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TOWARDS AN OPTIMIZATION OF URBAN LIGHTING THROUGH A COMBINED APPROACH OF LIGHTING AND ROAD BUILDING ACTIVITIES

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Abstract

The objective of this work is to develop tools and methods for managers, lighting designers and road builders to optimize lighting both in interurban and urban areas. The goal is a complete characterization of the photometry of a large pavement sample panel, according to the criteria usually used in lighting such as Q_0 and S_1 and a characterization with an observation angle more adapted to the urban environment. In this contribution, the results of the initial characterisation of the pavement sample panel at 1° are presented.

Keywords: Road photometry, Road lighting design, Gonioreflectometer

1 Introduction

Designing a road lighting installation requires a combination of the photometric properties of the road surface and the optical characteristics of the luminaires to guarantee visual comfort for the driver while ensuring road safety and minimal energy consumption. Road lighting installations are designed by calculating the performance in terms of luminance distribution as defined in the EN13201 standard (CEN, 2015). Since the photometric characteristics of the pavements are generally not measured, a reference *r-table* as defined in (CIE, 1984); (CIE, 2001) is often used for lighting design.

The Pavement and Lighting working group (P&L group or in French *Revêtement et Lumière*) is composed of project managers and public authorities[a], professional associations and unions of lighting designers[b] and road builders[c], public and private research organisations[d] and expert consultants. This working group was established on the basis of several observations.

- The reference CIE *r-tables* R1 to R4 that are used in France for lighting design are more than 70 years old and several studies have shown that these tables are no longer representative of actual pavements (Dumont, 2007a); (Dumont et al., 2007b); (Jacket et al., 2010); (Ylinen et al., 2010); (Petrinska et al., 2007); (Muzet et al., 2017); (Muzet et al., 2018). Their use can generate important errors (more than 30%) for the average luminance (Chain et al., 2007).
- The lack of consideration for the real pavements characteristics may be due to the partitioning of professions between pavement and lighting actors who are not accustomed to work together. Indeed, few are the actors in the road sector who are specialists in the photometry of pavements and/or lighting and conversely, when renewing a lighting installation, the real characteristics of the road are rarely taken into account. In addition, the life cycles of the pavements and of the lighting installations are very different, which probably also explains the little interaction between the two professions.

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[b] AFE Association Française de l'Eclairage

[c] EUROBITUME, Office des Asphaltes, ROUTES DE France, SPECBEA (Spécialistes de la Chaussée en Béton Et des Aménagements), CIMbéton (Centre d'information sur le ciment et ses applications)

[d] Cerema (Centre d'Etudes et d'expertise sur les Risques, l'Environnement, la Mobilité et l'Aménagement), CERIB (Centre d'Etudes et de Recherches de l'Industrie du Béton).

- Moreover, in urban areas, lighting renovations and road maintenance are often separate contracts, awarded and monitored by different departments.
- Today, the urban surfaces currently in use are characterised by a very rich range of techniques and finishing whose relevance is justified by the diversity of uses in the urban environment. There is also a significant potential for energy savings in the optimization of public lighting projects by considering the actual characteristics of the pavement. Indeed, what is important for the user is not the quantity of the luminous flux projected on a surface (illuminance), but the light reflected by the pavement or obstacle (luminance). The perception is made by contrast of object / background luminance (Blackwell, 1946) and this mainly depends on the reflective properties of the pavement, the light distribution of the luminaire and the user position. Last but not least, there was a major interest in moving from "doing as usual" to an optimal lighting.
- Nowadays, most of the lighting is urban and yet the standard EN 13201 observation angle is 1° corresponding to a distance around 86m, which makes no sense for city driving where speeds are generally around 30 and 50km/h (Chain et al. 2008); (Stockmar, 2015); (Winter et al., 2016).
- However, technologies have evolved, both in terms of pavements and lighting solutions. This offers new opportunities, concerning the optimization of lighting design and the possibilities of retrofitting (Tardieu et al., 2017).

Since the Pavement and Lighting working group is composed of people of very different backgrounds (project managers, industrials organisations, research centres), it guarantees the ability to move from concept to practical applications. A first step consisted in organizing and monitoring demonstrators and operations on real sites to show the relevance of the challenges and concepts of optimal lighting; then to popularize the results and good practices (Abdo et al., 2010); (Batista et al., 2012); (Christory et al., 2014); (Muzet et al., 2018). The second step, presented here, consists in elaborating a library of actual and innovative pavements available on the French market to:

- facilitate the choice of lighting designers,
- develop tools and methods for managers, lighting designers and road builders to optimize lighting both in interurban and urban areas.

Our goal is a complete characterization of the photometry of a large pavement sample panel, according to the criteria usually defined in CIE144 (CIE, 2001) with the *r-table*, Q_0 and S_1 and in a next step, a characterization with an observation angle more adapted to the urban environment.

The collection of on-site photometric measurements will be an input for the European EMPIR SURFACE project (EMPIR, 2017); (Iacumussi et al., 2017), which collects the *r-tables* of current and innovative road pavements across Europe in the context of a pre-normative study.

The paper is organized as follows. In the first part, we recall the basics of road lighting and describe the Cerema gonioreflectometer measuring device. Then we describe our selection of pavements and our analysis methodology. In the second part, the results of the study regarding road surface photometry are given and discussed in comparison with seventies data and more recent French data. The third part presents the first results of the lighting calculations.

2 Methodology

2.1 Road lighting basics

The reflection properties of the road surface are used for the computation of a lighting installation. The luminance coefficient q of a surface element in a given direction, under specified conditions of illumination (Figure 1a) and an observation angle of 1° is defined by

$$q(\beta,\gamma) = L(\beta,\gamma)/(E_h) \quad (1)$$

where L is the observed luminance in cd/m² and E_h the horizontal illuminance in lux.

The reduced luminance coefficient *r* is defined by:

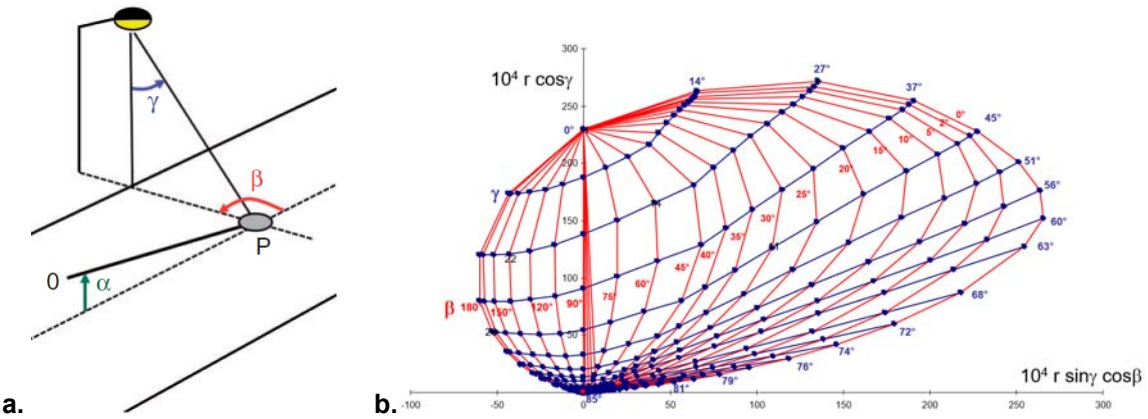
$$r(\beta,\gamma) = 10^4 \times q(\beta,\gamma) \times cos^3\gamma \tag{2}$$

The angle of observation α is set at 1°, which corresponds to a driver looking at about 90m. The *r-table* is a two-dimensional table with a number of standardized combinations of the incidence lighting angle γ and orientation angle *β*, the boundaries of which define a solid angle *Ω*. This table can be represented by a reflexion indicatrix as shown in Figure 1b. To simplify the description of photometric performance of road surfaces, the additional parameters Q_0 and S_1 can be calculated from the previous matrix as following

$$Q_0 = \int_0^{\Omega} \frac{q(\beta, \tan\gamma)\cdot d\Omega}{\Omega} \tag{3}$$

$$S_1 = \frac{r(\beta=0, tan\gamma=2)}{r(\beta=0, tan\gamma=0)}. \tag{4}$$

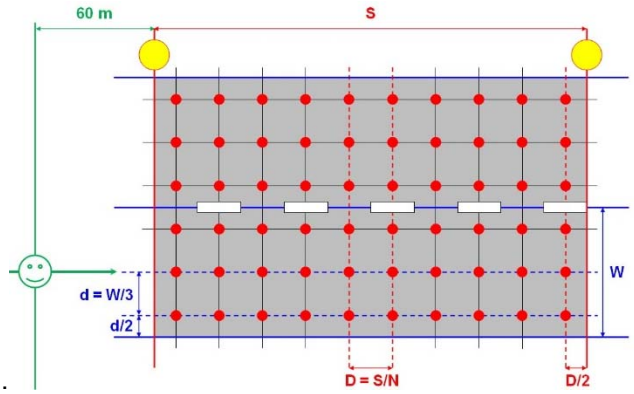
Q_0 is the solid angle weighted average of all the luminance coefficients and is also called lightness (van Bommel, 2015) and the specularity factor S_1 represent the shininess of the pavement (see example of figure 2b).



a. **b.**

Figure 1 – a. The photometric characteristics of the road surface depend on the angles of observation *α*, sight *β* and incidence *γ*. *0* represents the driver and *P* the point of observation. b. Representation of a pavement reflection indicatrix (angle *β* in red, angle *γ* in blue).

Guidelines and road lighting standards in Europe give values for illuminance and luminance and their distribution on the road surface according to a grid of points whose number N depends on the pole spacing *S* and number of traffic lanes (Figure 1a). The average luminance (L_{ave}), overall luminance uniformity ratio (U_0) and longitudinal luminance uniformity ratio (U_l) are computed according to the standard specifications (CEN, 2015).

a. 

b.

Figure 2 – a. Example of a calculation /measurement grid points (in red) in road lighting design/evaluation, according to the standard (w is the traffic lane width, d the transversal distance between two lines of points and D the longitudinal distance between two columns of points). b. Picture of a very specular road surface.

The CIE has defined different set of standard *r-tables* that are directly available in all lighting design software (CIE, 1984). Since 2001, the CIE144 (CIE, 2001) recommends a scaling of the chosen standard table according to the average luminance coefficient parameters Q_0. It is obvious that the design of a road lighting system should be based on the knowledge of the actual luminance coefficient for the actual road. Because the actual quantity of q is not known, nor is listed as reference values in the EN standard (it provides only the directions in which q should be known), designers use in the calculations as q reference values the ones given in CIE 144 scientific publication. In France the CIE *r-tables* type R are mostly used.

2.2 Description of the Cerema gonioreflectometer

The Cerema gonioreflectometer in Clermont-Ferrand measures the reflection of road surfaces under the observation conditions of a motorist at an observation angle of 1° according to CIE specifications. It gives the 580 reflected luminance coefficients $q(\beta,\gamma)$ of the *r-table*, and the parameters Q_0 and S_1.

The mechanical positioning unit consists of a steel base on which is adapted a rotating measuring arm to change the sight angle β from 0 to 180° and a light source positioning system to vary the angle of incidence of light γ from 0 to 90° (see picture of Figure 3a). The mechanical movement system of the lamp and the arm carrying the photometer is computer controlled, so the data acquisition is fully automated.

The reference source is a type A halogen lamp (Philips PAR38 Spot bulb with a power of 120W, a nominal voltage of 24 V, a nominal flow rate is 1545 lm) with a color temperature of 2700K (warm light) and an angle of diffusion of 10°. The light source is a fixed on a metal arc with a radius of 2.05 m, whose movement corresponding to the incidence angle is ensured by a motor connected to an indexer-transformer. The illuminated area is a 10×10 cm square, always at the center of the sample.

The “sample holder device” consists of a turntable allowing to adjust the height of the sample, its lateral positioning and inclination to obtain the horizontality of the sample upper surface (Figure 3b). This allows the measurement area to be centered on the sample without having to change the luminance meter and source settings.

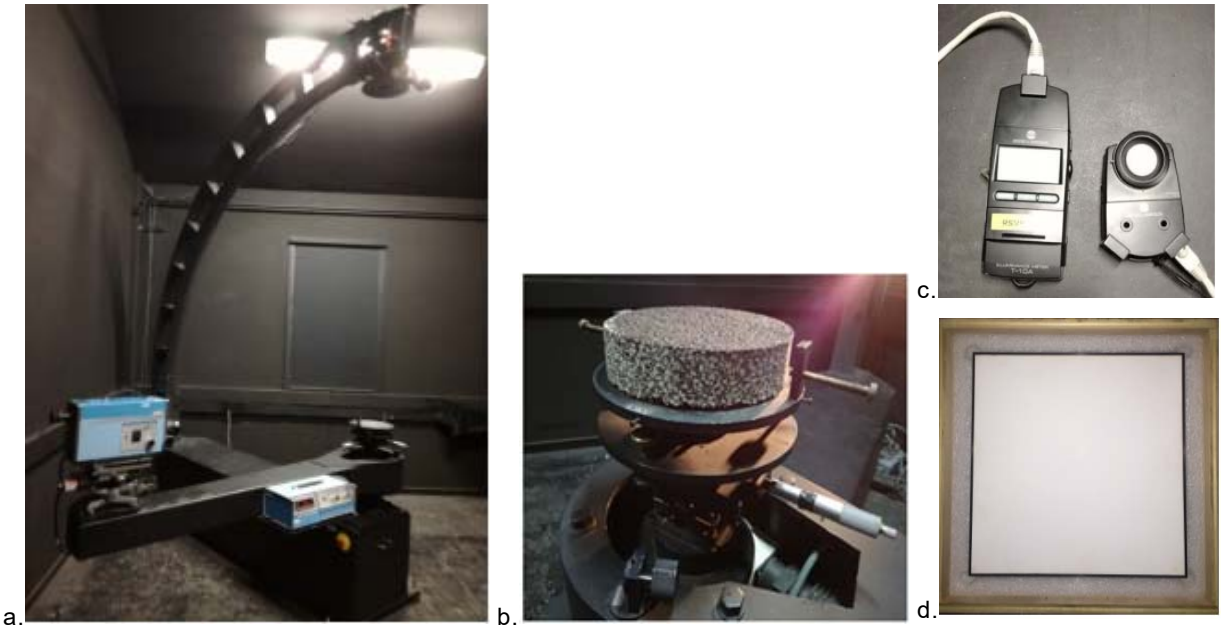


Figure 3 – Pictures of the Cerema gonioreflectometer with the Pritchard photometer (a), a sample of road pavement (b), the perfect diffuser used to check the reference luminance values (c) and the illuminancemeter to control the light source (d).

The luminance sensor is a Pritchard PR1980A Luminancemeter. It consists of the optical sensor and a control panel. The optical housing incorporates a trapezoidal diaphragm that precisely limits the measurement area to the projection of the 10x10 cm square on the sample. It is equipped with a spectral luminous efficiency filter, V(λ) as defined by the CIE. This sensor is fixed on an articulated arm, made of light alloy that is driven by a gear motor for the 20 positions of β from 0 to 180°.

The electronic control unit includes an indexer-translator which, in conjunction with the microcomputer, controls the stepper motors of the source carriage and the turntable. A Labview program manages the control and data acquisition process and calculates the photometric parameters of the sample such as the luminance coefficient for all the angular combinations considered, the average luminance coefficient and the specular factors. The program ensures the presentation of the results in the form of a matrix of reduced luminance coefficients (*r-table*) and its corresponding reflection indicatrix.

The measurement protocol is the following:

1. Measurement of the source level of illumination at the level of the measurement area on the sample with an illuminancemeter (picture on figure 3c). The value (E_h in the Equation (1)) is entered into the software for the calculation of the luminance coefficient.
2. Measurement of the luminance on a reference sample. A reference test is performed on a perfect diffuser (spectralon 99%, picture on figure 3d) to check the luminance values and shape of the measured diffusion indicator, thus attesting correct functioning of the goniophotometer.
3. Then the test is carried out as follows: the lamp is in the first position (angle γ=0°), the arm rotates: the angle β varies and luminance measurements are taken for 20 β values over a half turn (between 2 and 180°). The γ angle varies for its 29 positions and measurements are still taken each time for the 20 values of β, for a total of 580 values.
4. Finally, the software calculates complete r-table, then computes Q_0, S_1 and S_2.

2.3 The choice and characterisation of the pavements

The first step was to establish a panel of urban and interurban surfacing that contains representative and innovative French technologies. This panel includes 35 different pavements used in roads and sidewalk with two samples for each pavements. These pavements are composed of more or less light aggregates.

- Bituminous pavements with classic or synthetic binder, including Very Thin Asphalt Concrete (VTAC) that are continuous or not and soft mastic asphalts. In the case of the synthetic binder, there is adding of $Ti0_2$. Some are raw pavements and others received an initial surface treatment like sandblasting. The aim of this initial surface treatment is to remove the bituminous layer to bring out the color of the aggregates.
- Cement concrete pavements and paving blocks. Again there are raw and treated surfaces. Different surface treatments were used (smooth, polished, brushed, shotblasted, sandblasted,…) to change the visual appearance and to give a better initial road skid resistance.

Our objective was to have a big variability to represent nowadays methodologies. There are 12 raw surfaces and 23 pavements with an initial surface treatment.

Figure 4 – Picture of the samples exposed outdoor

Half of the samples are stored in fridges and half of them are placed outdoor for natural ageing (Figure 4). The photometry of all the samples was characterized in their initial condition at the observation angle of 1° with the Cerema's goniophotometer. A second series of measurements will be carried out after 3 years of ageing.

2.4 The lighting computations

The aim of the lighting calculations is to assess the impact of the use of the characteristics of actual surfaces. We compare all our calculations to the reference CIE *r-table* R3 (CIE, 1984), because it is used in France for lighting design and close to the CIE *r-table* C2, which is used in different European countries (Gidlund al., 2019). In order to assess the impact of the pavement and luminaire photometry, we propose several approaches:

- Case 1: Study of the effect of a measured pavement photometry compared to CIE *r-table* R3. The optimization of the lighting design is done with a CIE R3 pavement and comply with the EN 13201 standard. Then, without changing the luminaire, we calculate the effect of different actual pavement photometry for the average luminance, uniformities, and the Threshold Increment *TI*.
- Case 2: Study of the effect of a lighting renovation with an imposed geometry taking into account the actual pavement photometry.

- Case 3: Complete optimization of the lighting design for a new road taking into account the actual pavement photometry. The lighting photometry and pole distance are optimized for each *r-table*.

Since the study is still going on, we focus here on 2 typical lighting installations proposed in the standard (CEN, 2015e) and a small set of pavements from our database with very different photometry. We choose LED for the lamps and the chosen lighting installation are:

- An interurban road with 2 x 2 lanes road for motorized traffic (road profile A) with the theoretical normative values of the lighting class M3 class (L_{ave}>=1.00cd/m² ; U_0>0.40 ; U_l>0.60, *TI* 10, with no maintenance factor).

- A two-way traffic flow urban road with a sidewalk on the side of lighting arrangement (road profile C) of with the theoretical normative values of the lighting class M4 class (L_{ave}>=0.75cd/m² ; U_0>0.40 ; U_l>0.60, *TI* 15, with no maintenance factor).

Table 1 – Input parameters for the lighting design

	Lighting class	Road width	Pole height	Pole arrangement	Pole road side distance	Lamp tilt	Lamp spacing[e]
Profile A	M3	7 m	1 0m	Opposite side	5 m	5°	40 m
Profile C	M4	6 m	8 m	Single side	2 m	5°	25 m

3 Results

3.1 Concerning photometry

The photometric characteristics of all the samples was measured in their initial condition (called " P&L new" later on) with the Cerema's gonioreflectometer. The results of the measurements are presented in the Figure 4, and could be compared with all the typical CIE *r-tables* (R, C, N and W for wet) (CIE, 2001), with an old database (Sorensen, 1975) of 285 measurements on samples mostly from the Nordic countries and also with the data of a French previous study (Dumont, 2007a). In this study, the photometry of VTAC road surfaces with no initial surface treatment was followed during 3 years with regular extraction of cores measured with the Cerema's gonioreflectometer.

The initial measurements done on the P&L pavement samples show a high variability in the photometric characteristics of the pavements and confirm, as in other studies that the typical CIE tables are not representative of nowadays pavements (Dumont et al., 2007b); (Jacket et al., 2010); (Ylinen et al., 2010); (Petrinska et al., 2007); (Muzet et al., 2017); (Muzet et al., 2018) and have a greater variability than the Sorensen study (Sorensen, 1975). It shows the huge influence of raw material and treatments as well on the photometric characteristics.

[e] Imposed for case 1 and 2

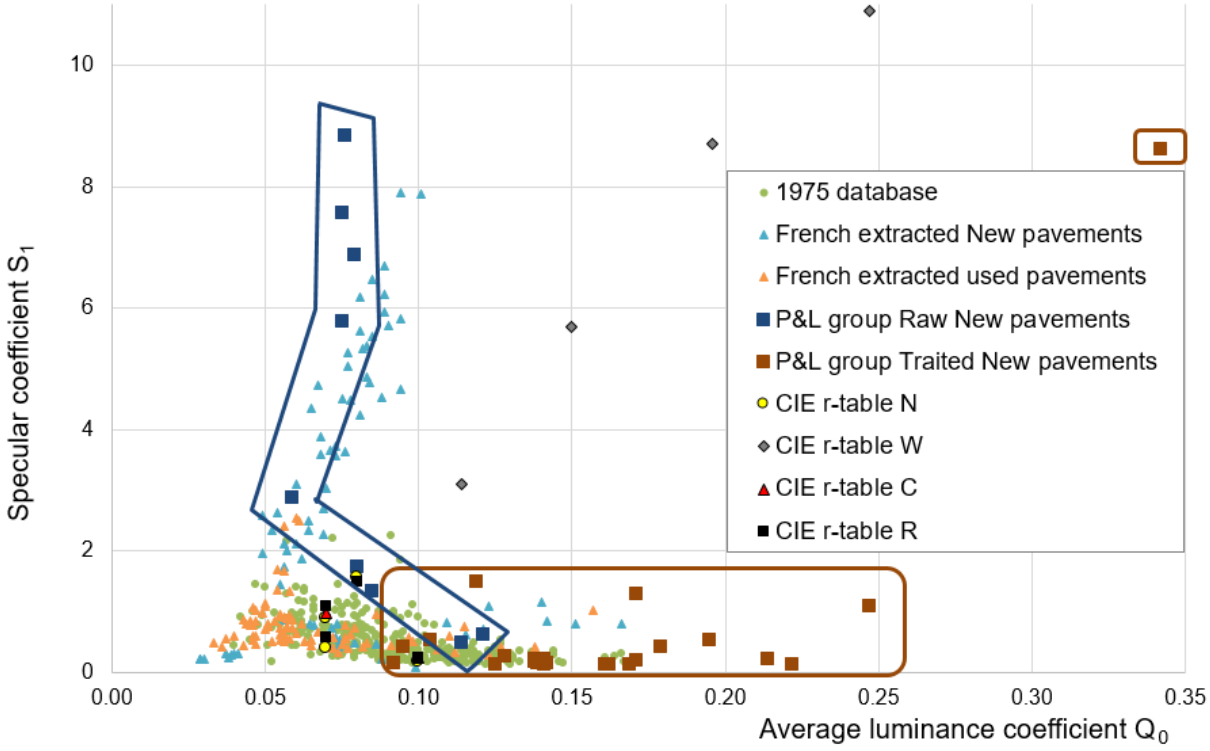


Figure 5 – Representation of the P&L initial measurements for raw pavements (dark blue squares), initially treated ones (brown squared). Sorensen 1975 data are in green circles, the French new pavements in light blue triangles and the used ones in pink triangle. The reference CIE *r-tables* are also presented.

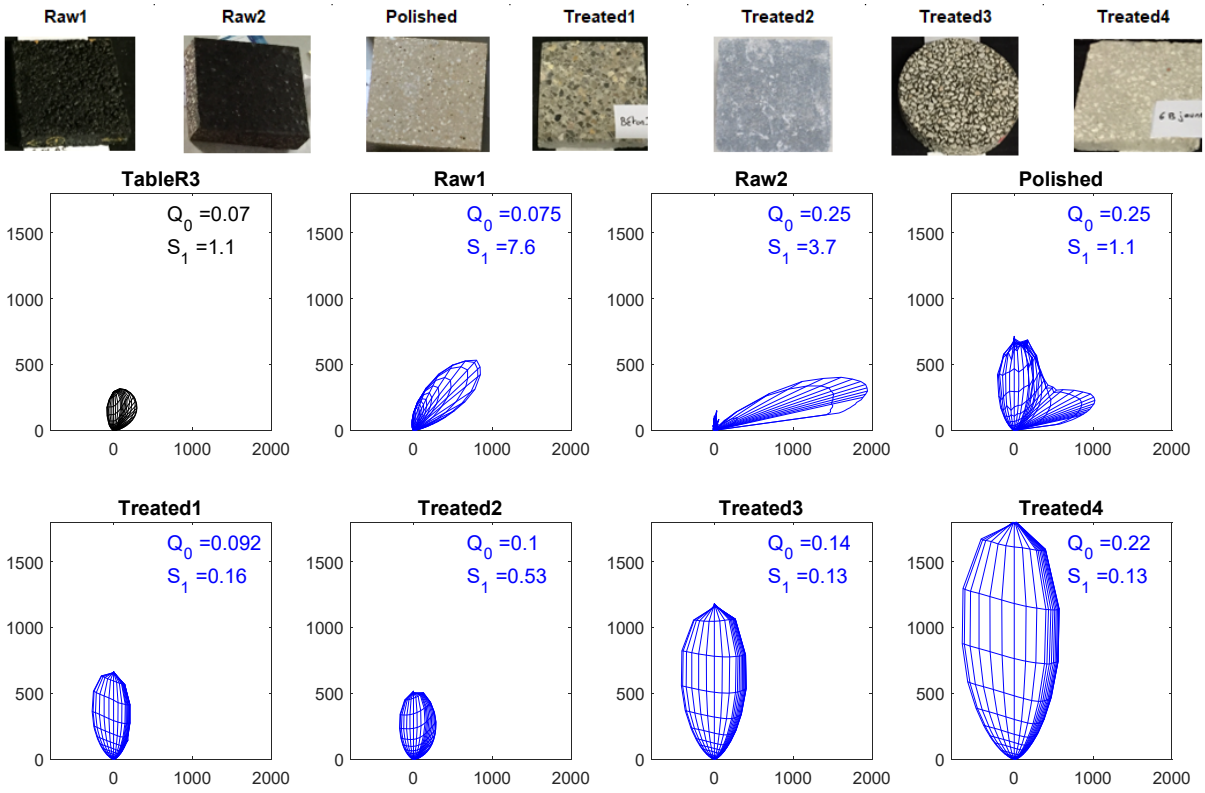


Figure 6 – Pictures of the selected samples. Representation of the pavement reflection indicatrix of the CIE *r-table* R3 in black and in blue of the selected *r-tables* of our database of initial characterisation. We have two raw pavements with a high specularity, a polished one and also four initially treated surface.

Our results obtained with the raw pavements (dark blue) are in accordance with the measurements done on the French extracted core of the new pavements with a high specularity (light blue). We measured very specular behaviour on some of our new samples, close to the CIE *r-tables* W (CIE, 2001), representative of wet pavements.

For our P&L samples of initially treated surfaces, we obtained a lower specularity and for some samples a high Q_0. We confirm, as in (Muzet et al., 2018), that surface processing sharply decreases the specularity of new pavements.

To validate our lighting design protocol, we selected extreme pavements from our database to study their effect on lighting design and energy consumption. A picture and their reflexion indicatrix is presented in the figure 6, in comparison with the CIE *r-table* R3.

3.2 Concerning lighting design

The results of the case1 lighting design that assess the effect of an actual pavement in a lighting design done with CIE reference R3 is presented in the table 2.

- For the type A road with M3 theoretical normative values (L_{ave}>=1.00 cd/m²; U_0>0.40; U_l>0.60; TI<10), the optimised design for a LED lamp and type R3 reference pavements gives a power of 46.7W, a flux of 7 100 lm, and an illuminance of 13.5 lux.

- For the type C road with M4 theoretical normative values (L_{ave}>=0.75 cd/m²; U_0>0.40; U_l>0.60; TI<15), the optimised design for a LED lamp and type R3 reference pavements gives a power of 20.6 W, a flux of 3 200 lm, and an illuminance of 11.1 lux.

Table 2 – Results of case1 lighting design: Impact of actual photometry for the two road profiles. When the standard requirement is not fulfilled, the figures are in red.

		Reference	Name of pavement						
		CIE R3 type	Raw1	Raw2	Polished	Treated1	Treated2	Treated3	Treated4
Pavement Photometry	**Q_0**	**0.07**	**0.08**	**0.25**	**0.25**	**0.09**	**0.10**	**0.14**	**0.22**
	S_1	**1.11**	**7.57**	**3.74**	**1.10**	**0.16**	**0.53**	**0.13**	**0.13**
Class M3 Power 46.7 W, Flux 7 100 lm, Illuminance 13.5 lux	**L_{ave}**	1.00	1.48	1.05	2.31	1.26	1.37	1.95	3.02
	U_o	0.43	0.21	0.05	0.34	0.51	0.52	0.47	0.49
	U_l	0.62	0.26	0.17	0.55	0.57	0.75	0.49	0.50
	TI	12.0	8.7	11.5	6.1	10.0	9.3	7.0	4.9
	Fulfill M3	Fully	None	None	None	None	Fully	None	None
Class M4 Power 20.6 W, Flux 3 200 lm, Illuminance 11.1 lux	**L_{ave}**	0.77	1.08	2.44	1.80	0.85	1.07	1.58	1.01
	U_o	0.46	0.20	0.56	0.38	0.04	0.57	0.55	0.58
	U_l	0.85	0.71	0.56	0.69	0.23	0.81	0.57	0.63
	TI	8.3	6.3	3.3	4.2	7.7	6.4	4.7	6.7
	Fulfill M4	Fully	None	None	None	None	Fully	None	Fully

These calculations show quite similar results for both type of roads.

When the lighting design is optimised for a CIE reference R table (R3 in our case) to comply with the standard, the impact of the actual photometry of new pavements is very high.

For very specular pavements like in our case Raw1, Raw2 and Polished pavements, we do not respect the standard at all, especially for both uniformities, with a percentage error that could reach 90 % for U_0 et 70 % for U_l.

In our calculation based on new pavements, we had classic and also very light pavements. We obtain an overestimation of luminance that could even reach 200% and in the case of the treated2 pavement for example we overpass the required uniformity specifications.

As in (Chain, 2007); (Christory, 2014); (Muzet, 2018), (Gidlund, 2019), these results confirm the importance of measuring and taking into account the actual photometry of pavements. The impact of initial treatment is good because it decreases the specularity and then, the uniformities are closer to the standard requirements.

Calculations of case 2 and 3 are still ongoing and their results are not available yet.

4 Conclusions

The initial measurements done on the “Pavement and Lighting group” pavement samples show a high variability in the photometric characteristics of the pavements. Our results confirm that the CIE standard *r-tables* are not representative of actual French pavements. In particular, the impact of surface processing on initial photometry is very significant and with the use of light aggregates and initial treatments, it is possible to have diffuse material with high Q_0. With the use of a standard *r-tables*, the standard requirements are not fulfilled and this could generate safety problems. The contribution of the use of specific pavements to achieve energy savings will be studied in the next steps of the study and is very promissing.

Another measurement will be done after 3 years at 1° and 10° characterizations will be carried out in new and aged condition. Indeed, 10° corresponds to an observation distance of 8.5 m, which could be relevant in an urban environment for drivers when they are close to intersections, cyclists and pedestrians. An adaptation of the lighting design will also be proposed, taking into account this new geometry.

At the end of our study, a catalogue will be presented in the form of files for managers and lighting designers and road builders. We will propose a technical pavement sheet, that could be used by pavements builders, lighting designers and infrastructure managers. It will contain a pavement description, initial and after 3 year photometric characteristics in the 1° and 10° geometry and also usage and maintenance recommendations.

With the constitution of a measurement database of actual pavements and the proposal of new lighting designed adapted to different uses in urban environment, this project will contribute to the CIE TC 4.50 (Road surface characterization for lighting applications) and the Empir SURFACE project (EMPIR, 2017); (Iacumussi, 2017).

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