LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
LUT School of Engineering Science
Technical Physics Major

Basov Alexander

DEVELOPMENT OF A GONIOPHOTOMETER FOR MEASURING REFLECTIVE PROPERTIES OF ROAD SURFACES

Examiners:
Erkki Lähderanta
Yeliseev Nikolai Petrovich

ABSTRACT

Lappeenranta University of Technology

LUT School of Engineering Science

Technical Physics Major

Basov Alexander

Development of a gonioreflectometer for measuring reflective properties of road surfaces

Master thesis

2017

74 pages, 46 figures, 11 tables

Examiners:

Erkki Lähderanta

Yeliseev Nikolai Petrovich

Keywords: photometry, road lighting, luminance coefficient, gonioreflectometer

Roads are areas of increased danger. Road lighting is one of the main tasks of lighting engineering. To calculate on the road the luminance, which is normalized in most countries of the world, and to design road lighting installations, it is necessary to know reflective properties of road surfaces. Concrete asphalt coatings have unusual spatial characteristics of reflection, which can be found in measurements. This work describes the stages to create an installation to measure reflective properties of road surfaces.

TABLE OF CONTENTS

1 INTRODUCTION

Road lighting is one of the most important problems in lighting engineering. Highways are areas of increased danger. According to statistics, annually in Russia there are about 200 thousand accidents, in which 26 thousand people die. Russia ranks first among the countries of Europe and North America in terms of fatal road accidents per 100000 inhabitants and the sixth place in terms of recalculation for 100000 cars. In the period from 1990 to the present, the number of fatalities on the roads of Europe has decreased by half, and in Russia it has practically not changed. There are many reasons why the situation in Russia is so bad: poor condition of roads, large number of drunk drivers, negligent attitude of drivers to the efficiency of vehicles and severe climatic conditions. Second important reason is the low culture of driving, although it is typical for all countries of Eastern Europe. One of the key factors affecting safety and comfort on highways is lighting. Therefore, the world lighting engineering community considers road lighting as one of the most important tasks of lighting engineering. High-quality lighting helps to increase safety and reduce the number of accidents and deaths on roads.

How can high-quality road lighting be characterized? The main function which road lighting has to provide is detection by a driver of other cars, pedestrians, any foreign object on the road, which facilitates immediate action to stop vehicle (braking). This ensures road safety. The main characteristic of the outdoor lighting installation for a road is the visibility of objects on the surface of a carriageway. However, direct rationing by visibility is very difficult, and devices for its control are not currently available. The human eye reacts to luminance. An important feature of lighting installations of road lighting is the absence of walls and the presence of only one main surface that reflects light - road. The human eye reacts to luminance of the road in this situation. If to talk about rooms, then most of the surfaces in them reflect diffusely. Reflective characteristics of concrete asphalt coatings, which are most often used as a material for highways, can not be described by Lambert's law. Reflection of light from such a coating has a directed-scattered character, that is, reflected light has not only a diffuse component, but also a pronounced mirror component. That is why the average luminance levels of the roadway are normalized in most countries of the world, including in Russian standard R 55706-2013 [1]. The levels are set depending on the category of streets (road), traffic intensity, the nature of the surrounding situation and geographical location. Also some quality parameters of installations of external lighting of highways are normalized - longitudinal and transverse uniformity of luminance and disability glare of luminaires.

The luminance of concrete asphalt coatings strongly depends on their reflective properties. To increase the accuracy in designing road lighting installations and to calculate both luminance and quality parameters, it is necessary to know the properties of reflection of road surfaces, the patterns of their variation over time and their dependence on the composition and technology of laying concrete asphalt pavements. Knowing the reflective characteristics of a real pavement, it is possible to calculate the ideal distribution of luminous intensity of a light device that will provide the best quantitative and qualitative characteristics of the pavement, and then design the corresponding light device. The spatial distribution of light reflected from the concrete asphalt coating has a complex shape. The nature of the distribution can be obtained analytically, based on the composition of concrete asphalt, the particle size and the laws of reflection. However, the actual spatial reflective properties of the concrete asphalt used is almost impossible to find analytically, but it can be found as a result of measurements on special installations - gonioreflectometers. There are laboratory and mobile versions of such measuring systems. Finding the characteristics of the reflection of road surfaces is a complex photometric task. The accuracy of such measurements depends on many factors. In the world practice, systems for measuring the reflective characteristics of pavements are created quite a long time, there are databases and classifications with characteristics of various asphalt concrete pavements. In Russian practice, the fundamental measurements were made by Ostrovskij M.A. in 1971. These results were the basis for the Russian standard R 55708-2013 [2]. The standard specifies 5 different asphalt-concrete coatings, 3 of which are currently not used (so-called clarified coatings). For 46 years, which have passed after Ostrovskij's research, new coatings have appeared using modern technologies. There are big doubts that the reflective characteristics of modern coatings correspond to those specified in the standard R 55708-2013. This is confirmed by the discrepancies in the results of calculations and design in the program Light-In-Night Road, in which the reflective characteristics of asphalt concrete coatings are based on this standard, and the results of measurements of luminance on the roads. Therefore, there is a need to carry out measurements of the reflective characteristics of modern concrete asphalt coatings. Perhaps, it is also necessary to create a new classification of road surfaces by reflective properties containing more types of asphalt concrete pavements. To achieve this goal, it is necessary to create a modern measuring system. An important characteristic of the measurements carried out on such an installation is their accuracy, which greatly affects the calculations of luminance on roads and, ultimately, on the safety of people. The accuracy of measurements can be characterized by errors. Gonioreflectometers are complex systems consisting of many elements. This is the reason for the occurrence of a large number of errors associated with both individual elements and with the interaction of various elements of the measuring setup. Unfortunately, in Russia measurements of the reflective characteristics of concrete asphalt coatings have not been carried out for a long time because of the complexity of the measurements, the insufficient accuracy of the measuring technique and the lack of processing power. Modern equipment makes it possible to measure and process the results with rather high accuracy (low error). The errors of the measuring system are associated not only with the individual elements of the complex and their interaction, but also with the chosen measurement method. Modern equipment makes it possible to implement a method that could not be implemented earlier. Therefore, the estimation of the errors of such a modern method is an urgent task.

The aim of this work is to develop a system for measuring the spatial properties of reflection of concrete asphalt pavements.

To achieve this goal, it is necessary to solve the following scientific and applied problems:

- to choose and justify the measurement method and the type of measuring system;
- to develop the kinematic and optical scheme of the installation;
- to develop the measuring methodology;
- to classify the errors that may occur during measurements;
- to estimate errors and to impose requirements to structural elements of the installation;
- to select the structural elements of the installation according to the requirements.

1.1 Values, that characterize the reflective properties of asphalt concrete coatings

The reflective properties of asphalt concrete coatings strongly affect the luminance of the road surface, which is normalized in many countries of Europe and in Russia [1]. The reflection coefficient ρ, which is the ratio between the luminous flux that is reflected by a surface and the luminous flux that fell on this surface, does not allow to determine the luminance of the road surface in various directions. To solve this problem it is necessary to know how the light is redistributed in space after falling on a concrete asphalt coating. It should be noted that this distribution also depends on the direction from which the light falls on the surface. Thus, we are interested in the spatial reflective properties of concrete asphalt coatings. We need to determine angles that are used in road lighting in accordance with [2] [Figure 1]:

- α is the angle of observation;
- β is the angle of sight;
- ε is the incidence angle;
- δ is the angle of orientation

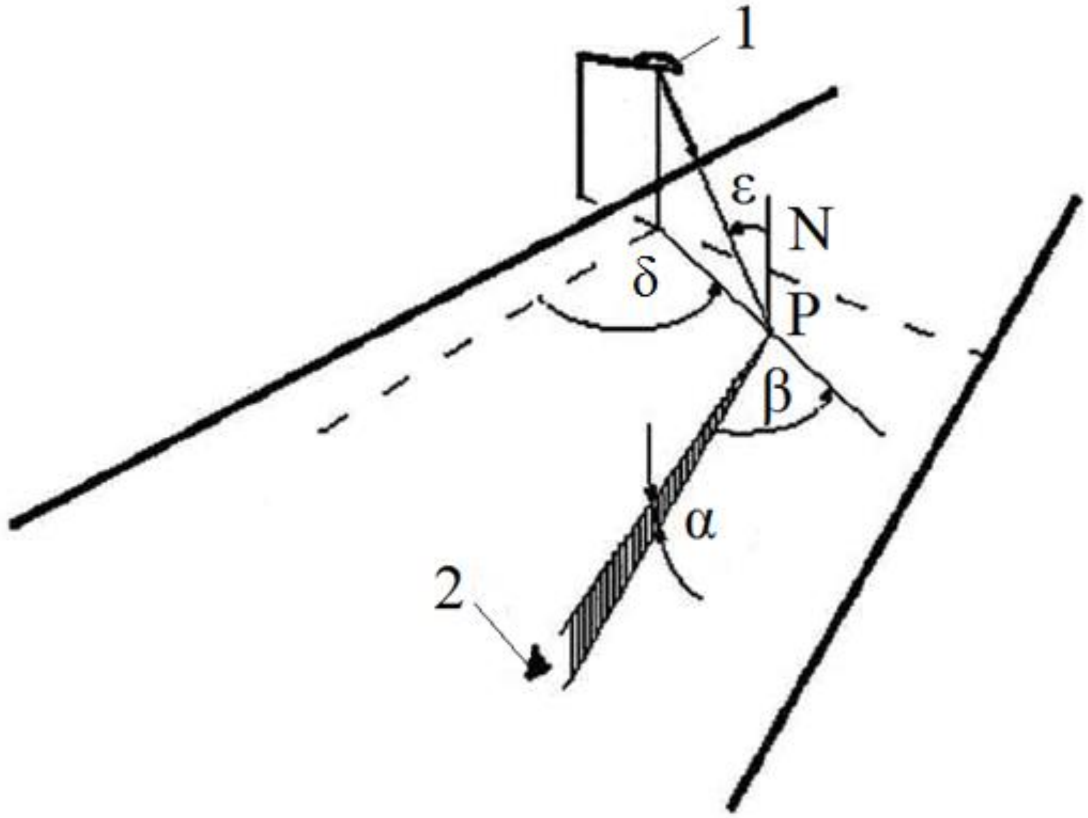


Figure 1. 1 is a luminaire; 2 is an observer's eye; P is a point of calculation; N is a normal to the road surface [2].

In Russian practice for a long time the direction-scattered reflection of the luminous flux was customarily characterized by the luminance factor $r(\varepsilon,\beta)$, which is determined as the ratio between the luminance $L(\alpha)$ of the reflecting surface in a given direction in space and the luminance L_d of a diffuse uniform surface with a reflection coefficient $\rho = 1$. It is not necessary to determine the complete photometric body of the luminance factors for a road surface. This is due to the visual perception of the street panorama by drivers of motor transport. Concentration and consequently the direction of view are mainly concentrated along the road in the direction of movement. The intersection of the line of sight with the horizontal plane at the level of the road surface depends on the speed of the vehicle and on average it is considered to be located in the 80 ÷ 160 m distance in front of the car, which corresponds to the slope of the driver's sight line at an angle of $\alpha = 1°$. However, taking into account the dynamics of the movement of vehicles, as well as the local arrangement of luminaires relative to the carriageway, the luminance of individual sections of a road will be perceived by drivers at different angles of incidence of the luminous intensity $I(\varepsilon,\beta)$ to the elementary pavement areas ΔA that necessitates the determination of the luminance factors for different angles of incidence of the luminous flux on the road surface. Then the luminance factor of the road surface can be defined for a single direction of observation $\alpha = 1°$ and different angles of incidence and sight of the luminous flux:

$$r'(\varepsilon,\beta)=\frac{L(1^{\circ})}{L_D}, \tag{1.1}$$

where $r'(\varepsilon,\beta)$ is the luminance factor due to a falling light in the direction that is determined by the angles (ε,β) and the direction of sight $\alpha = 1^{o}$ relative to the horizontal plane; $L(1^{o})$ is the luminance of the road surface in the direction of the sight and L_D is the luminance of a conventional diffuse surface with $\rho = 1$.

When evaluating the light qualities of road surfaces we can use some other values [3]:

- the luminance factor in scattered light R;
- the coefficient of reflectivity χ.

In world practice, the spatial reflective properties of road surfaces are commonly characterized by the luminance coefficient. Now this coefficient is used in Russian practice too.

Taking into account the angular agreement adopted in standards [4] and quality definition, the luminance coefficient can be presented:

$$q(\varepsilon,\beta,\alpha,\varphi)=\frac{L(\varepsilon,\beta,\alpha,\delta)}{E(\varepsilon,\beta)}, \tag{1.2}$$

where q is the luminance coefficient of an element of the road surface for the incident light with the angular coordinates (ε,β) and the direction of view with the angular coordinates (α,φ), sr^{-1};

L is the luminance of an element of the road surface, when the direction of view has the angular coordinates (α,δ), cd/m^2;

E is the illuminance of an element of the road surface that is created by the direct light with the angular coordinates (ε,β), lx.

It is generally acknowledged that the surface of the road is almost isotropic and the influence of the angle δ is negligible. The standards assume the observation angle to be constant and equal to $\alpha = 1°$. Then the luminance coefficient can be written in the following form:

$$q(\varepsilon,\beta,\alpha)=\frac{L(\varepsilon,\beta,1^{\circ})}{E(\varepsilon,\beta)}=q(\varepsilon,\beta) \tag{1.3}$$

In this case it turns out that the luminance coefficient is a function of two angles: ε and β. If to collect all values of this function, it is possible to form the indicatrix of luminance coefficient – a three-dimensional photometric body, which characterize reflective properties of concrete asphalt coverings in space. Theoretically, it is possible to construct a number of indicatrices for a pavement for different angles of observation, which can be useful for example in tunnels. However, if we do not depart from the requirements of the standards, then only one indicatrix is interesting for us for the angle $\alpha = 1°$.

In Russian and world practice so-called reduced luminance coefficient *r* is used for standardization of the luminance properties of road surfaces. This coefficient is basic for the calculation of luminance of road surfaces in Russia [2]. Reduced luminance coefficient is determined as follows:

$$r\left(tg\,\varepsilon, \beta\right) = q\left(tg\,\varepsilon, \beta\right) \cdot \cos^3 \varepsilon \tag{1.4}$$

The distribution of the reduced luminance coefficient *r* of the coating of the explored section of the road is represented in the form of the *r*-table containing the values $r \cdot 10^4$ depending on $tg\,\varepsilon$ and β. The values $tg\,\varepsilon$ and β should correspond to those given in the table [Figure 2]. The cells of the table, which must contain the values of the reduced luminance coefficient, are marked with the sign «**x**».

tg ε	$r \cdot 10^4$, sr^{-1}, for the angle β																			
	0°	2°	5°	10°	15°	20°	25°	30°	35°	40°	45°	60°	75°	90°	105°	120°	135°	150°	165°	180°
0	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
0,25	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
0.5	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
0,75	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
1.0	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
1.25	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
1,5	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
1,75	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
2.0	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
2.5	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
3.0	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
3.5	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
4.0	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
4.5	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
5.0	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
5.5	x	x	x	x	x	x	x	x	x											
6.0	x	x	x	x	x	x	x	x	x											
6.5	x	x	x	x	x	x	x	x												
7.0	x	x	x	x	x	x	x	x												
7.5	x	x	x	x	x	x	x													
8.0	x	x	x	x	x	x	x													
8.5	x	x	x	x	x	x	x													
9.0	x	x	x	x	x	x														
9.5	x	x	x	x	x	x														
10.0	x	x	x	x	x	x														
10.5	x	x	x	x	x	x														
11.0	x	x	x	x	x	x														
11,5	x	x	x	x	x															
12.0	x	x	x	x	x															

Figure 2. r-table format [2].

In addition to the *r*-table, two more parameters are used to describe the reflective properties of the road surface: Q_0 and S_1. The parameter Q_0 characterize the degree of "clarity" of the coating and is defined as the average over the solid angle $\Omega(\varepsilon,\beta)$ luminance coefficient q:

$$Q_0 = \frac{\int_{\Omega} q \cdot d\Omega}{\Omega} \tag{1.5}$$

The value $\Omega(\varepsilon,\beta)$ is determined only by the significant area of the r-table marked with cells with the sign «**x**».

The parameter S_1 characterizes the degree of specularity of the coating and is defined as follows:

$$S_1 = \frac{r(2,0)}{r(0,0)}, \tag{1.6}$$

where $r(2,0)$ is reduced luminance coefficient for $tg\,\varepsilon = 2$ and $\beta = 0$;

$r(0,0)$ is reduced luminance coefficient for $tg\,\varepsilon = 0$ and $\beta = 0$.

It should be noted that according to these two parameters road coverings are classified according to reflective properties in international practice.

1.2 Measuring methods of the spatial reflective properties of concrete asphalt pavements

Measuring of the spatial reflective properties of concrete asphalt coverings is a complex photometric challenge. All quantities describing the reflection of the coating in any direction are the ratio of light quantities that are actually measured. Direct measuring of luminance coefficients or luminance factors is impossible.

To measure the luminance factor or coefficient the following methods are known: a) method of determining the luminance factor/coefficient from the measured values of illuminance and luminance of the studied sample; b) method of comparison with the standard sample.

To measure the luminance, it is necessary to select with a high accuracy the desired directions of observation and small solid angles. The allocation of small solid angles is conditioned by the requirements to measure the narrowly directed indicatrices of the luminance factor/coefficient. Measuring of the luminance is associated with the use of measuring instruments such as luminance meters. Modern luminance meters based on the CCD matrices allow to measure the average luminance of complex luminance fields. High performance of such devices and the resulting luminance image in a digital format [Figure 3] are the result of carrying out direct measurements of the luminance of concrete asphalt coatings and the subsequent obtaining of luminance factors or coefficients without using a standard reflecting surface.

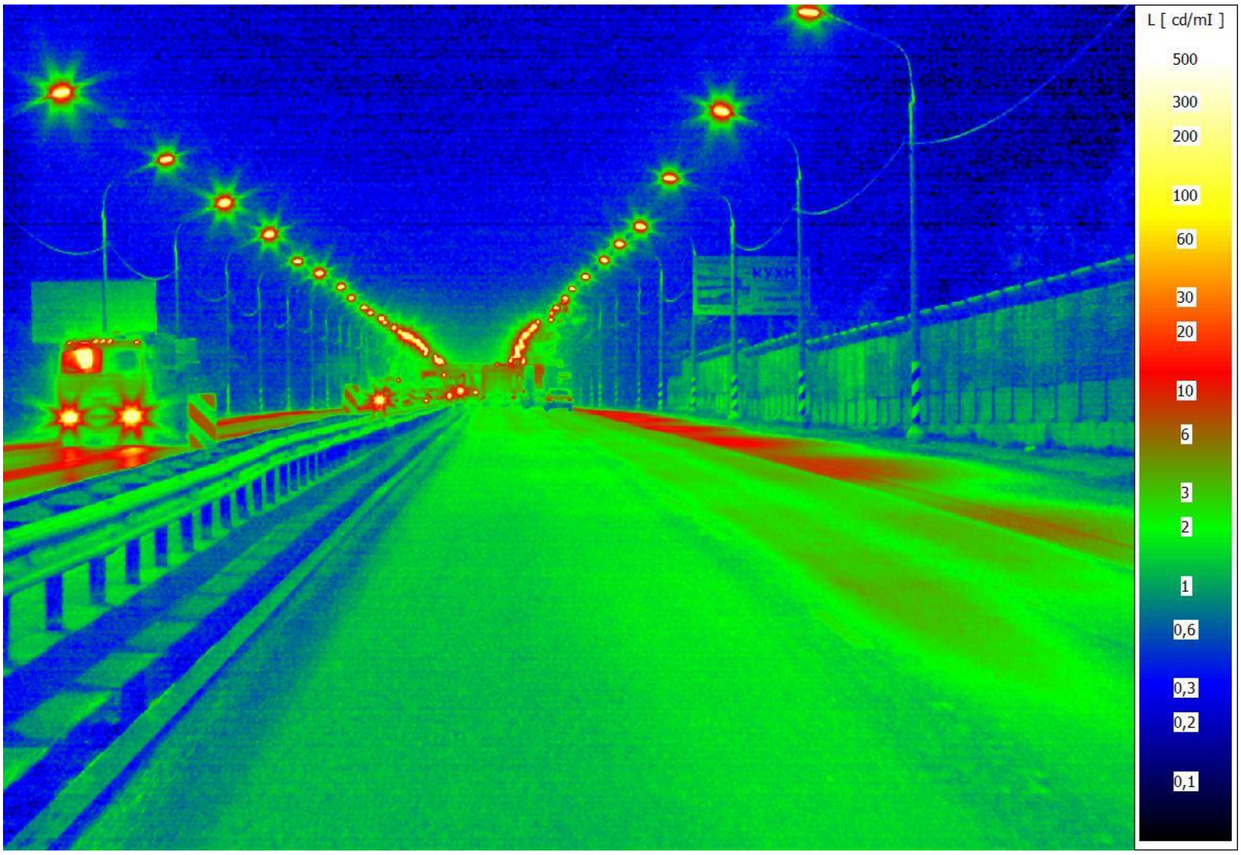


Figure 3. Luminance image obtained with the help of the luminancemeter.

The comparison method is a kind of relative methods, based on obtaining the installation indications proportional to the measured value. The installation is graded according to the sample, the measured characteristics of which (luminance factor/coefficient) is known, Further the luminance factor or coefficient is obtained with the help of the graduation characteristic.

$$r_s(\varepsilon_s, \beta_s) = r_{known}(\varepsilon_{known}, \beta_{known}) \frac{L_s(\varepsilon_s, \beta_s)}{L_{known}(\varepsilon_{known}, \beta_{known})} \tag{1.7}$$

$$q_s(\varepsilon_s, \beta_s) = q_{known}(\varepsilon_{known}, \beta_{known}) \frac{L_s(\varepsilon_s, \beta_s)}{L_{known}(\varepsilon_{known}, \beta_{known})} \tag{1.8}$$

The ratio between luminances can be measured by various known methods.

The scheme of a simplest luminance meter is provided in [5] [Figure 4].

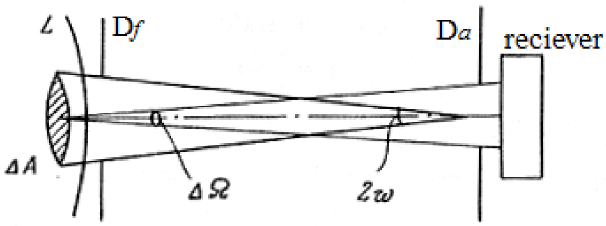


Figure 4. The scheme of a simplest luminance meter [5].

It consists of a receiver and two diaphragms. The field diaphragm D_f determines the field of view of the luminance meter ΔA (angular field 2ω). The aperture diaphragm D_a limits the solid angle, within which the measured luminance is averaged. Sometimes the frame of the receiver can carry out a role of an aperture diaphragm. To obtain a high angular resolution in this scheme, a considerable distance between the object and the receiver is necessary. The optical scheme, which is the cornerstone of the majority modern photo-electric luminance meters, has much bigger potential [Figure 5]. In this scheme the lens *O* constructs in the plane of the diaphragm D_f a picture *S'* of the studied surface *S*, the illuminance at each point of which is proportional to the luminance of the corresponding point of the surface *S*.

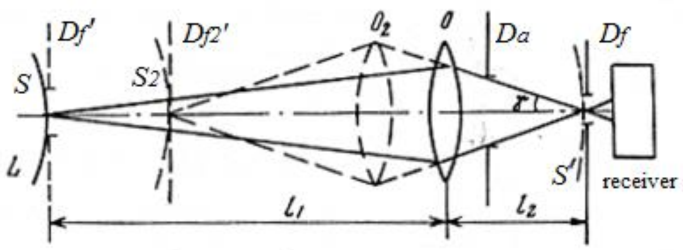


Figure 5. The scheme that is the cornerstone of a photo-electric luminance meter [5].

One of the most common ways to determine the luminance factor $\beta(\varphi)$ of the light-scattering surface is the scheme, which is represented in [Figure 6] [6]. A measurement takes place relative to one of the angles characterizing the direction of the indicatrix, while the second angle remains fixed. The plane surface *S* of the light-scattering layer is illuminated by a beam perpendicular to it emanating from a light source *LS* located at a distance *r* from *S*. Let the point *A* be the center of a uniformly illuminated section of the plane. The positive lens *PL* represents the point *A* spaced from it by a distance *r'* in the middle of the hole *H* passing a luminous flux $\Phi(\varphi)$ in the Ulbricht sphere *US* on the wall of which there is a photocell *P* closed on a sensitive galvanometer *G*. The hole *H* can have the shape of a narrow rectangle of the size for example 10 x2 mm^2, its long side is perpendicular to the plane of the drawing. This shape and position is given to the hole *O* so that for large angles of inclination φ the section of the plane *S* sending the light in the hole H is not too large. Directly behind the lens PL there is a circular aperture CA limiting the luminous flux entering the sphere; h is the distance between the parallel planes in which there are the holes H and CA.

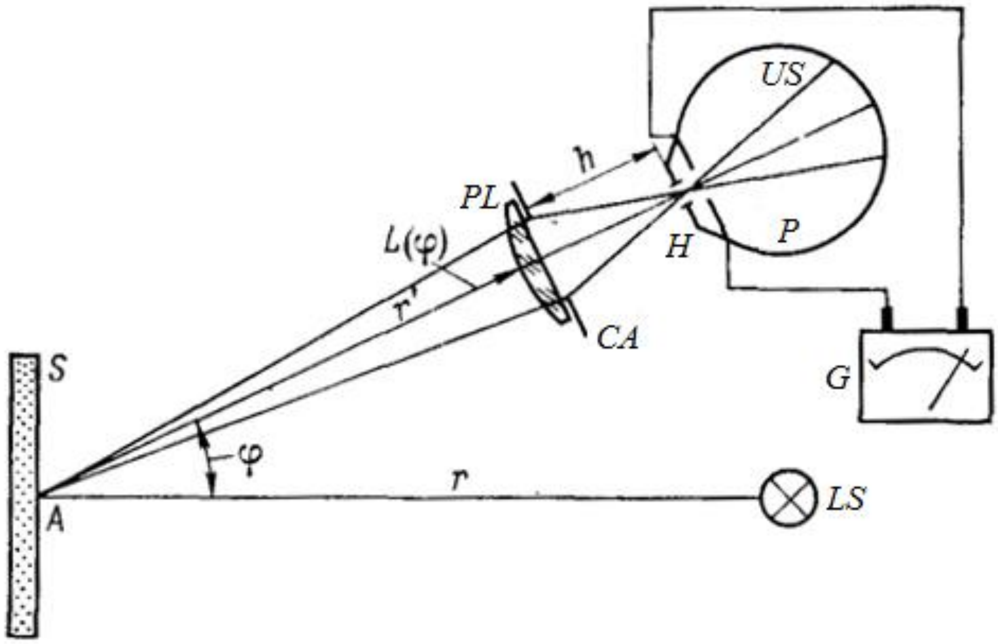


Figure 6. A way to determine the luminance factor β(φ) [6].

Let us consider in more detail the ratio of reactions of the receivers when measuring the luminance factor of the standard sample and the sample under study using the comparison method:

$$\frac{r_s(\varepsilon_s,\beta_s)}{r_x(\varepsilon_x,\beta_x)} = \left. \frac{L_s(\varepsilon_s,\beta_s)}{L_D} \middle/ \frac{L_x(\varepsilon_x,\beta_x)}{L_D} \right. = \frac{L_s(\varepsilon_s,\beta_s)}{L_x(\varepsilon_x,\beta_x)}, \tag{1.9}$$

where $L_s(\varepsilon_s,\beta_s)$ is the luminance of the standard sample in the selected direction and $L_x(\varepsilon_x,\beta_x)$ is the luminance of the sample under study in the selected direction.

By definition the luminance $L_s(\varepsilon_s,\beta_s)$ and $L_x(\varepsilon_x,\beta_x)$ are calculated in accordance with the formula:

$$L(\varepsilon,\beta) = \frac{dI(\varepsilon,\beta)}{\cos\beta \cdot dA}, \tag{1.10}$$

where $dI(\varepsilon,\beta)$ is the luminous intensity in the direction *(ε,β)* and dA is surface area.

We substitute (1.10) in (1.9):

$$\frac{r_s\left(\varepsilon_s,\beta_s\right)}{r_x\left(\varepsilon_x,\beta_x\right)}=\frac{L_s\left(\varepsilon_s,\beta_s\right)}{L_x\left(\varepsilon_x,\beta_x\right)}=\frac{dI_s\left(\varepsilon_s,\beta_s\right)\cdot\cos\beta_x\cdot dA_x}{\cos\beta_s\cdot dA_s\cdot dI_x\left(\varepsilon_x,\beta_x\right)} \tag{1.11}$$

Thus, if to provide the same angles ε and β and sample areas in the measuring system, then in accordance with 1.11 we get:

$$\frac{r_s\left(\varepsilon_s,\beta_s\right)}{r_x\left(\varepsilon_x,\beta_x\right)}=\frac{dI_s\left(\varepsilon_s,\beta_s\right)}{dI_x\left(\varepsilon_x,\beta_x\right)} \tag{1.12}$$

This means that the method is based on measuring not luminance but luminous intensity.

The measuring of the luminous intensity based on the application of the photometric inverse square law can be called an old method, since it has been used since the beginning of the 17^{th} century. Let us consider a modern method, the distinguishing feature of which is the independence of the result from the distance between the source and the receiver [6]. The telecentric method of measuring of the luminous intensity is based on the possibility of allocation (using simple optical means) and measuring the luminous flux $\Delta\Phi$, which is propagating from the source inside the constant solid angle $\Delta\omega$ and thus determining the luminous intensity in the corresponding direction.

Let *S* be the light source [Figure 7], the luminous intensity of which we need to determine. Let its radiation falls on the positive lens *PL*, the optical axis of which coincides with the direction of the measured luminous intensity. Let, moreover, the size of the lens *PL* exceeds the size of the source *S* to such an extent that allows it to intercept all parallel beams of rays, which diverge from the source within a small solid angle $\Delta\omega$. In the main focal plane of the lens an opaque obstacle *O* is placed with a circular hole *H*, whose center coincides with the main focus of the lens *F*. Behind the aperture *H* there is a photocell *P* connected to an electrical measuring instrument *MI*. The current *i* flowing through the photocell is proportional to the incident luminous flux. With the help of this device we can measure the intensity of the light sources, the dimensions of which do not extend outside a circular cone with a solid angle $\Delta\omega$ at the vertex based on the operating area of the lens *PL*.

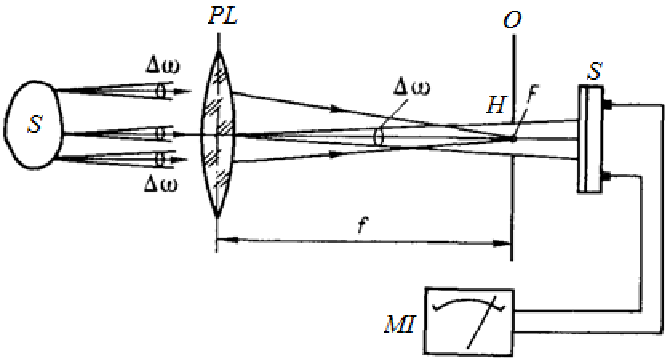


Figure 7. A scheme to measure the luminous intensity [6].

In [7], in order to find the reduced luminance coefficient of the asphalt coating, the luminance of the sample (matte white paper) with the known reduced luminance coefficient was measured to find the illuminance. The error on finding the illumination turned out to be less than in the direct measurement of illuminance or in the modeling of the measurement of illuminance (2.2%).

1.3 Ways to measure the spatial reflective properties of concrete asphalt coatings (luminance factors and coefficients)

Two ways to measure the spatial reflective properties of concrete asphalt coatings are known.

The first way (classical) is a laboratory way. Measurements, as the name implies, are made in a photometric laboratory using a goniophotometric installation. The main feature of such measurements is the need for extraction of fragments (samples) of road surfaces. This requires not only money but time. The fundamental question is: whether two or three of the extracted samples can characterize the whole road? Because it is impossible to find two fully identical samples. The advantage of this system is its unlimited size because of the lack of need of transportation, and time of measurement as there is no need to block the road. Based on this, the accuracy of such measurements is likely to be higher than that of similar mobile installations. The creation of a laboratory measuring system requires less time and money, as its design is significantly simpler and cheaper compared to the mobile analog. The disadvantage of this setup is the inability to study changes in the characteristics of the coating during its life because the extracted smples will never be “aging”.

The second way is known as “on-site” or “field”. This method is modern. Measurements are carried out directly on the road. Special measuring complexes are used for it, which are called mobile gonioreflectometers. Since the laboratory measurements are often expensive, that is connected with the local destruction and the subsequent repair of the roadway, and only a limited number of samples can be extracted, carrying out on-site measurements on such a gonioreflectometer can solve this problem. A mobile gonioreflectometer allows you to hold a large set of measurements on different road sections on the road network, which is an important factor in the development of the classification of road surfaces by reflective properties. The on-site way of measuring does not require transportation and storage of samples of coatings in the laboratory. Measurements shall be carried out during a limited amount of time because the road should be closed. Due to the possibility of a large number of measurements on different sites of the same roadway, the results can be more indicative in comparison with the laboratory measurements of a limited number of samples. Second advantage of the on-site measurements is the possibility to study changes in the reflective properties of the road surfaces during their life. In addition, if it is necessary, the setup for on-site measurements allows carrying out measurements on samples of coatings in the laboratory conditions. The word “mobile” most often implies the possibility of carrying out measurements while moving. In the case of a gonioreflectometer for measuring the spatial properties of reflection, a complete experiment to determine the reflective properties of one area of pavement (the indicatrix) takes about five minutes, during which the setup is fixed in one position on the road. Thus, the word “mobile” in this case means the ability to move the installation manually from the laboratory to any section of the road and ensuring the autonomous operation of the measuring system.

1.4 Measuring systems of spatial reflective properties of road surfaces used in the Russian practice

In Russian practice of measuring the spatial reflective properties of road surfaces, the studies of Ostrovskij M.A. during 1950-1970 are fundamental [8][9][10][11]. These studies played an important role in the transition in 1963 from the normalization of illuminance to the normalization of luminance on roads. As it was noted earlier, in Russian practice the main value characterizing the spatial reflective properties of road surfaces is the luminance factor *r’*. Therefore, Ostrovskij used an apparatus to measure the luminance factor during his studies [Figure 8]. A selenium photocell 1 is fixed on a two-meter bar that rotates around the axis *OO’* freely, which provides any angle of observation α in the vertical plane. Turning the bar around the axis *a-a’* ensures the selection of the required meridional section β. The lighter 2, the optical scheme of which provides a parallel beam of light, can be established at any angle ε in the limits 0-85°, which is achieved by turning the bar with the lighter around the axis that is perpendicular to the plane of the drawing. The road sample 3 is mounted on a turntable 4, the height of which must be adjusted depending on the thickness of the sample. The values of the luminance factors $r'_{\varepsilon,\alpha,\beta}$ can be determined from the ratio of the galvanometer readings when installing the sample under study $i_{\varepsilon,\alpha,\beta}$ and a standard barium plate with the reflection coefficient ρ_s having the cosine law of light reflection, i.e.:

$$r'_{\varepsilon,\alpha,\beta} = \frac{i_{\varepsilon,\alpha,\beta}}{i_s} \rho_s \tag{1.15}$$

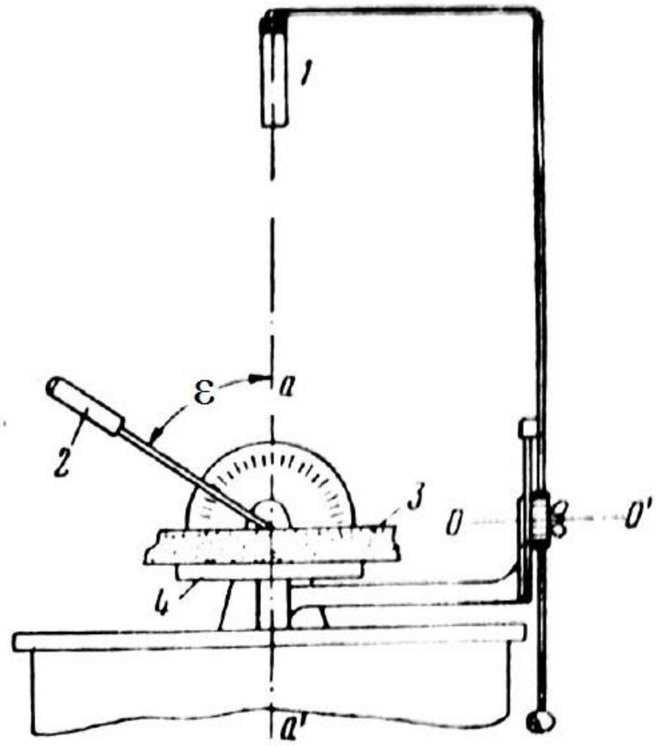


Figure 8. The Ostrovkij's apparatus to measure the luminance factor [8].

The result of the research was not only the formula proposed for the approximation of the indicatrix of the luminance factor, but also the classification of asphalt coatings by reflective properties. Ostrovskij came to the conclusion that the Russian road surfaces can be classified depending on the structure of their surface on the rough and smooth. The results of the research became the basis for the standard for external utilitarian lighting. The modern standard [2] is also based on the results of this research. The research of Ostrovskij, undoubtedly, are fundamental and somewhat revolutionary in the normalization of the lighting on roads. Unfortunately, the using of the results of the research that was conducted more than forty years ago as a basis of the modern standard is rather a forced decision, since in Russia this issue has not received adequate attention. At the same time road surfaces have been improved for several decades (asphalt coatings were replaced by more technological and high-quality coatings – concrete asphalt) and their reflective properties most likely have changed too.

The difference of the results of road luminance calculations with the use of the modern standard [2] from the results of the measurements of the luminance on roads revealed the need to study the reflective properties of modern concrete asphalt coatings. New technologies, more accurate fast measuring equipment and the increase in computing capacities have allowed to develop new measuring systems.

At the department of Lighting Engineering of Moscow Power Engineering Institute a scientific and technical work was carried out to develop an installation for measuring luminance factors [12]. Two variants of the mobile installation were proposed.

The first version of the scheme [Figure 9] is identical to the scheme corresponding to the real conditions of observation. It is performed in a reduced (in comparison with the on-site conditions) scale within the reasonable dimensions for the use of the installation on the roadway. For example, the dimensions of the installation should not exceed dimensions of the vehicle on which the installation will be based (in particular, the car trailer). The measured sample is an element of a real road surface, allocated by a superimposed stencil with an aperture and (or) a light spot formed on the sample with a lighter (lighters).

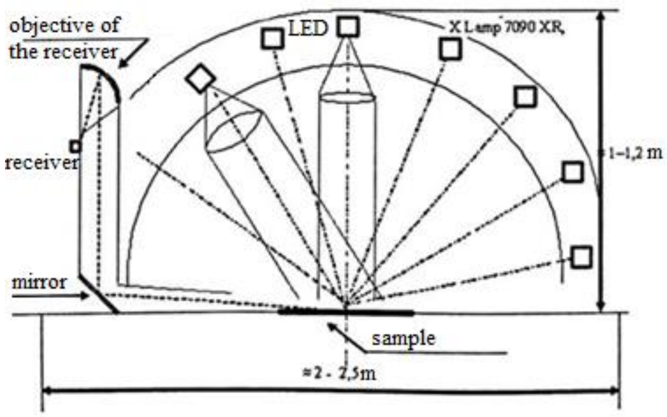


Figure 9. The scheme of an installation for measuring luminance factors by Moscow Power Engineering Institute [12].

It can be seen from the scheme that on a rigid hemispherical frame with the necessary density (it is determined by the accuracy of obtaining the photometric body of the reflected light) the lighters that provide a parallel beam of light to the sample under study are located. High-intensity LED of white light can play the role of light sources. They are installed in the focus of lenses, whose parameters are defined by the required degree of parallelism of the incident luminous flux and the density of the lighters. The radiation reflected in the direction of the observer forms the image of the sample on the receiver, which is mounted in the focal plane of the objective of the receiver. A mirror element of a concave paraboloid can serve as the objective. A silicon photodiode is the receiver. In order to increase noise immunity, the LED radiation can be modulated, and a synchronous detection is used in the signal-processing block from the receiver. Thus, each lighter has definite coordinates of the position of the incident parallel beam and their alternately inclusion (for example, according to a given program from the control unit) with simultaneous measuring of the radiation reflected in the given direction will allow constructing the required function of the luminance factor. The graduation of the installation in the offered scheme happens as follows: instead of the sample being studied, a standard sample is mounted, for example, a diffuse reflective plate with a known reflection coefficient, the signals from the receivers corresponding to each lighter are picked up, and these values are assigned the values of the reference reflection coefficient. The installation made according to the proposed scheme is quite simple, sufficiently technological, does not require very high expenses. To increase the accuracy of the measurements and the reliability of the results, several (may be several tens) measurements are necessary, each time shifting the sample under study, and averaging the obtained values for each point of the photometric body. This operation is necessary due to the fact that by modeling the real conditions of the observation on a reduced scale, it is impossible to change the scale of the structure of the real object of measurement.

The second variant of the measuring system assumes the principle of reversibility of the path of the rays (one of the basic laws of geometrical optics). In the scheme [Figure 9] instead of the receiver in the focus of the mirror in the form of an off-axis paraboloid, a light source is mounted, illuminating the sample with a light beam close to a parallel one. Instead of the lighters with LEDs with the required density, video cameras of television type with matrix photo-sensor elements are placed. According to the images on the matrix of the illuminated sample, the luminance of the sample in each camera in each of the direction of the hemispherical space is determined. Thus, a photometric body of the reflected light is formed. The proposed scheme requires a certain software for the operation of a set of cameras in order to "stitch together" images obtained from different cameras and averaging signals of a large number of measurements at specific angles from different cameras and from several measurements when the sample is displaced. However, the angular accuracy of obtaining a photometric body is very high. It is determined by the resolution of the cameras. The grading is similar to the grading of the variant 1.

In [12], structural elements of the installation were also designed and measured. Unfortunately, the proposed variants have not been implemented and measurements have not been carried out.

During the interaction of Russian Lighting Research Institute named after S.I. Vavilov and the department of Lighting Engineering of Moscow Power Engineering Institute, scientific and technical work was carried out [13]. A laboratory installation for measuring luminance factors was developed and manufactured [Figure 10].

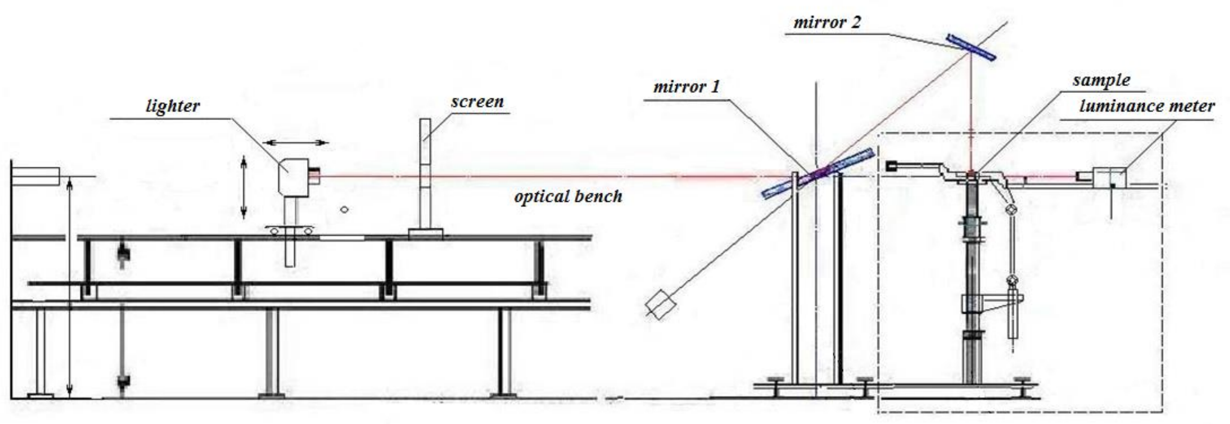


Figure 10. The installation for measuring luminance factors by Russian Lighting Research Institute [13].

The lighter is fixed to an optical bench together with the screens installed in a certain way to minimize the amount of scattered light propagating in the direction of measuring. The incidence angle of radiation of the lighter depends on the location of the mirrors, which are regulated with the help of a rotary lira, and the observation angle depends on the wings with a counterweight. One sample of a road surface was studied [Figure 11]. Measurements have been made for various angles of incidence of light and different observation angles. Also during the measurements different diaphragms and multipliers were set up. Functional dependences of the luminance factors on different angles were found and constructed. Thus, a methodology of measuring was developed. The model of the laboratory installation allowed to formulate some requirements for a laboratory installation consisting of creating conditions for improving the performance of measurements, increasing the accuracy and repeatability of measurement results. Extremely low accuracy of manufacturing of the attachment points of the sample and receiver, insufficient reliability and reproducibility of photometric measurements, as well as the need to use large-size samples of concrete asphalt coatings led to the termination of studies of the reflective properties of road surfaces on this installation. It is clear that the obtained measurement results are interesting, but can not be the basis for the standard, since a small number of measurements of only one sample of the pavement was carried out.

Figure 11. Road sample with the size 25x105x15 cm [13].

At the department of Lighting Engineering of Moscow Power Engineering Institute an installation for measuring the luminance factors based on a goniometer was developed [14] [Figure 12].

Figure 12. Goniometer [14].

The optical scheme of the device [Figure 13] has been developed. A parallel beam is obtained here from the source of light *LS* with the help of the Galilei pipe, which is already provided by the design of the goniometer. The final divergence of the beam is determined by the focal length of the system of the lighter and the size of the filament source. The Galilei pipe is formed by the lenses L_1 and L_2. The photometric head consists of a lens L_3, in the focus of which a diaphragm *D* is placed. Behind the diaphragm is a receiver. The photometry of a sample *S* occurs against the background of the plane *P*. The high accuracy of positioning of the object relative to the lighter and the photometric head can be achieved by applying the goniometer.

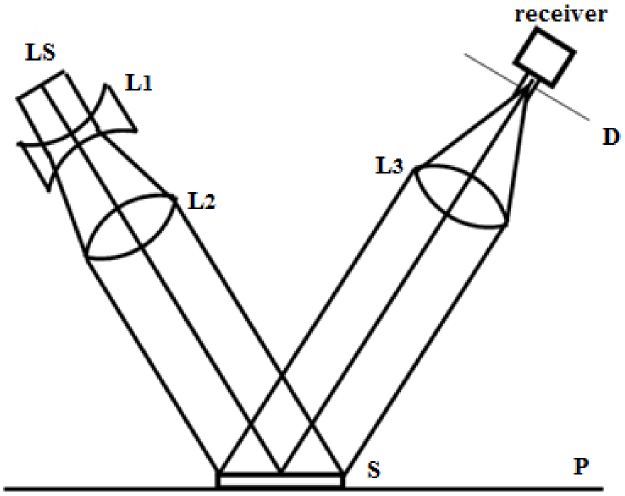


Figure 13. The optical scheme of an installation based on the goniometer [14].

During the development of the device an optical scheme was calculated, an energy calculation was performed, an optical scheme of the lighter and the receiving-recording part was developed. The procedure of the measuring was developed; the graduation was carried out with the help of standard plates. Such an installation for measuring the luminance factors can be called a complex measuring system, although it had many disadvantages that were supposed to solve in the future. However, the development ended at this stage, and the measurements of real samples of concrete asphalt pavements has not been carried out.

1.5 Measuring systems of spatial reflective properties of road surfaces used in the world practice

In the world practice, the main value describing the spatial properties of the reflection of roads is the luminance coefficient *q*. Measuring systems (including mobile) are being developed (in some cases several copies are produced) for a long time, and the development are being continued by various companies to this day.

A variant of a such laboratory installation was developed in Germany [15] [Figure 14]. The installation requires a large area (at least two building modules with size 6x12 m). Illumination of the horizontally placed samples is carried out by a system consisting of a light source *L* with a capacity of 0.95 kW and a pair of mirrors, one of which M_0 is taken out at a distance of 12 m, and the second oblique mirror *M* is located between the sample and *L* and is rigidly connected with it. The angular aperture of the beam is equal to $5.8 \cdot 10^4$ sr. Rotary devices allow setting angles of observation in the meridional (from 0 to 180^{o}) and equatorial (from 0 to 360^{o}) planes.

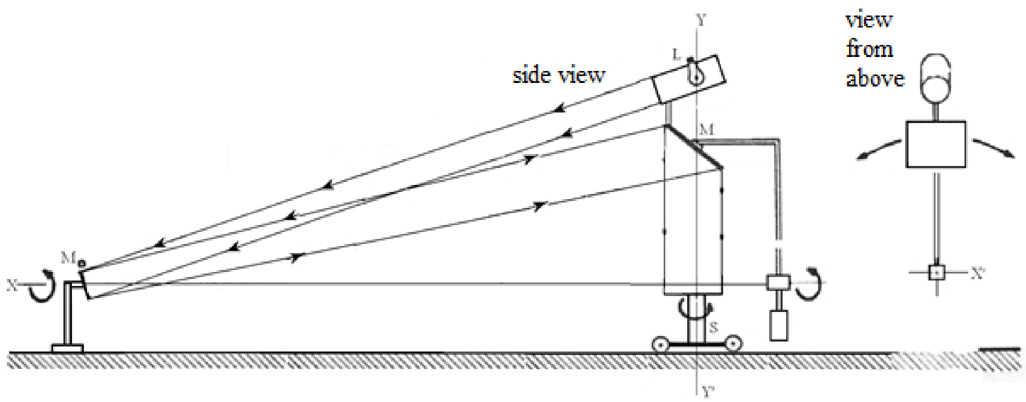


Figure 14. A system for measuring luminance coefficients (Germany) [15].

In the Netherlands, a methodology for measuring luminance coefficients was adopted and a corresponding measuring device was created [16] [Figure 15]. Using this scheme, a system for on-site measurements can be created (mobile installation). Instead of the conventional rotary motion of the lighter it moves horizontally. In this case, the optical axis of the lighter is always directed to the center of the sample of the coating, which ensures the constancy of the luminous intensity towards the sample. Measuring the luminance of the sample at a constant observation angle equal to 1°, the value $f(\varepsilon) = \frac{q_{\varepsilon,\beta} \cdot \cos^3 \varepsilon}{n}$ is directly determined, where $q_{\varepsilon,\beta}$ is the luminance coefficients for the angles of incidence ε and the meridional cross section β. The measuring head is rigidly connected to the rotating platform, on which the sample of the coating is installed, which allows to obtain the values $f(\varepsilon)$ for any meridional cross-section β. The following values of the angles β are recommended: 0° (when the lighter, the normal to the sample and the measuring head are in the same plane), 2, 5, 10, 15, 25, 35, 45, 60, 75, 90, 120, 150 and 180° when the angle ε changes from 0 to 85°. A meridional cross-section β-const is set manually and the horizontal movement of the lighter and registration of the values $f(\varepsilon)$ is automatic.

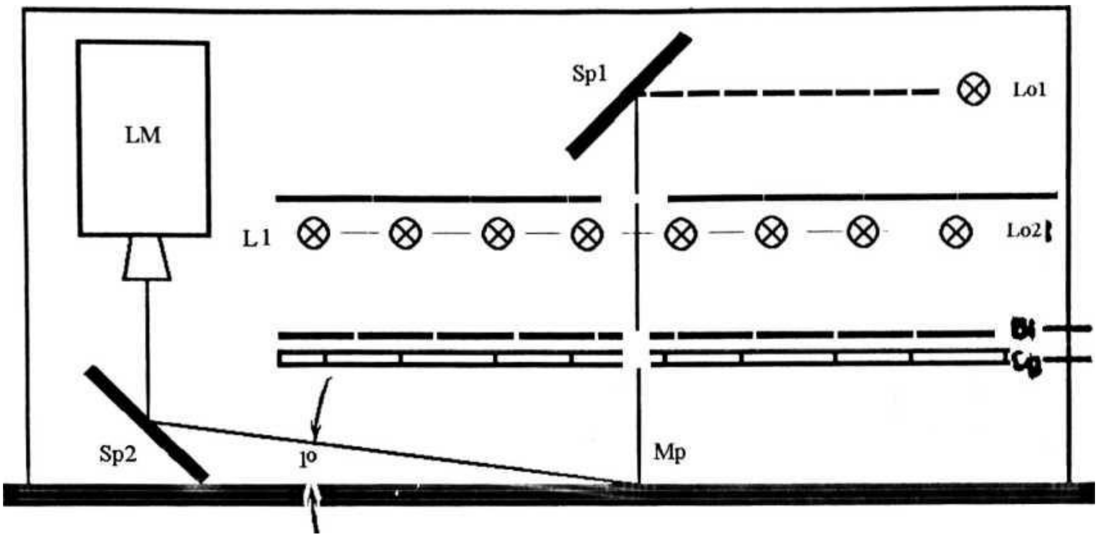


Figure 15. A device to measure luminance coefficients (Netherlands) [16].

In [17], a laboratory measuring setup was developed [Figure 16]. The measuring device fixes signals at angles ε and β. The light source *A* moves in a straight line at a constant height above the sample. In this way, various angles ε are provided while the rotation of the table *B*, on which the sample *P* and the luminancemeter *K* is fixed, allows different angles β to be set up. In addition to the requirements for accurate reproduction of the directions of the action of the luminous intensity, the precise setting of the sample the design of the luminancemeter is critical for the accuracy of the measurements.

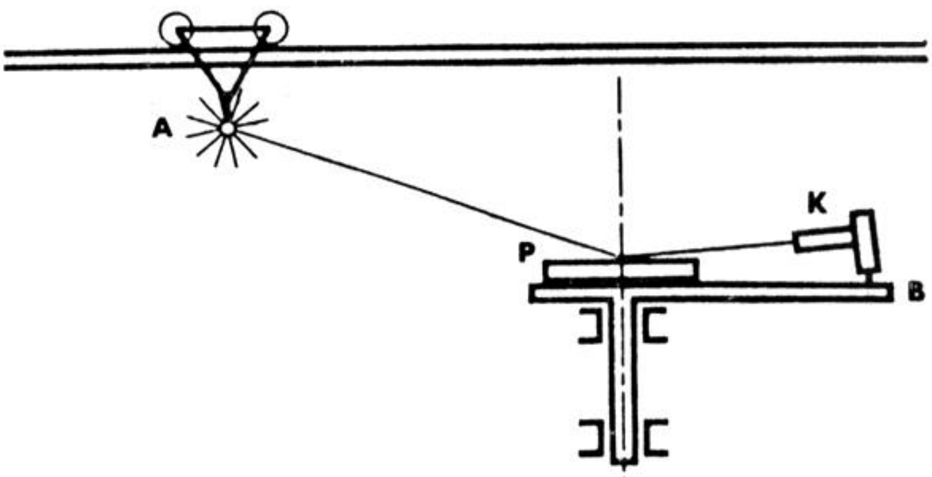


Figure 16. A system with a moving light source for measuring luminance coefficients [17].

A complete mobile measuring system Coluroute (from French – luminance coefficient of a road) was created by the regional laboratory of Strasbourg (France) in collaboration with Philips [18] [Figure 17].

Figure 17. Mobile gonioreflectometer COLUROUTE [18].

In 2003, the installation was patented. Coluroute corresponds to the recommendations of CIE. As a result of measurements on the setup, a filled *r*-table, Q_0 and S_1 can be obtained. Coluroute consists of two modules:

- the mobile device for receiving the radiation, which is placed on the surface under study. Due to the geometrical constraints, all the angles of incidence of light (about 400 of combinations of angles ε and β) can not be realized on the portable device. Coluroute includes 27 light sources located on a quarter of the sphere in such a way that the directions of the incident light correspond to a limited but consciously chosen set of positions from the full *r*-table and a sensor that “sees” the roadway at an angle of 1^o. The specularity factor, which is the ratio of the luminance coefficient corresponding to two directions of illumination is the ratio of two lighting sources of Coluroute;
- a computer which controls and records the signal and calculates the complete *r*-table.

The lighters are composed of high power white LEDs and an optical system that generates a parallel ray of light of 5 cm diameter. Thanks to an elliptic diaphragm adapted to the emission angle, the shape of the illuminated surface is always circular [Figure 18]. The reflected signal is focused with a converging lens and transmitted to the detector by an optical fiber. Due to the small observation angle and thus to the small amount of reflected light, a photomultiplicator is used. Since the emitted light is modulated, synchronous detection is done electronically to eliminate the influence of parasite light and especially the sun. The resulting signal is converted by an analogic/numeric card and recorded on the computer.

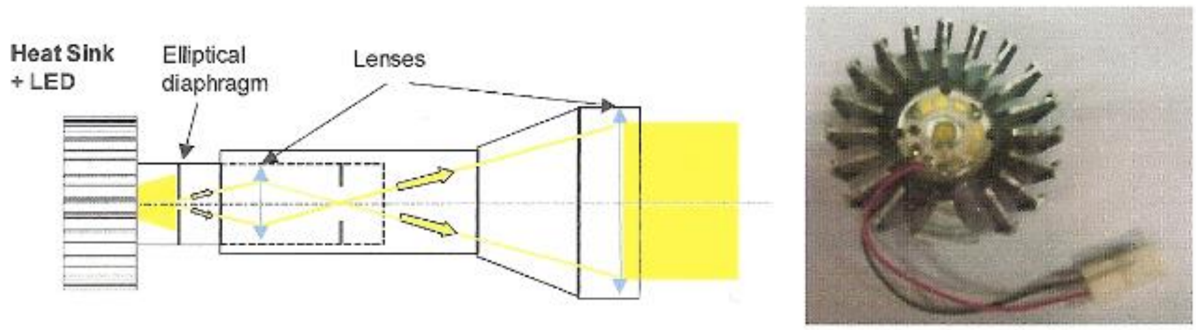


Figure 18. The lighter for COLOROUTE [18].

To establish the relation between the voltage measured by the photomultiplicator and the reduced luminance coefficient *r*, a calibration is performed. Standard surfaces measured with a fixed-base goniophotometer located in a laboratory are used.

Since Coluroute measures the reduced luminance coefficient for 27 lighting directions instead of about 400, it is necessary to reconstruct the complete *r*-table. The reconstruction is made by interpolation and extrapolation where the 27 source positions constitute the control points. The error between the complete measured r-table and the reconstructed one in term of average luminance coefficient Q_0 is 4% in average.

The performance evaluation of Coluroute was first made in laboratory with comparative measurements on samples with the laboratory gonioreflectometer and in real conditions. Then, lighting calculation results were compared using CIE standard *r*-tables and *r*-tables measured by these two equipments. A laboratory experiment was conducted on 27 samples measured with Coluroute and with the laboratory gonioreflectometer. The error factor is about 4% in average for average luminance coefficient.

For many years, the Belgian company Schreder was the pioneer in the field of research of reflective properties of roads and among the first developed a stationary installation allowing to measure characteristics of pavements, in particular the luminance coefficient [19]. The gonioreflectometer [Figure 19] is able to measure reflective characteristics of road surfaces depending on the direction of incident light and the line of sight forming with the surface of the sample an angle 1^o, which corresponds to the direction of the line of vision of a driver of a vehicle, while the observation angles (up to 90^o) are designed to measure, for example, characteristics of reflection of the walls in tunnels. These measurements are carried out in the laboratory on the sample with the diameter from 100 mm to 200 mm, extracted from the real road surface of the road.

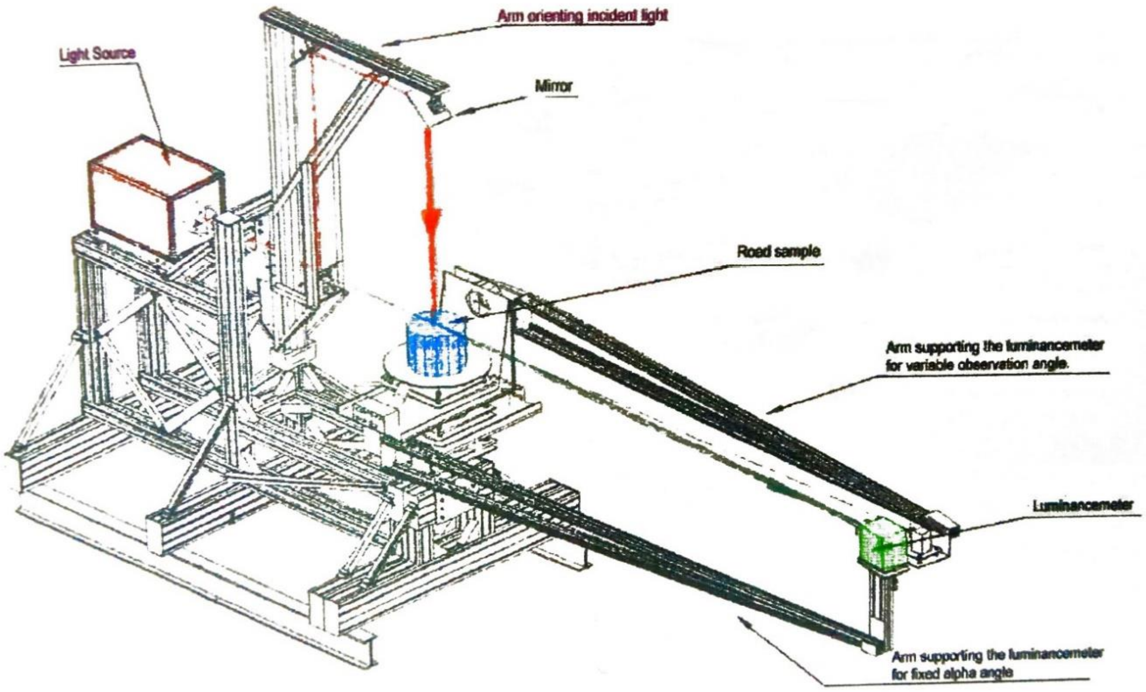


Figure 19. The laboratory gonioreflectometer of the Schreder Group [19].

At the time of the creation, the gonioreflectometer Schreder was the only one in Europe allowing to measure the luminance coefficient of a sample in any direction, while others measured it only for different angles of incidence. The laboratory equipment made it possible to interpolate discrete measurement results and reproduce with high accuracy the dependence of the values of the luminance coefficient of the sample from the required values of the incident angle and the angle of observation.

The company Schreder in collaboration with the University of Liege has launched a research project in order to create a mobile system for measuring the luminance coefficient without extracting samples [19]. A mobile gonioreflectometer was the result of the research [Figure 20]. The mobile equipment allows to set many combinations of incidence-observation angles (up to 576). For each of these ones, the luminance coefficient is then directly calculated without any previous calibration on-site. The complete system (control of the source, sensors and data acquisition) is entirely automated thanks to a dedicated software. For on-site measurement, a laptop can control all the measurement process and collect the data. The entire system is powered by batteries.

Figure 20. Mobile gonioreflectometer of the Schreder Group [19].

The lighters are designed in a such way that the illuminated spot (100 mm) on the surface is the same for each incidence angle. Each lighter is composed of lenses systems in order to achieve this. Once the road surface is correctly and uniformly illuminated, the quantity of reflected light must be measured. The second arm (called observation arm) is equipped of 9 light cells that will do this job [Figure 21]. Each of the light cells is equipped with a small and calibrated black tube that gives us a very simplified luminancemeter. Each of these systems is calibrated in luminance in cd/m^2.

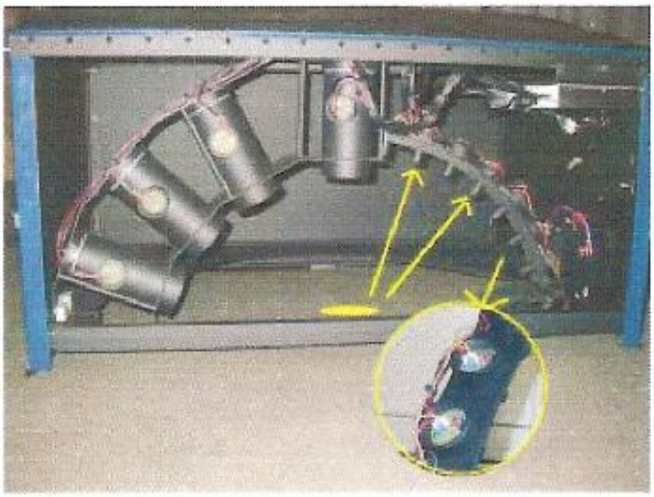


Figure 21. The arm of light cells [19].

One a measurement is realized for $\beta = 0^o$, the observation arm must be moved manually. Then the following β planes can be measured. The equipment can measure β planes from 0^o to 150^o.

In order to validate the concept and the equipment, measurements with the mobile gonioreflectometer have been realized on-site. In parallel to these measurements, extractions of road samples have been done and measurements of these last ones on the lab gonioreflectometer have been realized with the same incidence-observation sequences. Having both results [Figure 22], it is possible to obtain a comparison and to see that they are excellent (Lab refers to laboratory gonioreflectometer and Mob to mobile gonioreflectometer; angles 0, 30, 50 and 70^o correspond to incidence angles ε).

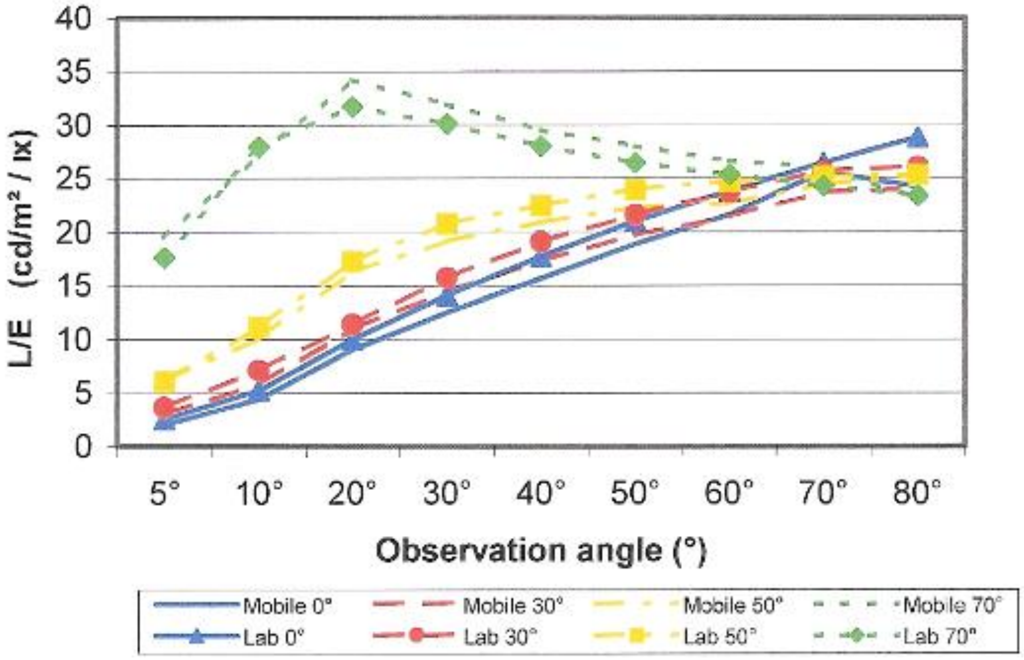


Figure 22. Comparisons of the results of the gonioreflectometers by Schreder Group [19].

The system gives us data describing the reflective characteristics of the road surface. But these data do not represent an r-table since we have only 4 incidence angles. Most of the observation angles are different from 1^o. Indeed, for mechanical and geometrical reasons, it is not feasible to place a light cell measuring the reflected light under an observation angle of 1^o with the desired accuracy. Therefore, a solution was developed in order to estimate the luminance levels from the measured data. 3 ways were achieved:

- comparison of measurements;
- estimation of the luminance from 2 parameters;
- mathematical modelisation of the *r*-table from a reduced number of measurements.

The principle of the method of comparison is following: after having measured the road surface characteristics on-site, the collected data is compared to all the measurements (realized with the mobile system). By comparing these data, it is then possible by using the "least square method" to determine the road surface present in the database that presents the closest reflection characteristics to the studied one. Once the road surface type is determined, the r-table can be used (measured by lab gonioreflectometer) in the calculation software in order to predict luminance and uniformity levels. The comparison method gives a good result: the error in determining of luminance with the help of results obtained on the mobile gonioreflectometer is 6.2%. The error when using standard CIE tables is 17.3%.

The method to estimate the luminance level from 2 parameters (Q_0 and Q_d) and mathematical modelisation of *r*-tables led to good results too (error up to 15%).

For the next generation of the system the designers wanted to reduce the size of the system, to speed up measurements by avoiding arm manual rotation. The installation "Memphis" was the result [Figure 23].The new measurement was fully driven by the computer. In order to reduce the dimensions, the solution was to reduce the number of β planes: receivers are located for the angles β = 0, 10, 20, 30 and 150º. The reduced number of β planes involved an increasing of the error in the luminance prediction of ±1.5%. This gives then a relative error of 7.7%. 180 measurements for all combinations of angles are fixed for 12 seconds. The small increase of the error is balanced by the reduced time, which allows the user to do more measurements on-site. 18 "Memphises" were produced and used in several countries for studying the reflective properties of roads.

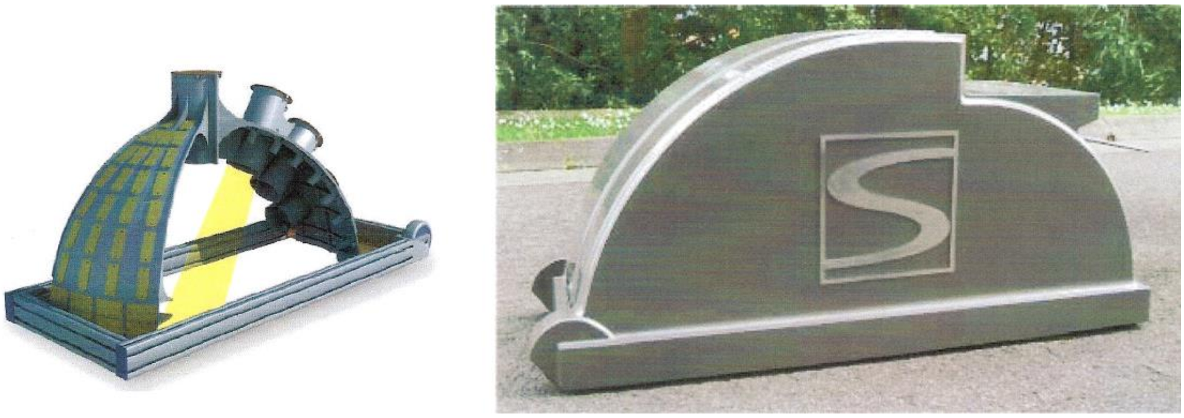


Figure 23. The installation "Memphis" [19].

The research result of the reflective characteristics of European asphalt coatings was the creation of a database and a classification. The results are presented in the form of *r*-tables. Measurements of *r*-tables took place for twenty years. The tables were corrected as there were a set of mistakes caused by imperfection of the measuring equipment and methods of measuring. A rather complex computer program with the ability to detect and locate various types of errors and print out the diagnosis checked all *r*-tables. The *r*-tables containing serious mistakes were rejected. The remaining errors in *r*-tables were corrected if it was possible. In some cases, errors of cosmetic importance, being difficult to correct, were ignored. As a result all dry road surfaces were divided into 4 classes: RI, RII, RIII and RIV. The w-classification was offered for wet coatings. There is a classification according to S_1 and Q_0. These classifications are the basis for the calculation of luminance on roads in the software Dialux. As shown in the studies [19], the use of standard CIE tables (*r*-tables) for coatings from the R-classification sometimes leads to very large errors (from -40% to 60%). So the use of such tables and existing classifications is still not optimized at the moment, and the error in finding the luminance coefficient on roads is too high.

1.6 Methods of approximation of the indicatrix

The spatial properties of the reflection of road surfaces are characterized by the indicatrix of luminance coefficient/factor. The luminance coefficient/factor depends on different angles, i.e. are a function of these angles. Therefore, measurements of the luminance coefficient/factor have the following featues: no matter how angles are “close” in two different measurements, there is always one more angle between them (ε, α or β). It is necessary to apply some mathematical apparatus that will connect “two neighboring points” to itselt to find the functional dependence of the luminance coefficient/factor (the indicatrix), since the number of measurements necessary for finding all the values of the function in the space tends to infinity (in fact, only a quarter of the space is interesting). Several authors proposed the mathematical description of the indicatrix of luminance factor/coefficient (approximation).

Ostrovskij M.A. in the analysis of the results [8] concluded that regardless of the type of the asphalt coating, the degree of its dustiness and the lifetime, the indicatrix of luminous intensity for different incidence angles consists of two parts: diffusely scattered 1 and specularly scattered 2, and the full indicatrix is described by the sum of these two components [Figure 24]. Ostrovskij was interested in the distribution of luminous intensity of the light reflected from a road surface because he used a standard sample and could find the luminance factor with the help of luminous intensity. The value of the luminous intensity at a given angle of incidence ε in the direction of the angle α for the section β = const is determined as the sum of diffuse and specular components:

$$I_{\varepsilon,\alpha,\beta} = I_{dif} + I_{spec\,\alpha,\beta} \tag{1.16}$$

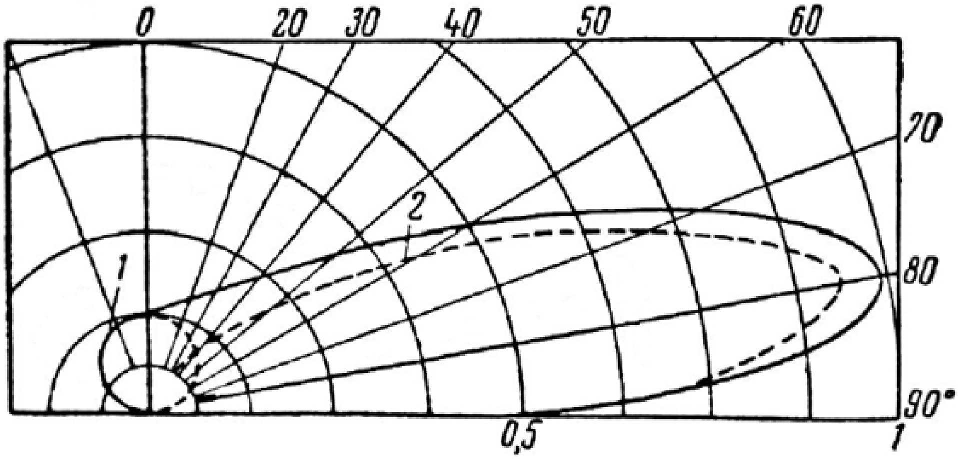


Figure 24. The indicatrix of luminous intensity [8].

The studies showed that the diffuse component of the luminous intensity I_d is almost independent of the angle of incidence ε and its distribution in the space is close to a cosine. The specular component $I_{spec\ \alpha,\beta}$ strongly depends on the angle ε:

$$I_{spec\,\alpha,\beta} = F\left(\varepsilon\right) \cdot e^{-c\beta^2} , \tag{1.17}$$

where the constant *c* depends on the condition of the coating.

Accordingly:

$$I_{\varepsilon,\alpha,\beta} = I_0 \cos\alpha + F\left(\varepsilon\right) e^{-c\beta^2} , \tag{1.18}$$

Based on the foregoing, the luminance factor of the road pavement can be written using the following equation:

$$r'_{\varepsilon,\alpha,\beta} = r'_0 + \frac{a}{\left(1 + b \cdot ctg^2\varepsilon\right)\cos\alpha} \cdot e^{-c\beta^2} , \tag{1.19}$$

where $r'_0 = \frac{I_0}{I_m}\rho_{known}$ is the luminance factor of the diffuse reflection, where $I_m = \frac{I_{known}}{\cos\alpha}$.

The determination of the constants *r'*$_0$, *a*, *b*, and *c* was carried out both in the laboratory and directly by measuring the luminance and illuminance of pavements outdoors in Moscow and comparing the obtained data with the calculated ones. The values of these constants for two types of asphalts (fine-grained and medium-grained) were found in various conditions: at the beginning of operation, after five years of operation, dusty asphalt, pure asphalt. Such a model of the indicatrix of luminance factor of asphalt coatings was presented more than forty years ago, so the applicability of the model for modern concrete asphalt pavements needs to be checked.

In [20], a formula was proposed for approximating the indicatrix of luminance factor of the surface of a material with specular-scattered reflection. The luminance factor can be represented as a sum of two functions:

$$r(\alpha) = r_d + r_s = \cos\alpha + \frac{2\cos(\alpha-\gamma)\cdot b^2 a}{\cos(\alpha-\gamma)\cdot b^2 + a^2\sin^2(\alpha-\gamma)}, \tag{1.20}$$

where a, b and γ are constants.

Such an approximation of the luminance factor only gives the idea of the general form of the specular-diffuse distribution of light in one section.

An approximation of the indicatrix of luminance coefficient was proposed in [19]. The mobile gonioreflectometer of the company Schreder measured the values of the luminance coefficients for some angles from the *r*-table, but not for everyone. To restore the complete *r*-table from a limited number of measurements, the following approximation was proposed. The model consists of two functions. The first function «fitup» is for the top of the *r*-table ($tg\ \varepsilon < 5$), the second function «fitdown» is for the bottom of the *r*-table ($tg\ \varepsilon > 5$):

$$fitup = \left(x^2 - 2x + 5\right)^{a1}\left(\left(4^{-a1} r_{0,0} + a2 + a3\right)x - a2 + \left(a4 - a3\right)x^{-1} - a4x^{-2}\right) \tag{1.21}$$

$$fitdown = \left(x^2 - 2x + 5\right)^{a1}\left(\left(4^{-a1} r_{0,0} + b2 + b3\right)x - b2 - b3x^{-1}\right), \tag{1.22}$$

where $x = tg\varepsilon + 1$. In (1.21) and (1.22) $r_{tg\varepsilon,\beta}$ denotes the measured reduced luminance coefficient; a_i, b_i are pavement parameters that depend on the azimuth angle β. The equalizing of these functions for some tgε and the fixation of the pavement parameters a_i and b_i allow to restore the entire *r*-table and then the indicatrix. The reconstruction error of the *r*-table according to this approximation was up to 15% for coatings from the R-classification.

The leading research assistant of Russian Lighting Research Institute Korobko A.A. offered an analytical model of the luminance coefficient of road surfaces [21]. The model is based on the physical nature of the measured value. The photometric body was presented in the form of an ellipsoid of scattering, on of the focuses of which is aligned with the point of the reflecting surface to which the incidence ray is directed and the main axis is oriented in the direction of the specular reflection. The error in calculating the luminance when using such a model was 15% and

6% for the observer, located respectively on the far and near the lane of a number of luminaires. Thus, the representation of the indicatrix of luminance coefficient in the form of an ellipsoid, which can be characterized by semi-axes (i.e. by three numbers), on the one hand, speeds up calculations and reduces the amount of memory needed to store information about the reflective properties of the coating (in comparison with r-table), and on the other hand, allows to obtain the results of calculations of the luminance on roads with fairly high accuracy.

Knowledge of the spatial properties of reflection of concrete asphalt pavements is necessary for calculating the luminance of highways and designing outdoor lighting installations. To measure the reflective properties, whether it is an indicatrix of luminance coefficient or luminance factor, special measuring installations (gonioreflectometers) are used, which are complex photometric systems consisting of several elements. There are several variants of European gonioreflectometers. A classification and a database of road surfaces were created on the basis of measurements on such instruments in Europe. Recently, in the Russian practice, unfortunately, the reflective properties of road surfaces have not been given due attention. The existing Russian classification is based on the results of measurements carried out more than forty years ago. The use of data on reflective properties of both Russian and European coverings leads to large errors in calculating the luminance on roads, which was repeatedly confirmed by the results of luminance measurements. Therefore, it is necessary not only to study the reflective properties of modern Russian concrete asphalt coatings and to create new databases, but also to create a new classification of coatings. Attempts to create Russian instruments in recent years have not been successful, since the accuracy of the results obtained on these installations were extremely low. To obtain measurements with the high accuracy (small error) a comprehensive approach to the consideration of the elements of the measuring system is necessary. The estimation of the errors arising during the measurements allows not only to predict the accuracy of the measurement results, but also to make demands on the elements of the measuring device to ensure the necessary accuracy of measurements. Many of the errors that occur in photometric measurements are fairly standard and typical. But in gonioreflectometers there is a number of errors related to alignment, ensuring the constancy of the measuring field, the unevenness of the surface of concrete asphalt coatings, the study for the observation angle of 1^{o} and some others that are not easy to take into account and evaluate. Producers or developers in any public document do not give the measurement errors of the indicatrix of luminance coefficient. There are doubs about the fact that manufacturers conduct a comprehensive analysis of all possible arising errors. Measurement errors are estimated only on the basis of comparison with the results of luminance measurements, which, as has been said, often lead to large discrepancies. However, these errors can be estimated before the installation is created with the help of calculations. It is possible to present requirements for the elements of the installation, select these elements, calculate the errors for the selected elements and then make measurements and compare the results of calculations with the results of measurements, Therefore, the estimation of errors arising when measuring the indicatrix of luminance coefficient of concrete asphalt coatings is an actual task.

2 DEVELOPMENT OF THE INSTALLATION

2.1 The choice of the investigated quantity

The spatial properties of reflection of road surfaces are usually characterized by the indicatrix of luminance factor or by the indicatrix of luminance coefficient. The luminance factor was used in the Russian practice, while in the European practice the luminance coefficient was used. Which of these two values would be desirable as a result of the measurements?

To select the value, it is necessary to take into account not only the difficulty of obtaining it, but also the convenience of its further use. From the point of view of obtaining the value, the luminance coefficient and the luminance factor are quite similar. However, the luminance coefficient has advantages in terms of further use.

The luminance coefficient can be written in the form (1.2). The luminance coefficient characterizes a selected point on the surface of the road (point *P*). In the denominator of the expression (1.2) there is the illuminance in a point that is characterized by the angles *(ε,β)*. Thus, knowing the illuminance at the point *P* from a luminaire and the luminance coefficient we can calculate the luminance in the necessary direction:

$$L_P\left(\varepsilon,\beta,\alpha,\delta\right)=q\left(\varepsilon,\beta,\alpha,\delta\right)\cdot E_P\left(\varepsilon,\beta\right) \tag{2.1}$$

The luminance, which is characterized by the angles *(ε,β)*, is created by the light from a luminaire. The distribution curve of luminous intensity is most often known, so there is no problem to find the luminous intensity in the direction *(ε,β)*. Then, according to the photometric distance law, the illuminance in the point *P* created by the light from the luminaire in the direction *(ε,β)* [Figure 25]:

$$E_P\left(\varepsilon,\beta\right)=\frac{I\left(\varepsilon,\beta\right)\cdot\cos\varepsilon}{\left(H/\cos\varepsilon\right)^2}=\frac{I\left(\varepsilon,\beta\right)}{H^2}\cdot\cos^3\varepsilon \tag{2.2}$$

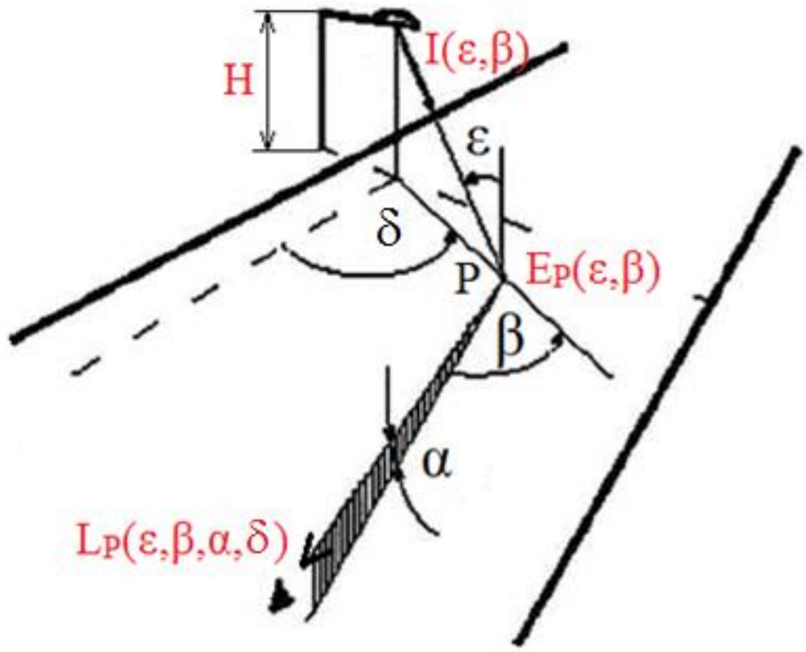


Figure 25. The illuminance of the road in the point P.

From (2.1) and (2.2) it is possible to find the luminance characterized by the direction *(ε,β,α,δ)*:

$$L_P(\varepsilon,\beta,\alpha,\delta)=q(\varepsilon,\beta,\alpha,\delta)\cdot\frac{I(\varepsilon,\beta)}{H^2}\cdot\cos^3\varepsilon=r(\varepsilon,\beta,\alpha,\delta)\cdot\frac{I(\varepsilon,\beta)}{H^2}, \qquad (2.3)$$

where $r(\varepsilon,\beta,\alpha,\delta)$ is the reduced luminance coefficient.

Knowing the geometry of the road and the lighting installation (the width of lanes, the number of lanes, the distance between luminaires and the height of the luminaire suspension), the distribution curve of luminous intensity of luminaires and the reduced luminance coefficient, we can calculate the luminance created by each luminaire in any direction (in our case in the direction of the driver's eye):

$$L_P(\varepsilon,\beta,\alpha,\delta)=\sum_{i=1}^{n}r_i'(\varepsilon_i,\beta_i,\alpha,\delta)\cdot\frac{I(\varepsilon_i,\beta_i)}{H_i^2} \qquad (2.4)$$

Thus, the reduced luminance coefficient, as one of the variations of the luminance coefficient, is a very convenient value for calculating the luminance on roads. Therefore, the reduced luminance coefficient is the value that should be obtained as a result of the research at the measuring installation and which can characterize the spatial characteristics of the reflection of concrete asphalt pavements. For convenience, the values of the reduced luminance coefficient are multiplied by 10^4.

2.2 The choice of the type of the installation to be developed

The present work is carried out on the basis and in the interests of the Russian Lighting Research Institute named after S.I. Vavilov (VNISI). Currently, an installation is being developed to measure the reflective properties of concrete asphalt pavements in accordance with contract No. 478/21 of 11/07/2016 with OOO BL TRADE. The result of this work will be taken into account when designing the measuring system. Therefore, the solution of the tasks is closely connected with the installation.

Choosing the type of the installation is an important step of the development. As it was mentioned earlier, there are two types of installations for measuring the spatial properties of reflection of road surfaces: laboratory and on-site. Advantages and disadvantages of such installations were also considered above. When choosing the type of the installation being developed, the key factors are the scope of application of such measuring complex and the purpose of the development. The ultimate goal of developing the gonioreflectometer is to measure the spatial properties of reflection of concrete asphalt coatings used throughout Russia and the creation of a modern database and a classification of surfaces. For this, it is necessary to carry out a lot of measurements, the accuracy of the results of which should be as high as possible. The vast expanses of Russia create difficulties for carrying out on-site measurements with the help of a mobile system, which are associated with the costs of transportation of the equipment (including time ones), the work of an operator and a driver. A mobile system is a more complex one. Its development will take longer than the development of a laboratory complex. The accuracy of the results of measurements on a mobile system is lower than on a laboratory installation. Extraction of samples of concrete asphalt pavements of roads all over Russia, which is necessary for carrying out laboratory researches, in the Russian realities is not more expensive than on-site measurements. Although there are no problems with measuring of samples using a mobile instrument, it was decided to develop a laboratory gonioreflectometer. If we take into account the world experience, then the laboratory setup is a “step back”. However, this move is compulsory, since with the deficit of information on the reflective characteristics of modern concrete asphalt coatings, the choice is made in favor of higher measurement accuracy and less time required for the development of the measuring complex.

2.3 The choice of the method for measuring the indicatrix of luminance coefficient

The choice of the method for measuring the indicatrix of luminance coefficient plays one of the key roles in the design of the installation. The method of measuring can be characterized by its errors (methodological errors). Therefore, it is necessary to select and describe in detail the features of the method.

The method is based on finding the luminance and illuminance and the use of mathematical models. The luminance coefficient is the ratio between the luminance of the surface of a sample $L(\varepsilon,\beta,\alpha,\delta)$ and the illuminance $E(\varepsilon,\beta)$ that caused this luminance. The idea of measuring the luminance and illuminance and further finding the luminance coefficient is clear, but the requirements of measuring the luminance at an observation angle of 1^o to the measured surface creates big problems. With such an observation angle, the visible surface area of the sample is 1.7% of its area, visible along the normal to the sample. Therefore, in order to increase the sensitivity of the receiver to ensure the required measuring accuracy it is necessary to increase significantly the dimensions of the reflecting surface of the sample. However, the dimensions of the sample are limited, on the one hand, by the technology of its extraction from the road surface and subsequent transportation to the laboratory for measuring, and on the other hand, by the dimensions of the measuring installation, into which it must be installed. For real practical reasons, it was decided to use the standard cores of the upper layer of the pavement in the form of disks with the diameter of 150 mm and the thickness of 40- 60 mm as samples of the road surface. Consequently, the visible projection of the sample in the observation plane is $150 \cdot \sin 1^\circ \cong 2.6$ mm. It should be taken into the account that the diameter of the light spot created by the collimated beam of the lighter on the sample will be much less than the diameter of the sample – 80 mm. Therefore, the visible size of the light spot in the observation plane will be $80 \cdot \sin 1^\circ \cong 1.4$ mm. Considering that the valleys and protrusions on the surface of the real pavement have the sizes on height about 5 - 7 mm, the results of the measurements of the luminance become unpredictable. In addition, the correct reading of the observation angle $\alpha = 1^o$ relative to the plane of the reflecting surface of the sample is also difficult, since the position of this plane depends on the random location and height of the protrusions on the reflecting surface of the sample and can vary within a few degrees.

For these reasons, following method to measure the luminance coefficient was adopted:

- measurements of the average luminance of the light spot formed on the surface of the sample under illumination are carried out at different angles ε, β and α. The angles of observation α are much larger than 1^{o};
- on the basis of the approximation of the luminance measurement results a mathematical model of the photometric luminance body of a sample for each angle of incidence ε is constructed;
- using the constructed approximation model, the values of the luminance of the sample at an angle $\alpha = 1^{o}$ by extrapolation are determined;
- measurements of illuminance are carried out at normal incidence light. The illuminance for other angles *(ε,β)* is found by the known formula;
- the luminance coefficient is found as the ratio between the luminance for the observation angle of 1^{o} $L\left(\varepsilon,\beta,1^{\circ}\right)$, which is the result of approximation and extrapolation, and the illuminance $E\left(\varepsilon,\beta\right)$;
- the indicatrix of luminance coefficient is the result of an approximation.

2.4 The kinematic and optical scheme of the measuring system

For measuring the spatial light distribution of sources and lighting devices a distributive photometers (goniophotometer) is used, whose kinematic measuring scheme is based on one of the standard photometric systems: *A-α*, *B-β*, *C-γ* [22]. The most universal is the *C-γ* system, the *B-β* system is used mainly for the photometry of projectors with non-axisymmetric light distribution, the *A-α* system is essentially a variation of the *B-β* system and is rarely used, mainly for the photometry of automobile headlights.

In the laboratory of VNISI, there was a goniophotometer measuring by the *B-β* system [Figure 26]. This goniophotometer was chosen as the basis for the installation.

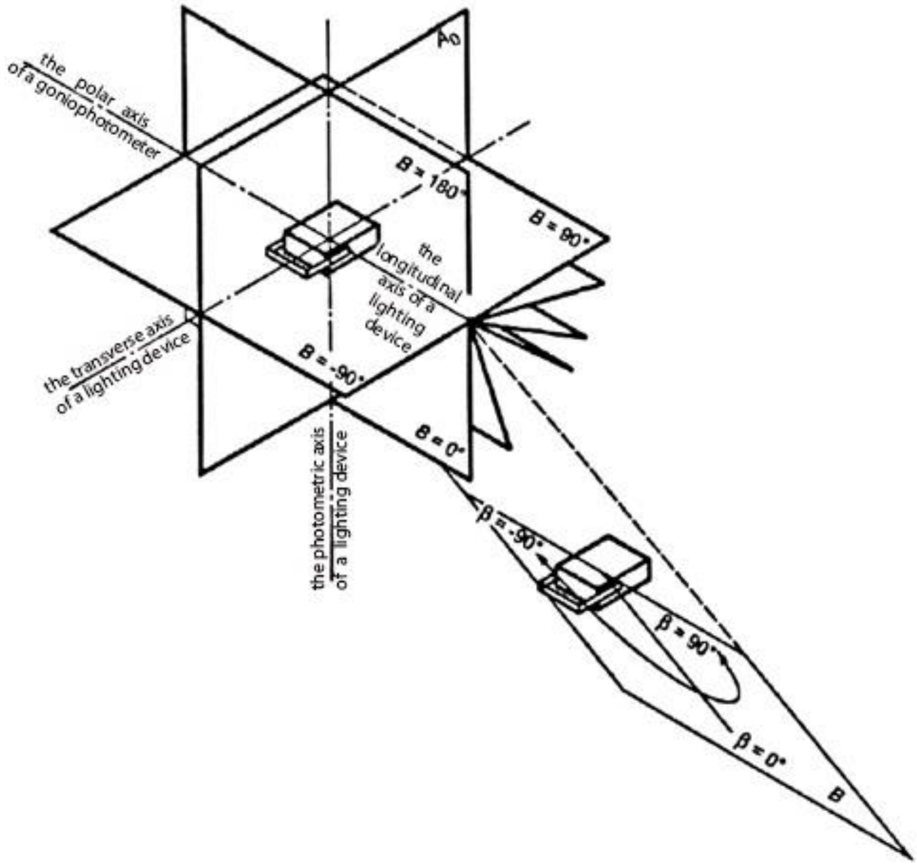


Figure 26. The B-β photometric system based on the example of photometrics of a projector [22].

To realize the measurement of the spatial distribution of the radiation reflected from the sample (the luminance), a lighter is introduced into the measuring circuit, for which it is possible to change the angle of incidence of light. A receiver is necessary for measuring the luminance (a luminancemeter).

On the basis of the existing goniophotometer, a lighter and a receiver, a basic kinematic scheme of the installation for measuring the luminance coefficient of road surfaces was developed [Figure 27]. The measured sample of the road surface (1) in the form of a disk is located so that the center of its illuminated surface is combined with the photometric center of the installation (2) and the normal N to the sample from the center is directed along the photometric axis (7). The rotation of the sample is produced relative to the vertical (3) and horizontal (4) axis of the device lying in a plane passing through the specified illuminated surface. The positive direction of rotation of the sample in the horizontal and vertical planes are shown by arrows. The corresponding rotation angles are designated U_h and U_v, which are introduced instead of the corresponding B and β to avoid confusion between the angle β of the photometric system and the angle β between the planes of incidence and observation. The lighter (5) is positioned so that its optical axis is always directed to the center of the sample (2). The change of the angle of incidence to the sample ε is made by

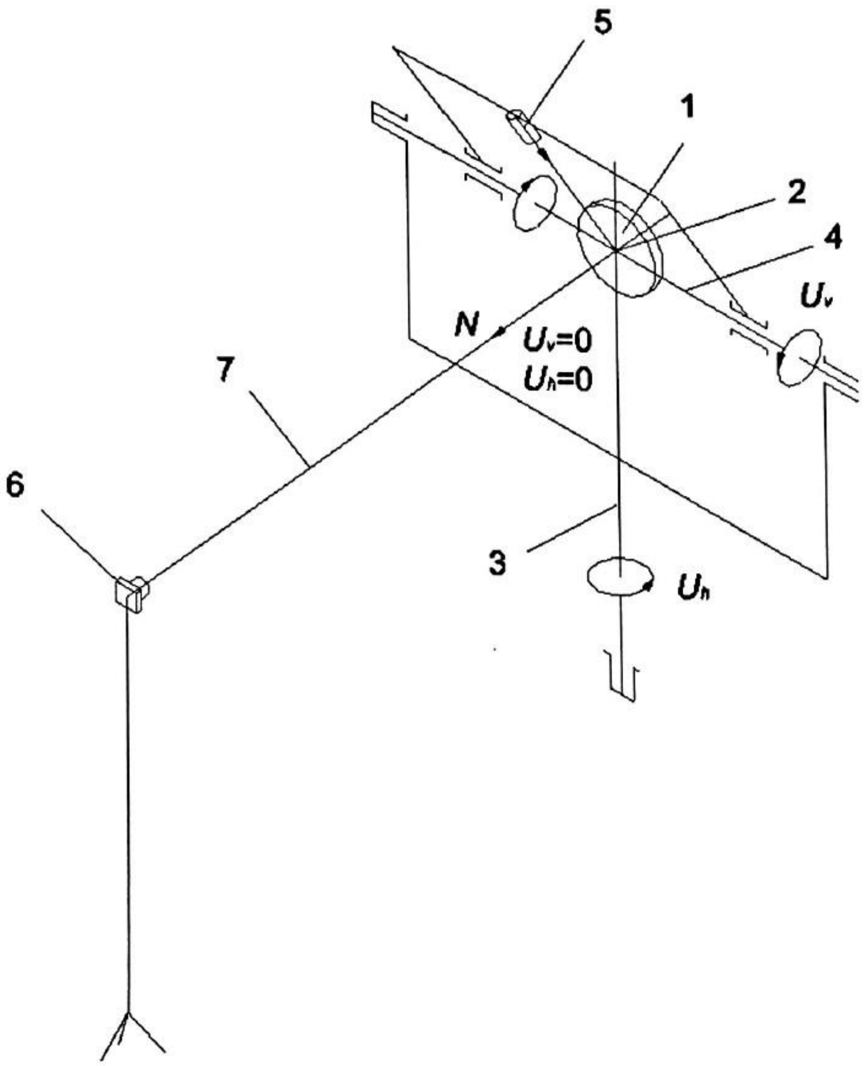


Figure 27. The basic kinematic scheme of the installation. 1 is the measured sample; 2 is the photometric center of the installation; 3 and 4 are the vertical and horizontal axis of rotation of the sample respectively; 5 is the lighter; 6 is the receiver (luminancemeter); 7 is the photometric axis of the installation.

turning the lighter relative to the horizontal axis (4). The rotation of the lighter (5) does not depend on the rotation of the sample (1) relative to the same axis. The radiation receiver (6) is located at a certain distance from the photometric center of the installation (2) along its photometric axis (7) passing perpendicular to the rotation axis (3) and (4). In the initial installation position, i.e. when $\varepsilon = 0$, $U_h = 0$ and $U_v = 0$, the lighter shields the receiver. To eliminate such a problem, a mirror will be introduced into the scheme in the future. With independent rotation of the sample, not only the observation angle α varies, but also the angle of incidence ε. For the transition from the angles of rotation of the gonioreflectometer U_h and U_v to the angles α and β that determine the direction of observation, the following formulas are used:

$$\cos\theta = \cos U_v \cos U_h \tag{2.5}$$

$$\sin\beta = \frac{\sin U_h}{\sqrt{1-\left(\cos U_v \cos U_h\right)^2}}, \tag{2.6}$$

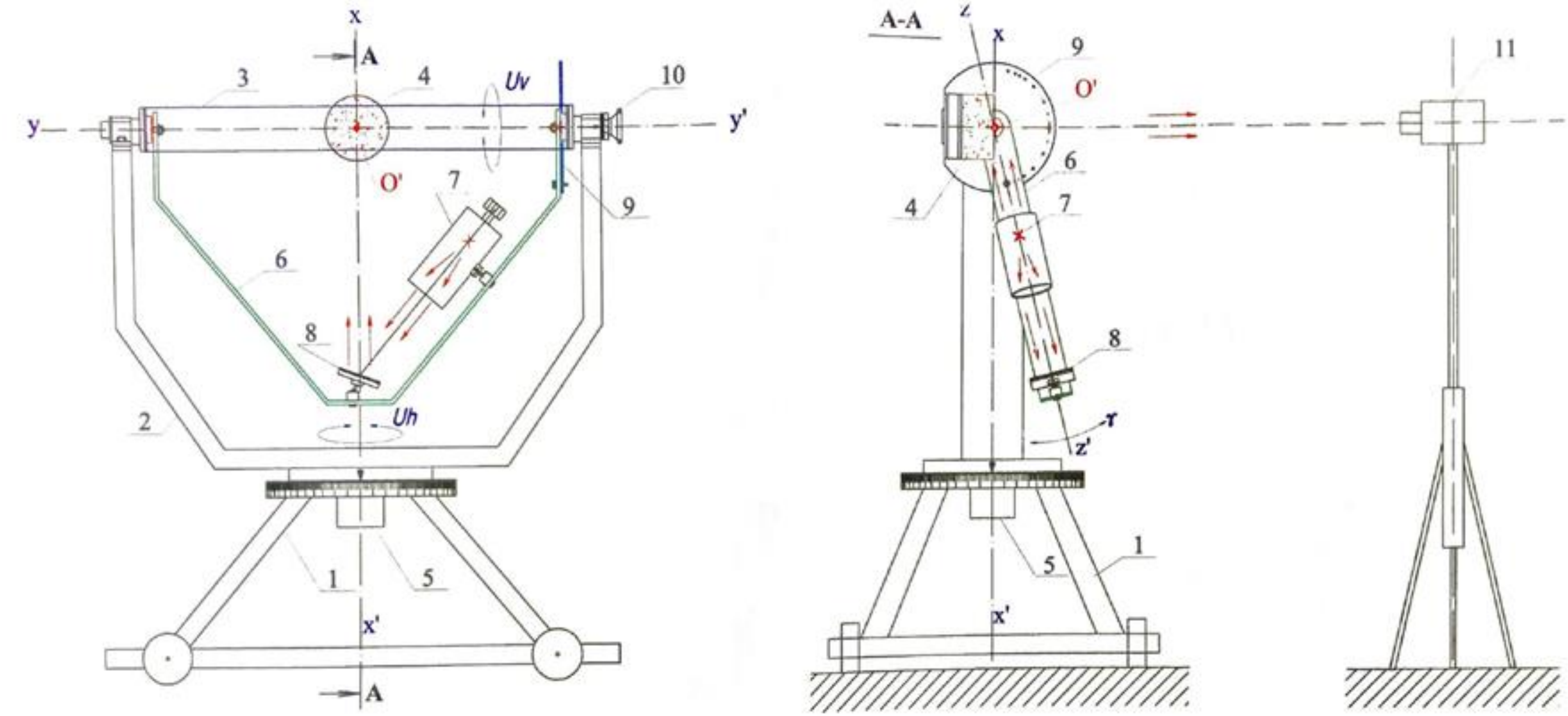
where θ is the angle between the direction of observation and the normal to the sample, i.e. additional to the angle α: $\alpha=90^o - \theta$. If $U_h = 0$ and $U_v = 0$, the angle β is equal to 0.

If the rotation of the sample relative to the angle U_v causes changing the angle of incidence ε and the angle of observation, then the rotation of the sample relative to the angle U_h is not the rotation relative to the angle between the planes of incidence and observation β. Therefore, the angle β must be calculated. Such a recalculation is a necessary compulsory solution related to the feature of the photometric system and the existing goniophotometer.

A kinematic scheme of a laboratory measuring device to investigate the reflective properties of road surfaces was developed [Figure 28]. The installation is mounted on the base (1), equipped with elements of alignment of the entire structure in the horizontal position relative to the ground. On the basis (1) the external lira rotated relative to the vertical axis *XX'* is mounted and the rotation mechanism (5) along the horizontal angles U_h with the limb is mounted. The external lira (2) is supplied with flanges for mounting along the axis *YY'* of a U-shaped swivel bracket (3) and the rotating device (10) along the vertical angles U_c with the limb. In the central part of the swivel bracket there is a mechanism, adjustable in two planes, on which, with the help of four blades with fixing bolts, the sample of the concrete asphalt (4) with the diameter of 150 mm is mounted. In addition, coaxially with the swivel bracket on the same flanges the internal lira (6) is mounted with the possibility of independent but fixed on the angles ε rotation along the axis *YY'*. The countdown of the fixed angles ε is carried out using the limb (9). The photometric center of the installation *O'* is at the point of intersection of the axis *XX'* and *YY'* and is located in the central part of the sample under study on its external surface. The lighter (7) with the light source and the optical system is mounted on the internal lira (6). A fixed flat mirror reflector (8) is mounted on the same lira.

Proceeding from the specificity of the problem solved in the work, the light beam falling on the sample from the source must be collimated, i.e. have a small angular divergence of the rays. A collimated beam can be obtained in one of two ways. In the first way, the source moves away from the illuminated sample at a such distance along the normal that any beam emitted by the source at an angle not exceeding the divergence angle. For the selected sample size and the point source, the indicated distance should be about several meters for ensuring rather small divergence of the beam. In the second way, a lens collimating system is used, which provides the necessary degree of divergence of the beam rays. Considering the requirement of compactness of the measuring system, the second way is selected. The input of the mirror reflector was necessary, since it helps to avoid screening of the receiver for many combinations of angles.

The main elements of the installation are: the rotary internal lira (6), the mechanism for mounting the sample (4), the lighter (7), the mirror reflector. They have regulation elements for the purpose to define the photometric center of the installation and alignment of the axial beam of the lighter and the mirror reflector relative to the photometric center of the installation. The radiation receiver (11) is set at the calculated distance from the investigated sample in the direction of its normal under the initial conditions: $U_v = 0$, $U_h = 0$, $\varepsilon = 0$. In the figure [Figure 29], the measuring system is assembled.



1 The basis of the installation
2 The external lira
3 The swivel bracket
4 The sample of the concrete asphalt
5 The rotation mechanism along the angle U_h
6 The internal lira
7 The lighter

8 The mirror reflector
9 The limb with the fixed angles ε
10 The rotation mechanism along the angle U_v
11 The receiver of radiation
O' The optical center of the installation
xx' The vertical axis of the sample rotation
yy' The horizontal rotation axis of the sample and the lighter
zz' The optical axis of the lighter

Figure 28. The kinematic scheme of the laboratory measuring device (goniophotometer) for investigating the reflective properties of road surfaces.

Figure 29 The measuring system in assembled condition

Based on the developed kinematic scheme of the installation and the selected scheme of the lighter, the optical scheme of the installation was developed. The optical scheme of the installation can not be clearly illustrated in the figure, since it must be represented in 3D space, so it can be viewed only in parts. If we consider the optical scheme and the propagation of radiation from the source to the receiver, then the first part of the optical scheme consists of an illuminator, a mirror and a sample of the road surface [Figure 30]. The second part of the scheme consists of a receiver (luminancemeter), which is in the plane parallel to the plane of the image. The lighter consists of a LED, a diaphragm *d* and a two-lens glued objective *O* with the diameter *D* with the focal length f that allows to obtain a collimated light beam. The LED has a long service life, stable light parameters, small size, so this is the source that is optimal for the system being developed. However, the light from the lighter has some divergence. The divergence depends on the parameters of the elements of which the lighter consists. Light falls on the mirror and then is reflected on the sample of the road surface. Since the mirror reflects according to the law "the reflection angle is equal to the angle of incidence", it is possible to construct the path of rays from the lighter to the sample. The angular divergence of the beam does not change after passing through the mirror. In the figure [Figure 30], the divergence of light from the lighter is quite large for clarity (in fact, there are no problems with providing a smaller divergence). It is also worth noting that in the figure the sample is perpendicular to the optical axis. When the sample of the road surface tilts, the optical path length of the various rays changes. The light spot formed on the surface of the sample will be asymmetric in this case. The light spot is investigated with the help of a receiver (luminancemeter). It is difficult to depict the path of the rays from the sample to the luminancemeter, since the concrete asphalt is a rough surface and does not reflect like a mirror.

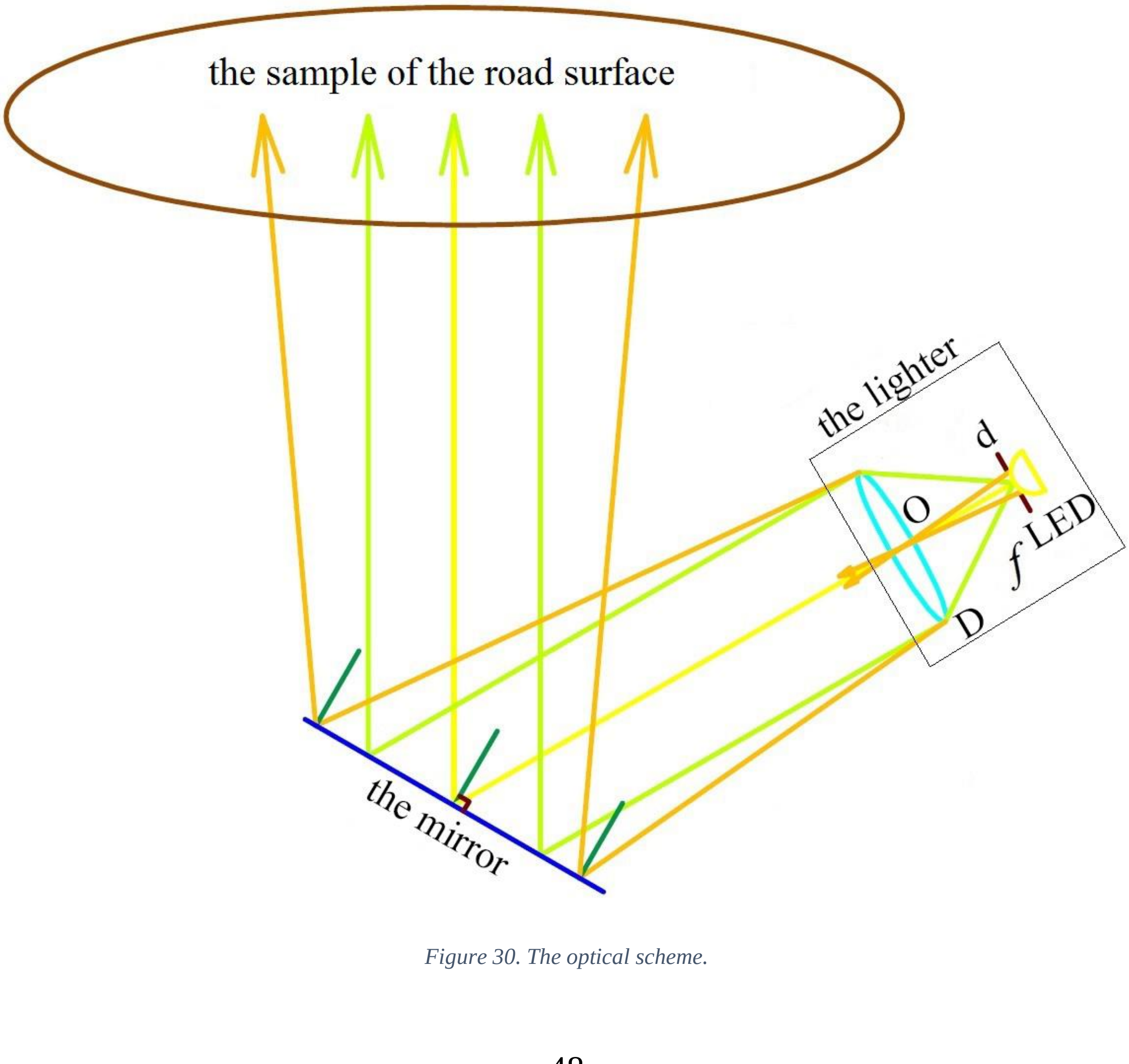


Figure 30. The optical scheme.

2.5 Measuring technique

Measuring out the luminance of the sample is carried out in the following sequence:

1. The initial values of the angles of rotation are set: $U_h = 0$ for the external lira, $U_v = 0$ for the swivel bracket, $tg\varepsilon = 0$ for the internal lira. The luminance value of the sample is not fixed in this situation, since the receiver is shielded by the internal lira with the lighter and mirror reflector mounted on it. The value of $tg\varepsilon$ is fixed;
2. The swivel bracket is sequentially rotated along the angle U_v with a certain step in the range from -80° to +80°. For each value of the angle U_v, the external lira is sequentially rotated along the angle U_h with a certain step from -80° to +80°. On each step the values of the angles U_h and U_h and the luminance of the sample $L_\varepsilon(U_v,U_h)$ are fixed. The steps for changing U_h and U_h will be determined in the result of the studies in such a way that each subsequent measurement result differ from the previous one by more than 10%;
3. The internal lira is sequentially set to a position for which the value of $tg\varepsilon$ [Table 1] is determined from the following set: 0.25, 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, and for each position the procedure from the step 2 is repeated, taking into account the fact that for each value of tgε there will be a zone of screening of the light spot on the sample by elements of the internal lira. In addition, the set of angles U_v and U_h will be unique for different tgε.

Table 1. Values of the angle ε for measuring.

№	tgε	ε, °
1	0	0
2	0.25	14
3	0.5	26.5
4	1.0	45
5	1.5	56.3
6	2.0	63.4
7	2.5	68.2
8	4.0	76.0

As a result, 15 two-dimensional arrays of luminance values of the sample $L_\varepsilon(U_v,U_h)$ will be formed [Table 2].

Table 2. An example of the luminance table $L_\varepsilon(U_v,U_h)$ for some $tg\varepsilon$.

The angle $U_{v\,i}$, º	The angle $U_{h\,i}$, º								
	$-U_{h\,n}$	…	$-U_{h\,2}$	$-U_{h\,1}$	0	$U_{h\,1}$	$U_{h\,2}$	…	$U_{h\,n}$
$-U_{v\,n}$									
…									
$-U_{v\,2}$									
$-U_{v\,1}$									
0									
$U_{v\,1}$									
$U_{v\,2}$									
…									
$U_{v\,n}$									

The illuminance of the sample is calculated by the formula:

$$E(\varepsilon) = E_0 \cos\varepsilon = \frac{E_0}{\sqrt{1+tg^2\varepsilon}}, \qquad (2.7)$$

where E_0 is the normal illuminance of the sample. The illuminance *E(ε)* is defined as the average illuminance in the light spot on the sample, created by the light of the lighter after reflection from the mirror reflector. The normal illuminance E_0 is measured in the central part of the sample by an illuminancemeter in the plane perpendicularto the optical axis of the light beam of the lighter.

2.6 Calculation of the lighter

The lighter of the installation should provide necessary illuminance of the sample of the road surface, the geometric parameters of the illuminated area on the sample and the required angular divergence ω_l (the spatial structure of the beam) [Figure 31].

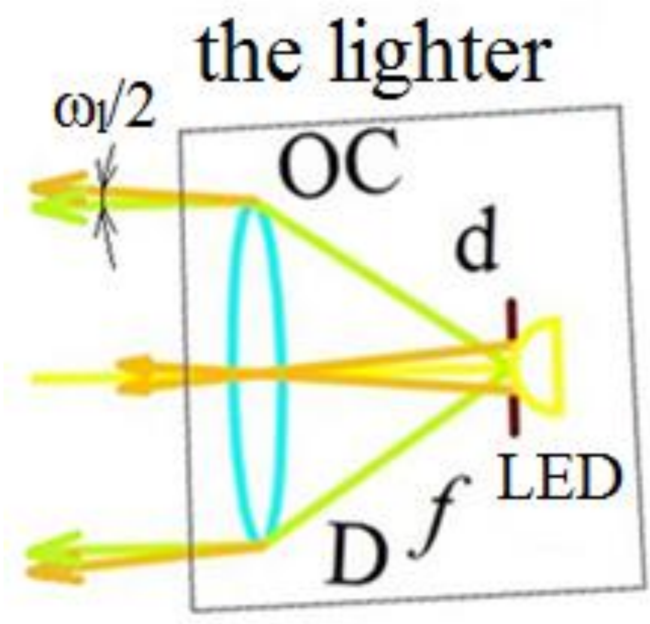


Figure 31. The optical scheme of the lighter.

At small angular divergence of the beam, the illuminated area of the concrete asphalt sample located perpendicular to the optical axis of the lighter is equal to the area of the objective. To obtain statistically reliable results of measurements, the linear dimensions of the illuminated site must be much greater than the maximum size of the heterogeneity of the concrete asphalt coating. Proceeding from this, the diameter of the objective *D* was chosen equal to 80 mm. The relationship between the angular divergence of the beam and the geometric parameters of the lighter is determined by the relation:

$$\omega_l = 2arctg\left(\frac{d}{2f}\right) \tag{2.8}$$

Since the aberrations of the two-lens glued objectives do not exceed 3 angular minutes for *f*-numbers (the ratio *D*/*f*) smaller than 2.5, the focal length of the objective should not be less than 200 mm. The result obtained allows us to calculate the diameter *d* of the diaphragm, which forms (together with the objective) the divergence of the light beam of the lighter:

$$d \le 2f \cdot tg\frac{\omega_l}{2} = 2 \cdot 200mm \cdot 0.0044 = 1.76\,mm \tag{2.9}$$

We choose *d* = 1.5 mm, which ensures an angular divergence of the beam of 25.8 angular minutes.

A standard LED Cree XP-G with the following parameters is used as the light source [Table 3]:

Table 3. Parameters of the LED Cree XP-G.

Parameter	Value
Luminous flux *Φ*	130 lm
Current *I*	350 mA
Voltage when I = 350 mA	2.9 V
Operating temperature range	-40 - +85 °C
Size	3.45 x 3.45 mm
Viewing angle	125°
Color rendering index R_a	80 - 90

2.7 The electrical scheme of the installation

The electrical scheme of the installation is shown in the figure [Figure 32]. Double stabilization is carried out in terms of voltage and current. For this purpose, a stabilized power supply unit 12V by the Robion company (*PS*), a power module with a stabilized output current 500 mA by the Mean Well company (*PM*) and a Zener diode (*VD1*) are introduced in the scheme. Thus, the LED voltage and the current consumed by the LED are constant.

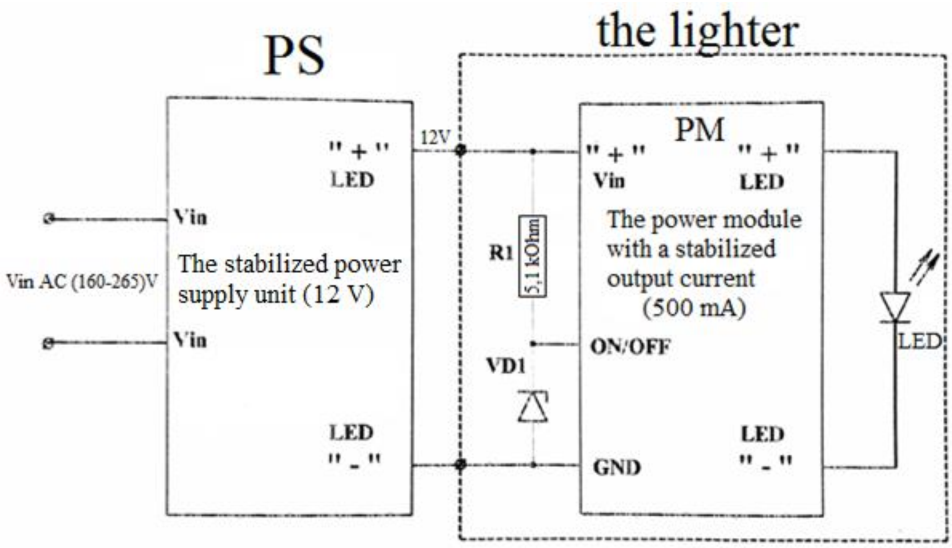


Figure 32. The electrical scheme of the installation.

One of the most important problems when using LEDs as light sources is heat removal since the lighting characteristics of a LED strongly depend on temperature. Since temperature control is difficult, the dependence of the light characteristics of the LED during operating was studied. It was found that after 25 minutes of operating the lighting characteristics of the LED are stable. It was decided to carry out all measurements 25 minutes after the LED is turned on.

3 CALCULATIONS AND RESULTS

3.1 The illuminance of the sample

The illuminance of the sample can be calculated. First we consider that the LED will consume 500 mA current. For this current the luminous flux of the LED is [Figure 33]:

$$\Phi = 1.37 \cdot 130\,lm = 178.1\,lm \tag{3.1}$$

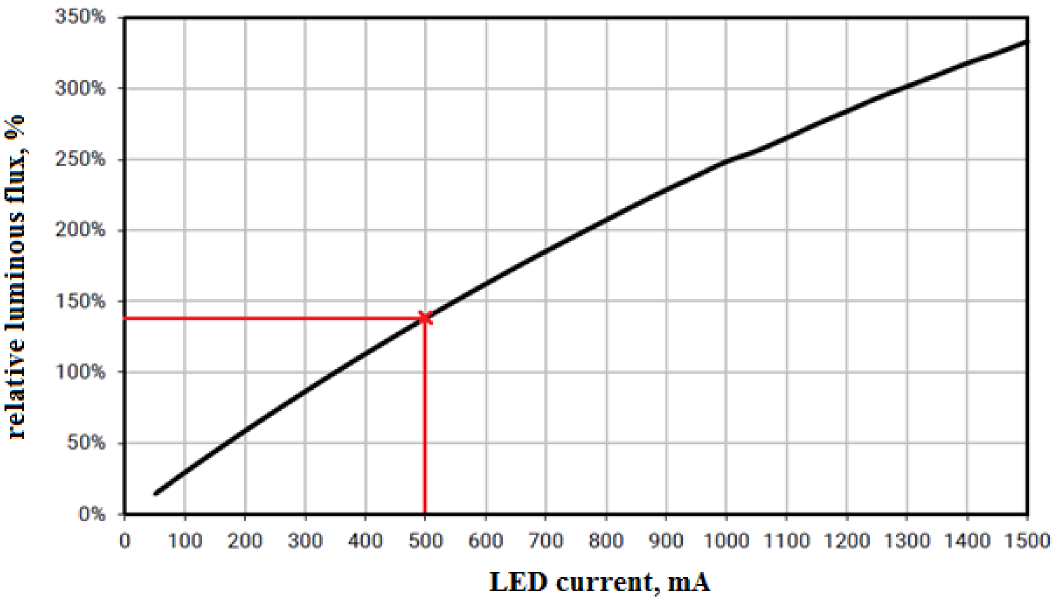


Figure 33. The dependence of the luminous flux of the LED on current [24].

To determine the area of the emitting part of the LED, we use the mechanical size of the lens [Figure 34] and the laws of geometry.

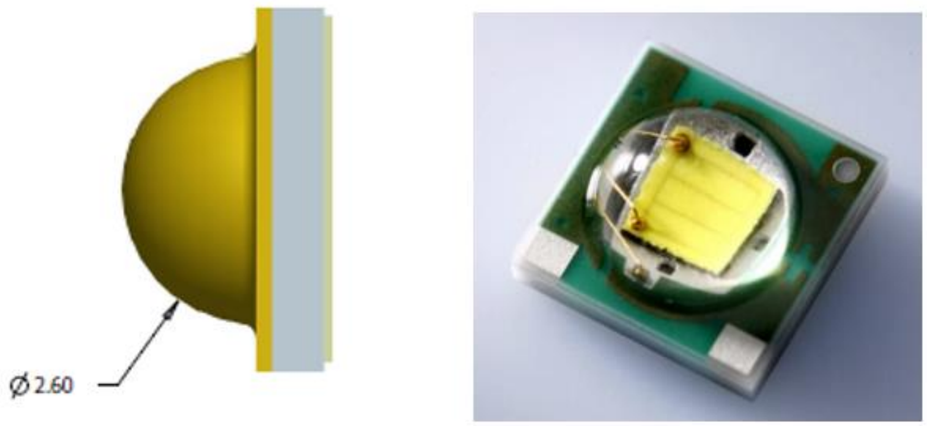


Figure 34. The LED Cree XP-G: mechanical size (left), general view (right) [24].

The emitting surface is a square inscribed in the circle, which is the base of the LED lens. The side of this square is:

$$a = 2.6 \cdot 10^{-3} m \cdot \frac{\sqrt{2}}{2} = 1.84 \cdot 10^{-3}\, m \tag{3.2}$$

However, after the LED there is a diaphragm *d*, whose diameter is smaller than the side of the square *a*, that is, the diaphragm *d* will be completely filled with light. To calculate the illuminance of the sample, it can be assumed that the light source is an circle with diameter *d* and constant luminance along its area. We will assume that the LED surface emits uniformly, then the luminous flux emerging from the diaphragm *d*:

$$\Phi_d = \Phi \cdot \frac{\pi d^2 / 4}{a^2} = 178.1 lm \cdot \frac{\pi \cdot \left(1.5 \cdot 10^{-3}\right)^2 / 4}{\left(1.84 \cdot 10^{-3}\right)^2} = 93.1(lm) \tag{3.3}$$

The flux falling on the objective can be found by the formula:

$$\Phi_o = \int I(\alpha, \beta)\, d\Omega \approx I_{90}\Omega = \frac{\Phi_d}{\pi} \cdot \left(\frac{0.5 \cdot D}{f}\right)^2 = \frac{93.1 lm}{\pi} \cdot \left(\frac{0.5 \cdot 80 \cdot 10^{-3}}{200 \cdot 10^{-3}}\right)^2 = 1.2\, lm \tag{3.4}$$

This formula can be used to estimate the flux, neglecting the change in the luminous intensity in the plane of the objective. Also, this calculation does not take into account the presence of a hemispherical lens on the LED. The average illuminance of the objective is:

$$E_o = \frac{\Phi_o}{S_o} = \frac{\Phi_o}{\pi D^2 / 4} = \frac{1.2}{\pi \left(80 \cdot 10^{-3}\right)^2 / 4} = 235.9\, lx \tag{3.5}$$

The light that falls on the objective passes it, then falls on the mirror and is reflected on the sample. There are losses in the mirror and in the objective associated with absorption and scattering. However, the transmission coefficient of the objective and the reflection coefficient of the mirror are unknown. The illuminance in a parallel beam of light does not depend on distance. However, the beam from the lighter in our installation has some divergence, so the illuminance should vary with the distance.

For illuminance measurements the illuminancemeter LMT Pocket-lux 2 Version B [Figure 35] was selected. The characteristics of the device are specified in the table [Table 4]:

Table 4. The characteristics of the illuminancemeter LMT Pocket-lux 2 Version 2 B [25].

Parameter	Value
Measuring ranges	0.01-199.99 lx 1-19999 lx
Light sensitive surface	10 mm diameter
Integration time	100 ms
Operation temperature	0-50 ^oC

Figure 35. The illuminancemeter LMT Pocket-lux 2 Version B [25].

The normal illuminance in the plane of the sample was measured at 7 points [Figure 36] [Table 5]. The point 1 lies on the optical axis. The location of the points was calculated in such a way that the average illuminance could be found as the arithmetic mean. A circle with the diameter of 70 mm, whose center coincides with the optical axis, was chosen as the photometric area. The rationale for the selection of such a diameter can be found in the section “The luminance of the sample”.

Table 5. The illuminance at the points in the plane of the sample.

№ of the point	Illuminance, lx
1	162.9
2	153.4
3	148.8
4	151.9
5	159.0
6	163.4
7	160.6

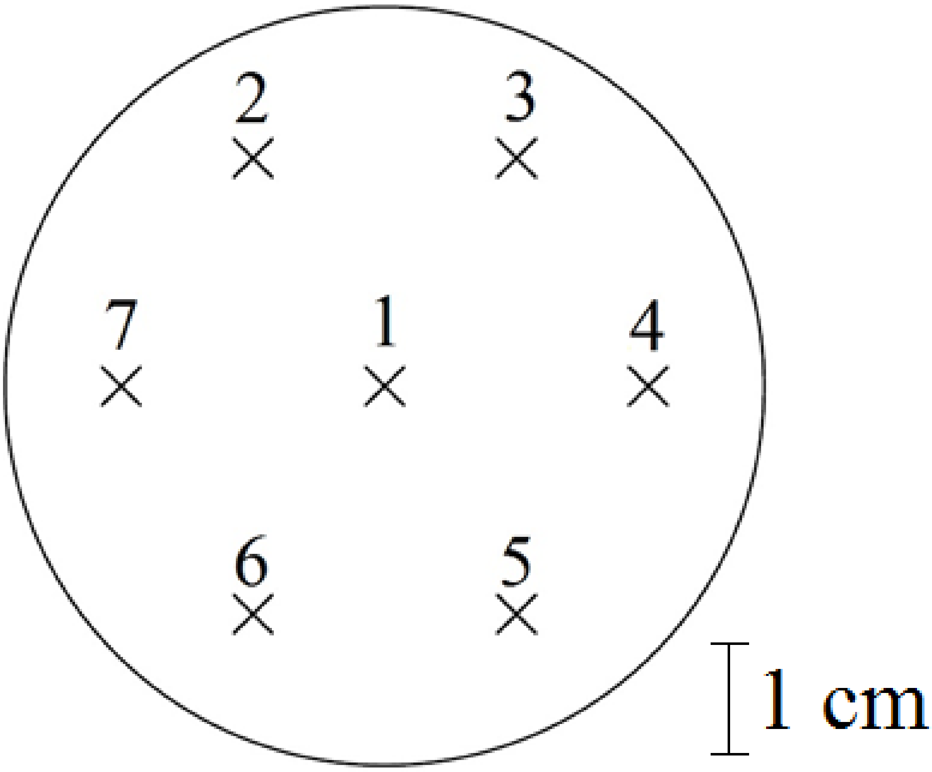


Figure 36. The location of the points in the plane of the sample for illuminance measurements.

Apparently, the range of values is quite large, which may be due to the inaccuracy of mounting of the LED in the focus of the objective, the mismatch between the optical axes of the LED and the objective, the inaccuracy of the mirror mounting. The average illuminance of the sample, created by the light spot with the diameter of 70 mm:

$$E_{av} = \frac{\sum_{i=1}^{7} E_i}{7} = 157.1 lx \qquad (3.6)$$

The measured average illuminance of the sample correlates with the results of the calculation of he illuminance on the sample. To estimate the accuracy of the calculation, the illuminance along the optical axis was measured [Figure 37]. The results of the measurements are given in the table [Table 6]:

Table 6. The illuminance at the pointsalong the optical axis.

№ of the point	Illuminance, lx
1	289.5
2	287.7
3	230.0
4	203.6
5	177.5

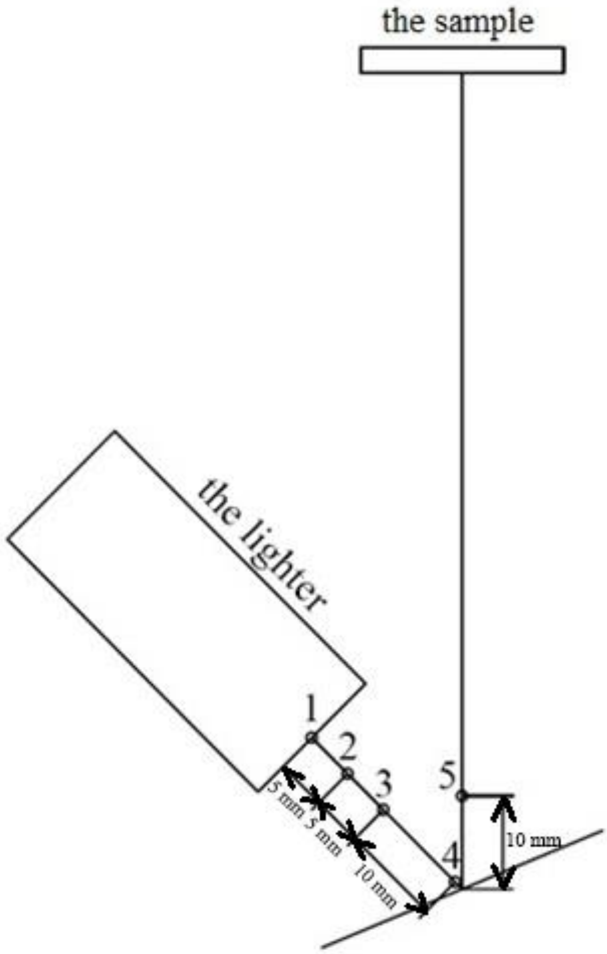


Figure 37 The location of the points along the optical axis for illuminance measurements

The measured illuminance on the optical axis immediately after the objective of the lighter greatly exceeded the calculated illuminance. This is due to the fact that only the direct component was taken into account, but in reality the internal surface of the lighter reflected the light, which was noticeable even by the eye. Also, the results of measurements showed that the illuminance in the light beam strongly depend on the distance, although in the theory in a parallel light beam such a dependence should be very weak.

3.2 Errors in measuring the illuminance

The average illuminance of the sample was measured only once. However, these measurements are made with a certain error, which must be taken into account when finding the luminance coefficient. The accuracy of measuring the illuminance is primarily associated with the measuring instrument (illuminancemeter), but other elements of the installation also have an effect. The estimation of errors is based on the modern standard CIE ISO/CIE 19476: 2014 [23]. The documentation of the illuminancemeter LMT Pocket-lux 2 shows the errors according to the standard [Table 7] for the illuminant A (an incandescent lamp with the correlated color temperature

2856 K). Therefore, it is necessary to investigate the illuminancemeter errors for the spectrum used in the setup, and to exclude some error.

Table 7. Errors of the illuminancemeter LMT Pocket-lux 2 [25].

Designation	Name	Value
f_1	V(λ)-adaptation	< 2.5%
f_2	spatial evaluation	< 1.5%
f_3	error by non-linearity	< 0.1% ± 1 digit
f_4	error by display unit	< 0.55%
f_5	fatigue	< 0.1%
f_7	error due to modulated light	< 0.1%
f_{11}	range change	< 0.1%
u	UV-response	< 0.1%
r	IR-response	< 0.1%

The error connected with the spectral correction of the sensitivity of the receiver *S(λ)* to the sensitivity of the eye *V(λ)*:

$$f_1 = \frac{\int_{380}^{780} \varphi(\lambda) S(\lambda) d\lambda \int_{380}^{780} \varphi_A(\lambda) V(\lambda) d\lambda}{\int_{380}^{780} \varphi(\lambda) V(\lambda) d\lambda \int_{380}^{780} \varphi_A(\lambda) S(\lambda) d\lambda}, \tag{3.7}$$

where $\varphi_u(\lambda)$ is the relative spectral density of the luminous flux incident on the sample and $\varphi_A(\lambda)$ is the relative spectral density of the luminous flux of the A illuminant.

The sensitivity of the illuminancemeter $S(\lambda)$ is given in the documentation for the instrument. $\varphi_u(\lambda)$ is the spectrum of the LED (we assume that the radiation incident on the sample does not change its spectral composition after passing through the objective of the lighter and the mirror). For the calculation we use the spectra from the documentation for ranges of color temperatures 3700 - 5000 K and 5000 - 8300 K. For a more accurate calculation, we will measure the spectrum of the LED with the UPRTek MK350N PLUS spectrometer [Figure 38]:

Figure 38. The UPRTek MK350N PLUS spectrometer [26].

All the spectral distributions required for the calculations of f_1, are shown in the figure [Figure 39].

The maximum error was obtained using the measured spectrum of the LED:

$$f_1 = \frac{\int_{380}^{780} \varphi(\lambda) S(\lambda) d\lambda \int_{380}^{780} \varphi_A(\lambda) V(\lambda) d\lambda}{\int_{380}^{780} \varphi(\lambda) V(\lambda) d\lambda \int_{380}^{780} \varphi_A(\lambda) S(\lambda) d\lambda} = 0.9\% \tag{3.8}$$

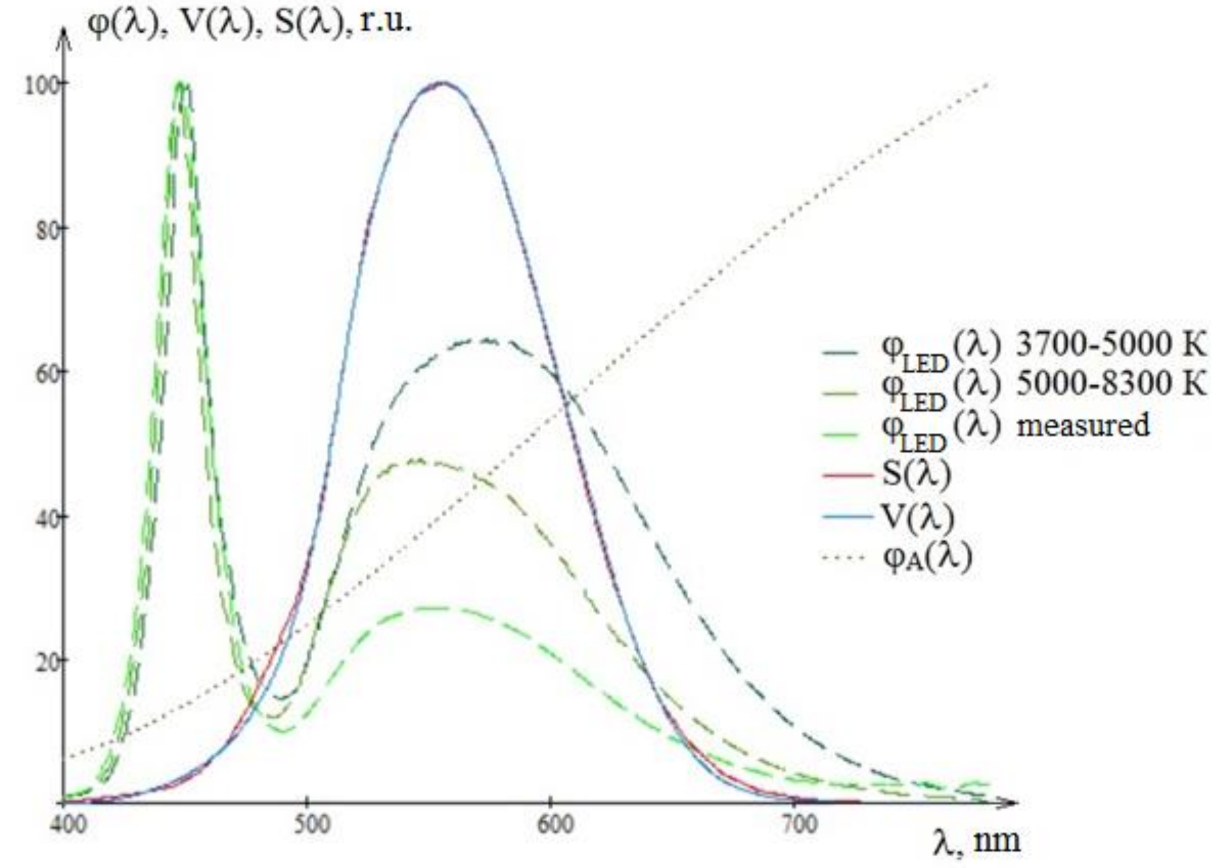


Figure 39. The spectral distributions for the f_1 calculation.

The error of the angular dependence f_2 can be excluded from the general measurement error, since measurements are made only for the normal incidence. To exclude this error, it is necessary to ensure an accurate installation of the photosensitive surface of the illuminancemeter in the plane of the sample. For this purpose, the electronic level ADA ProDigit MICRO with the measurement accuracy ±0.2° [Figure 40], a measurement table and a wooden sample that repeats the shape and the size of the concrete asphalt coating with a perfectly flat and smooth surface are used. Therefore, we can conclude that the error of the angular dependence in the measurements of the illuminance does not exist.

Figure 40. The electronic level ADA ProDigit MICRO.

To test the fatigue f_5, the illuminancemeter was kept in the dark for 24 hours. Then the illuminance measurements were made in the plane of the sample at the point №6 [Figure 36] 10 seconds and 30 minutes after turning the illuminancemeter on. At the same time, the stability of the light parameters of the lighter was ensured. It was senseless to carry out measurements with an illuminance of 1000 lx (that is specified in the documentation of the illuminancemeter), since the maximum illuminance during the measurements is observed at the point №6 was 10 times less than 1000 lx. Based on the measurements, the error associated with fatigue of the device was found:

$$f_5 = \frac{E_6\left(t = 10\,s\right)}{E_6\left(t = 30\min\right)} - 1 = \frac{163.4}{163.2} - 1 = 0.12\% \tag{3.9}$$

The error due to the influence of the inhomogeneous sensitivity of the receiving surface f_9 was estimated. This error is not specified in the illuminancemeter documentation, but it is in the standard CIE ISO/CIE 19476:2014 [23]. To find the effect of the inhomogeneous surface sensitivity, measurements of the illuminance were made in five different locations of the photosensitive surface of the illuminancemeter. To do this, black cardboard masks with holes were applied to the photosensitive surface [Figure 41]. Since the maximum illuminance that can be created by the lighter does not exceed 300 lx, the illumination during measurements with the masks is too small [Table 8]. The error f_9 is calculated using the following formula:

$$f_9 = \frac{\sum_{i=2}^{5} |E_i - E_1|}{4E_1} = 7.5\% \quad (3.10)$$

The obtained error is large, since the illuminance generated in areas with the diameter 0.5 mm is too small. Therefore, this error estimate is incorrect. In fact, the error f_9 of such a high-quality instrument as LMT Pocket-lux 2 should not exceed 0.1%. To conduct a correct assessment in the future, it is planned to conduct similar studies in high illuminance with the same spectral composition. At this stage, the error f_9 is not taken into account when finding the general error of illuminance measurements.

Table 8. The illuminance when testing the inhomogeneous sensitivity of the receiving surface of the illuminancemeter.

№ of the point	Illuminance, lx
1	1.0
2	0.9
3	1.0
4	0.9
5	0.9

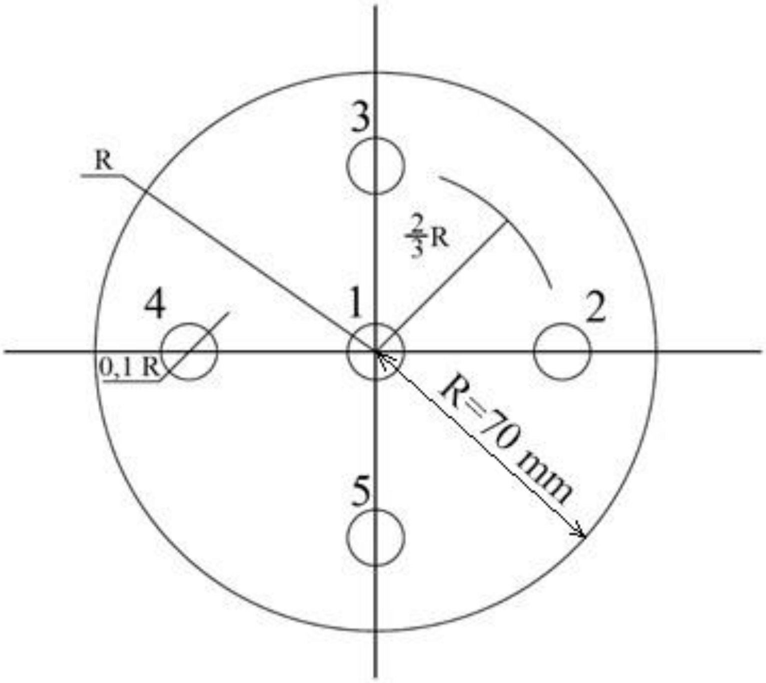


Figure 41. The layout of the holes in the masks for measuring the error f_9.

The errors *u* and *r*, which are associated with the residual sensitivity in the UV and the IR parts of the spectrum, are zero in our measurements, since there is no UV and IR radiation in the spectrum of the LED that is used.

Thus, the general measurement error of the illuminance is:

$$f_{gen} = f_1 + f_2 + f_4 + f_5 + f_{11} + u + r = \\ = 0.9\% + 0\% + 0.55\% + 0.12\% + 0\% + 0\% + 0\% = 1.57\% \quad (3.11)$$

The following errors are not taken into account: the error of nonlinearity f_3, the effect of temperature and humidity f_6, error due to modulated light f_7, the effect of polarization f_8 and the inhomogeneous surface sensitivity f_9. The influence of these factors, perhaps, will be studied in the future. It is expected that the general error of illuminance measurement will not exceed 3%.

3.3 The luminance of the sample

The estimation of the luminance of a sample of concrete asphalt is practically impossible, because for this it is necessary to know the reflective properties of the coating, which are the result to be obtained on the measuring installation. Therefore, the luminance is found only as a result of measurements.

To measure the luminance, the Konica Minolta luminancemeter LS-150 was chosen [Figure 42]. The characteristics of the device are indicated in the table [Table 9]:

Table 9. The characteristics of the luminance meter Konica Minolta LS-150.

Parameter	Value
Measuring angle	1^{o}
Minimum measuring area (diameter)	1.3 mm
Shortest measuring distance	213 mm
Luminance range	0.001-999990 cd/m^2
Integration time	0.1 – 3.0 s
Operation temperature	0 - 40 ^{o}C

Figure 42. The luminancemeter Konica Minolta LS-150.

The key factors in choosing the luminancemeter were the measuring range, the measuring angle and the ability to control the measurements on the computer.

The measurements of the luminance should be carried out at a small angle. The smaller this angle, the better the capture of rays corresponding to the required angle of observation (closer to parallel rays) is provided [Figure 43].

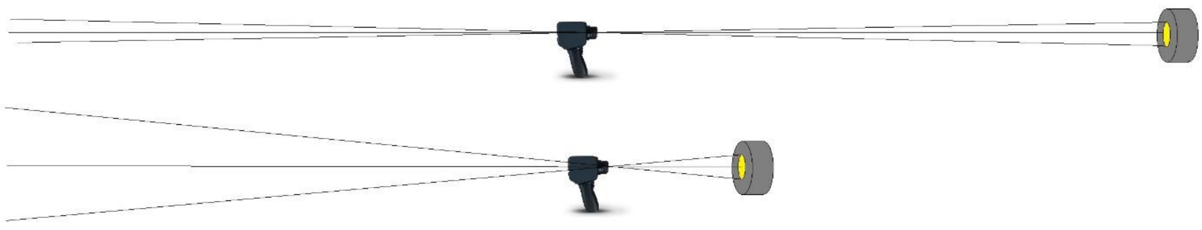


Figure 43. The measurement of the luminance at a small angle.

The diameter of the light spot, the average luminance of which is measured, should be chosen so that the presence of stones or other irregular inclusions on the concrete asphalt coating sample does not affect the result of averaging. Therefore, the spot diameter should be at least 60 mm. In addition, when the sample of the concrete asphalt coating is rotated at the installation along the angle U_v, the projection of the light spot on the plane parallel to the plane of measurement of luminance becomes an ellipse, the smaller axis of which is smaller than the diameter of the spot. Thus, at some position of the sample, the measured field of the luminancemeter will not be completely filled with light, which will lead to incorrect measurement results. Therefore, as the photometric area, a light spot with the diameter of 70 mm was chosen.

To calculate the diameter of the light spot that will be on the sample, taking into account the angular divergence of the beam, we find the distance r_s between the lighter and the sample with the help of the laser range finder RGK D100 determining the distance with an accuracy ±1.5 mm: r_s = 0.800 m. Then the diameter of the light spot on the sample is:

$$d_s = 0.08 + 2 \cdot tg\left(\frac{\omega_l}{2}\right) \cdot 0.800 = 0.08\,m + 2 \cdot tg\left(\frac{25.8'}{2}\right) \cdot 0.800\,m = \\ = 0.086\,m = 86\,mm \qquad (3.12)$$

The diameter of the light spot on the sample formed by the lighter, taking into account the angular divergence of the beam, found in the measurement, was 90 mm, which correlates with the calculated value. Thus, the picture observed by the operator when measuring the luminance in the normal direction without taking into account the stretching of the spot (which depends on the angle ε) is as follows [Figure 44]:

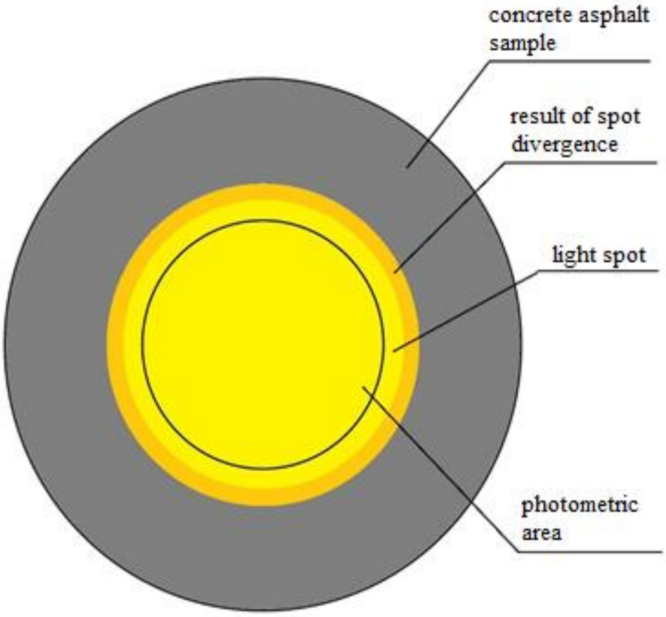


Figure 44. The picture observed when measuring the luminance.

Since the measuring angle of the luminancemeter is 1°, the distance r at which measurements are to be taken for providing the photometric area with the diameter of 70 mm:

$$r = \frac{70\,m \cdot 10^{-3} / 2}{tg\,0.5^{o}} = 7.01m \qquad (3.13)$$

Such distance can be provided in the room where the measurements are done. When using the luminancemeter Konica Minolta LS-160 with the measuring angle $(1/3)^{o}$, the distance r is approximately 12 meters. Such a distance can not be provided in the room where the measurements are done, so the luminancemeter Konica Minolta LS-150 with the measuring angle of 1° was chosen for measurements.

The luminance measurements were carried out according to the developed method. At this stage, there was only one sample of concrete asphalt. The measurements were carried out for two angles of incidence: $tg\varepsilon = 0$ and $tg\varepsilon = 1.5$. As a result of the measurements, the screening areas of the sample by the lira and the lighter were found, the values of the angles U_v for the measurement. Also, the extreme values of the angles U_v were found at which the photometric area is completely filled with light. The results of the measurements are presented in the tables [Table 10] [Table 11]. The combinations of angles at which the photometric area is not completely filled with light are marked with a "-" sign. The combinations of angles at which measurements are possible, but not necessary, are marked with a "+" sign. Combinations of angles at which the screening is observed are marked with the "s" sign.

Table 10. The luminance measurement results $L_{\varepsilon}(U_h,U_v)$ for $tg\varepsilon=0$.

$L_{\varepsilon}(U_h,U_v)$, cd/m^2		The angle U_h, °				
		-30	-15	0	15	30
The angle U_v, °	37.5	-	-	3.459	-	-
	32.5	-	-	3.568	-	-
	29.5	-	3.573	+	3.569	-
	27.5	-	3.606	3.655	3.586	-
	22.5	-	3.688	3.732	3.655	-
	17.5	-	3.759	3.824	3.717	-
	15.5	3.612	+	+	+	3.488
	12.5	3.638	3.819	3.941	3.779	3.513
	9	s	3.868	4.034	3.819	3.539
	0	s	s	s	s	s
	-9	s	s	4.108	3.835	3.573
	-11	s	3.851	+	+	+
	-12.5	s	3.835	4.001	3.804	3.557
	-13.5	3.622	+	+	+	+
	-15.5	3.607	+	+	+	3.539
	-17.5	-	3.768	3.886	3.774	-
	-22.5	-	3.702	3.792	3.686	-
	-27.5	-	3.639	3.717	3.627	-
	-29.5	-	3.610	+	3.593	-
	-32.5	-	-	3.619	-	-
	-37.5	-	-	3.522	-	-

Table 11 The luminance measurement results $L_\varepsilon(U_h,U_v)$ for $tg\varepsilon=1,5$

$L_\varepsilon(U_h,U_v)$, cd/m^2		The angle U_h, °				
		-30	-15	0	15	30
The angle U_v, °	60	s	s	s	s	s
	56.4	s	s	s	s	s
	52	s	s	3.148	s	s
	50	s	s	+	2.938	s
	48	s	s	+	+	-
	47	s	S	3.083	2.839	-
	45	-	2.826	+	+	-
	42	-	2.729	2.811	2.681	-
	38	2.462	+	+	+	-
	37	2.452	2.571	2.625	2.537	-
	32	2.382	2.452	2.478	2.475	-
	27	2.289	2.342	2.356	2.326	2.269
	22	2.230	2.253	2.258	2.240	2.217
	17	2.181	2.179	2.194	2.176	2.172
	12	2.142	2.124	2.132	2.125	2.134
	7	2.112	2.081	2.097	2.087	2.113
	0	2.079	2.047	2.051	2.054	2.070
	-7	2.064	2.036	2.039	2.032	2.053
	-12	2.065	2.098	2.039	2.027	2.062
	-17	2.070	2.057	2.058	2.038	2.066
	-22	2.087	2.071	2.086	2.068	2.080
	-27	2.103	2.105	2.140	2.099	2.102
	-32	2.154	2.164	2.193	2.160	2.135
	-36	2.175	+	+	+	-
	-37	-	2.245	2.281	2.240	-
	-42	-	2.357	2.417	2.357	-
	-47	-	2.495	2.579	2.468	-
	-52	-	2.681	2.921	2.628	-
	-56.4	-	2.845	3.050	2.799	-
	-60	-	-	3.268	-	-

The results of the measurements are shown in the figures [Figure 45] [Figure 46]. One of the main problems detected is the impossibility of making measurements for the angles at which the maximum luminance is expected. This is connected with screening. Therefore, the points are connected by means of the B-spline. B-spline is a function that is often used for approximation. Using of this approximation allows us to see the extremum. To construct a large number of indicatrices, it is necessary not only to carry out measurements for all other angles *tgε* and U_h, but also to transit from the angles of the photometric system to the angles α, β and ε. However, the results and the dependences obtained at this stage correlate with the expected results.

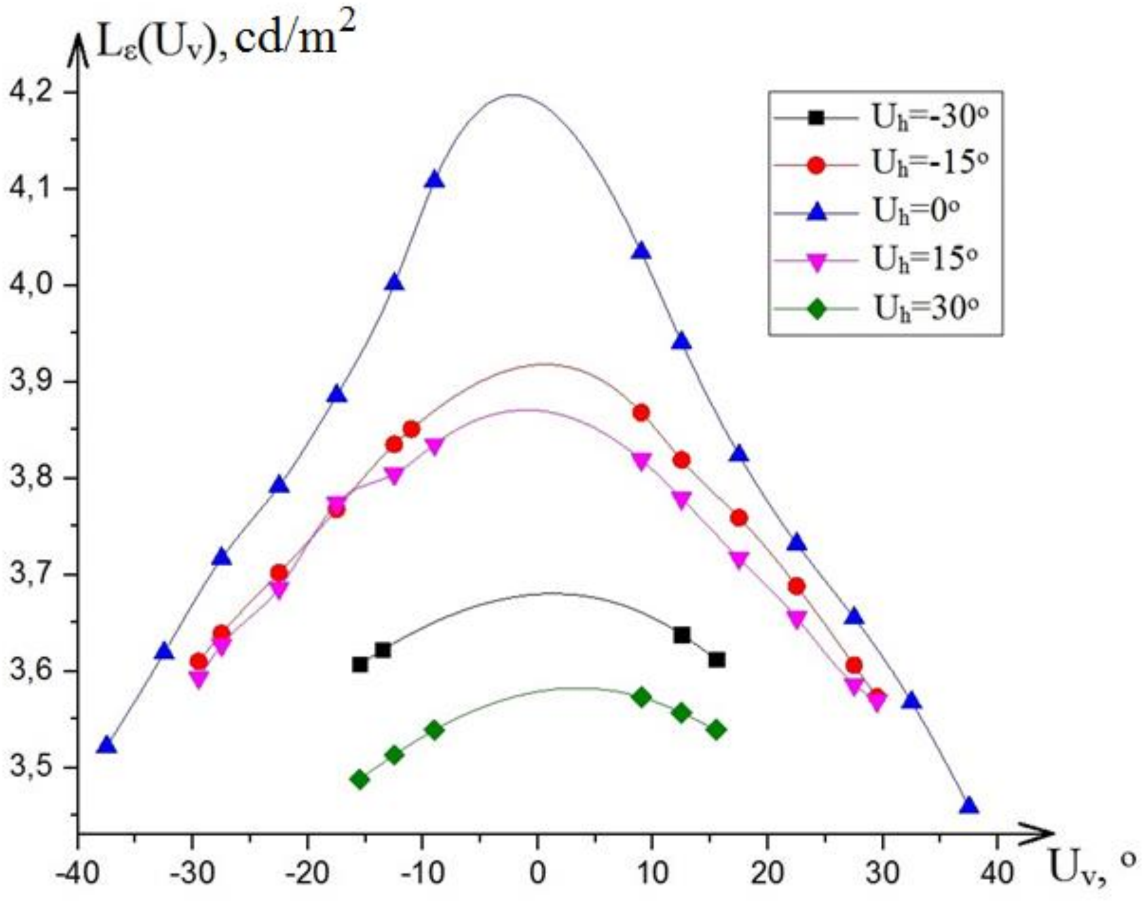


Figure 45. The luminance measurement results for tgε=0.

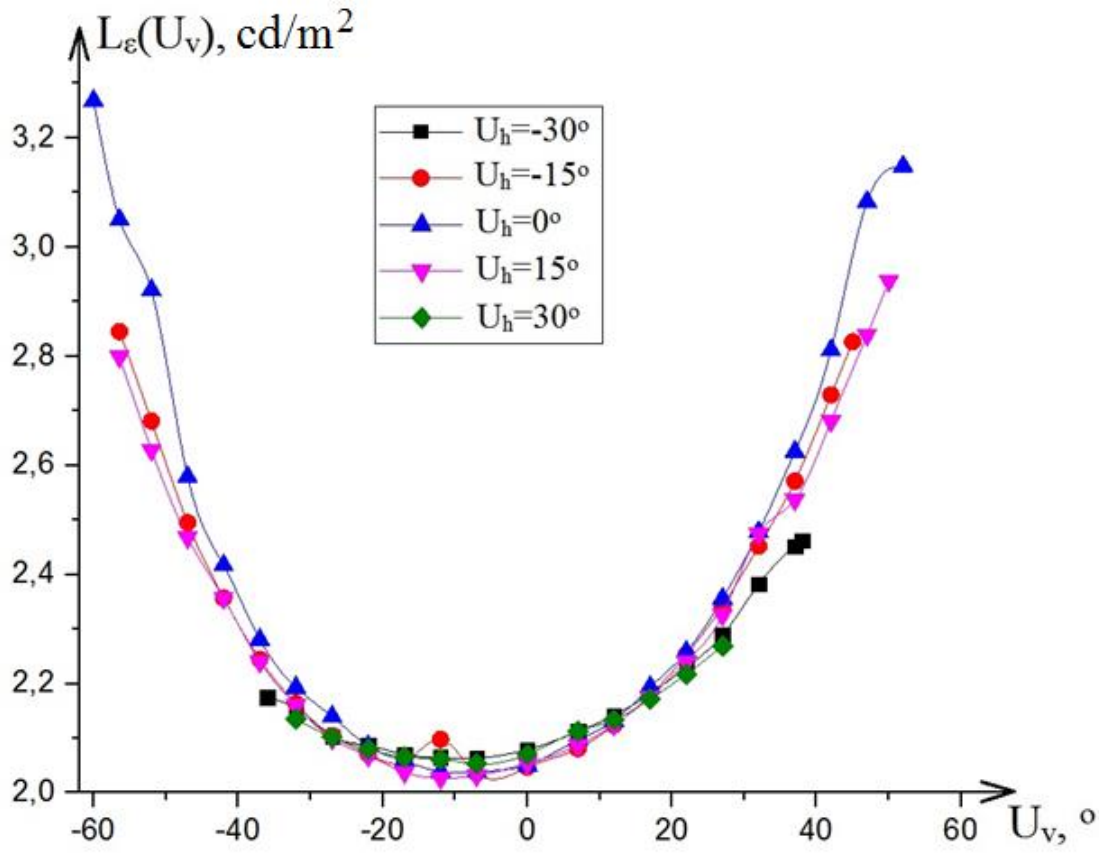


Figure 46. The luminance measurement results for tgε=1.5.

3.4 Errors of measuring the luminance

The accuracy of luminance measuring is primarily associated with the measuring device (luminancemeter). The device Konica Minolta LS-150 belongs to class *B*, which corresponds to the overall measurement error not greater than 4%. Let us investigate the error of spectral correction f_1, which is usually the largest in photometric measurements. The spectral composition of the radiation reflected from the sample of the concrete asphalt coating depends on the spectral reflection coefficient. Perhaps, the spectral composition also depends on the angles of incidence and observation. To estimate the spectral reflection coefficient, attempts were made to measure the spectrum reflected from the concrete asphalt coating at different angles U_v and $tg\varepsilon$. However, the illuminance created on the spectrometer was too small for a correct measurement of the spectrum. Therefore, we assume that the spectral composition of the radiation does not change when reflected from concrete asphalt. The spectral sensitivity of the luminancemeter is given in the documentation, then the error of the spectral correction f_1 when measuring the luminance is:

$$f_1 = \frac{\int_{380}^{780} \varphi(\lambda) S(\lambda) d\lambda \int_{380}^{780} \varphi_A(\lambda) V(\lambda) d\lambda}{\int_{380}^{780} \varphi(\lambda) V(\lambda) d\lambda \int_{380}^{780} \varphi_A(\lambda) S(\lambda) d\lambda} = 0.3\% \tag{3.14}$$

In addition to the errors specified in CIE ISO/CIE 19476:2014 [23], the error associated with the inaccuracy of the aiming of the luminancemeter on the photometric area may be significant. In the near future it is planned to estimate this error. It is expected that the overall error of the luminance measurement will not exceed 5%.

4 CONCLUSIONS

The main result of the work, in my opinion, is the operating measuring system, on which it is possible to measure the reflective characteristics of concrete asphalt coatings.

In this thesis the errors are estimated, which exist now when using the developed installation. Solutions are proposed to exclude or reduce some of the errors, that is more important.

In the near future, all possible errors will be studied (and, if possible, excluded) in order to obtain the most accurate results. The measurement technique will be refined, optimum combinations of angles will be found for carrying out measurements of any concrete asphalt coatings and all shading zones will be found. To assess the accuracy of the results that is obtained with the installation, studies of the reflective properties of white plates will be conducted, the reflective properties of which are known and recorded in passports.

One of the main problems to be solved is to find and select mathematical models and approximations to obtain luminance coefficients for the observation angle of 1^{o}. At this stage are available luminance and illuminance of a sample only for angles which strongly differ from 1^{o}. It is expected that the error in finding luminance coefficients as a result of measurements and mathematical operations will not exceed 12 - 14%.

In the future, it is planned to study the reflective properties of a large number of samples from all over Russia on the well-developed and well-functioning installation. On the basis of these measurements, a base will be constructed with road surfaces and their reflective properties. This base will form the basis for a new standard in the field of road lighting. The developed installation, a database with coatings and a new standard can form the basis for the development of a mobile installation for measuring the reflective properties of concrete asphalt pavements.

5 SUMMARY

The main results of the thesis are following: the kinematic and optical scheme of an installation for measuring the reflective properties of road surfaces are developed. The measurement technique is developed based on a photometric system, which has never been used by anyone before in the photometry of road surfaces. The electrical scheme of the installation is developed and the calculation of the lighter is carried out. On the basis of the calculations and developed schemes, the measuring installation is created. It consists of a lighter, of a rotary system and receivers. Errors that may occur during measurements are classified and evaluated. Requirements to the elements of the installation are identified. The structural elements of the installation are selected according to the requirements and solutions are proposed to reduce errors and to increase the accuracy of measurements; the measurement error of illuminance is ≤3% and of luminance is 5%. The measurements of the illuminance in the plane of the sample of concrete asphalt are carried out. The measurements of the luminance of a test sample for some combinations of angles are carried out. Only one sample was measured.

REFERENCES

[1] State Standard R 55706-2013. Road lighting. Classification and requirements. Moscow, Standartinform Publ., 2016. 12 p. (In Russian)

[2] State Standard R 55708-2013. Road lighting. Design methods of normative permormances. Moscow, Standartinform Publ., 2013. 37 p. (In Russian)

[3] Zaluga V.P. *Magazine of Avtomobil'nye dorogi.* 1965. No. 11. Pp. 23-24 (In Russian)

[4] CEN 2015b. EN 13201-3:2015. *Road lighting – Part 3: Calculation of performance.* Brussels: CEN

[5] Gurevich M.M. Fotometrija. Teorija, metody i pribory *[Photometrics. Theory, methods and devices]. Leningrad, Jenergoatomizdat Publ., 1983. 272 p. (In Russian)*

[6] Zakaznov N.P., Kirjushin S.I., Kuznetsov V.I. Teorija opticheskih sistem [The theory of optical systems]. Moscow, Mashinostroenie Publ., 1992. 448 p. (In Russian)

[7] Rossi G., Lacomussi P., Radis M. On-site road surface characterization. *PROCEEDINGS of CIE 2016 "Lighting Quality and Energy Efficiency".* Melbourne, 2016. Pp. 334-344

[8] Ostrovkij M.A. *Magazine of Svetotehnika.* 1956. No. 1. Pp. 11-16 (In Russian)

[9] Ostrovskij M.A. *Magazine of Svetotehnika.* 1956. No. 2. Pp. 14-18 (In Russian)

[10] Ostrovskij M.A. *Magazine of Svetotehnika.* 1961. No. 5. Pp. 1-6 (In Russian)

[11] Ostrovskij M.A. Razrabotka novyh norm ulichnogo osveshhenija [Development of new standards of road lighting]. 1971. (In Russian, unpublished)

[12] Boudak V.P., Karachev V.M. Razrabotka ustanovki dlja izmerenija kojefficientov jarkosti dorozhnyh pokrytij [Development of an installation for measuring the luminance factors of road surfaces]. 2009. (In Russian, unpublished)

[13] Karachev V.M. Issledovanie metoda dlja izmerenija kojefficientov jarkosti dorozhnyh pokrytij v naturnyh uslovijah s cel'ju povyshenija kachestva proektirovanija osvetitel'nyh ustanovok v interesah jenergosberezhenija [Investigation of the method for on-site measuring the luminance factors of road surfaces with the aim of improving the design quality of lighting installations in the interests of energy saving]. 2012. (In Russian, unpublished)

[14] Volobyev S. Razrabotka ustanovki dlja issledovanija otrazhatel'nyh svojstv dorozhnyh pokrytij [Development of an installation for studying the reflective properties of road surfaces]. 2012. (In Russian, unpublished)

[15] Peiner P. Die Erfassung der lichttechnischen Eigenschaften von Strabendecken – Ergebnisse einer Mebreihe [The detection of the light properties of overhead tiles – results of a meteor series]. *Magazine of Lichttechnik.* 1973. No. 25. (In German)

[16] Verbeek T.G., Vermeulen J. Laboratory method for measuring luminance factors of road surfaces. *Light and Lighting*. 1971. No. 64. P. 132.

[17] Frederiksen E., Gudum L. The quality of street lighting installation under changing weather conditions. *Lighting Research and Technology*. 1972. No. 4.

[18] Muzet V., Paumier J.-L., Guillard Y. COLOROUTE: a mobile gonio-reflectometer to characterize the road surface photometry. *CIE international symposium on road surface photometric characteristics.* Torino, 2008.

[19] Maghe L. Characterization of Road Surfaces using a Mobile Gonio-reflectometer. *CIE international symposium on road surface photometric characteristics.* Torino, 2008.

[20] Zamjatin V.A. Svojstva issleduemyh poverhnostej [Properties of the surfaces under study]. 2013. (In Russian, unpublished)

[21] Korobko A.A. Approximation of road surface luminance coefficient. *CIE International Lighting Conference.* Paris, 2013.

[22] State Standard R 54350-2015. Light devices. Light requirements and test methods. Moscow, Standartinform Publ., 2015. 45 p. (In Russian)

[23] ISO/CIE 19476:2014. *Characterization of the performance of illuminance meters and luminance meters.* 50 p.

[24] Cree XLamp XP-G LEDs Data Sheet. URL: http://www.cree.com/led-components/media/documents/XLampXPG.pdf

[25] Illuminance Meters LMT POCKET LUX 2. URL: http://www.lmt.de/xtra/img/plux2.pdf

[26] UPRTek MK350N PLUS User Manual and Warranty. URL: http://www.uprtek.com/v_comm/inc/download_file.asp?re_id=2724&fid=20381