Photometric characteristics variation of stone pavements under traffic loads

Giuliani Felice
Rastelli Silvia

Dipartimento di Ingegneria Civile, dell'Ambiente, del Territorio e Architettura – Università di Parma

SYNOPSIS

The light required for a distinct and easy perception of road environment depends on several factors: the contrast of luminance and colour, the detail size in the perspective frame and the perception distance. The road lighting design plays a crucial role in assuring the driver's ability to correctly recognize the elements in the roadway and the presence of possible obstacles.

The most used parameters for evaluating the road surface from a photometric point of view are the coefficient of luminance and the specularity factor, characterizing the pavement brightness and shininess respectively. The Italian regulation summarizes those parameters in two classes.

Although the physical properties of the road pavement surface are fundamental because of their influence on the night time driving safety, in tunnels and also in daylight conditions, how much attention does the road designer pay to them? How much does the typological choice of materials for pavement surface affect the right calculation of road lighting system?

This paper, which is the synthesis of a complex theoretical and experimental investigation, aims to give a contribution to the study of the interaction between pavement and light, through the analysis of the evolution of photometric characteristics of stone road coatings, from the manufacturing to the service conditions.

Advanced equipments allowed to determine the field variability of colour, the luminance factor in diffuse light conditions (daylight and street lighting) and the retro reflection coefficient in conditions of vehicle lamp illumination. These quantities have been evaluated as functions of polishing level and wet condition.

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The study of performance characteristics of road surfaces is closely correlated to the analysis of all the properties that affect the traffic safety, particularly in terms of friction and regularity. Nevertheless, the active role of road surface, together with suitable road marking, in assuring the driver's correct perception of road environment should not be neglected. The colour and luminance of the road pavement can greatly affect traffic safety during night time and in tunnels, also when an adequate road lighting system is present.
Based on the significant evolution of vehicles and luminous sources of lanterns, it is necessary to investigate the capability of road pavement surface to correctly diffuse light rays incident on it.
Moreover, the urban traffic environment is characterized by heterogeneous road pavements, that often mark specific areas of the city (historic city centre, residential areas, commercial and craft areas) and are lighted by different public lighting system.
The current regulations (UNI 10439, 2001) classify, from a photometric point of view (the coefficient of luminance and the specularity factor), the road surfaces in only two classes neglecting, for example, the peculiarity of stone pavements, which are essentially polychrome and polycrystalline. Moreover the recommendations do not take into account explicitly the driver's point of observation (the luminance factor in diffuse light conditions and the retro reflection coefficient in conditions of vehicle lamp illumination).
In this paper it will be analyzed the variability of photometric parameters of different road surfaces subjected to a gradual smoothing action and to a progressive artificial "rubberizing" action with the aim of quantifying the luminosity and colour stability of each employed material in condition of traffic simulation.

ESSENTIAL ELEMENTS OF PHOTOMETRY

To study the propagation of luminous wave energy in space, that is to perform photometric studies, means to take into account the visual effects the energy produces on the observer and to study the light emission in terms of the response of human visual system. The described parameters have to consider the spectral response (called sensitivity distribution curve) of visual system; these units are defined referring the radiometric parameters to the spectral response curve of human eye. This curve is identified with the photopic curve for day-light vision (spectral response associated with cones) and with the scotopic curve for night-time vision (spectral response associated with rods; Schreuder, 1998).
The photometric units play an important role in establishing an objective evaluation of luminous sensation, providing parameters for reaching a correct definition of visual problem (Giuliani & Rastelli, 2003).
The photometric units closely connected to vision and perception of road environment are the illuminance and the luminance, that represent the effect of light on the surface.
The *illuminance E* (lux) is the ratio between the luminous flux incident on a surface and the area A of that same surface. It is the quantity of light incident on the unit of surface.

The illuminance on a horizontal plane is $E_o = \frac{d\Phi}{d\omega}\frac{1}{r^2}\cos\alpha$, because $dA_o = \frac{r^2 d\omega}{\cos\alpha}$ (Figure 1A).

The illuminance on a vertical plane is $E_v = \frac{d\Phi}{d\omega}\frac{1}{r^2}\sin\alpha$, because $dA_v = \frac{r^2 d\omega}{\sin\alpha}$ (Figure 1B).

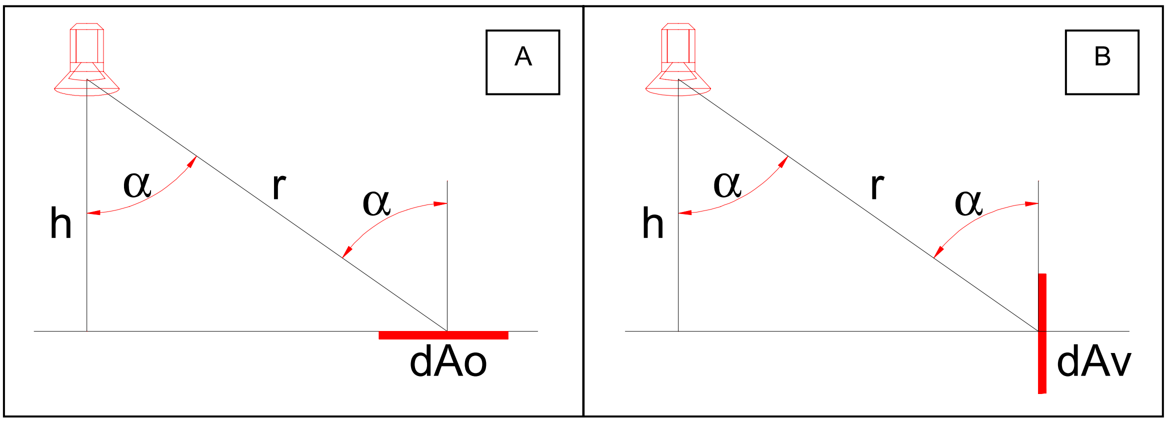


Figure 1: The concept of illuminance.

The *luminance L* (cd·m^{-2}) is the ratio between the luminous intensity of a light source in a fixed direction and the apparent area of the surface (the projection of the surface on a plane perpendicular to the same fixed direction, Figure 2). The luminance represents the luminous sensation that is received from a primary light source (an object that emits light itself) or from a secondary light source (an object that reflects light emitted by a primary source).

The luminance is $L = \frac{dI}{dA \cos \alpha}$.

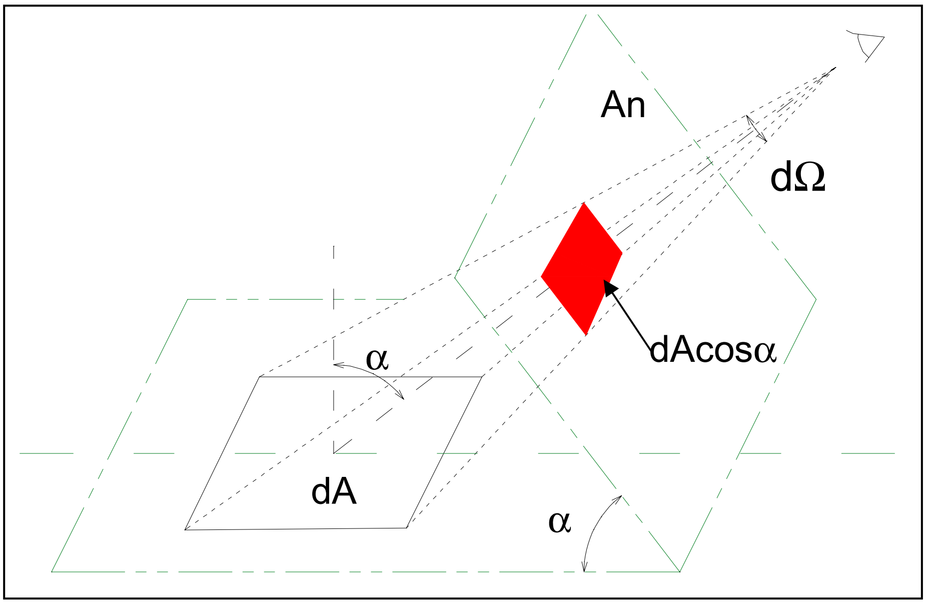


Figure 2: The concept of luminance.

The current reference regulations for design of road public lighting installations in different European Countries are based on lighting installation performances and consist in studying and evaluating the photometric characteristics of road pavements, essentially through the analysis and the knowledge of three parameters: the *average luminance*, the *luminance uniformity* and the *glare control.*
The parameters used in lighting installation design are the *specularity factor* (S1) and the *medium luminance coefficient* (Q0), characteristic of the reflection properties of road pavement and of its brightness (UNI 10439, 2001; Ministerio de Fomento, 2000).
This common line derives from the origin of reference documents regarding photometry and road lighting design: they are all delivered by the *Commission Internationale de l'Eclairage* (*CIE*) at international level and by a prevost organ in each European State (UNI in Italy) that participates to CEN activity, publishes regulations in the language of each specific Country and delivers additional regulations in absence of specific CEN regulations.
In current regulations it is present the common need of subdividing road pavements in classes and defining classes of lighting according to road type and traffic. This classification aims to give recommendations about levels of average luminance, minimum luminance uniformity and maximum value of glare index.
The classification of road pavements is made by means of their characterization through the employment of the two parameters Q0 and S1 in dry conditions. This required specification, present in all regulations, is due to the poor knowledge of characteristics and behaviour of road pavements in wet conditions.
The classification strictly regards asphalt and cement mixture pavements, neglecting stone pavements that are commonly used in historic city centre both in Italy and in Europe.
In France it has been studied the variation of Q0 and S1 parameters of road pavements with porous asphalt mixtures (Brusque et al., 1996).
A further analysis of photometric properties is possible borrowing what required as standard to road marking: the measure of the *luminance factor Qd* in diffuse light conditions (daylight and street lighting) and the *retro reflection coefficient Rl* in conditions of vehicle lamp illumination. These parameters indicate the daylight vision (or vision in presence of artificial lighting) and the night time vision respectively, and they vary during time because of the polishing due to the traffic and the rubberizing of the surface.
Both coefficients represent the ratio between luminance and illuminance, expressed in mcd·m^{-2}·lx^{-1}, according to a fixed geometry (Figure 3). The observer is the vehicle driver, who observes a point on the road surface at a distance of 30 m with an angle of 2.29°.

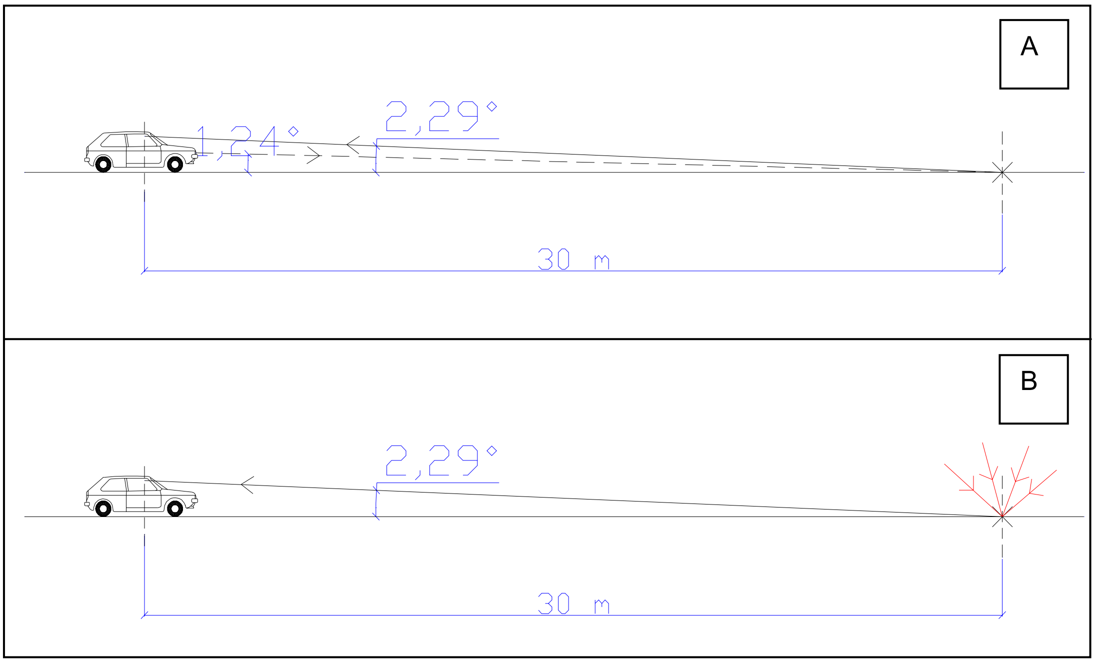
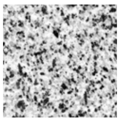
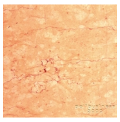
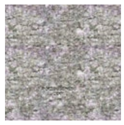
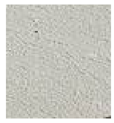


Figure 3: Geometry of RI (A) and Qd (B) coefficient measurement.

TYPES OF INVESTIGATED ROAD SURFACES

The materials studied in the laboratory experimental investigation are the most widespread stone materials for pavements used in Italy and in several European Countries, especially in urban roads and areas.
In particular, the improvement of city centre is possible by means of the rehabilitation and the restoration of stone pavements.
Different types of pavements made of stone elements often trace back to structures historically thought in local sphere realized by laying methodology and by employment of autochthonous materials.
Nevertheless the most frequent solutions, for mixed traffic pedestrian/vehicle, in function of shape and size of elements, are three: the stone paving, the cobbled paving and the pavè (Tomio & Filippi, 1996), briefly represented in figure 4.
The *stone paving* is made by slates of hard rock that have high resistance to smoothing action (granite, porphyry, syenite). The slates have rectangular shape and variable size, but they are not too long to be able to follow the possible road bend.
The *cobbled paving* is made by elements with oblong shape (8÷15 cm x 4÷10 cm) rounded, hard and resistant rock (granite, porphyry, syenite) often of fluvial origin, the elements are naturally ready for the use and are employed without any further manufacture.
The *pavè* is different from cobbled paving because the stone elements employed have small sizes and are manufactured to guarantee a regular shape with coarsely squared surface. The pavè is usually made by porphyry, granite, diorite or basalt, however employing igneous rocks, particularly micro-rough and resistant to polishing.
In commerce products are sold with rough surfaces, that is not using blade tools for polishing surfaces, and they have a basically regular geometry.
Materials for pavè and stone paving can be easily tested in laboratory for photometric properties specific measurements. Materials for cobbled paving, due to their size and surface convexity intrinsic heterogeneity, have not been investigated.
In table 1 are illustrated the materials for stone pavements investigated in this experimental research.

Tab 1: Materials studied in the laboratory experimental investigation.

NAME	***Granite Tonalite***	***Granite Silver Beola***	***Lessinia stone (Prun)***	***White marble Carrara***	***Trentine Porphyry***	***Argentine Porphyry***	***Luserna stone***	***Sand-stone***
PICTURE								
ORIGIN	Italy (Trentino Alto Adige)	Italy (Piemonte)	Italy (Veneto)	Italy (Toscana)	Italy (Trentino Alto Adige)	Argentina	Italy (Piemonte)	Italy (Toscana)
FAMILY	Granite of Adamello	Granite	Scaglia Rossa	Marble	Porphyry	Porphyry	Gneiss	Sandstone
COLOUR (primary)	light grey	light grey	pink	white	grey	grey	grey green	grey
COLOUR (secondary)	white black	dark grey	white	grey	white brown	pink brown	dark grey white	grey
CRYSTALS DIMENSION	medium	medium	medium	very fine	fine	fine	fine	fine

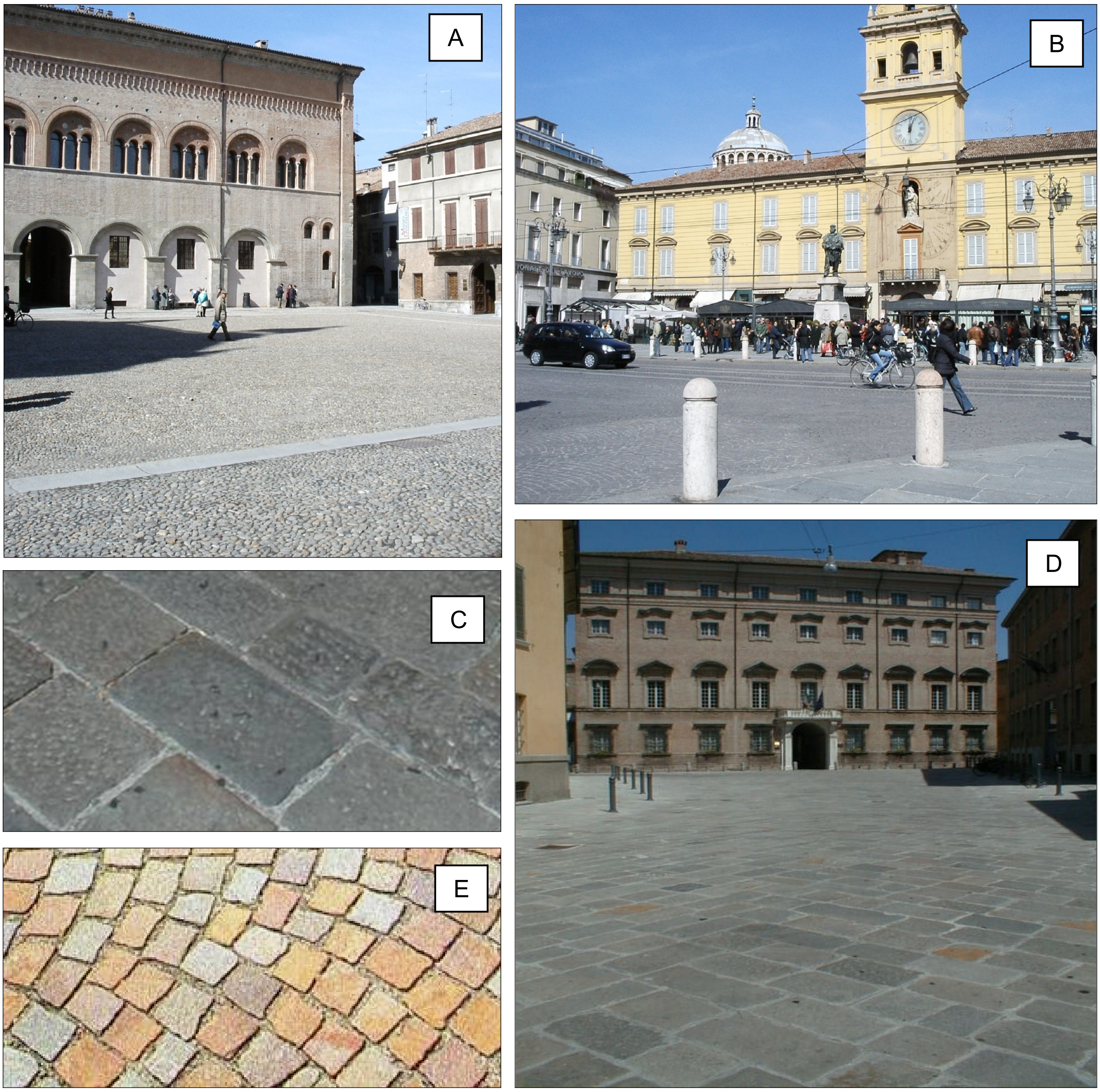


Figure 4: Cobbled paving (A), pavè (B,E) and stone paving (C,D) in Parma city centre.

LIGHT-SURFACE INTERACTION

The experimental investigation has been carried out in laboratory with the aim of evaluating the behaviour of stone materials when they interact with light, in the different conditions in which they can be when they are laid in service. The purpose of this research is a qualitative and quantitative evaluation of the photometric properties variation of materials subjected to artificial polishing and rubberizing processes, that simulate the conditions of in-service life of roads after months or years of traffic.
The wear condition of stone element surface has been reproduced by means of the use of grinding wheel (specific grinding wheel for stone materials) for 20 seconds, in three different sessions (Figure 5).
The initial phase (state I) represents the condition of new material with rough surface and the final phase (state IV) represents the condition of limit smoothing. During all phases measurements of Skid Resistance (in BPN units) have been carried out on the surfaces of stone materials by means of the British Pendulum Tester (ASTM E 303-93).

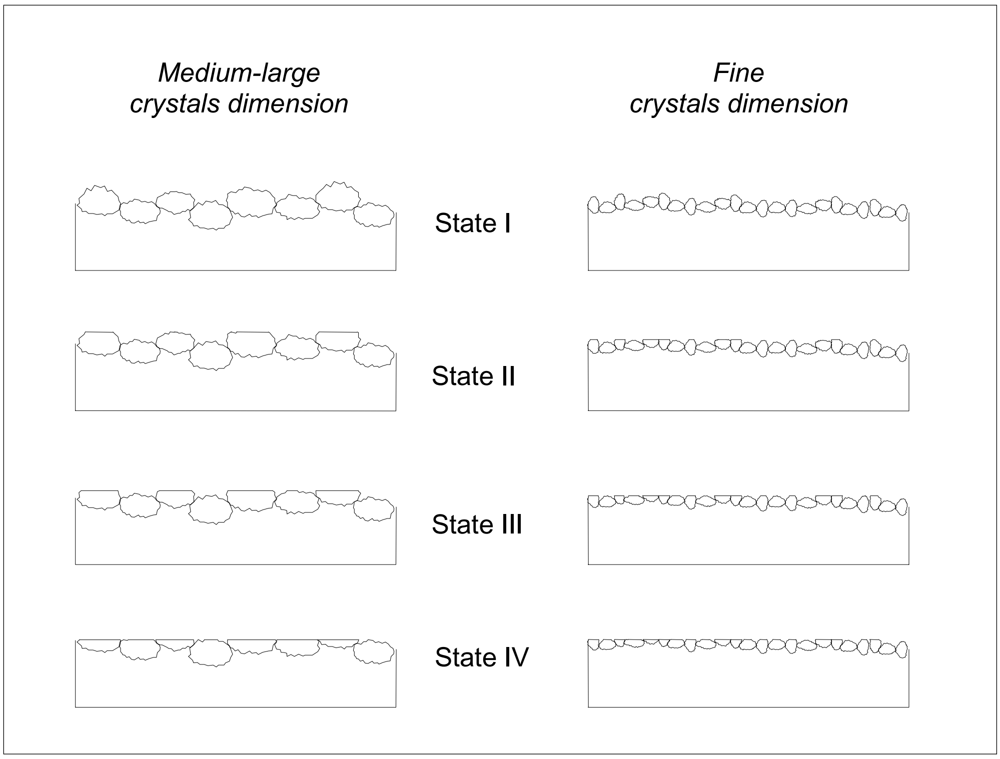


Figure 5: Condition of simulated polishing in laboratory.

The rubberizing has been artificially reproduced by means of a tyre assembled on an engine that allows the slithering of the tyre itself with the stone elements. They have been set in contact with the rotating tyre for a period of 15 seconds and three subsequent sessions of rubberizing have been done. The initial phase (state I) represents the condition of new material with rough surface and the final phase (state IV) represents the condition of rubberizing limit. Also after the rubberizing sessions, measurements of Skid Resistance have been carried out on the stone samples.

Measurements of the luminance factor and retro reflection coefficient

Measurements of the luminance factor in diffuse light conditions (Qd) and the retro reflection coefficient (Rl) in conditions of vehicle lamp illumination have been carried out on the samples of stone materials subjected distinctly to accelerated polishing and rubberizing. The measurements have been executed by means of the retroreflectometer ZRM1013+, according to EN 1436 (PRIN 2003).
The results, showed in table 2 and table 3 are the average values of three independent measures and take into account the measurements on dry and wet surfaces.

Tab 2: Retro reflection measurements on artificially polished surfaces.

ACCELERATED POLISHING	*Dry surface*				*Wet surface*			
	RI [$mcd \cdot m^{-2} \cdot lx^{-1}$]		Qd [$mcd \cdot m^{-2} \cdot lx^{-1}$]		RI [$mcd \cdot m^{-2} \cdot lx^{-1}$]		Qd [$mcd \cdot m^{-2} \cdot lx^{-1}$]	
STATE	*I*	*IV*	*I*	*IV*	*I*	*IV*	*I*	*IV*
Argentine Porphyry	26	42	87	90	13	9	85	45
Trentine Porphyry	28	35	74	92	20	13	64	44
Granite Tonalite	14	17	18	80	11	6	17	73
Granite Beola	46	51	139	136	21	35	71	39
Marble Carrara	37	41	211	207	50	84	95	59
Lessinia stone	19	36	18	127	26	19	71	102
Luserna stone	29	15	109	120	5	9	111	77
Sandstone	30	19	182	200	18	7	122	104

Tab 3: Retro reflection measurements on artificially rubberized surfaces.

ACCELERATED RUBBERIZING	*Dry surface*				*Wet surface*			
	RI [$mcd \cdot m^{-2} \cdot lx^{-1}$]		Qd [$mcd \cdot m^{-2} \cdot lx^{-1}$]		RI [$mcd \cdot m^{-2} \cdot lx^{-1}$]		Qd [$mcd \cdot m^{-2} \cdot lx^{-1}$]	
STATE	*I*	*IV*	*I*	*IV*	*I*	*IV*	*I*	*IV*
Argentine Porphyry	93	12	56	47	5	3	91	90
Trentine Porphyry	24	8	74	50	5	3	122	90
Granite Tonalite	32	22	124	109	10	5	130	104
Granite Beola	27	15	114	79	4	1	122	111
Marble Carrara	32	8	226	117	42	18	124	66
Lessinia stone	107	15	89	40	27	5	109	30
Luserna stone	27	13	110	92	3	2	90	107
Sandstone	22	14	175	136	7	9	183	140

Tab 4: Skid Resistance measurements in BPN units.

SKID RESISTANCE	*Accelerated polishing*			*Accelerated rubberizing*		
	BPN State I	*BPN State IV*	*BPN*	*BPN State I*	*BPN State IV*	*BPN*
Argentine Porphyry	70	68	-2	70	68	-2
Trentine Porphyry	65	63	-2	65	70	5
Granite Tonalite	75	76	1	75	72	-3
Granite Beola	83	62	-21	83	83	0
Marble Carrara	66	56	-10	66	53	-13
Lessinia stone	77	--	--	77	80	3
Luserna stone	52	53	1	52	63	11
Sandstone	47	64	17	47	41	-6

Results analysis

A clue to the general interpretation of the behaviour of materials so heterogeneous and intrinsically distinct by mineralogical nature and microcrystalline structure is certainly forced and does not allow an exact interpretation of each stone surface response to the interaction with light. However, it is possible to observe a general increase of Rl coefficient corresponding to the increase of polishing level, except few materials (Luserna stone, sandstone and granite Tonalite).

It could be the consequence of smoothing process of superficial macro-roughness of crystalline matrix of investigated surfaces. Indeed, due to the measurement typical geometry of the retro reflection coefficient (Rl) in conditions of vehicle lamp illumination, characterized by a small angle of incidence of light (1°24’), the macro-roughness can be an obstacle to the return of light to the driver’s eye. This interpretation is congruent with the noticed increase of luminance factor in diffuse light conditions (Qd) at increasing the polishing level for dry materials, except marble and granite Beola. For these two materials the value of Qd coefficient is almost constant. This behaviour is caused by the reduction of the usable surface for generating reflection in the observation direction, and a consequent assumable decrease of Qd value. Moreover there is a simultaneous reduction of *hot-spot* effect (Iaquinta et al., 2003), that is the interference of crystals close to areas which reflect light rays. Therefore the result is a general increase of reflection of luminous rays (Figure 6).

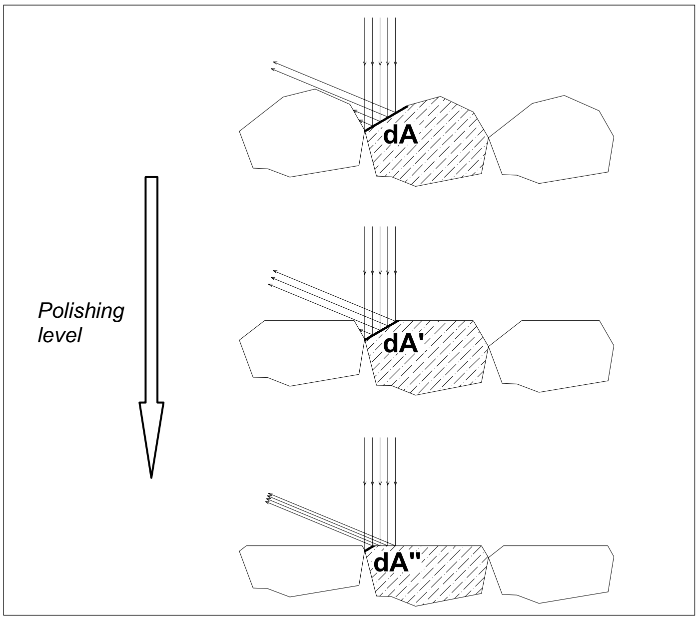


Figure 6: Light incident on superficial micro-crystals with polishing level variation.

In wet conditions it is believed that surfaces show a greater capability of reflecting diffusely light incident on them, with a consequent reduction of Qd values.
The catadioptric properties practically humble themselves, this phenomenon is quantifiable by the drastic reduction of Rl values.
About the variation of parameters analysed after the rubberizing sessions, it is observed that the Rl coefficient significantly decreases when the material changes from state I (clean material) to state IV (the last rubberizing phase), both in dry and wet conditions.
In particular, Rl values corresponding to the last rubberizing level in dry conditions are very low for all materials, 10÷15 $mcd \cdot m^{-2} \cdot lx^{-1}$. This means that the vision and the perception change significantly with the settling of tyre rubber on the surface. The deposit, with different level and placing for the analysed materials, surely brings to a reduction of mineral surface that is able to return to the driver's eye a part of light emitted by luminous sources (Figure 7).
The Qd coefficient shows the same behaviour, but it has smaller variations and assumes final values of 80÷100 $mcd \cdot m^{-2} \cdot lx^{-1}$.

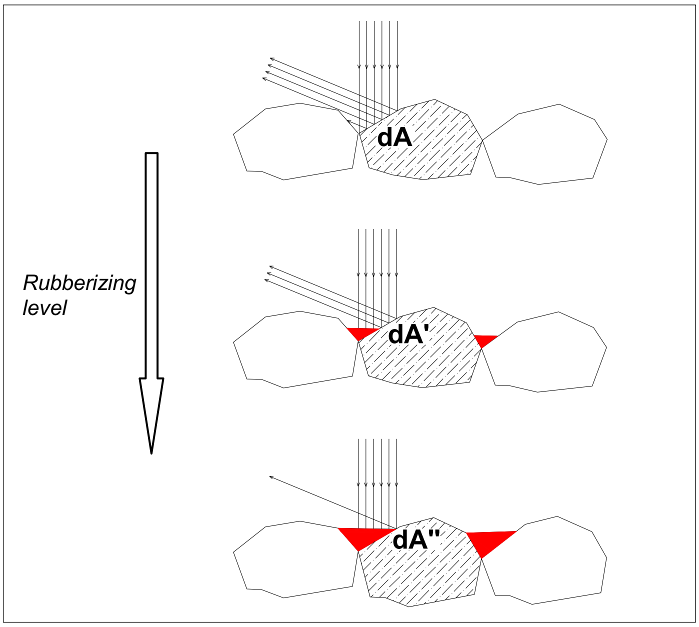


Figure 7: Light incident on superficial micro-crystals with rubberizing level variation.

Measurements of colour

The objective evaluation of colour is performed by means of CIE system, that is able to univocally identify (through the trichromatic coordinates) the luminous radiation in terms of colour (Moncada lo Giudice & De Lieto Vollaro, 1999).
The equipment used for the measurement of colorimetric characteristics of samples is a colorimeter with a total/0° geometry, specific for the measurements of colour quality in car factory.
The colorimeter allows to dissociate the beam of polychromatic radiations in its components, a selection not possible to the human eye. The equipment geometry allows a standardized diffuse illumination and the possibility to read the trichromatic coordinates with two different width of observation (2° and 10°, Figure 8).
The light source is D65, that emits the spectral energy distribution typical of daylight in North Europe; this light is adopted as standard light to determine colour.
The equipment geometry places the observer at 8° and not at 0° to avoid reflection phenomena (Figure 9).

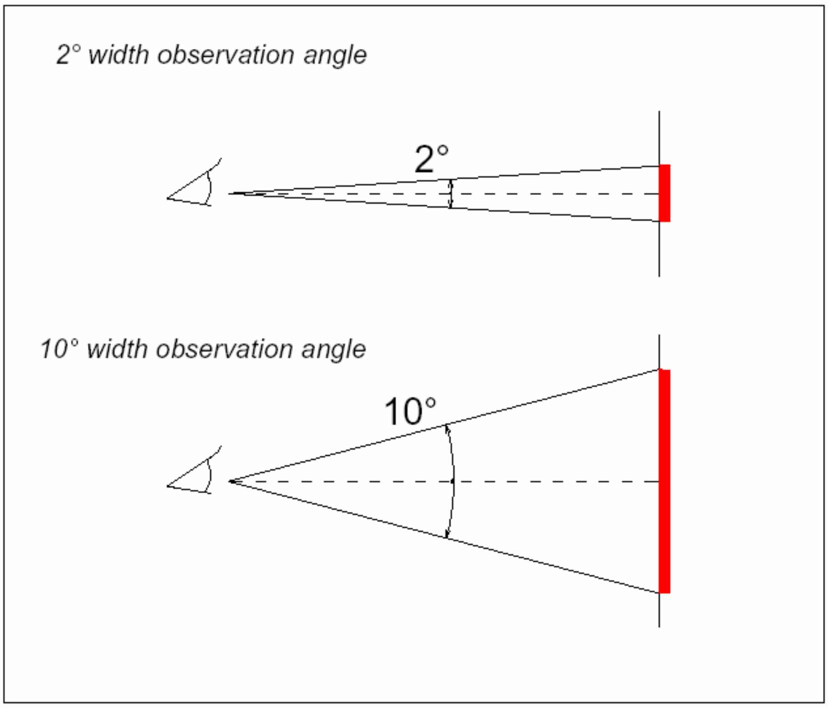


Figure 8: Geometric scheme of observer for colorimeter measurements.

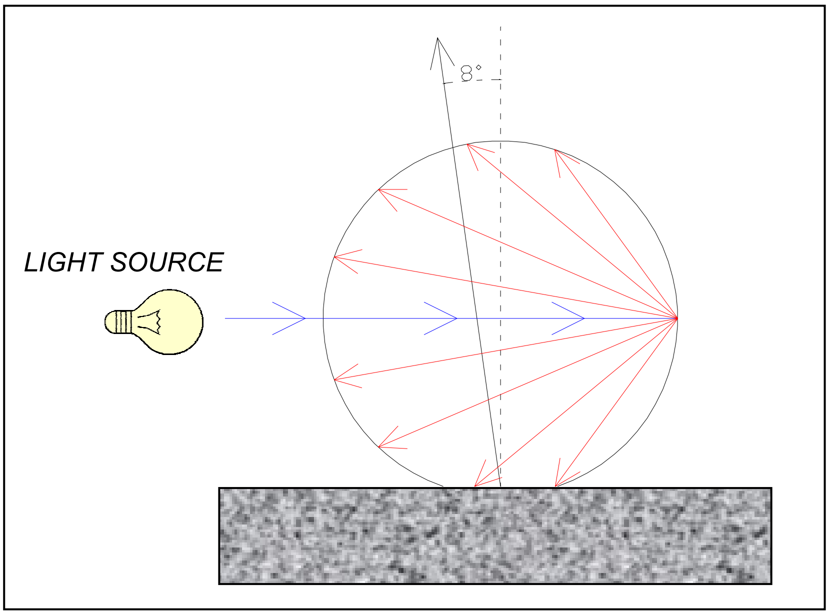


Figure 9: Geometric scheme of colorimeter measurement method.

The measurements on stone material samples have been carried out in dry and wet conditions, in correspondence of state I and state IV (the last phase of accelerated rubberizing). The variation of colour of the materials surface due to the tyre rubber deposit has been measured.
Figures 10 and 11 are the representation, for granite and porphyry samples, of the light reflected by the material.

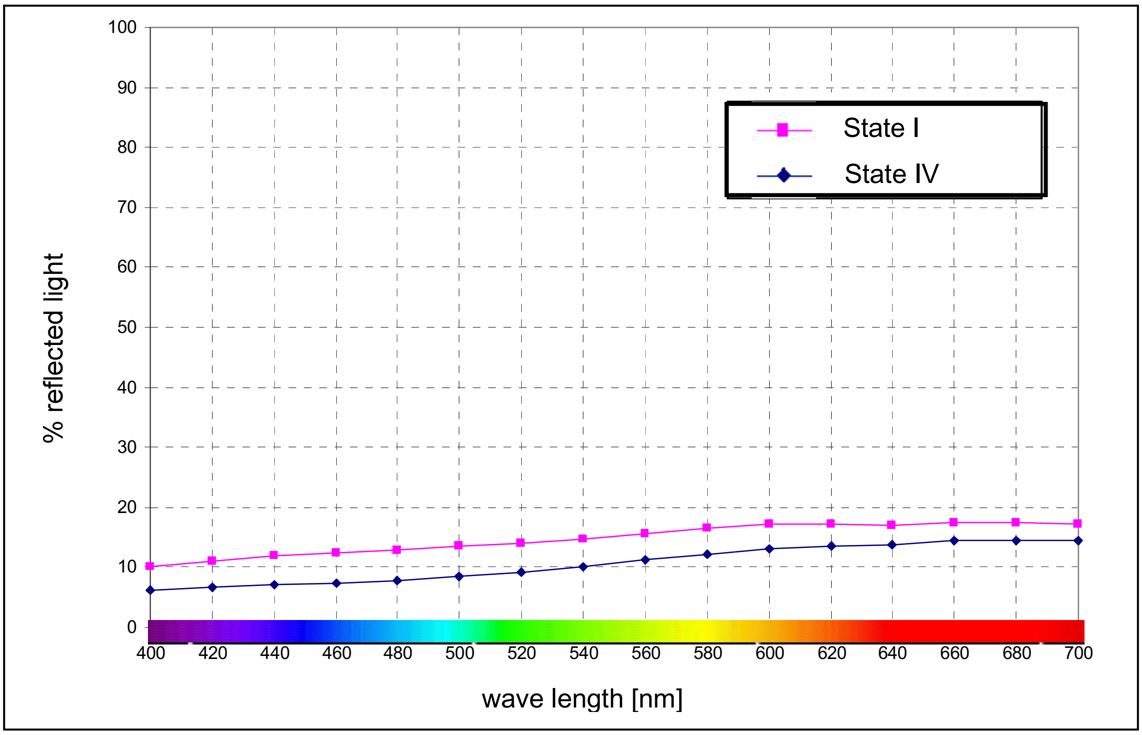


Figure 10: Example of measurement of colour on new granite and after accelerated rubberizing.

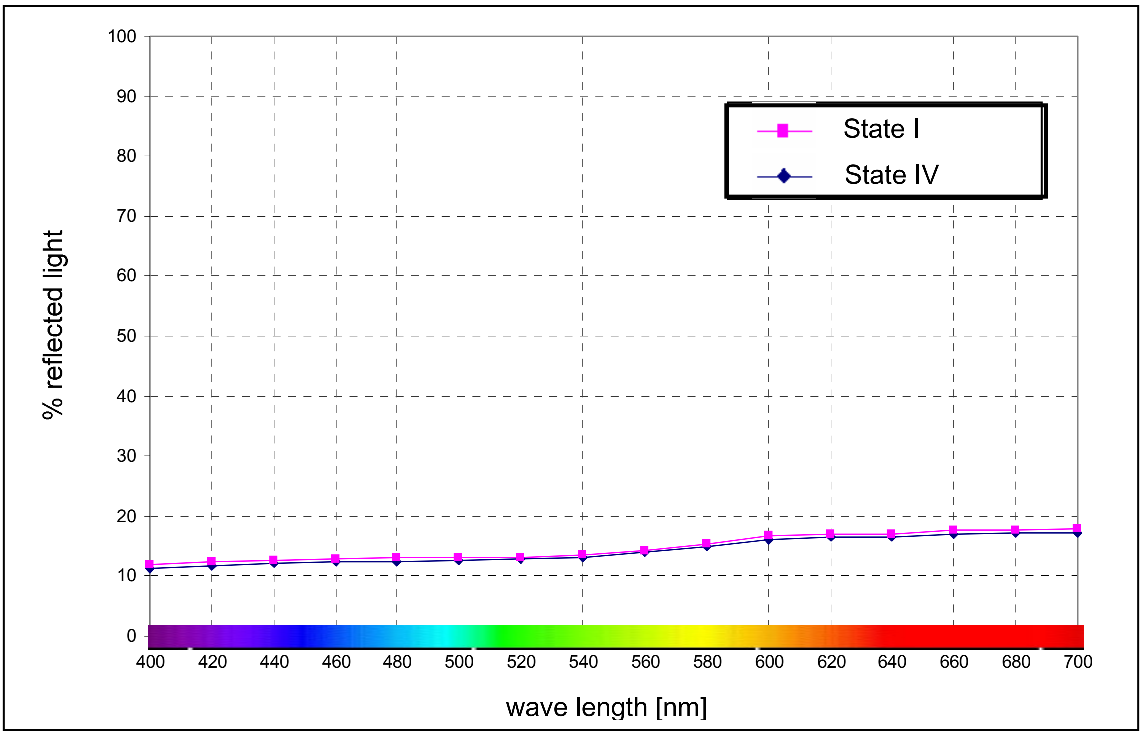


Figure 11: Example of measurement of colour on new porphyry and after accelerated rubberizing.

Tab 5: Granite: trichromatic coordinates with D65 illumination.

Coordinates CIELab 1976	new	rubberized	Δ	Coordinates CIE 1931	new	rubberized	Δ
observation width angle: 2°				observation width angle: 2°			
L	46.15	39.54	-6.61	X	14.92	10.98	-3.93
a	1.81	4.13	2.83	Y	15.38	10.98	-4.40
b	7.89	11.73	3.84	Z	13.32	8.08	-5.24
observation with angle: 10°				observation with angle: 10°			
L	45.90	39.17	-6.73	X	14.79	10.84	-3.95
a	2.36	4.89	2.53	Y	15.20	10.76	-4.44
b	7.71	11.35	3.64	Z	13.02	7.88	-5.14

Tab 6: Porphyry: trichromatic coordinates with D65 illumination.

Coordinates CIELab 1976	new	rubberized	Δ	Coordinates CIE 1931	new	rubberized	Δ
observation width angle: 2°				observation width angle: 2°			
L	45.00	44.42	-0.58	X	14.53	14.07	-0.47
a	4.45	4.05	-0.40	Y	14.54	14.13	-0.41
b	4.44	4.91	0.47	Z	13.91	13.31	-0.60
observation width angle: 10°				observation width angle: 10°			
L	44.84	44.25	-0.59	X	14.39	13.93	-0.46
a	4.46	4.13	-0.33	Y	14.43	14.01	-0.42
b	4.25	4.73	0.48	Z	13.67	13.07	-0.60

Tab 7: Trichromatic coordinates with D65 illumination and 10° observer width angle.

Coordinates CIELab 1976	new	rubberized	Δ	Coordinates CIE 1931	new	rubberized	Δ
Lessinia stone				Lessinia stone			
L	80.82	68.64	-12.18	X	55.58	37.22	-18.36
a	1.13	1.28	0.15	Y	58.15	38.84	-19.30
b	5.78	8.41	2.63	Z	56.13	34.88	-21.25
Sandstone				Sandstone			
L	77.72	75.65	-2.07	X	50.32	47.39	-2.93
a	0.85	1.74	0.89	Y	52.74	49.33	-3.42
b	5.01	9.27	4.26	Z	51.49	44.15	-7.34
Carrara white marble				Carrara white marble			
L	84.15	67.20	-16.95	X	57.63	34.85	-22.78
a	0.35	0.47	0.12	Y	54.17	36.90	-17.27
b	1.15	0.89	-0.26	Z	59.12	38.85	-20.27

Results analysis

In figures 10 and 11 it is highlighted how the tyre rubber presence significantly affects the granite colour (the curve is shifted below), while it is practically negligible on porphyry.

In tables 5 and 6 are listed the trichromatic coordinates *L-a-b* (CIELab 1976) and *X-Y-Z* (CIE 1931) of granite and porphyry samples brought as example.

There is a small variation of porphyry trichromatic coordinates (Δ=0.4÷0.5) and a greater variability of granite coordinates, as for other "bright" stone materials (marble, Lessinia stone and sandstone, see Tab 7), that show Δ = 3÷7.

The negative variation of *L* means material surface darkening, indeed the white colour corresponds to L=100; the increase of both *a* and *b* shows the tendency to brown colour with the presence of red on the

sample, while the increase of *b* and the decrease of *a* show the tendency to brown colour with the presence of green (these tendencies are caused by the colour of the deposit of tyre rubber).
In general, dark materials like porphyry do not vary considerably their surface colour even after the deposit on the surface of tyre rubber, while “brighter” materials (granite, marble, Lessinia stone and sandstone) have greater variations in their colour due to traffic exposition simulation, at the same rubberizing level.
The colour variation is perceived by the observer, creating a different image of road environment and obviously it affects the response of the material to light. Moreover the colour variation distorts the contrast, which is fundamental for perception of objects on the road surface.
An other aspect to be highlighted is that the variation of observation angle width (from 2° to 10°, Figure 8) does not affect significantly the trichromatic coordinates values, that is the same colour is perceived both “fixing” one specific point on the road surface (2° vision) and watching with a wider perspective, similar to the driver’s one when he is driving on the road (10° vision).
In figure 12 is graphically showed the variation of *L*, *a* and *b*. In this figure it is immediately defined the variation of colour of rubberized material compared to the new material used as reference (it is represented by 0).

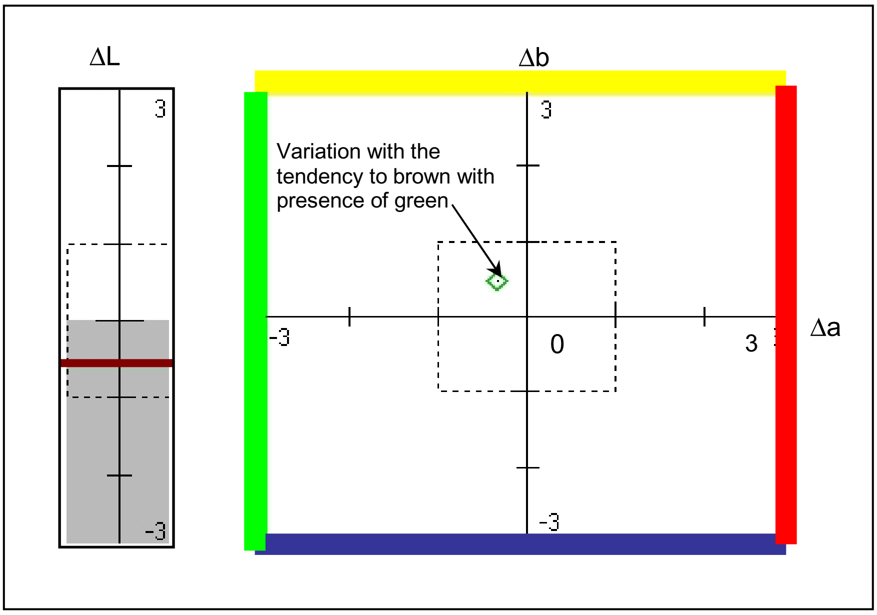


Figure 12: Cylindrical representation of coordinates of ΔL, Δa e Δb of porphyry sample lighted by D65 and 10° observer direction.

CONCLUSIONS

The study of photometric properties variation of stone pavements under traffic loads is an essential aspect in road lighting design, indeed to guarantee the correct perception of road environment and obstacles on the road it is needed the right illumination and contrast.
By means of laboratory accelerated polishing and artificial rubberizing of several materials, typical of stone pavements, it has been observed that the capability of road pavement surface to diffuse light rays incident on it vary significantly during pavement service-life. This fact makes it indispensable to revise the current classification of road surface (referred in European regulations) in order to design a more specific, suitable and useful lighting system. The variations of two parameters have been studied, Rl and Qd typical of road marking, that are able to take into account the driver’s point of view. This is an aspect neglected in current regulations, where photometric parameters (except for glare index), are exclusively correlated to the lighting system geometry.
The variation of Rl values on dry surfaces can be standardized increasing between 1/4 and 1/2 for materials after accelerated polishing, that means several years of service-life; Qd is evaluated increasing 1/5 after polishing (in dry conditions). The deposit of tyre rubber affects the Rl parameter decreasing it to 1/2 of initial value and decreasing Qd of 1/3 (in dry conditions). The accelerated rubberizing last phase corresponds to 2÷3 months of service-life.
Through the evaluation of materials colour it has been noticed that traffic simulation affects the aspect of road surface, especially for “bright” stone pavements. This fact influences the perception of contrast on road surface and consequently the perception of obstacles on it. So it is necessary, when the lighting system is in designing phase, taking into account all these factors that vary during road service life.

In terms of stability of photometric characteristics, porphyry and granite assure the well-known good performances after polishing and rubberizing processes and guarantee small variation in friction properties after traffic simulation. Moreover, in terms of colour, the porphyry is more lasting and the stone colour remains almost unchanged after artificial rubberizing, while granite tends to change its colour after the deposit of tyre rubber.
Sandstone and Luserna stone show higher variation in RI and Qd (besides skid resistance) and also from the colorimetric point of view they presents significant differences after traffic simulation. So their employ for road pavements should be limited confining them to sidewalks or areas for pedestrians to avoid a substantial chromatic variation during service-life.

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