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3D printed Reference Materials for optical properties

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Abstract **– INRIM developed and patented digitally designed Reference Materials (RM) for luminance coefficient quantity, manufactured by 3D printing. This method offers IoT (Internet of Things)solutions for producing RM representative of perceived properties as the spatial distribution of the luminance (luminance coefficient) a quantity crucial for lighting design, especially in road lighting. Dedicated RMs for luminance coefficient enhance metrological capabilities, and lead to safer and better-illuminated roads.**

I. INTRODUCTION

A Reference Material is defined as *'a material sufficiently homogeneous and stable with respect to specified properties, which has been established to be fit for its intended use in measurement or in the examination of nominal properties'* (definition 5.13 [1]). While RMs are typically associated with chemical properties, physical properties related to *Visual Appearance* can also benefit from reproducible dissemination by RM. *Visual Appearance* encompasses the perception of object attributes such as color, texture, gloss, sparkle, transparency, ... It is a critical parameter to be measured influenced by material-light-observer interactions, and relevant in industry and commerce, but also in metrology, and road lighting. Existing RMs (ceramic, plastic, glass) provide traceability just for a few visual properties (color, gloss and sparkle). Color RMs range from low accuracy sample like fabric swatches to highest accuracy RM ceramic samples, gloss RM are black glass tiles, while sparkle RM are brand new samples made by ceramic.

The landscape of RMs is increasingly expanding beyond single-use chemical standards or color/gloss references to materials representing specific (perceived) qualities. Renault exemplify this trend, by developing in early 2000 a set of tactile reference samples called Sensotact® linking tactile feedbacks to roughness and density measurable physical characteristics.

Consumer preference for a given object *Appearance* drives market opportunities and sales emphasizing the need for consistent production and higher accuracy in properties measurements.

Surface characteristics are also crucial for functional quality and safety, as in road pavements where affect mechanical, dynamic performances, visual perception and so nighttime safety of all road users. For example, road lighting designers determine the required number and spacing of road luminaires along a road on the knowledge of the spatial reflectance behavior of the road pavements. The task is to design road lighting system compliant with road lighting standard [2], namely for Europe minimum road luminance (and other quality parameters) requirements. Measuring this spatial reflectance is challenging, and dedicated RMs can improve reproducibility and accuracy, and finally, road safety.

II. SPATIAL REFLECTANCE BEHAVIOUR OF SURFACES

The knowledge of the Reflectance, i.e. the ratio of the reflected luminous flux over the incidence luminous flux, it is a descriptor of the interaction between light and surface of low relevance in advanced material characterization. The Luminance Coefficient q eq. (1) is the most relevant quantity: it is defined as the ratio between the reflected luminance L [cd/m²] in a given direction and the illuminance E [lux] on the surface [3].

The luminance coefficient spatially describes the reflectance behavior of any surface with reference to the observer position (e.g. luminance in the viewing direction identified by the angles (α, δ)) to the lighting source position (e.g. lighting direction identified by the angles (ε, β)) and the quantity of light (e.g. illuminance on the surface). It is also known as BRDF (Bidirectional Reflectance Distribution Function), and it is used in realistic simulations (including VFX effects in movies), digital twins, and lighting design, particularly in road lighting.

$$q = \frac{L(\alpha,\delta)}{E(\varepsilon,\beta)} \qquad [rad^{-1}] \tag{1}$$

Where:
L measured luminance, in cd/m^2, in the viewing direction identified by the angles (α, δ) Fig.1;
E measured illuminance, il lx, on the sample by the lighting direction identified by the angles (ε, β) Fig. 1.

In road lighting, the lighting angle δ is typically 0°.

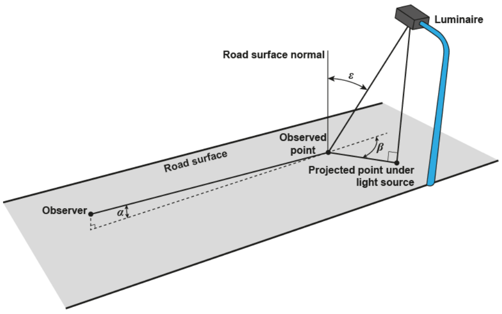

Fig. 1. The reference geometrical system for Luminance Coefficient for road lighting design (angle δ=0).

For practical reasons since the eighties in road surface characterization, the luminance coefficient was replaced by the reduced luminance coefficient *r* cd/m²/lux, derived from *q*:

$$r = q\cos^3\varepsilon \qquad [\mathrm{rad}^{-1}] \qquad (2)$$

Where:
ε is the lighting angle of incidence of Fig.1.

The standardized observation direction is constant at α=1° from the horizontal surface, and the lighting angles of incidence are identified as the most relevant directions of lighting in a portion of the road having a length and wide related to the mounting heigh of the road luminaire.

Results are tabulated as *q* (or *r*) values for the most relevant lighting directions.

The methodology of pavement photometry characterisation was developed in the seventies and eighties, CIE (Commission International Eclairage [5]) defined several *Reference r*-tables representative of the most significative road surfaces (based on data measured in the seventies and eighties), and despite the age are still used in road lighting calculations.

Usually, the luminance coefficient is measured for given directions of illumination and of observation by absolute method with calibrated illuminance and luminancemeter, installed on specifically designed goniometers or by relative methods using some sort of RMs not specifically designed (namely different tiles).

Devices for luminance coefficient measurement are either [6]:

A. laboratory goniometry instruments, which are used to make absolute measurements of r-tables and can serve as a reference device.
B. portable devices, which are used to measure the road surface in situ and provide a relative measurement.

Laboratory goniometry instruments consist of a light source, a sample holder and a detector to measure the reflected luminance. They have typically a large distance between the source and the sample (1 to 5 m), which results in good collimation angles (below 1° for most instruments), limiting the uncertainty on the illumination angle. The detector is often placed at a distance such that the acceptance angle of the detection is small. These devices mostly (or fully) fulfill the geometry set-up of the different lighting and observation directions and are expected to have relatively small measurement uncertainty, typically evaluated to be around 10 % (for industrial laboratories) in the most suitable angular set-up. They are therefore used to make the reference measurements necessary to calibrate the portable devices. The main disadvantage of laboratory instruments is that they require samples to be extracted from the road, which is destructive and costly. Furthermore, the handling of the extracted samples makes their positioning and alignment in the centre of rotation of the goniometer very complicated due to the mass of the sample itself and to the irregularities on the surface which makes it difficult to define the sample reference plane.

Portable devices are measuring instruments that can be transported and used for in-situ measurements: these devices always contain some compromises on the measurements, either with restricted measurement geometry combinations, or with larger measurement uncertainties. The solutions adopted are very varied in their mechanical and optical solutions and a full list is available in [6].

However, currently a uniform approach is not available in calibration methodology, measurement procedure, some measurements lack traceability, and the measurement uncertainty of these instruments is hardly considered and evaluated.

With this scenario, data can barely compared, commercial devices reliability is undefined and trustworthiness has been tested to a limited extent. The first, and currently only, Inter Laboratory Comparison (ILC) on luminance coefficient has been carried out during the Euramet Funded project 16NRM02 SURFACE (Pavement surface characterization for smart and efficient road lighting) [7].

III. THE DESIGN OF RM FOR LUMINANCE COEFFICIENT

The SURFACE project, among other relevant commitments, aimed to design dedicated RM for luminance coefficient and to organize the firs ILC on luminance coefficient for the geometrical configurations proper of road surface characterization. To avoid issues with sampling and handing of actual road surface samples and to ensure stable and reproducible ILC artefacts, the designed RMs were used.

The design of RM turned toward 3D printing facilities because 3D printing is an additive manufacturing process that builds artefacts from a digital model.

The artefacts designed during the project and subsequently used in the ILC are a first application of 3D printing to RM in the NMI community and are patented.

Two design approaches of the RM were implemented:

A. Design by reflectance properties: RM designed to have a given spatial distribution of q values;
B. Design by road attributes: RM designed to be similar to actual road samples, with enhanced stability, reproducibility and alignment.

A. Design by reflectance properties

As stated above, several CIE reference *r*-tables of road surfaces are available and ordinarily used in road lighting design. In this approach, the goal was to create 3D artefact with a predetermined spatial reflectance distribution, namely a CIE reference *r*-table.

In this design the reflectance properties of the printed material play the most relevant role, and together with shape and surface finishing allowed the design a 3D model of a surface having the chosen *r*-table.

B. Design by surface attributes.

In this approach the artefacts mimic the physical properties of road surface by having three-dimensional irregular solids (the stones or aggregates of tarmac) emerging from a more uniform mass (the binder or bitumen of tarmac). The binder is responsible of diffuse reflectance behavior of road surface, while the faces of the solids contribute to the specular component. Each CIE reference *r*-table refers to a different type of road in term of color and aggregate size. In the designed RM, the aggregates are 3D solids structures of designed shape, position, tilt and dimension, while the potholes among the structures represent the binder.

IV. 3D PRINTING MATERIALS

Several printable materials have been tested, especially for their spectral reflectance properties to avoid influences of reflectance spectrum spatial distribution. Fig.2 shows the spectral reflectance curve in the visible range (380 nm – 730 nm) measured in the geometrical condition 8/d (specular component excluded).

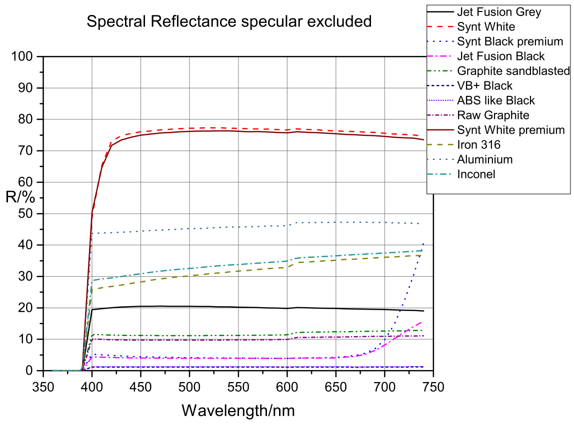

Fig. 2. Spectral reflectance of different 3D printable materials

V. 3D PRINTED ARTEFACTS FOR ILC

All artefacts were specifically designed and 3D printed for the ILC to establish traceability and evaluate measurement uncertainty of participant's instrument measuring luminance and reduced luminance coefficients of road surfaces.

The ILC artefact set comprised two subsets:

- SET A: flat RM samples in matte grey, matte black, and glossy black.
- SET B: RM samples designed by road attributes chosen in agreement with the consortium (ref. D3 for detailed description), made in matte grey, matte black, glossy black.

SET A, consisting of diffusing flat samples aimed to assess instrument linearity. Measurement discrepancies would relate to linearity or severe calibration issues, including the angular misalignment (e.g. wrong placement of the specular peak).

SET B, consisting of artefacts with geometrical attributes similar to road surface (varying height of solids structures mimicking road tarmac aggregates) to assess angular capabilities and detector performances. Measurement discrepancies would relate to alignement, angular resolution, measuring area (detector acceptance area vs lighted area), and calibration.

For alignment with the measuring device (either laboratory goniometer or a portable device), each sample has a metallic frame with tags on two sides to identify the center of the surface to be measured. The reference sample plane is the top surface of each sample: for SET B samples, the top surface is defined by the three tallest solid structures. Once the reference plane is defined, the detector must be put in place to satisfy the constraint of having α=1° from the horizontal reference plane. With reference to Fig.1, the center of the reference plane (identified by the two tags on the side) is the observed point that should lie in the center of the measured area.

VI. CONCLUSIONS

ILC data analysis revealed a lack of robust and validated uncertainty evaluation approach in all participants, and some issues in the detector's dynamic and systematic errors of some participants.

Regarding RM performances during the the stress test of ILC, it is possible to say:

- The RM design ensured high repeatability in positioning and alignment.
- The peculiarities of some samples of SET A, put measuring devices and laboratory measurement procedure under great stress, yielding unreliable data, thus proving such RMs samples ineffective for instrument performance evaluation
- Grey and diffuse samples of both sets showed better laboratory agreement than diffuse black samples. While black glossy samples revealed linearity problems in portable devices at low values.
- Metallic frames and reference for top surface definition, enabled good reproducibility in positioning and alignment, bringing participant repeatability around 1,5 % (including detector repeatability)
- The feasibility of IoT 3D printed RM was demonstrated.

The design and use of RM made during SURFACE project represent an early application of IoT to metrology and RM production. However, further research is needed for fruitful IoT RM implementation.

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