concrete R values were significantly different in the early years of the pavements lifetime (0 to 4 years). Whereas, the measured concrete R values were insignificantly different between the pavements from 4 years to 16 years old. Therefore, concrete pavements tend to have some reflective characteristic changes over its lifetime but in general concrete's reflective characteristics tend to stabilize in the first quarter of its life span. Whereas, assuming asphalt follows similar stabilization, the pavement's reflective characteristics will be consistently changing over the course of its shorter life span.

Incandescent on Averaged (Diffused and Specular) Concrete

Table 7. Incandescent on Concrete vs. Current R1 Values

Concrete $\gamma°$	$\beta°$			
	0	15	30	45
	Incandescent on Concrete (Standard Deviation) / Current R1 Values			
0	**658 (260)** / 655	**673 (265)** / 655	**677 (283)** / 655	**680 (284)** / 655
27	**585 (263)** / 539	**559 (237)** / 539	**540 (232)** / 521	**527 (220)** / 521
45	**342 (173)** / 341	**290 (118)** / 323	**266 (105)** / 296	**259 (103)** / 278
63	**113 (60)** / 162	**93 (36)** / 153	**84 (30)** / 94	**84 (30)** / 85
79	**8 (3)** / 57	**7 (3)** / 14	**6 (2)** / 9	**6 (2)** / 9

Figure 13. Incandescent on Concrete vs. R1

Table 7 displays the measured incandescent on concrete R values. The measured values are the top bolded number (along with its respective standard deviation) and below are corresponding current R1 values. Figure 13 compares the measured R values to the current R tables, where Figure 13 (a) is the measured incandescent on concrete R values and Figure 13 (b) is the current R1 table values.

There was an insignificant statistical difference between the incandescent on concrete data and the current R1 data sets at a 95% confidence level (p-value = 0.13 > 0.05). Therefore, incandescent lights can be verified as an equivalent representation of the "traditional" light source used to develop the current R table values (R1 or R3) regardless of the reflective pavement type. This initial analysis also validates that the current R1 values are adequately representative of modern concrete pavement types. In summary, the results indicate that concrete used today has insignificant differences to the concrete used 30 years ago.

Incandescent on Averaged (Diffused and Specular) Asphalt

Table 8. Incandescent on Asphalt vs. Current R3 Values

Asphalt	$\beta°$			
$\gamma°$	0	15	30	45
Incandescent on Asphalt (Standard Deviation) / Current R3 Values				
0	**120 (68)** / 294	**121 (69)** / 294	**121 (67)** / 294	**117 (62)** / 294
27	**124 (67)** / 344	**112 (55)** / 326	**99 (42)** / 298	**91 (36)** / 262
45	**86 (48)** / 362	**72 (32)** / 276	**57 (21)** / 204	**49 (17)** / 140
63	**38 (18)** / 326	**29 (9)** / 136	**22 (5)** / 71	**18 (4)** / 48
79	**3 (2)** / 145	**3 (1)** / 16	**2 (1)** / 8	**1 (0)** / 6

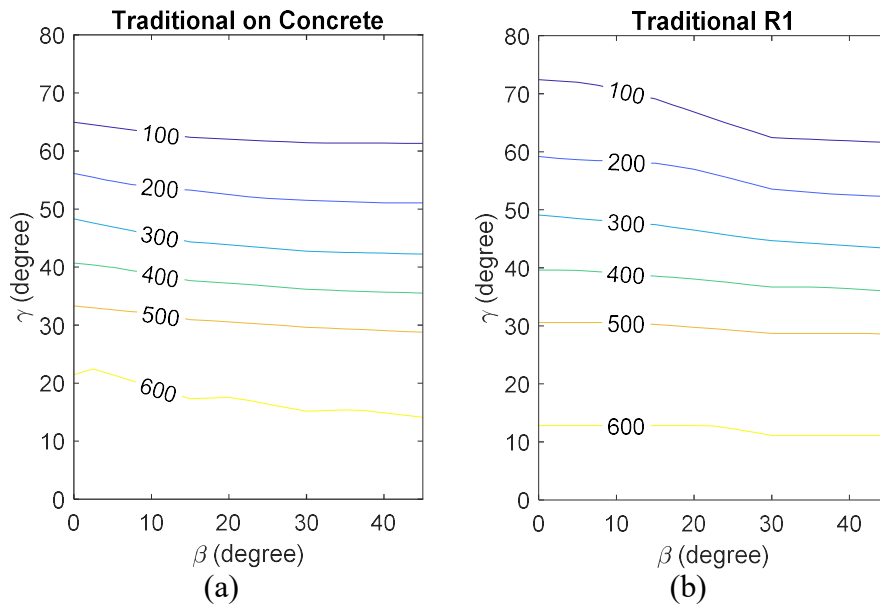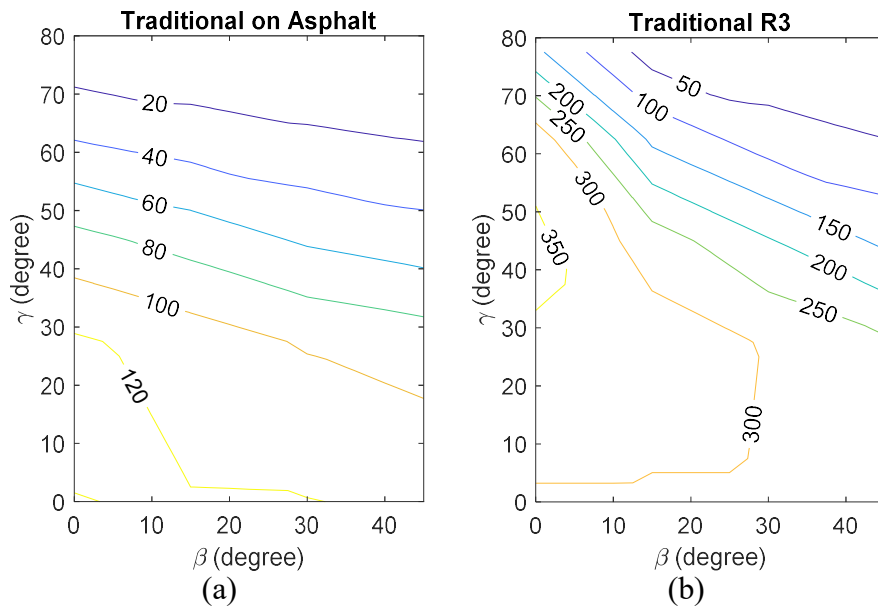(a)   (b)

Figure 14. Incandescent on Asphalt vs. R3

Table 8 displays the measured incandescent on asphalt R values. The measured values are the top bolded number (along with its respective standard deviation) and below are corresponding current R3 values. Figure 14 compares the measured R values to the current R tables, where Figure 14 (a) is the measured incandescent on asphalt R values and Figure 14 (b) is the current R3 table values.

There was a statistically significant difference between the incandescent on asphalt data and the current R3 data sets at a 95% confidence level (p-value = 0). The previous analysis indicates that the statistically significant difference between each data set is not a result of the light source itself but the reflective pavement. In summary, the current R3 values are not an adequate representation of modern asphalt pavement types. Asphalt is heavily dependent on the availability of an oil refined byproduct called bitumen. Due to the recent spike in bitumen prices, less and less of it is used in asphalt pavements. As a result, the composition of asphalt has changed dramatically. This information coincides with the statistical analysis and indicates that modern asphalt is completely different from the asphalt used 30 years ago.

LED on Averaged (Diffused and Specular) Concrete

Table 9. LED on Concrete vs. Current R1 Values

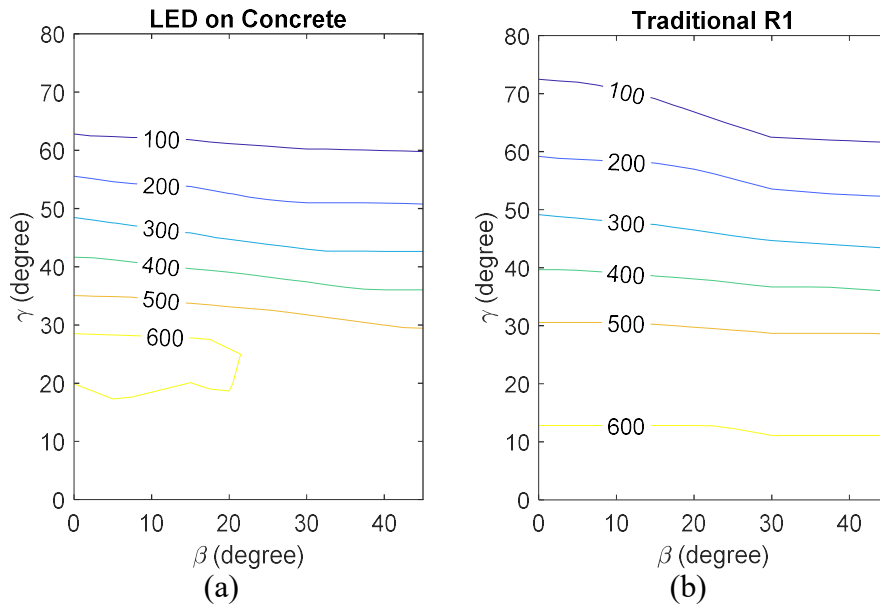| Concrete	$\beta°$			
$\gamma°$	0	15	30	45
	LED on Concrete (Standard Deviation) / Current R1 Values			
0	**536 (276)** / 655	**561 (288)** / 655	**574 (284)** / 655	**553 (277)** / 655
27	**623 (328)** / 539	**613 (333)** / 539	**584 (317)** / 521	**537 (277)** / 521
45	**349 (213)** / 341	**310 (149)** / 323	**265 (128)** / 296	**264 (127)** / 278
63	**95 (52)** / 162	**85 (44)** / 153	**70 (38)** / 94	**64 (35)** / 85
79	**6 (3)** / 57	**6 (3)** / 14	**4 (1)** / 9	**4 (1)** / 9

Figure 15. LED on Concrete vs. R1

Table 9 displays the measured LED on concrete R values. The measured values are the top bolded number (along with its respective standard deviation) and below are the corresponding current R1 values. Figure 15 compares the measured R values to the current R tables, where Figure 15 (a) is the measured LED on concrete R values and Figure 15 (b) is the current R1 table.

There was a significant statistical difference between the LED on concrete data and the current R1 data sets at a 95% confidence level (p-value = 0.02 < 0.05). It is important to note that this was the only significantly different statistical analysis with a p-value close to the evaluation criteria (p-value = 0.05). Therefore, the difference in data is most likely the result of the LED light and not the concrete pavement. The incandescent bulbs used in the experimental program diffused the light in a uniform manner. Whereas, the LED light used in the experimental program produces a much more concentrated, non-uniform light. These results indicate that when the angular light is considered, LED lights distribute light differently than traditional (incandescent) lights do. When the angular light is neglected, LED lights reflect approximately the same amount of light as traditional (incandescent) lights do (see Figure 10 (a)). Therefore, while the current R1 table is representative of modern concrete illuminated by traditional (incandescent) lights the R1 table does not necessarily account for the different angular light distribution caused by LED lights.

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LED on Averaged (Diffused and Specular) Asphalt

Asphalt	$\beta°$			
$\gamma°$	0	15	30	45
	LED on Asphalt (Standard Deviation) / Current R3 Values			
0	**111 (62)** / 294	**118 (63)** / 294	**122 (66)** / 294	**120 (68)** / 294
27	**154 (95)** / 344	**150 (98)** / 326	**138 (94)** / 298	**120 (81)** / 262
45	**113 (98)** / 362	**91 (77)** / 276	**72 (52)** / 204	**63 (42)** / 140
63	**35 (18)** / 326	**29 (14)** / 136	**21 (8)** / 71	**16 (7)** / 48
79	**3 (1)** / 145	**2 (1)** / 16	**1 (1)** / 8	**1 (0)** / 6

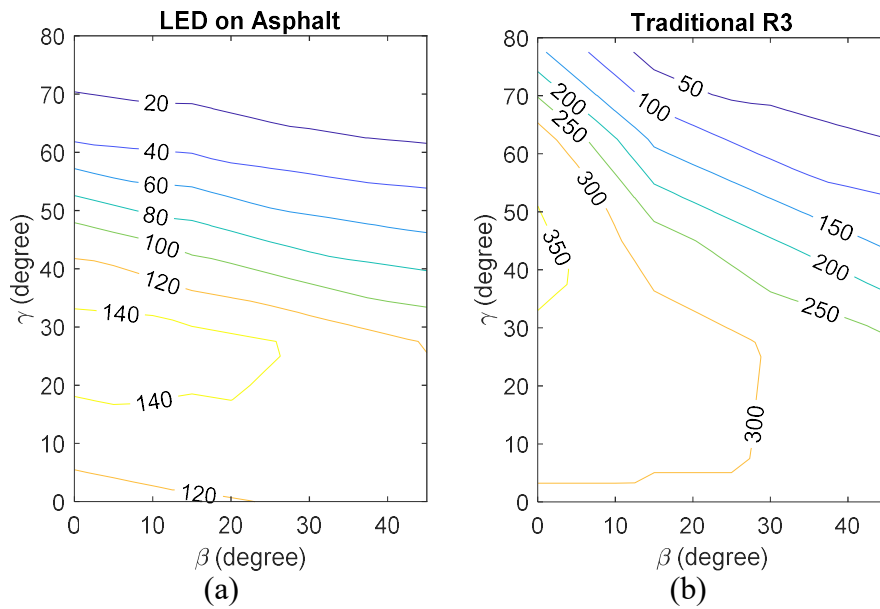**Table 10.** LED on Asphalt vs. Current R3 Values

Figure 16. LED on Asphalt vs. R3

Table 10 displays the measured LED on asphalt R values. The measured values are the top bolded number (along with its respective standard deviation) and below are the corresponding current R3 values. Figure 16 compares the experimental R values to the current R tables, where Figure 16 (a) is the experimental LED on asphalt R values and Figure 16 (b) is the current R3 table.

There was a statistically significant difference between the LED on asphalt data and the current R3 data sets at a 95% confidence level (p-value = 0). As previously discussed, while LED lights produce approximately the same amount of reflected light as traditional (incandescent) lights (see Figure 10 (a)) they do not distribute that light in the same angular manner. The previous analysis already indicated that the current R3 table is not representative of modern asphalt even when illuminated by traditional lights. In summary, these results revalidate that the current R3 values are not representative of modern asphalt pavements regardless of the illuminating light source (incandescent or LED).

Confidence Interval Estimation

Table 11. Traditional on Concrete 95% Confidence Interval

Concrete	$\beta°$			
$\gamma°$	0	15	30	45
Traditional on Concrete				
0	557 - 758	571 - 776	565 - 788	569 - 790
27	483 - 687	466 - 652	445 - 636	436 - 618
45	274 - 410	242 - 338	220 - 311	214 - 304
63	89 - 136	79 - 108	71 - 97	70 - 97
79	7 - 10	6 - 8	5 - 7	5 - 7

Table 12. Traditional on Asphalt 95% Confidence Interval

Asphalt	$\beta°$			
$\gamma°$	0	15	30	45
Traditional on Asphalt				
0	71 - 169	71 - 170	72 - 169	72 - 161
27	76 - 172	73 - 151	69 - 129	65 - 117
45	52 - 121	49 - 95	43 - 72	36 - 61
63	25 - 50	22 - 35	18 - 26	15 - 21
79	2 - 5	2 - 3	1 - 2	1 - 2

Table 13. LED on Concrete 95% Confidence Interval

Concrete	$\beta°$			
$\gamma°$	0	15	30	45
LED on Concrete				
0	407 - 665	427 - 696	441 - 707	424 - 683
27	469 - 776	458 - 769	436 - 733	408 - 667
45	249 - 449	240 - 380	205 - 325	205 - 324
63	71 - 120	65 - 106	52 - 88	48 - 81
79	5 - 8	4 - 7	3 - 5	3 - 4

Table 14. LED on Asphalt 95% Confidence Interval

Asphalt	$\beta°$			
$\gamma°$	0	15	30	45
LED on Asphalt				
0	67 - 155	73 - 163	75 - 169	72 - 169
27	86 - 222	80 - 220	71 - 205	62 - 179
45	42 - 183	36 - 147	35 - 110	33 - 93
63	22 - 48	19 - 39	15 - 27	11 - 21
79	1 - 4	1 - 3	1 - 2	1 - 1

Table 11 through Table 14 are the calculated 95% Confidence Interval (CI) range between the measured values and the current R table values.

Confidence Interval Analysis

Table 15. R1 (Concrete) vs. R3 (Asphalt)

Concrete	$\beta°$				Asphalt	$\beta°$			
$\gamma°$	0	15	30	45	$\gamma°$	0	15	30	45
Traditional R1					**Traditional R3**				
0	655	655	655	655	0	294	294	294	294
27	539	539	521	521	27	344	326	298	262
45	341	323	296	278	45	362	276	204	140
63	162	153	94	85	63	326	136	71	48
79	57	14	9	9	79	145	16	8	6

Table 16. Traditional 95% Confidence Interval Analysis

Concrete	$\beta°$				Asphalt	$\beta°$			
$\gamma°$	0	15	30	45	$\gamma°$	0	15	30	45
Traditional on Concrete					**Traditional on Asphalt**				
0	TRUE	TRUE	TRUE	TRUE	0	**NULL**	**NULL**	**NULL**	**NULL**
27	TRUE	TRUE	TRUE	TRUE	27	**NULL**	**NULL**	**NULL**	**NULL**
45	TRUE	TRUE	TRUE	TRUE	45	**NULL**	**NULL**	**NULL**	**NULL**
63	**NULL**	**NULL**	TRUE	TRUE	63	**NULL**	**NULL**	**NULL**	**NULL**
79	**NULL**	**NULL**	**NULL**	**NULL**	79	**NULL**	**NULL**	**NULL**	**NULL**

Table 17. LED 95% Confidence Interval Analysis

Concrete	$\beta°$				Asphalt	$\beta°$			
$\gamma°$	0	15	30	45	$\gamma°$	0	15	30	45
LED on Concrete					**LED on Asphalt**				
0	TRUE	TRUE	TRUE	TRUE	0	**NULL**	**NULL**	**NULL**	**NULL**
27	TRUE	TRUE	TRUE	TRUE	27	**NULL**	**NULL**	**NULL**	**NULL**
45	TRUE	TRUE	TRUE	TRUE	45	**NULL**	**NULL**	**NULL**	**NULL**
63	**NULL**	**NULL**	**NULL**	**NULL**	63	**NULL**	**NULL**	**NULL**	**NULL**
79	**NULL**	**NULL**	**NULL**	**NULL**	79	**NULL**	**NULL**	**NULL**	**NULL**

Table 15 shows the current R table values of R1 and R3 which are used to verify whether the measured values are equivalent to the current R table values. Table 16 and Table 17 are the 95% confidence interval range checks to verify if the current R table values fall within the measured values acceptable range. "TRUE" indicates the current R table values are within the acceptable range and "NULL" indicates values are not within the acceptable range. The previous *p*-value analysis approach was similar to this statistical analysis except this method allows differential analysis for each individual angle. Therefore, "TRUE" is identical to "Not significant" and "NULL" is identical to "Significant".

It is important to note that the larger γ angles ($>45°$) and smaller β angles ($<30°$) had a greater influence on the statistical differences between corresponding R values. This angular influence could possibly be the result of using such a large observation angle ($\alpha = 30°$). An insignificant difference was indicated between the traditional and LED concrete (R1) results at the γ angle ranging from 0 to 45°. Whereas, there was significant difference between the measured asphalt values and the current R3 values.

Lightness (Q₀) and Specularity (S1) Analysis

Table 18. Pavement Groups Lightness and Specularity Results

Light Source	Specularity Description	Pavement Type	Group (1-8)	Sample Name	Lightness (Q_0)	Specularity ($S1$)
Traditional	Diffused	Concrete	#1	FC-DF	0.05	0.15
				FC-01	0.06	0.16
				FC-02	0.08	0.15
				FC-03	0.05	0.17
				FC-04	0.04	0.14
		Asphalt	#2	LA-DK	0.01	0.26
				FA-02	0.01	0.19
	Specular	Concrete	#3	LC-40	0.11	0.18
				LC-45	0.13	0.21
				FC-SP	0.04	0.19
		Asphalt	#4	LA-LT	0.02	0.36
				FA-01	0.01	0.32
LED	Diffused	Concrete	#5	FC-DF	0.05	0.09
				FC-01	0.06	0.14
				FC-02	0.10	0.13
				FC-03	0.04	0.17
				FC-04	0.02	0.18
		Asphalt	#6	LA-DK	0.01	0.31
				FA-02	0.01	0.11
	Specular	Concrete	#7	LC-40	0.10	0.24
				LC-45	0.12	0.25
				FC-SP	0.03	0.25
		Asphalt	#8	LA-LT	0.02	0.41
				FA-01	0.01	0.26

Table 18 shows the designated grouping system used to define each pavement sample into generalized categories based on their specularity. Groups were defined by separating the concrete and asphalt samples into four groups with respect to each of their calculated *S1* values. The specular defined groups are; diffused concrete, diffused asphalt, specular concrete, and specular asphalt. The four groups were applied to each light source (incandescent and LED) which created a total of eight groups. For example, incandescent on diffused concrete is defined as group #1, incandescent on diffused asphalt is defined as group #2, incandescent on specular concrete is defined as group #3, incandescent on specular asphalt is defined as group #4, and LED on the preceding pavement groups is defined as groups #5-8, respectively.

The current R tables (R1, R2, and R3) have their own individual values which define a pavement's lightness (Q_0) and specularity ($S1$). Because there are only three values of Q_0 and $S1$ to categorize them, groups must be generalized further to yield equivalent values. Therefore, the incandescent and LED on diffused and specular concrete (groups #1, #3, #5, and #7) were averaged to yield equivalent values to compare with the R1 values. Whereas, the incandescent and LED on diffused asphalt (groups #2 and #6) were averaged to yield equivalent values to compare with the R2 values. Lastly, the incandescent and LED on specular asphalt (groups #4 and #8) were averaged to yield equivalent values to compare with the R3 values. These averages were compared to the current R table's Q_0 (lightness) and $S1$ (specularity) values. The percent difference was calculated between the current R1, R2, and R3 values and each average corresponding measured value.

Table 19. Lightness and Specularity Statistical Analysis

R Table (Q_0)	Q_0 (Average)	Q_0 (% Difference)	R Table ($S1$)	$S1$ (Average)	$S1$ (% Difference)
R1 ($Q_0 = 0.10$)	0.068	32.5%	R1 ($S1 = 0.25$)	0.18	26.4%
R2 & R3 ($Q_0 = 0.07$)	0.013	**82.1%**	R2 ($S1 = 0.58$)	0.22	**41.8%**
			R3 ($S1 = 1.11$)	0.34	**80.4%**

Table 19 defines the current R1, R2, and R3 values for Q_0 and $S1$, the corresponding average measured values, and the percent difference between them. Calculated percent difference values greater than 40% are denoted by bolded values. As seen in the Table 19, the greatest percent difference values were observed in two R tables of asphalt pavements (R2 and R3). Whereas, the measured Q_0 and $S1$ exhibited about 30% lower than the values of the R table of concrete pavement (R1). These two values qualitatively represent the reflective characteristics. The greater the value of $S1$, the more specular the pavement is. Similarly, the greater the value of Q_0, the lighter the pavement's surface is. When comparing the value of Q_0 between concrete (R1) and asphalt (R2 and R3), concrete's lightness is about five times greater than asphalt. This indicates that the lightness of concrete is significantly higher than the modern asphalt tested in this study.

Angular Light Interaction Analysis

The proceeding sections present the data results measured in the experimental program with consideration of the angular parameters (β and γ). The R tables represent the angular behavior of different surfaces with respect to the β and γ angles. In the following sections, the measured angular results from the experimental program are analyzed and discussed.

The initial figures are the 3D surface plots and 2D contour plots for the current R1, R2, and R3 table values. For the intuitive and visual comparison, assume incandescent and LED lights behave similarly to the lights used to develop the current R tables. With that assumption, each of the three current R tables can be matched with equivalent (corresponding) measured sample groups. While there are three current R tables intended to describe asphalt pavements there is only one table intended to describe all concrete pavements. The R1 concrete table neglects (incorporates both) specular and diffused concrete behavior. Therefore, the measured concrete was separated into specular and diffused concrete groups. Whereas, the R2 (diffused) and R3 (specular) asphalt intends to describe the behavior of all the different types of asphalt pavements (except for extreme cases defined by the R4 table).

For example, each of the measured specular and diffused concrete groups (#1, #2, #5, and #6) can all be considered as equivalent to the current R1 table. Whereas, the measured diffused asphalt groups (#4 and #8) can both be considered as equivalent to the current R2 table. Lastly, the tested specular asphalt groups (#3 and #7) can both be considered as equivalent to the current R3 table.
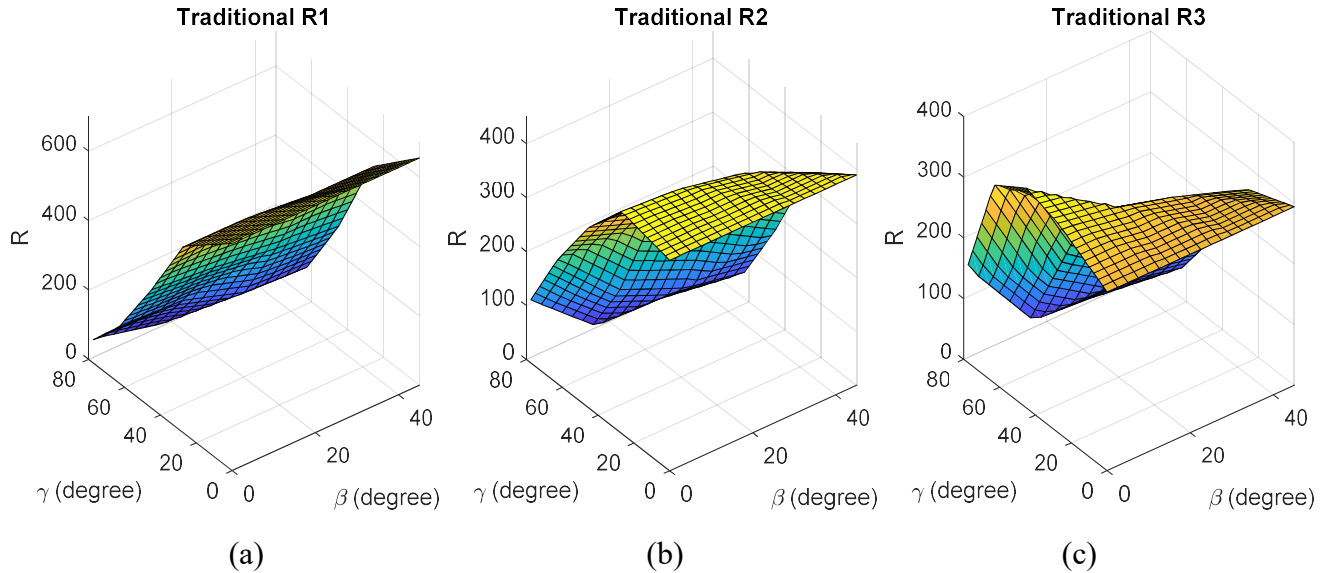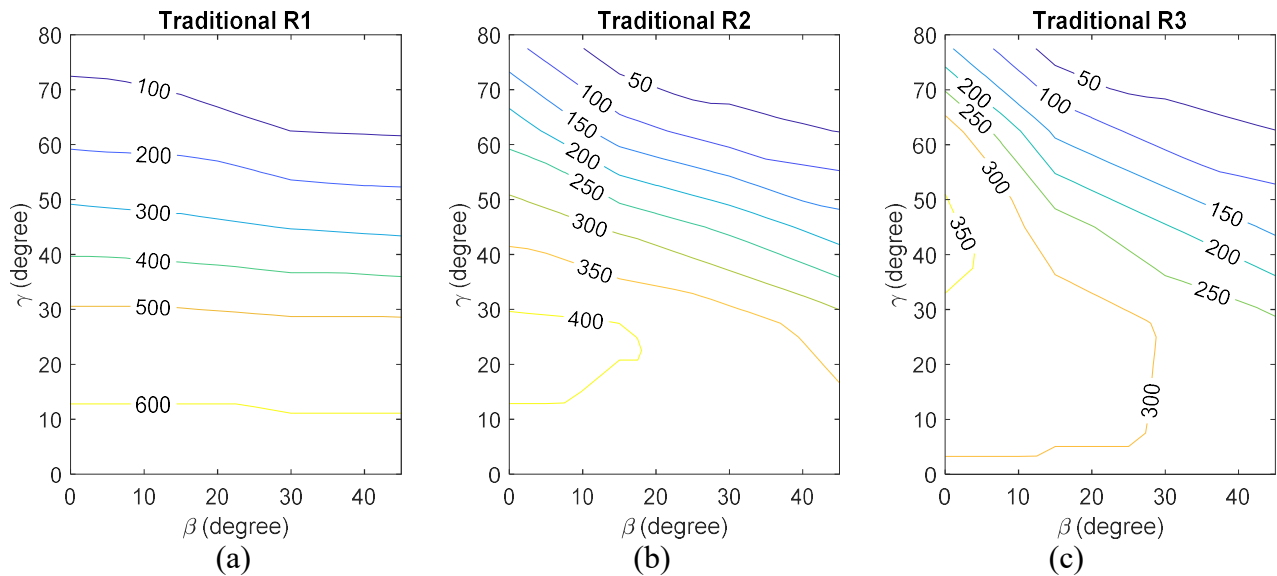

Figure 17. Current R1, R2, and R3 Surface Plots

Figure 18. Current R1, R2, and R3 Contour Plots

Figure 17 shows the 3D surface plots of the current R1, R2, and R3 tables, respectively. Figure 18 shows the 2D contour plots of the current R1, R2, and R3 tables, respectively. These plots can be used as visual comparisons for the following measured R value plots. As previously discussed, the R1 table represents the most diffused surfaces, the R2 table represents slightly specular surfaces, and the R3 table represents the most specular surfaces.
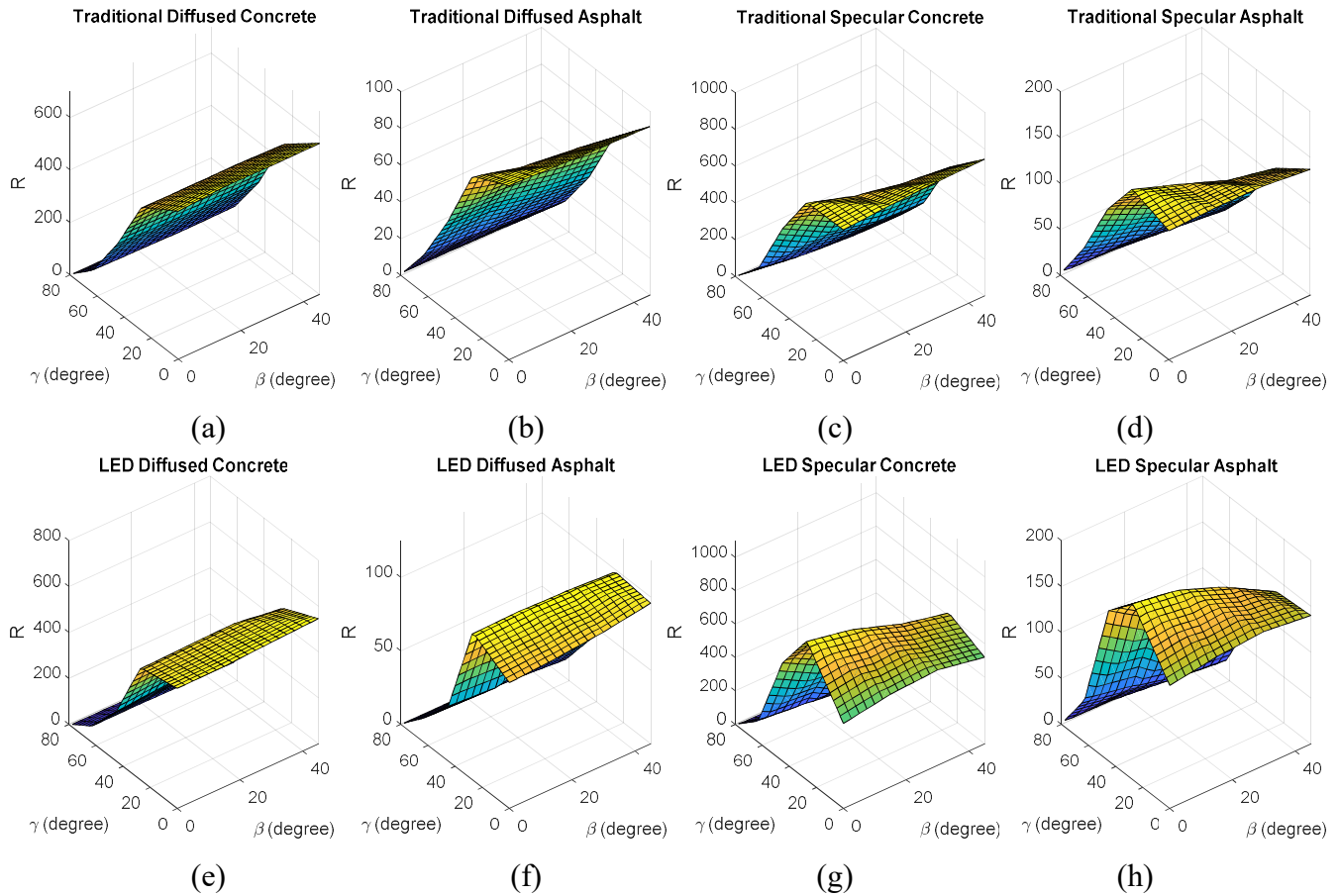
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Figure 19. Surface Plots of Groups 1-8

Figure 19 shows the 3D surface plots of the R values in groups 1-8, respectively. Where Figure 19 (a) through (d) are groups #1 through #4 illuminated by traditional (incandescent) lights and Figure 19 (e) through (h) are groups #5 through #8 illuminated by LED lights. These plots are displayed side-by-side to allow easy visual comparison of the behavior trends of each group. This visual analysis intends to capture the differences in the shape of each group to identify their reflective characteristics or behavior trends.

To summarize the behaviors, a "spike" in a surface plot indicates an influence on R values with respect to the *γ* angle only, whereas "twisting" indicates influence on R values with respect to both angles (*β* and *γ*). Less "twisting" and more "spike" indicates a smaller influence with respect to the *β* angle but a larger influence with respect to the *γ* angle. The greater the "twisting" effect, the greater the surface specularity. For example, a perfect "twisting" shape indicates a proportional influence on R values with respect to both the *β* and *γ* angles (very specular). Due to the diffusion (not specular) nature of concrete pavements the current R1 table indicates minimal influence on the R values with respect to the *β* and *γ* angles (See Figure 17 (a) and Figure 18 (a)).
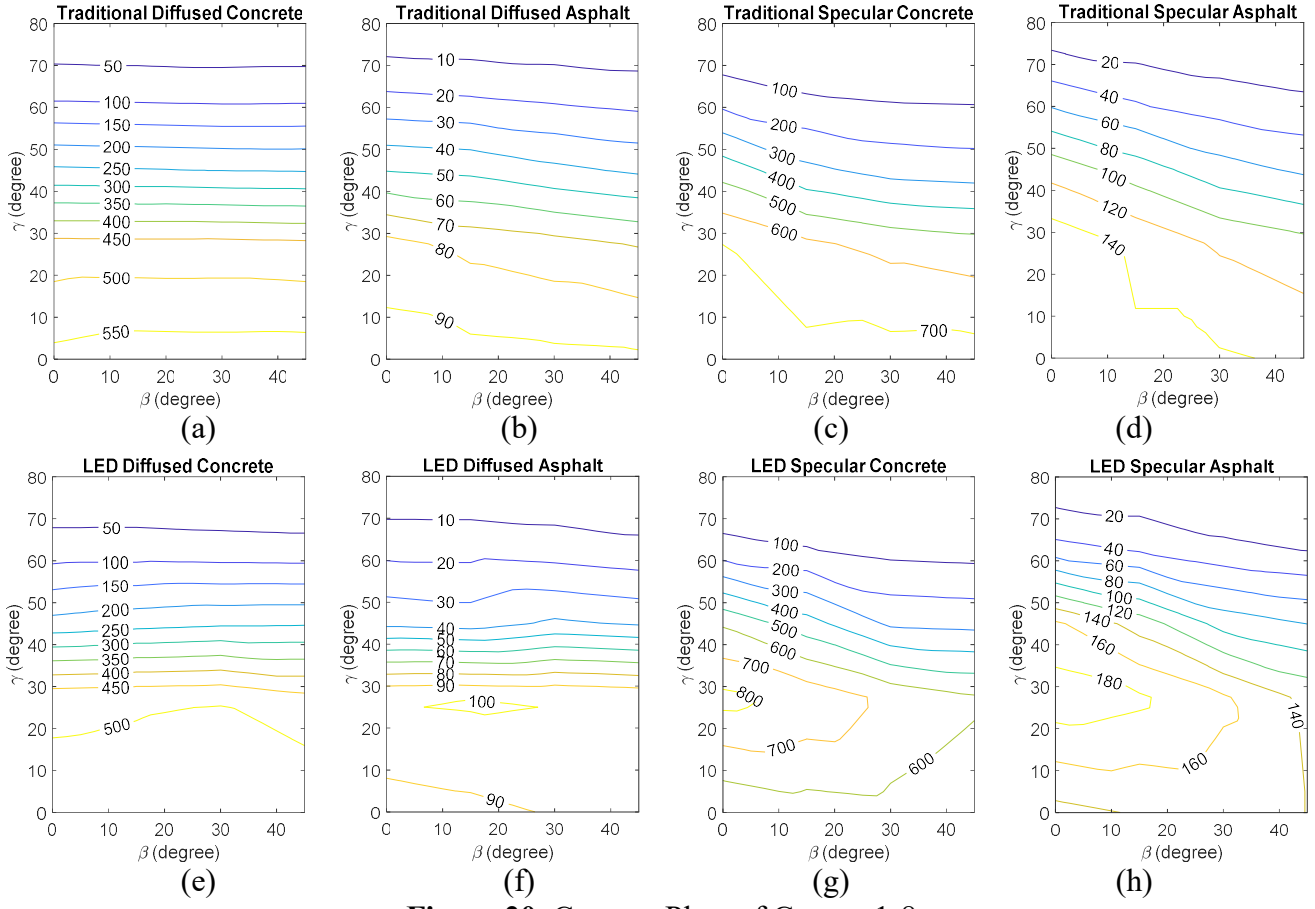
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Figure 20. Contour Plots of Groups 1-8

Figure 20 shows the 2D contour plots equivalent to 3D plots in Figure 19. The traditional (incandescent) peak R value occurs at the $\gamma = 0°$. As seen in the plots of the traditional (incandescent) groups (See Figure 20 (a) through (d)), as the pavement surface becomes more specular the contour lines show a dramatic change in the slope with respect to the β and γ angles (indicated by the diagonal contour lines). The plots of the LED groups exhibit similar trends except the trend stems from their peak value which occurs at the $\gamma = 27°$ (See Figure 20 (e) through (h)). The diagonal sloping of contour lines is equivalent to the "twisting" effect seen in the 3D surface plots. Whereas, non-uniform horizontal contour lines indicate similar trends as the "spike" effect seen in the 3D surface plots.

Assuming equivalent specularity among all of the reflective surfaces, concrete pavement is not significantly influenced by the low correlation between the β and γ angles. Inversely, asphalt (which tends to be more specular than concrete) is influenced by the high correlation between β and γ angle. The measured R table asphalt values validated this expected behavior. The influence of surface specularity with respect to the β and γ angles creates a "twisting" effect (as seen in the 3D surface plots). This behavior (twisting) was apparent by the decrease in the R values with respect to the increase in the β and γ angle.

In conclusion, the pavement surface specularity influenced the reflected angular light with respect to the change in both the β and γ angles. The smaller the "twisting" effect appeared the less specular the reflective surface was and vice-versa. Interestingly, the LED light had an additional influence on the angular distribution with respect to only the γ angle. The dramatic "spike" with respect to the γ angle (27°) was only apparent in the R values measured with the LED light source (See Figure 19 (e) through (h)).

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SUMMARY AND CONCLUSIONS

The objective of this study was to measure the luminance of two varied light sources (incandescent and LED) on two different pavement systems (concrete and asphalt). The measured luminance values were then converted into R table values so that they could be compared with the corresponding current R table values. Based on an analysis of the experimental test results the following conclusions can be made:

1. The experimental program test results indicate the portable goniometer testing program and design are an adequate method of reproducing (verifying) current R table values. Furthermore, the use of larger (30°) observation angles produced very similar patterns to current R table values. It is important to note that the only noticeable pattern (trend) variation between the measured R values and the current R table values occurred at larger γ angles (>45°) and smaller β angles (<30°). While this had a minimal influence on the generalized data, it did seem to have an influence on the angular data. This small variation was most likely the result of the large observation angle used in the experimental program ($\alpha = 30°$).

2. The median R value of concrete is about three times higher than that of asphalt. These results indicate that regardless of the angular contributions and type of light, concrete is up to three times more reflective than asphalt pavements.

3. The traditional (incandescent) lights measured on concrete pavements resulted in equivalent values compared to the current R table (R1 table). There were greater differences between the traditional (incandescent) asphalt data and current R3 tables, but the general trend was still apparent. Therefore, incandescent lights can be verified as an adequate light source to reproduce current R table values.

4. The measured LED light data indicated significantly different behavior (trends) than the measured traditional (incandescent) light data. There was a repeated "spike" seen in the measured LED R values (seen primarily at $\gamma = 27°$). It should be noted that the current R values are within the 95% confidence interval of the measured R values. Therefore, while traditional and LED lights reflect similar quantities of light, they do not reflect that light in the same angular manner.

5. Surface specularity also appeared to have dramatic effects on behavior (trends) of the R table values. While this effect has already been defined in the current R table system, it is important to note that the unusual angular behavior (trends) seen in the LED data was amplified with respect to the surface specularity.

6. The statistical analysis indicated an insignificant difference between the current R1 (concrete) table and the measured concrete (both diffused and specular) R values illuminated by traditional (incandescent) lights. Therefore, the current R1 table is adequately representative of modern concrete pavements illuminated by traditional lights.

7. Whereas, the statistical analysis indicated a significant difference between the current R1 (concrete) table and the measured concrete (both diffused and specular) R values illuminated by LED lights. Since the p-value was close to the evaluation criteria (p-value = 0.05) the difference in data is most likely the result of the LED light and not the concrete pavement.

8. The statistical analysis also indicated a significant difference between the current R3 (asphalt) tables and the measured asphalt (both diffused and specular) R table values regardless of the illuminating light source (incandescent or LED). Therefore, the current R3 table does not adequately represent modern asphalt pavements.

In conclusion, a statistical analysis of the test results verified the validity of the experimental program. These findings indicate that there are relatively inexpensive and practical methods of measuring in-situ pavement luminance values. Analysis verified that the current R1 tables are representative of modern concrete pavement, but the current R3 tables are no longer representative of modern asphalt pavements. The study indicated that the current R tables are applicable to concrete pavements ranging from 0-16 years.

The testing program indicated that LED lights provide equivalent levels of illumination with a 96% reduction in energy consumption as compared to traditional (incandescent) lights. The analysis also indicated that LED lights do not interact with reflective surfaces in the same way as the traditional lights used to develop the current R tables. Further in-situ luminance testing is recommended considering both traditional (incandescent) and LED lights. The measured R values of incandescent light illuminating modern concrete was the only set of data that was congruent with the current R table values. Therefore, it is recommended that the current R2, R3, and R4 tables be updated and the incorporation of separate LED reflection tables for all pavements should be considered.

Van Bommel (2015) summarizes the design process by stating, "since the performance of lighting calculations, especially those involving luminance, is relatively time consuming, extensive use is being made of computers. Universally-applicable computer programs are available for this purpose." One of the critical parameters utilized by all computer software (for luminance calculations) is the current R table values (R1, R2, R3, and R4). Therefore, updating the current R tables is necessary for existing computer software to provide optimal lighting on roadways and parking lots using new light systems such as LED.

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