

Building a Database of Opaque Materials for Lighting Simulation

J. Alstan Jakubiec¹

¹Singapore University of Technology and Design, Singapore

ABSTRACT: This paper describes the cataloguing of opaque visual material properties in a database structure based on various measurement processes from the simple (illuminance and luminance measurements) to the complex (spectrophotometers and goniophotometers). A standard rendering environment was setup in the Radiance simulation engine in order to enable comparisons of color and specularly via physically-based renderings. All materials are also organized by their surface type (wall, ceiling, floor, etc.), color, location of measurement, reflectance, specularity, roughness, and material type (plastic, metal, etc.). Furthermore, for the first time, a large amount of full-spectral measurements are available in the catalogue at 10 nm measurement increments. This is imperative for understanding circadian stimulation and photosynthetic potential in future simulation practice and architectural design analysis.

Keywords: lighting, simulation, measurements, materials

INTRODUCTION

The visible properties of glazing materials are well-described by laboratory measurements and documented in the International Glazing Database (IGDB). Such measures are highly precise and are taken at 5 nanometer increments throughout the ultraviolet, visible and infrared lighting spectra. They allow detailed understanding of glazing material performance. Thermal properties of opaque materials are also well-characterized; however, knowledge about the visible properties of opaque materials is sparse. Currently most designers assume a standard palette of materials which includes, 20% reflective floors, 50% walls, 70% ceilings, and 35% exterior facades (IES 2012). The basis for these default parameters is not established, to the author's knowledge, by any study. Yet at the same time the selection of visible material properties is critical to achieving well-daylit spaces which reflect large quantities of useful daylight deep into the space while also avoiding specular reflections which may contribute to visual discomfort. Therefore, material properties constitute an important component of design for visual quality, comfort and daylight availability inside of architectural spaces (Brembilla, et al. 2015).

When specialized materials that utilize color or with specular reflective properties exist in a design project, there is rarely any basis to assess the visual performance of such materials. As a result, lighting materials are almost always considered as grey and completely Lambertian diffusers, without any specular reflective or forward scattering properties. Specular reflections are mirror-like reflections of light, and forward scattering is when a specular reflection is spread out in an angular opening area due to the surface roughness properties of the reflecting object. Roughness therefore controls the

'specular diffusion' of a reflection, which is critical to predicting accurate light distribution and glare effects. Estimating such reflective properties without explicit examples or an intuitive knowledge gained from utilizing precise measurements over time is impossible. Failing to account for reflections from specular materials have led to numerous instances of glare documented in research. Jakubiec (2014) and Ho (2014) noted that an entire glare situation was caused by the specular material and rough surface combination of an array of photovoltaic panels, because only specularly was considered in lighting tests by the original designers of the array. Specular glare from glazed or reflective facades (Schiller and Valmont 2015) has been an issue of increasing importance as building materials reflect more light for performance-based or aesthetic reasons.

Therefore, the author has begun an effort to collect measurements of as many opaque materials as possible, to store the results in a material reflectance catalogue, and to make the data available via a website interface in order to have a realistic basis for defining opaque material properties. First this paper discusses simple measurement methods for determining material reflective properties. Following that, an organization scheme that allows robust searching of the catalogue by name, category, geographic location, reflective characteristics and color is presented. Finally, the usefulness of such data being made available is discussed with regards to the lighting community.

MEASURING OPAQUE MATERIALS

There are many standard and reasonably accurate ways in which to measure the reflective properties of opaque materials, which have been summarized by Gradillas (2015) and are described in Table 1. Overall, Gradillas

found that diffuse materials can most often be well-categorized by even very simple methods such as taking an (1) illuminance measurement towards and away from a surface (abstracting the shade of the sensor with your hand) or the (5) CIBSE and (6) RAL color-correlation charts. Still, most designers and students do not have access to these devices, opting to make estimations that may be physically inaccurate.

Table 1: Reflection measurement method comparisons by Gradillas (2015).

Method tested	Ease	Accuracy
(0) Spectrophotometer	Moderate	10%
(1) Up/down illuminance*	Easy	10%
(2) Luminance and illuminance*	Moderate	20%
(3) Macbethal*	Difficult	10%
(4) Benchmark surfaces*	Difficult	20%
(5) CIBSE color chart*	Easy	10%
(6) RAL color fan*	Easy	10%

* Cannot measure specularly of materials

The ideal method to measure opaque material properties is with a full bidirectional reflectance distribution function (BRDF) measurement using a goniophotometer, which can assess the spread of a reflection based on the incident lighting angle; however, a portable spectrophotometer at least quantifies the reflectance, color and specularly of a surface within a set opening angle, whereas the other methods tested by Gradillas cannot.

In addition, a spectrophotometer measurement can quantify the full visible wavelength of light (~400–700 nm) at periodic increments. For example, Fig. 1 below illustrates the diffuse and total reflection for three materials contained within the reflectance catalogue: a white painted wall (83.5% reflectance), a steel hand rail (41.3% reflectance), and the back side of a tree leaf (17.5% reflectance). Measurements taking account of the full visible lighting spectra, rather than simple red, green and blue (RGB) coefficients as per typical material models in lighting simulation, are critical for calculations that wish to account for non-visual effects such as circadian alertness (Moroder and Dur 2010, Andersen, et al. 2012, Amundadottir, et al. 2013) and plant photosynthetic activity.

ORGANIZING MATERIAL INFORMATION

A critical issue when collecting a large amount of any sort of information, is how to organize it in order to become useful to its public users. The material reflectance catalogue described in this paper contains measurements that include simple reflectance data, RGB

data, or full spectral information with or without the presence of specularly, roughness or BRDF information. Although 98.1% (514 of 526) of the measurements currently in the catalogue include full spectral color data, all reflectance information must be structured in some way.

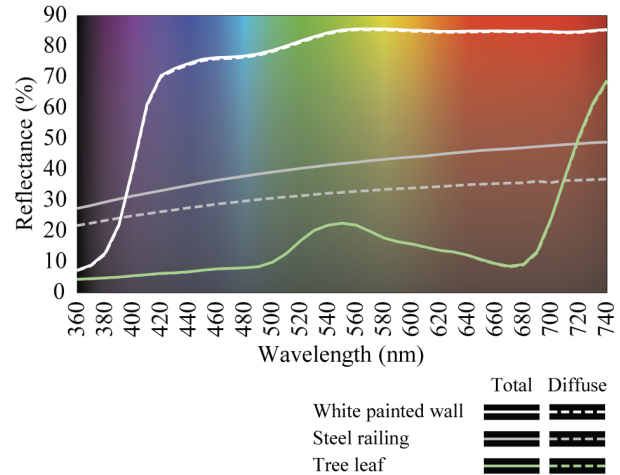
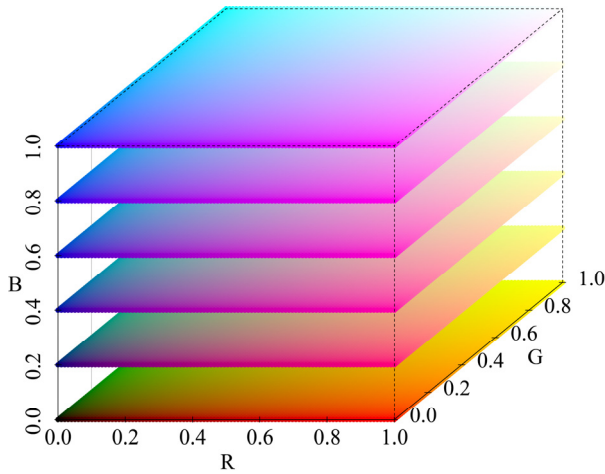


Figure 1: Spectrophotometer reflectance measurements of three sample materials

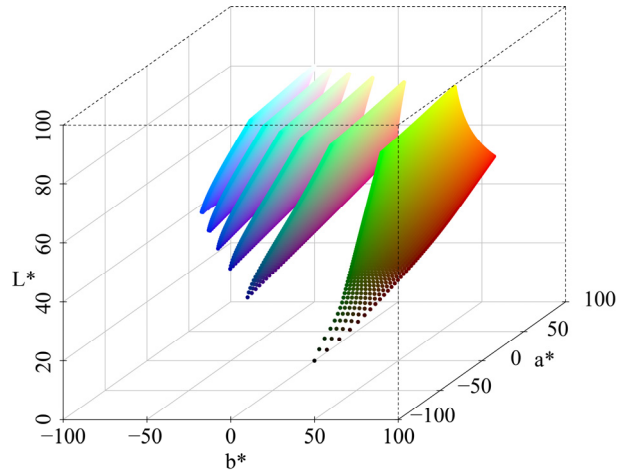
Lighting simulationists often need to find information about values of unknown materials. For example, a user might ask “what is the typical specularly of a white board?” or “what are the R, G and B reflective components of a standard blue painted wall?” Therefore, the ability to search for specific materials is key. Users of the catalogue can search using the following fields,

- Material name,
- Material category (furniture, plant, wall, floor, etc.),
- Visible reflectance range,
- Specularly range,
- Measurement type (spectrophotometer, illuminance / luminance measurements, color correlation, etc.),
- Geographic location of the measurement, and
- Color similarity.

Names and categories are well established criteria used by search algorithms on a plethora of popular websites. Even without knowing much about a material’s actual color, users can—for example—easily explore golden colored materials by entering “gold” as a search term. At the time of the authoring of this paper, such a search result returns the following measures: a polished gold metal, a yellow marigold flower and an orange marigold flower. A material categorization scheme also allows users to explore specific building elements when browsing materials. For example, users can choose to only search within the wall category.



(a) Six planes cut through the RGB color space



(b) The same six planes in the L*a*b* color space

Figure 2: Comparison of color and color difference perception in the RGB and L*a*b* color spaces

Another method to explore measurements are through important visible material properties such as reflectance and specularity, which are calculated based on the CIE 10 degree standard observer luminous efficacy curves when full spectral information is available (CIE 1964) and using weighted RGB coefficients (reflectance = $R \cdot 0.265 + G \cdot 0.670 + B \cdot 0.065$) or reported reflectance values when it is not. Users can define reflectance and specularity ranges (within the numerical range of 0–1) in order to narrow the range of material qualities they are presented with. The type of measurement allows users to know what kind of data to expect from a measurement. Measurements taken using a spectrophotometer will have full spectral information useful for detailed circadian calculations, but those using color chart methods only have RGB coefficients or are simply grey.

Where available, the latitude and longitude of measurement locations are recorded in addition to photometric, categorical and name information. This allows searching specifically for measurements in certain geographic regions of the world. A point can be selected on top of a map interface with a distance radius input. In the future when more measurements are recorded, this will allow fast comparisons between regional differences in material properties or to access reflective material properties from a specific place or culture.

Finally, users can search for materials by color similarity. Certain difficulties are inherent in this, as the Radiance software (Ward 1994) operates using RGB coefficient information, and most digital color information is transmitted in the RGB format; however, it is not trivial to understand how similar two colors are within the RGB color space. For example, Fig. 2(a) visualizes the RGB space as a three-dimensional volume with six planes cut through it at specific values of the

blue component: 0.0, 0.2, 0.4, 0.6, 0.8 and 1.0. Note that it is more difficult to tell the difference between the B=0.8 and 1.0 planes than between the B=0.0 and 0.2 planes. In essence, distances calculated between the coordinates of two colors in the three-dimensional RGB space do not relate to the perception of color difference. Fig. 2(b) displays the same six planes in the L*a*b* color space (ISO/CIE 2007), which is nearly perceptually uniform relative to distance calculated within its 3-dimensional space (Moroder and Dur 2009). To enable a search in the L*a*b* space, users are presented with an RGB color swatch chooser, which is then transformed to the CIE-XYZ color space as an intermediary step before being transformed into L*a*b*. All materials are then ordered by their calculated Euclidian distance (color similarity) from the chosen color. The degree of color similarity desired can also be controlled by adjusting the maximum distance from the selected color.

USABILITY OF MATERIAL DATA

An important issue to address with a growing database such as the material reflectance catalogue is to consider how relevant the information is to those who will use it. It is important for users to have access to detailed measured data, such as spectrally specific measurements, but also be able to understand material properties in a simple way and to be able to integrate the measurements into existing simulation workflows. Upon accessing the entry for any specific material definition, the user is presented with a series of information on the measurement. For full-spectral measurements, a reflectance graph is shown similar to the one displayed in Fig. 1. For measurements without spectrally specific information, a bar graph of the RGB components is displayed. Total visible reflectance, specularity and roughness information are also provided to the user.

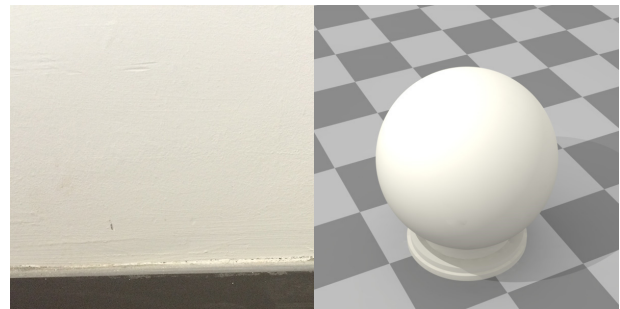
Beyond this abstract information, a full Radiance definition accounting for color and specularity is presented, and any necessary .CAL or .XML files are available for download. These material definitions can be copied-and-pasted into any Radiance simulation model or Radiance-based simulation tool which allows custom material inputs such as DIVA-for-Rhino, Groundhog, Honeybee, LiVi, SPOT Pro, and others. Furthermore, non-photometrically calibrated photographs of the material and standardized Radiance renderings are provided to aid visual understanding of material qualities and to help users identify similarities to materials they wish to account for in a lighting simulation. Fig. 3 illustrates such photographs and renderings for the three materials whose spectra were presented earlier in Fig. 1. The standardized rendering model used in the catalogue has two light sources: a diffuse encompassing dome and a 36° beam directional spotlight in order to illustrate the diffuse and specular reflection components of materials. Alternating tiles of neutral 25% and 50% reflectance serve as a ground plane in order to compare each material against standard values of known reflectance. By using a Radiance sphere primitive as the colored object, diffusion qualities related to the angle between incident light and the object that result from the combination of specularity and roughness properties can be observed as well.

DISCUSSION AND CURRENT LIMITATIONS

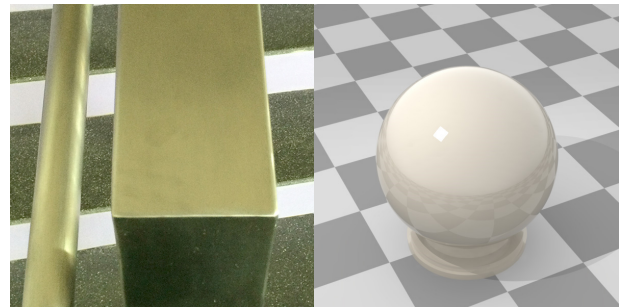
What does it mean for lighting simulationists to be able to access high-quality measured material reflectance data? Obviously this information will not allow perfectly calibrated material properties in predictive lighting models, because in a speculative lighting model, a measured surface can only approximate that of a similar surface being considered. Still, the catalogue addresses a serious lack of information for users looking for reasonably accurate material information. The author especially identifies three important concerns: (1) Default lighting materials which form the basis of many lighting simulations for standard compliance have little basis in reality; (2) The material properties of specularity and roughness can have strong impacts on the probability of experiencing visual discomfort, but little is known about realistic values of these properties when constructing material models; and (3) Full spectral colorimetric information is becoming critical when spatial aesthetics as well as lighting effects on the circadian system are to be considered.

A simple analysis of the measurements in the material reflectance catalogue thus far can provide further information regarding the sanity of typical default material properties in lighting simulation, the aforementioned 20% reflective floors, 50% walls, 70% ceilings, and 35% exterior facades (IESNA 2012). This

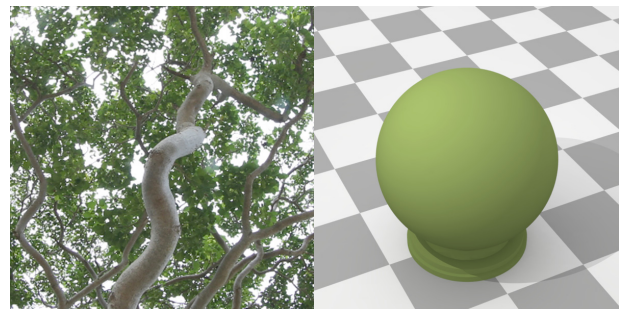
is depicted in Fig. 4 (on the following page) as a scatterplot illustrating the category and reflectance values of each measurement. Points are colored based on the $L^*a^*b^*$ values converted to RGB color values. At a glance, it is clear that white painted walls are approximately the same reflectance value as white painted ceilings (a range from 75.9–87.7%) and that walls of 50% reflectance are primarily colored or dark grey. Floors, on the other hand, show no such clear trends as they range from very dark (4.7%) to light (82.6%), although darker floors are more likely. At this moment, the statistical applications of this data are limited by the number of measurements present; however, the author anticipates gathering further data in order to build a critical mass appropriate for statistical analysis.



(a) White painted wall

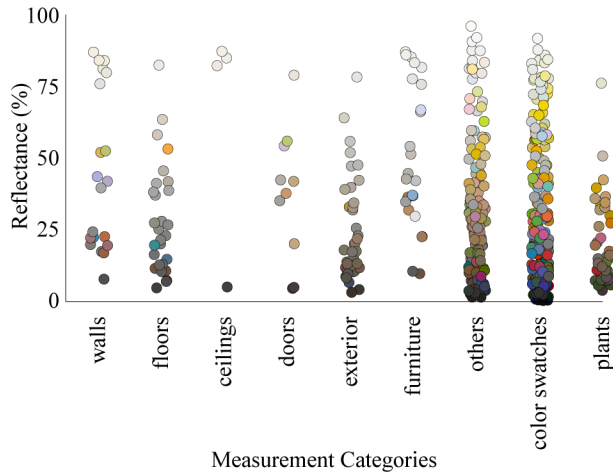


(b) Steel railing



(c) Tree leaf (back)

Figure 3: Photographs and Radiance renderings of three measured materials whose spectra are detailed in Fig. 1



Measurement Categories
 Figure 4: Plot of the material reflectance catalogue by selected categories and total visible reflectance

Specular reflections can redirect direct solar or bright artificial luminances directly towards a viewer causing visual discomfort or glare. By contrast, default material properties are completely Lambertian diffuse. This Lambertian assumption typically holds even when measured reflectance values are used. Therefore, the inclusion of measured specular values in the material reflectance catalogue is a step in the right direction in order to quantify the potential for glare caused by specular reflections. The strong impact that this can make relative to predicted luminance values can be seen in Fig. 5, which compares a rendering of a classroom using the aforementioned default material properties and precise measured materials. Glazing properties are the same in both simulations. Specular reflections from the whiteboard are up to 750% more luminous than the standard wall material and include light-scattering surface roughness properties.

In addition, Fig. 6 (following page) illustrates that a specular reflective component as little as 4.1% can have a significant impact. It portrays the cumulative annual luminances from direct sunlight in kcdh/m² of the

aforementioned specular scattering photovoltaic panels (Jakubiec and Reinhart 2014). The total reflective component of the panel cells is only 6.1%, yet the small specular component causes disabling glare a significant portion of the year, and the cumulative perceived reflections are higher than all of the more reflective diffuse surfaces in the rendered scene. However, one limitation of the measurement processes commonly used in the catalogue at this time is that roughness values are not accounted for in the vast majority of lighting measurements. This is a limitation in common measurement practices which needs to be addressed in the future.

When defining color primaries, a common practice is to select the desired reflectance value as well as an integer RGB color triplet. Then using weighted luminous response information, a material is created that corresponds to that perceptual color and a user-specified reflectance value (MIT Sustainable Design Lab 2016). The problem with this method is that it can result in physically impossible material definitions. For example, a user seeking a 50% reflective blue wall (■, R: 50, G: 75, B: 240) will be presented with a Radiance color triplet of R:0.316, G:0.474, and B:1.517. This is physically impossible, because the amount of blue light being reflected from the surface is greater than the incident amount of blue light hitting it by a factor of 151.7%. For the chosen blue color, only a 30% reflectance value is feasible, well below the standard 50% wall reflectance originally entered. In this case, it is helpful to have real, physical limitations and examples when determining such material properties. Searching the material reflectance catalogue, the closest entry at the time of writing determined by color similarity is Macbeth Blue from the Macbeth color checker chart, which is only 5.3% reflective.

CATALOGUE AVAILABILITY

The catalogue is freely available at <http://www.lighting-materials.com/>.



(a) Default material palette
 $E_v = 68.4 \text{ lx}$

(b) Custom, measured materials
 $E_v = 95.1 \text{ lx}$

(c) Percent luminance increase of
 b compared to a

Figure 5: Comparative renderings of a classroom model with standard materials as compared to detailed materials which account for color and specular

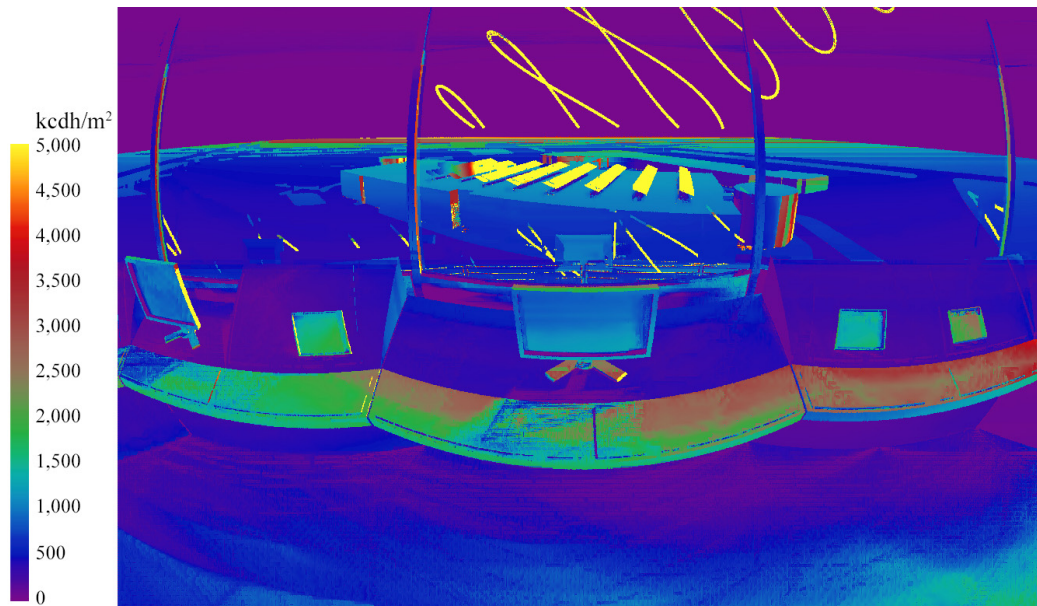


Figure 6: Comparative renderings of a classroom model with standard materials as compared to detailed materials which account for color and specularity

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