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The influence of optical properties of pavement materials on the safety of pedestrian crossings and the application of universal design principles to road infrastructure

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ABSTRACT

In response to the growing demands for road safety and the effectiveness of materials used in urban infrastructure, this article presents an in-depth analysis of how various surface material properties influence the visibility and functionality of pedestrian crossings. By evaluating the reflectivity and luminance of materials, such as light-colored granite and other high-luminance surfaces, the study demonstrates that these materials not only reduce glare but also enhance nighttime visibility and lower surface temperatures during hot weather, thereby contributing to a safer and more comfortable pedestrian experience. The article also examines the benefits of incorporating universal design principles, including contrasting textures, pulsating signals, and audible cues, which facilitate movement for individuals with disabilities and improve the overall readability of crossings for all road users. When integrated with advanced material technologies, such design elements can significantly reduce accident risks and enhance accessibility for various social groups. The comprehensive approach of this study combines rigorous data analysis with practical design and material recommendations, offering actionable insights for the creation of safer, more sustainable, and accessible urban infrastructure. The findings suggest that the thoughtful selection of materials and the integration of universal design elements not only improve safety and usability but also support the development of intelligent and inclusive urban spaces.

Keywords: architectural barriers; reflectivity; luminance; universal design; surfaces; safety; pedestrian crossings.

INTRODUCTION

In recent years, regulations regarding pedestrian right-of-way on roads have evolved to better protect vulnerable road users. According to the Regulation of the Ministry of the Interior and Administration of the Republic of Poland dated September 17, 2022 [1], pedestrians now have the right-of-way when entering a crosswalk, except in situations involving trams. However, despite these significant legal changes, the latest data from the Accident and Collision Record System (SEWIK) [2] indicates an increase in pedestrian-involved accidents since the introduction of these regulations in 2022 [3,4]. This trend suggests that legal changes alone, though essential, are insufficient to ensure real improvements in safety within urban spaces, highlighting the need for supportive infrastructure solutions.

Existing studies reveal a significant gap in the literature concerning the impact of optical properties of surface materials – such as luminance and contrast – on the visibility of pedestrian crossings, as well as the effectiveness of universal design principles in crosswalk design. Previous research has primarily focused on road design from the perspective of vehicle users, without fully addressing the growing accessibility and safety needs of pedestrians, particularly for older adults and people with disabilities. Findings show that legislation alone cannot fully address the challenges posed by contemporary road infrastructure, which requires innovative and inclusive solutions to accommodate diverse user needs.

This article thus focuses on analyzing the surface materials used on pedestrian crossings, particularly examining their luminance and anti-slip properties, which directly impact pedestrian visibility and safety. The selection of high-luminance, light-colored materials, such as certain types of granite, plays a crucial role, as these materials not only reduce glare but also improve nighttime visibility and decrease surface heating during hot weather, thereby enhancing pedestrian comfort.

The article also explores the implementation of universal design elements, such as contrasting textures, pulsating signals, and audible cues, which facilitate navigation for people with vision and hearing impairments while improving the overall readability of crossings for all road users. Such innovations, combined with modern surface materials, have significant potential to reduce accident risks and increase accessibility within urban spaces for various social groups.

This publication aims to address the identified research gap by providing detailed data on surface material properties and their impact on pedestrian safety at crossings. The solutions proposed in the article, including light-colored surfaces and active crossings that respond to pedestrian presence, offer a substantial opportunity to enhance visibility and functionality in road infrastructure. The conclusions and recommendations presented here can serve as a practical foundation for implementing design policies that consider both safety and accessibility for a wide range of users, supporting the development of more sustainable and intelligent urban infrastructure. Thus, this publication is significant not only from a scientific perspective but also practically, offering concrete recommendations and action paths to improve quality of life and safety in public spaces (Figure 1).

Measurement of road surface luminance

The measurement of road surface luminance allows for the determination of the brightness level of the road as perceived by the driver. While driving, the driver encounters various road users (both motorized and non-motorized), obstacles (such as surface damage, irregularities, and speed bumps), lane narrowings (traffic separators), curves (road geometry, shoulder width), and changes in traffic organization (temporary detours, additional road markings, road mergers, exits, and surface irregularities).

A driver can only notice an obstacle on the road if there is sufficient contrast between the object and the surface. At night, proper contrast is ensured by street lighting installed along

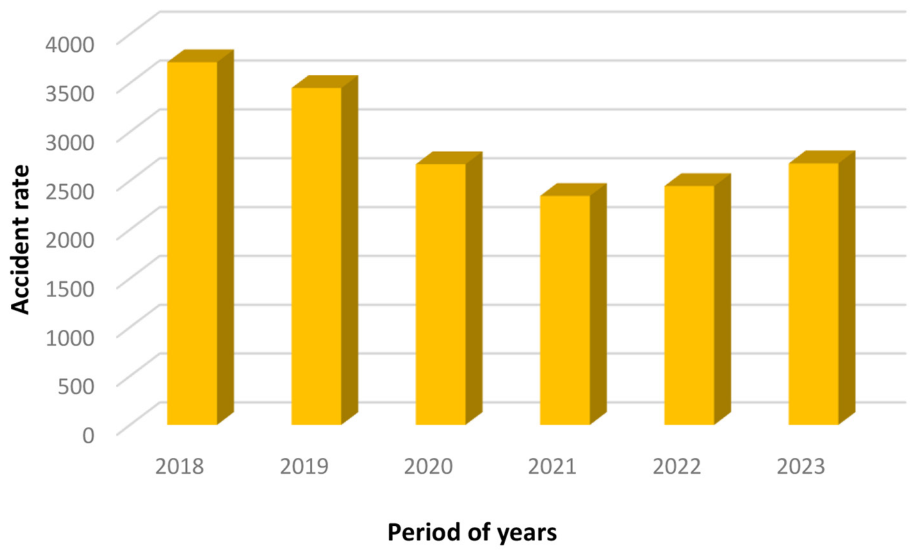

Figure 1. Accidents involving pedestrian victims at pedestrian crossings from 2018 to 2023 based on SEWIK [2] Database Data

roads. Additionally, visibility, which is crucial for accurately assessing road conditions, can be improved by using pavement materials with a texture that diffuses reflected light. This helps highlight dark obstacles against the road background [5,6].

Well-designed lighting ensures uniformity of reflected light, preventing drivers from encountering shadowed zones or areas of darkness that could obscure pedestrians or cyclists traveling at night without reflective elements. Using pavement mixtures that provide an appropriate level of luminance helps drivers navigate more safely at night under headlights and street lighting, allowing them to detect hazards earlier [7, 8].

Current road lighting standards are defined in the PN-EN 13201:2016 [9-12] regulation, which specifies the – selection of methods and procedures that must be followed when designing lighting systems. However, despite advancements in lighting technology, luminance is a crucial factor influencing the quality of illumination, not just light intensity.

A significant challenge is that asphalt and concrete do not evenly diffuse light, as their directional-diffuse reflection characteristics depend on the driving direction and weather conditions (temperature and humidity). Until a few years ago, luminance measurements in Poland were conducted only occasionally due to the limited availability and high cost of specialized equipment. However, they are now mandatory for surfaces in tunnels, roads with traffic categories KR5 to KR7, and engineering structures on major national roads and highways with concrete pavement [13, 14].

Currently, general knowledge on the subject allows for determining surface brightness only after construction, primarily through laboratory sample testing. The objective of my research is to establish a mathematical relationship between the intensity of reflected light and different mineral materials used as the base for asphalt mixtures (which constitute approximately 94% of the wearing course) [15]. Another research goal is to examine the relationship between surface texture, pavement color, temperature distribution, and thermal stress in asphalt pavement. The color and roughness of aggregate influence the amount of solar radiation reflected, which in turn affects the pavement temperature.

MATERIALS AND METHODS

The methodology presented in the article focuses on evaluating the luminance of different types of aggregates used in road surfaces, as well as on studies related to universal design for pedestrian crossings.

The goal of the research was to assess the impact of various aggregates on the luminance of road surfaces and to examine the benefits of bright surfaces and universal design in improving pedestrian crossing safety. Different types of aggregates were selected for the study, including light-colored ones (Devonian limestones, quartzites, granites) and dark-colored ones. Aggregates commonly available in the Świętokrzyskie Voivodeship were chosen. The aggregate samples were properly prepared through washing and compaction to ensure they were homogeneous and representative of typical conditions.

One of the main methods used was luminance measurement, employing a certified LTL-XL reflectometer, which allows precise determination of surface brightness. The samples were tested in laboratory conditions using various mineral mixtures. These mixtures were placed in specially designed molds to ensure standardized measurement conditions. The results were organized into a data set to determine the brightness parameters of the selected aggregates. Light-colored aggregates, such as granite, achieved a luminance factor close to 100 $mcd \cdot m^{-2} \cdot lx^{-1}$ making them ideal materials for bright road surfaces [16,17].

The research also included the incorporation of universal design elements, such as lowered curbs, textured paving slabs, and guiding paths for blind and visually impaired individuals. Additionally, the article discusses the application of technologies like Bluetooth systems and active pedestrian crossings that respond to the presence of pedestrians with warning lights and audio messages.

In summary, the research methods were carefully planned and executed using precise measurement tools. The results provide valuable data that can be used to enhance road safety and design more accessible urban spaces.

Directional-diffuse reflection

Light meters that measure the amount of light at a given point are relatively simple and now inexpensive devices, based on photosensitive elements that have been used in photography and related fields for years. However, it is important to note that such measurements do not accurately reflect the real conditions experienced by road users. To understand this phenomenon, we need to describe the way light behaves on road surfaces [18].

Let's consider a hypothetical scenario. Two identical vehicles are traveling in opposite directions on the same section of a two-lane road at dusk. The driver heading toward the sun experiences glare – everything outside the direct beam of light appears dim, indistinct, and dark. Meanwhile, the other driver, with the light source behind them, sees a uniformly illuminated roadway, clear details of the roadside, and even the distant horizon [19].

Although both drivers are on the same road, illuminated by a light source of the same intensity, their driving conditions are vastly different. This example reveals a fundamental principle: surfaces exhibit directional-diffuse reflection. What reaches our eyes in such situations is luminance – the visible brightness of a surface due to emitted or reflected light [20].

The phenomenon of luminance

Luminance refers to the perception of bright light emitted or reflected from a surface. It is a measure of light intensity in a given direction and can vary depending on the material and specific area being observed. Luminance can be described as perceptual brightness, meaning how bright a surface appears relative to its surroundings. This is a crucial concept in road engineering, where the luminance of road surfaces and infrastructure elements plays a key role in driver visibility and overall traffic safety. In road lighting, specific regulations and standards define minimum required luminance levels for different road areas to ensure adequate visibility for road users. The same applies to asphalt pavements, whose composition significantly influences their brightness [21].

Luminance and road safety

Understanding luminance is essential in road design to ensure safe conditions for all users. Research shows that luminance depends on the observer's viewing conditions and the type of pavement. The same pavement material can exhibit different reflective properties over time due to wear and aging, affecting its reflectivity. Weather conditions and surface imperfections, such as cracks or ruts, must also be considered.

Ultimately, luminance is closely linked to the type of aggregate used in pavement production – particularly its brightness. The composition and texture of road surfaces determine how light is reflected, influencing both visibility and safety [22, 23, 24].

Luminance measurement

While it is well known that the type of materials used in pavement production affects luminance, light reflection is not typically considered during the design phase of asphalt mixtures (MMA). Different countries have varying approaches to this issue, particularly in road lighting design. Over time, specialized regulations have been introduced to standardize the use of luminance coefficients. Initially, these regulations relied on the average luminance coefficient as a key parameter.

There are two primary methods for measuring luminance: photometry and reflectometry. A photometer is a device used to measure light intensity. It determines the amount of light falling on a given object. In road surface measurements, photometers typically use light sensors, such as photodiodes or photocells, to detect the amount of incident or reflected light with high sensitivity.

A reflectometer, on the other hand, measures light reflection. It is used to assess the degree to which a surface reflects light and has broader applications beyond road luminance measurements.

The key difference between a photometer and a reflectometer is that a photometer measures incident light (light falling on a surface), whereas a reflectometer measures reflected light (light bouncing off a surface) (Figure 2). Both devices serve specific functions in various fields and are essential for achieving optimal lighting conditions and brightness parameters (Figure 3).

Luminance coefficient

In road lighting, ensuring safety and functionality requires compliance with Polish Standards as well as European regulations. For many years, the document PKN-CEN/TR 13201 [25] has standardized road lighting based on the luminance coefficient (Qo).

In the 1990s, an alternative metric, the Qd coefficient, was introduced. This coefficient represents luminance in diffused light and was primarily developed to assess the visibility of road

Figure 2. Research using a reflectometer

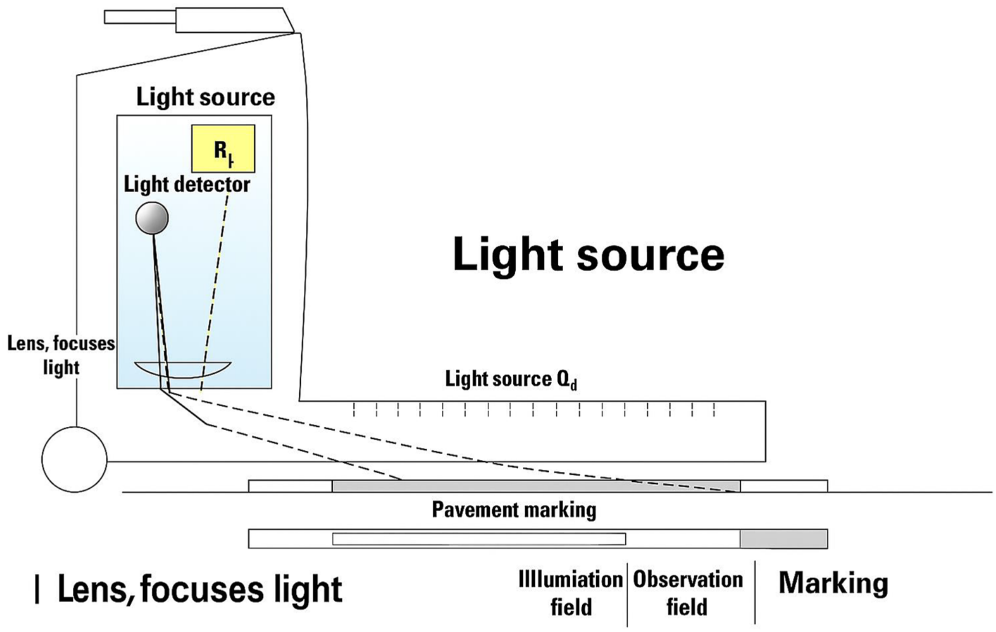

Figure 3. LTL-XL – principle of operation

markings under both daylight and artificial road lighting conditions.

The Qo coefficient is defined as the weighted average of the solid-angle luminance coefficients derived from R-tables. In this case, the measured illuminance level accounts only for the amount of light reaching the surface but does not consider the brightness of that surface 26]:

$$E = \frac{d\Phi}{dA} \tag{1}$$

where: E – illuminance, Φ – luminous flux, A – illuminated surface.

And luminance itself is defined as:

$$L = \frac{d\Phi}{d\Omega \cdot dA \cdot cos\Theta} \tag{2}$$

where: ϕ – luminance flux, A – area, Ω – noun angle, Θ – angle between Ω and area A.

And then going to the luminance coefficient q we have [13]:

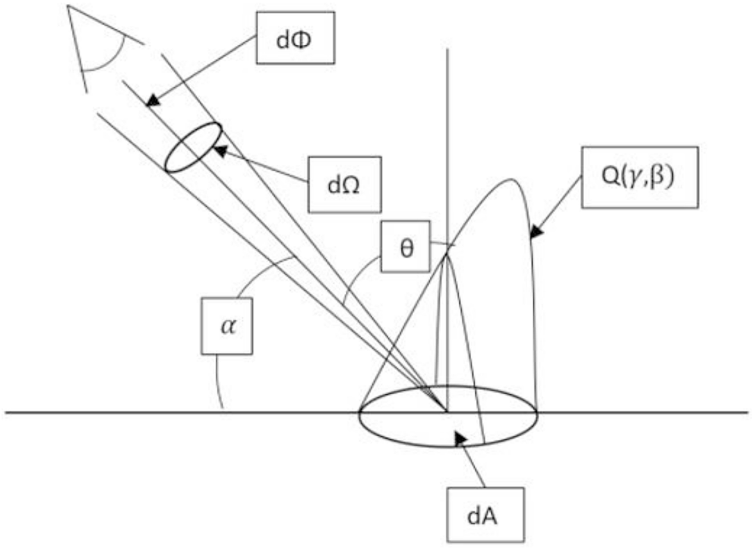

Figure 4. The geometry of the luminance coefficient: α (viewing angle), β (angle between the plane of incidence of light and the viewing plane), γ (angle of incidence of light) and δ (angle between the viewing plane and the axis of the road on which the luminance coefficient q of the road surface located depending on the point of view [13, 27]

$$q = \frac{L}{E} \quad (3)$$

Measure in:

$$mcd \cdot m^{-2} \cdot lx^{-1} \quad (4)$$

Luminance coefficient Qd in diffused light

The EN 1436 standard [28, 29] defines the spectral distribution of light. According to this standard, the luminance coefficient is measured by illuminating the test area with daylight while positioning the reflection sensor at an angle of 2.29° to the sensor. This setup simulates an observation distance of 30 meters, which corresponds to the maximum focal length of passenger vehicle headlights [30, 31].

In practice, the measured pavement luminance coefficient values typically range within a few dozen units. Darker pavements tend to have Qd values around 50–60 mcd·m^{-2}·lx^{-1}, while brighter pavements achieve values between 70–90 mcd·m^{-2}·lx^{-1} (Figure 5).

SELECTION OF INPUT MATERIALS

In the first stage, research will be conducted on the properties of selected aggregates. Both dark and light aggregates will be assessed. This stage will help determine the luminance distribution parameters of the aggregates in relation to their selected physical and mechanical properties.

The aggregates chosen for the study are natural, readily available, and represent four light and four dark varieties, preferably sourced from local open-pit mines whenever possible.

Dark aggregates

Amphibolite

Epidote-plagioclase amphibolites consist of hornblende, along with equal amounts of epidote and plagioclase. In epidote-albite amphibolites, all plagioclase is replaced by albite and epidote (Figure 6) [33].

Melaphyre

A Paleozoic (Carboniferous, Permian) basic volcanic rock with a porphyritic structure, amygdaloidal texture, and a gray-violet, reddish-brown, or greenish-black coloration due to secondary transformations. It is a younger Paleozoic equivalent of basalt.

Melaphyre is primarily composed of plagioclase, pyroxene, and olivine. In Poland, it is found in the Sudetes – in the Intra-Sudetic Basin (Kamienne Mountains, Wałbrzyskie Mountains, Wałbrzyskie Foothills) and the North-Sudetic Basin (Kaczawskie Mountains, Kaczawskie Foothills, Izerskie Foothills), as well as in the Silesian-Cracovian region (Rudno, Regulice).

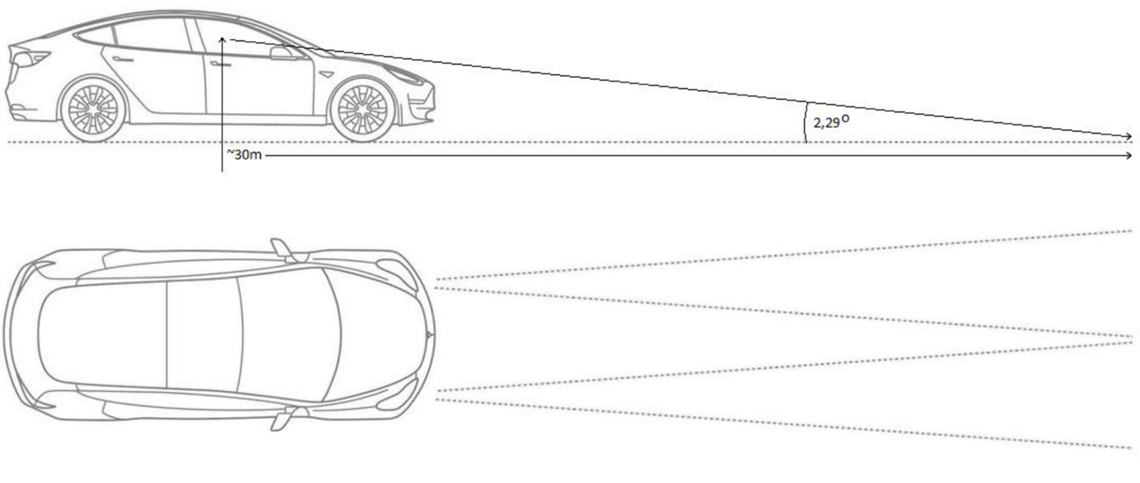

Figure 5. Diagram showing the conditions for measuring the luminance ratio [own figure [32]

Figure 6. Amphibolite (one of the tested samples)

Melaphyre is used in construction, particularly in railway infrastructure (crushed stone fractions) and road construction (gravel fractions) (Figure 7) [33].

Basalt

A basic volcanic rock with a very fine-grained (cryptocrystalline) or aphanitic texture, sometimes porphyritic, typically black, gray, or green. Small crystals or larger olivine inclusions (olivine bombs) are often visible in its fine-grained mass. On the QAPF classification diagram, basalt, along with andesite, occupies fields 9*, 10*, 9, 10, 9', and 10' (Figure 8). Its plutonic equivalent is gabbro (quartz monzogabbro, quartz gabbro, monzogabbro, gabbro, feldspathoid-bearing monzogabbro, and feldspathoid-bearing gabbro). Older, altered basalts are referred to as paleobasalts or melaphyres (Permian, Carboniferous) or diabases (Early Paleozoic) [33].

Gabbro

A basic plutonic rock, medium- to coarse-grained, belonging to the dioritoid and gabbroid group. It contains more than 90% plagioclase compared to potassium feldspar (up to 10%), up to 5% quartz, and 25–60% dark minerals.

Gabbro differs from diorite in the following ways (Figure 9):
- Gabbro's plagioclase contains more than 50% anorthite component (labradorite, bytownite, anorthite), while diorite's plagioclase contains less than 50%,
- Gabbro has more than 30% dark minerals, whereas diorite has fewer,
- pyroxenes dominate among the dark minerals in gabbro, while amphiboles dominate in diorite,
- olivine may be present in gabbro but is rare in diorite [33].

Light aggregates

Devonian limestone from the Miedzianka mine

Miedzianka, Poland's largest limestone mine and production facility, is located in the Piekoszów and Chęciny municipalities (Świętokrzyskie Voivodeship). The mine is named after the highest mountain in the area – Miedzianka – where metal and stone mining first began [34].

The raw material base of the Miedzianka Plant consists of 400-million-year-old Devonian limestone deposits, known for their excellent chemical

Figure 7. Melaphyre (one of the tested samples)

Figure 8. Basalt (one of the tested samples)

Figure 9. Gabbro (one of the tested samples)

Figure 10. Devonian limestone from Miedzianka (one of the tested samples)

properties (high calcium carbonate content) and outstanding physical strength (Figure 10) [35].

Limestone is a sedimentary rock (chemogenic or organogenic), primarily composed of calcium carbonate (calcite). It forms from loose lime deposits, which undergo lithification (hardening) through various processes.

In Poland, Devonian limestone outcrops are mostly found in the Świętokrzyskie Mountains and often contain numerous fossils. These formations also host pyrite, copper ores, zinc and lead ores, and carbonate (limestone, marl, dolomite) and clastic (quartz sandstones, phyllite shales) raw materials [36,37].

Devonian limestone from the Trzuskawica mine

Trzuskawica S.A., a leading Polish producer of construction materials, operates limestone mines that serve as the base for its lime products (Figure 11). The mines are located in Nowiny, Świętokrzyskie Voivodeship.

Quartzite

A dense rock primarily composed of quartz grains in the sand fraction, cemented by recrystallized silica. Quartzites are extremely hard, compact, and their quartz grains are not visible to the naked eye. They can be classified as either sedimentary (orthoquartzites) or metamorphic (metaquartzites) [38, 39, 40].

Metamorphic quartzites form through the metamorphism of quartz sandstones (consisting almost entirely of quartz grains). They emerge

Figure 11. Devonian limestone from Trzuskawica (one of the tested samples)

Figure 12. Quartzite aggregate (one of the tested samples)

even under low-grade metamorphism and do not transform into other rock types under higher-grade conditions.

In Poland, metamorphic quartzites occur mainly in the metamorphic massifs of the Sudetes.

Sedimentary quartzites include Upper Cambrian quartzites of the Świętokrzyskie Mountains (Wiśniówka Sandstone Formation), forming key parts of Łysogóry Ridge and local rock rubble fields.

Quartzites are exceptionally resistant to mechanical processing, even surpassing granites.

Granite

A coarse-grained intrusive igneous rock composed of quartz, potassium feldspar, plagioclase, and biotite. It has a holocrystalline texture, typically medium-grained, but can sometimes be coarse-grained, fine-grained, or porphyritic. Granite exhibits a massive (random) texture, though it can sometimes display oriented structures (Figure 13) [41].

RESULTS

Table 1 presents a summary of average Qd (luminance coefficient in diffused light) and RL (retroreflection coefficient) across different aggregate fractions. The results highlight how various fractions and aggregate types influence surface reflectivity and luminance, which are crucial for road safety and visibility at pedestrian crossings.

Light aggregates exhibit higher Qd and RL values:

Quartzite (KW) and Granite (GR) have the highest Qd values, reaching over 99 $mcd \cdot m^{-2} \cdot lx^{-1}$, indicating strong luminance performance. Devonian limestones from Trzuskawica (TRZ) and Miedzianka (Mie) also perform well, with Qd values exceeding 85 $mcd \cdot m^{-2} \cdot lx^{-1}$. These materials are excellent choices for pedestrian crossings as they enhance visibility in both daylight and artificial lighting conditions.

Dark Aggregates Have Lower Luminance and Retroreflection: Basalt (BA) and Melaphyre (ME) show the lowest Qd values, with Basalt reaching only 33.44–44.48 $mcd \cdot m^{-2} \cdot lx^{-1}$ across fractions. Gabbro (GA) and Amphibolite (AM) also exhibit lower luminance levels, making

Figure 13. Granite aggregate (one of the tested samples)

them less suitable for high-visibility applications. These materials absorb more light, which can reduce contrast and make pedestrian crossings less visible at night.

Impact of fraction size on luminance and reflectivity: for most aggregates, smaller fractions (0/2, 2/5 mm) tend to have slightly higher Qd and RL values than larger fractions (16/22 mm). This suggests that finer grain sizes contribute to increased surface brightness due to their ability to reflect more diffused light. However, in some cases (e.g., Miedzianka limestone), larger fractions maintain high reflectivity, indicating material-specific properties.

Granite (GR) and Quartzite (KW) Stand Out for Pedestrian Crossings: Granite reaches a Qd of 101.6 $mcd \cdot m^{-2} \cdot lx^{-1}$, confirming its suitability for high-luminance surfaces. Quartzite maintains consistently high values across different fractions, making it another excellent choice for improving pedestrian safety.

Analysis of Figure 14 average Qd values of aggregates across all fractions. Chart 6.1 visually represents the average Qd values (luminance coefficient in diffused light) for different aggregate types. This data helps determine which materials are best suited for improving visibility at pedestrian crossings. Light Aggregates Have the Highest Qd Values. Quartzite (KW), granite (GR), and Miedzianka limestone (Mie) exhibit the highest luminance, with Qd values approaching or exceeding 90 $mcd \cdot m^{-2} \cdot lx^{-1}$. These materials effectively reflect light and are ideal for pedestrian crossings, as they improve visibility in both daylight and artificial lighting. Dark aggregates show lower luminance. Basalt (BA) and Melaphyre (ME) have the lowest Qd values, ranging between 30–50 $mcd \cdot m^{-2} \cdot lx^{-1}$, making them less reflective.

Table 1. Summary of average Qd and RL values for a given aggregate type

Aggregate	Average	
	$\bar{x} \cdot$Qd	$\bar{x} \cdot$RL
Quartzite	86.76	50.78
Granite	97.97	48.89
Melaphyre	48.76	32.45
Reedstone	85.41	46.68
Gabro	57.12	35.17
Copper	88.83	50.47
Amphibolite	61.88	33.51
Basalt	38.28	25.73

These materials absorb more light, reducing contrast and making pedestrian crossings less visible, especially at night. Granite (GR) stands out as a high-performance aggregate. Granite reaches a Qd value close to 100 $mcd \cdot m^{-2} \cdot lx^{-1}$, confirming its excellent properties for road safety applications. Due to its mechanical durability and reflectivity, granite remains a top choice for enhancing luminance in urban infrastructure. Variation among light aggregates. While Quartzite (KW) and Granite (GR) consistently achieve high Qd values, Trzuskawica Limestone (TRZ) and Miedzianka Limestone (Mie) also perform well, supporting their use in high-visibility applications. Quartzite, Granite, and Devonian Limestones are the best choices for pedestrian crossings due to their high luminance. Basalt and Melaphyre are the least suitable materials, as they offer poor luminance and could reduce safety at crossings. This analysis supports the recommendation to prioritize light-colored aggregates in urban infrastructure for better pedestrian safety.

Figure 15 illustrates the average RL (retroreflection coefficient) for different aggregate types, showing how well each material reflects light from a direct source, such as vehicle headlights. Quartzite (KW) and Granite (GR) Have the Highest RL Values (Figure 15). These materials reach over 50 $mcd \cdot m^{-2} \cdot lx^{-1}$, meaning they reflect a significant amount of light back toward drivers. This property is essential for ensuring that road markings and pedestrian crossings remain highly visible at night. Miedzianka Limestone and Trzuskawica Limestone show high RL values, making them good candidates for surfaces requiring visibility improvements. Dark aggregates have low RL values. Basalt (BA), amphibolite (AM), and melaphyre (ME) exhibit the lowest RL values, meaning they absorb more light rather than reflecting it (Figure 16, Figure 17, Table 2). This makes them less effective in road safety applications, particularly in low-light conditions. Granite is a strong contender. Granite's high RL value confirms its ability to improve nighttime visibility and reduce accident risks at pedestrian crossings. Quartzite, granite, and limestones are best suited for pedestrian crossings due to their superior light reflection. Dark aggregates like basalt, amphibolite, and melaphyre are not ideal for high-visibility applications. Using high-RL materials in pedestrian crossings can significantly improve road safety by enhancing visibility under vehicle headlights.

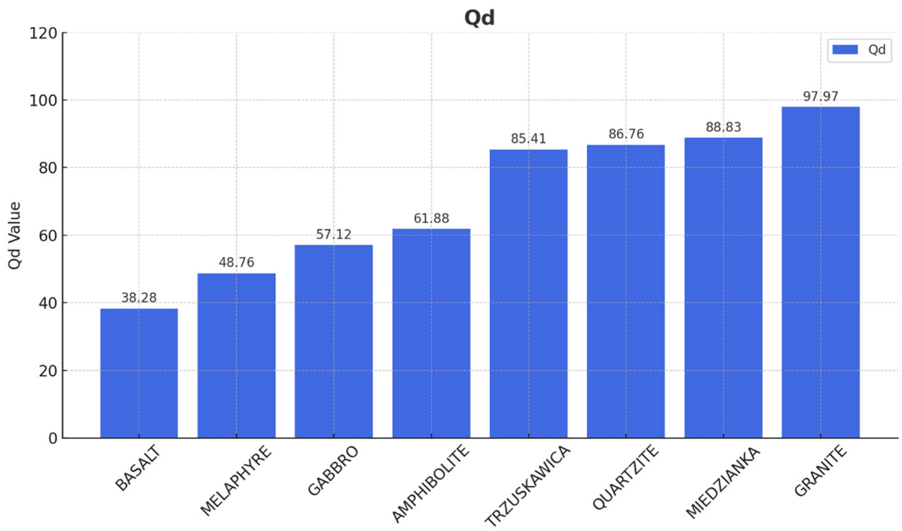

Figure 14. Average Qd values of aggregates from all gradations

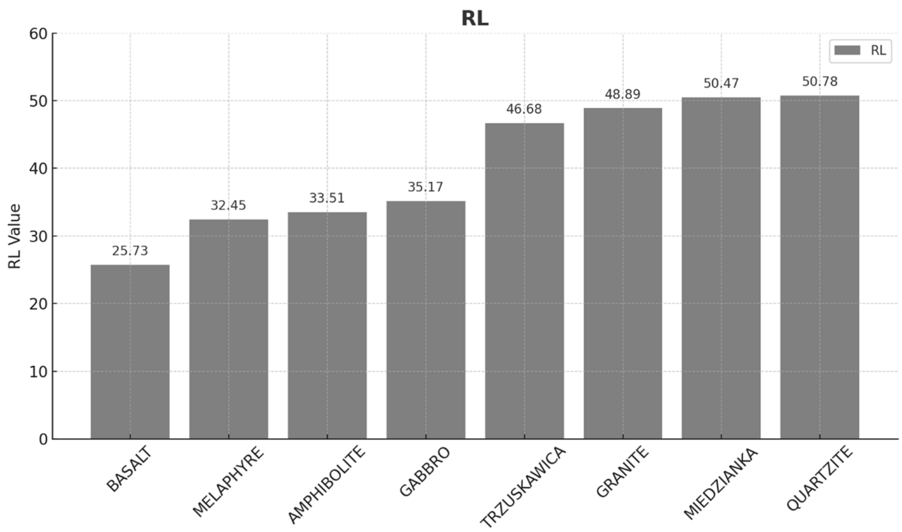

Figure 15. Average RL values of aggregates from all gradations

The reading difference δ Qd [%] for each aggregate fraction is calculated as (example quartzite 0/2):

$$\delta\, Qd\, [\%] = \frac{Qd - \bar{x}\, \mathrm{Qd}}{\bar{x}\, Qd} \cdot 100 \qquad (4)$$

The pace of technological development aimed at improving road safety has slowed, and changes in traffic regulations have not produced the expected results, leaving the number of fatal pedestrian accidents at crosswalks at a similar level. Installing additional streetlights and automated systems has also become economically unjustifiable due to their power consumption. The Ministry of Development and Technology estimates that there are around 3.4 million road lighting fixtures in Poland. Most of these fixtures are energy-inefficient sodium lights. Approximately 3 terawatt-hours (TWh) of electricity are required annually just to power these lighting installations.

It is worth noting that efforts to improve pedestrian visibility at crossings often involve simply replacing fixtures or using higher-wattage light sources. These measures seem largely arbitrary and based on outdated design concepts, as there has been a lack of clear and verifiable research defining the need for additional lighting. Moreover, there are no explicitly defined (by regulations) lighting requirements for pedestrian crossings.

Among other known solutions that show promise for improving safety but are generally rarely used are modified crossings in the form of

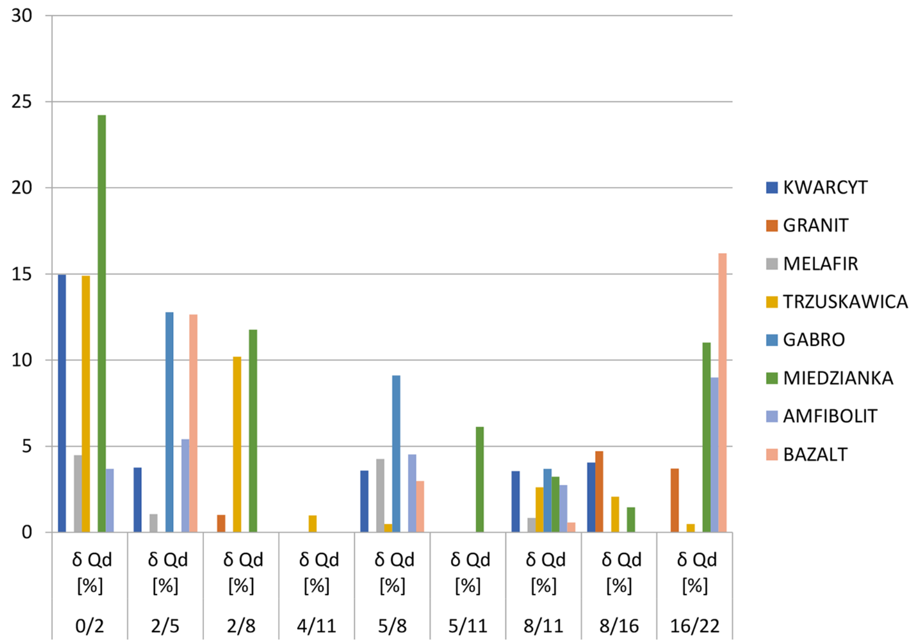

Figure 16. Illustration of Qd differences in percentage by fractions

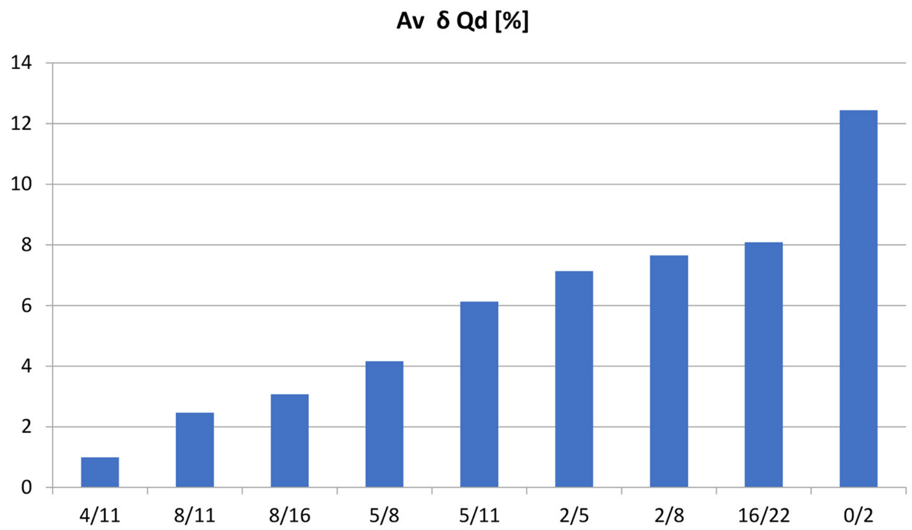

Figure 17. Averaging of differences $\bar{x}$ δ Qd [%]in percentage by fractions

islands that force drivers to reduce their speed, painting crossings in highly contrasting or warning colors (e.g., red crossings with white stripes), or using additional signaling lights and extra lighting points controlled by motion sensors. Each of these solutions has its drawbacks. Creating islands is expensive, time-consuming, and not feasible everywhere. It also faces opposition from drivers who are concerned about damaging their vehicles, despite being pedestrians themselves. Painting or applying horizontal markings provides only a short-term effect, as paint layers wear out quickly and require constant maintenance. Implementing additional signaling systems and motion sensors often requires building a costly new electrical and IT infrastructure along with additional automation systems. However, this issue can be viewed from another perspective.

The work by Mazurek and Bąk-Patyna [19] offers a fresh perspective on the issue of wear layers, focusing on developing mineral mixtures with high brightness. Such mixtures have the potential to significantly improve surface luminance, which could enhance obstacle visibility for both drivers and pedestrians (Figure 18). This is a promising research direction for the coming

Table 2. Illustration of Qd differences due to aggregate fractions

Fraction	0/2	2/5	2/8	4/11	5/8	5/11	8/11	8/16	16/22
	δ Qd [%]	δ Qd [%]	δ Qd [%]	δ Qd [%]	δ Qd [%]	δ Qd [%]	δ Qd [%]	δ Qd [%]	δ Qd [%]
Quartzite	14.95	3.76			3.59		3.55	4.05	
Granite			1.01					4.71	3.7
Melaphyre	4.48	1.06			4.26		0.83		
Reedstone	14.89		10.19	0.99	0.49		2.61	2.07	0.49
Gabro		12.78			9.1		3.68		
Copper	24.22		11.76			6.13	3.23	1.46	11.02
Amphibolite	3.68	5.4			4.52		2.75		8.99
Basalt		12.64			2.98		0.57		16.2
Average	12.44	7.13	7.65	0.99	4.16	6.13	2.46	3.07	8.08

years, as it may lead to significant improvements in road safety.

The article also discusses the concept of focusing on the area within 50 meters from the transverse axis delineating the pedestrian crossing (Scheme 2 – highlighted in yellow on the diagram). This distance is crucial because, at a speed of 50 km/h, a passenger vehicle typically requires an average of 30 meters to come to a complete stop [42]. Traversing this distance takes approximately 3.6 seconds, with the average reaction time to decide on an emergency stop being around 1.4 seconds [2]. The remaining 2 seconds account for factors such as the driver's age, psychophysical state, and atmospheric conditions. Concentrating on this area may field significant benefits in improving safety.

The application of a high-luminance road surface layer in the designated section of the road will ensure that pedestrians are visible as dark objects against a bright background both during the day and at night under conventional lighting conditions. From the pedestrians perspective, such a surface provides better conditions for observing the surroundings and approaching vehicles. Additionally, the use of a bright surface will alert drivers earlier to the presence of a pedestrian crossing, thereby increasing their vigilance. Implementing a high-luminance wearing course can be planned during the road design phase and does not require specialized or additional road machinery on-site. Unlike horizontal markings or other modifications, the effect of such a surface will remainconsistent throughout the road's service life. Moreover, it is important to note that bright surfaces offer several technical advantages: they provide better night-time visibility, absorb less heat during periods of high sunlight, reduce rutting phenomena, and contribute to cost savings in lighting design due to improved light reflection parameters. Achieving a mixture with a specific brightness (without modified additives) involves using aggregates with desired properties [43].

Research conducted by Mazurek and Bąk-Patyna [19] demonstrated that different types of aggregates have varying luminance coefficients, affecting surface brightness. Specially designer moldsfilled with various mineral mixtures

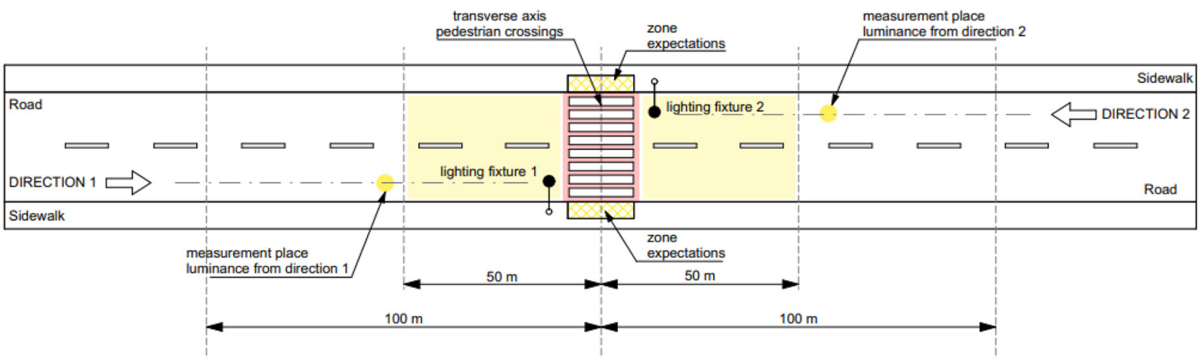

Figure 18. Geometry of pedestrian crossings (inspired by the Traffic Conference, Kraków 2016)

were used to test these aggregates under laboratory conditions using a road reflectometer. A data set was created from the measurements, which was then organized and analyzed to determine the brightness parameters of the selected aggregates. The results of these studies, based on the optical properties of aggregates, open new perspectives for technologies utilizing luminance in the production of mineral-asphalt mixtures.

To confirm these relationships, several selected types of aggregates were tested to determine their luminance coefficient in diffuse light [19]. Specially designer molds, filled with different mineral mixtures, were used for laboratory testing with a road photometer. The resulting dataset was organized and analyzed to determine the brightness parameters of the selected aggregates. The findings from these studies based on the optical properties of aggregates offer new perspectives for the development of technologies utilizing luminance in mineral-asphalt mixture production. In laboratory conditions [19], four types of aggregates considered light-colored and four types considered dark-colored were tested. A certified LTL-XL photometer was used for measurements. The sought luminance coefficient determines the properties of the tested material. Dark surfaces were found to field luminance values around 50–60 mcd·m^{-2}·lx^{-1}, while light surfaces achieved values in range 70–100. Aggregates widely available in the Świętokrzyskie Voivodeship, such as Devonian limestones, quartzites, and granite, were selected for the study. After proper sample preparation, which included washing and compacting, the analys is results were obtained (Figure 19).

The conducted studies revealed that limestone and quartzite achieved the highest luminance values. Granite, with a luminance coefficient close to 100 mcd·m^{-2}·lx^{-1}, is the most desirable material for creating bright road surfaces. Due to it is properties, such as high mechanical resistance and roughness, granite not only enhances the durability of the surface but also improves his skid resistance.

The value of granite as a paving material is significant. Based on the conducted research and analysis, several key advantages of using granite can be identified. Granite offers greater resistance to mechanical wear and superior roughness, which is crucial for pedestrian safety. Surfaces made of granite are more durable under heavy pedestrian traffic and varying weather conditions. Additionally, a bright granite surface significantly enhances the contrast of moving objects. Pedestrians will be more visible both during the day and at night, which is critical for their safety. Under artificial lighting, a bright granite surface increases the effectiveness of street lighting, which also contributes to reducing the risk of accidents.

Granite as a material also has economic benefits. Replacing the wear layer with a bright granite surface proves to be more economical in the long term. Unlike horizontal markings that require regular renewal and generate high costs, a bright granite surface maintains it is properties throughout the road's lifespan. The reduction in the need for frequent renovations translates into significant cost savings for road managers.

The use of granite in road surfaces also has important architectural merits. Granite, as a natural material with an aesthetic appearance, enhances

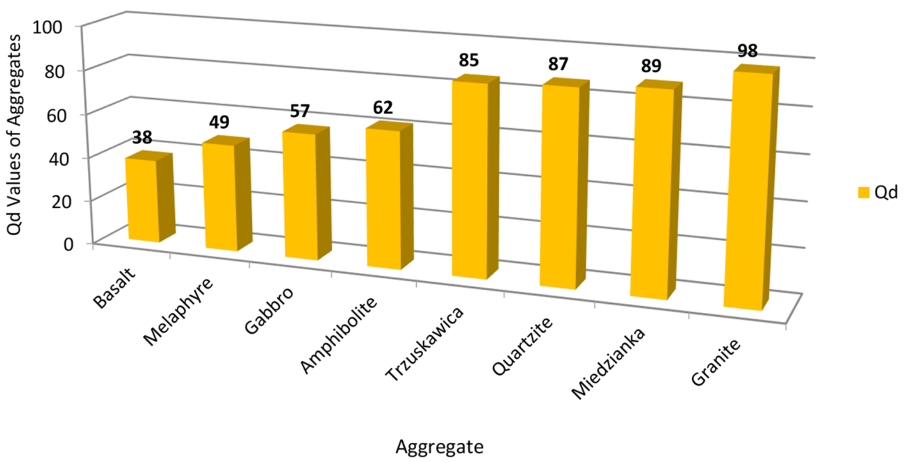

Figure 19. Average Qd values of aggregates

the visual appeal of urban spaces. Its application can improve the aesthetics of the surroundings, creating more cohesive and visually attractive public spaces. The aesthetic qualities of granite can influence the perception of urban areas as more modern and well-maintained, contributing positively to the overall image of the city.

DISCUSSION

Laboratory studies conducted by Mazurek and Bąk-Patyna [19] support these assumptions. In their research, four types of light-colored aggregates and four types of dark-colored aggregates were selected and tested. Measurements were carried out using a certified LTL-XL reflectometer, ensuring high precision. The results of the luminance analysis demonstrated that limestone and quartzite exhibited the highest luminance values, with granite achieving nearly 100 mcd/m²/lx – making it an ideal material for application in light-colored road surfaces.

This article highlights the importance of universal design in eliminating architectural barriers and enhancing safety at pedestrian crossings. Proposed interventions include curb lowering, the introduction of textured paving and guiding pathways, and the implementation of active pedestrian crossings equipped with Bluetooth systems and illuminated signals. Anna Jurkowska [44], in her work on universal design in spatial planning, also emphasizes the necessity of addressing the needs of individuals with various types of disabilities. Her research supports similar solutions, such as curb lowering and the use of contrasting textures, which reinforces the effectiveness of the methods proposed in this study. Additionally, Brutkowski et al. [45], in their handbook on accessibility standards for buildings for people with disabilities, advocate for the incorporation of textured elements and color contrasts – aligning with this article's conclusions regarding improvements in the readability and safety of pedestrian crossings.

The study further underscores that implementing light-colored pavements and universal design elements can significantly enhance pedestrian crossing safety, as evidenced by the research findings. Moreover, the adoption of active pedestrian crossing technologies will improve visibility and alert drivers to the presence of pedestrians. Jackett [46], in his research on the impact of road lighting on traffic safety, demonstrated that enhanced road lighting significantly reduces accident rates. His findings highlight the necessity of using bright and well-lit pavements, which is consistent with the recommendations of this article. Similarly, Jamroz et al. [3], in their handbook on pedestrian protection, suggest that active pedestrian crossings with illuminated signals substantially improve safety. Their research confirms the effectiveness of these solutions in reducing accidents, corroborating the results presented in this article.

Architectural barriers remain widespread and pose significant challenges to mobility for various groups, including individuals with disabilities, the elderly, the visually and hearing impaired, parents with strollers, and those with limited mobility. Given the increasing prevalence of lifestyle-related diseases and the fast pace of contemporary life, it is imperative to prioritize the elimination of architectural barriers and the enhancement of pedestrian safety [45]. The concept of universal design plays a critical role in shaping functional and accessible environments, offering substantial benefits to all members of society by ensuring equitable access to facilities, services, and urban spaces.

Therefore, it is essential to guarantee safe mobility for all social groups. A fundamental measure to improve pedestrian accessibility is the lowering of curbs (Figure 4), facilitating movement for wheelchair users. However, this modification introduced the challenge of reduced tactile cues for visually impaired pedestrians regarding the boundary between the sidewalk and the roadway. To mitigate this issue, tactile elements (e.g., textured paving) were introduced, helping to reconcile the diverse needs of various pedestrian groups.

Additionally, the readability of pedestrian layouts can be enhanced by incorporating dark-colored paving slabs, such as graphite, alongside tactile paving elements. This approach improves color contrast between the sidewalk and tactile indicators. Another key component of universal design is the development of guiding pathways at crosswalks [27,47]. For visually impaired individuals, additional communication aids can be implemented, such as Bluetooth-based modules installed on signal poles. These modules serve a dual purpose: activating the pedestrian green signal and providing auditory navigation cues to help users locate the crosswalk.

Active crosswalks are equipped with yellow warning lights that activate upon detecting a pedestrian in the waiting area. The lightis instantly directed toward approaching vehicles, enabling immediate driver response and heightened alertness. Additionally, the light signal is accompanied by an audio message directed at pedestrians, particularly those who are blind or have low vision [48] (Figure 20).

A safe and universally accessible pedestrian zone should be clearly and understandably defined [27]. The so-called natural directional lines, chich are utilized by blind and visually impaired individuals, include:

Contrasting textural differences in pavements: These allow for the quick and easydetection of important elements within the space:

- yellow tactile mats (sidewalk plates) with bumps: These serve as warnings when approaching pedestrian crossings, commonly known as “zebras.”,
- guiding mats: Installed on sidewalks, these enable the visually impaired to maneuver their canes between raised lines,
- curbs and building facades,
- vertical partition bases,
- horizontal elements of handrails and guardrails,
- linear floor lighting: many blind individuals possess a sense of light and can recognize directions indicated by lighting and color contrast,
- crossings equipped with buttons featuring pictograms: These inform users about the pedestrian crossing’s topography. The buttons vibrate when the green light is activated and allow for the extension of its duration.

CONCLUSIONS

Communication is an integral aspect of modern life, making it essential to ensure safety for all social groups and to facilitate efficient movement within urban spaces. The illumination studies presented in this article enabled a comprehensive assessment of the visibility of pedestrian crossings and the effectiveness of current design solutions. The analysis of surface reflectivity and pedestrian crossing functionality indicates the need for a reassessment and improvement of key communication nodes.

Ensuring road safety, particularly at pedestrian crossings, necessitates an integrated approach combining appropriate material selection, universal design principles, and advanced infrastructural solutions. The analysis of luminance (Qd) and retroreflection (RL) values presented in this study highlights the pivotal role that aggregate selection plays in enhancing pedestrian visibility and reducing accident risks. Materials such as quartzite, granite, and Devonian limestones exhibited the highest Qd and RL values, making them particularly effective for use at pedestrian

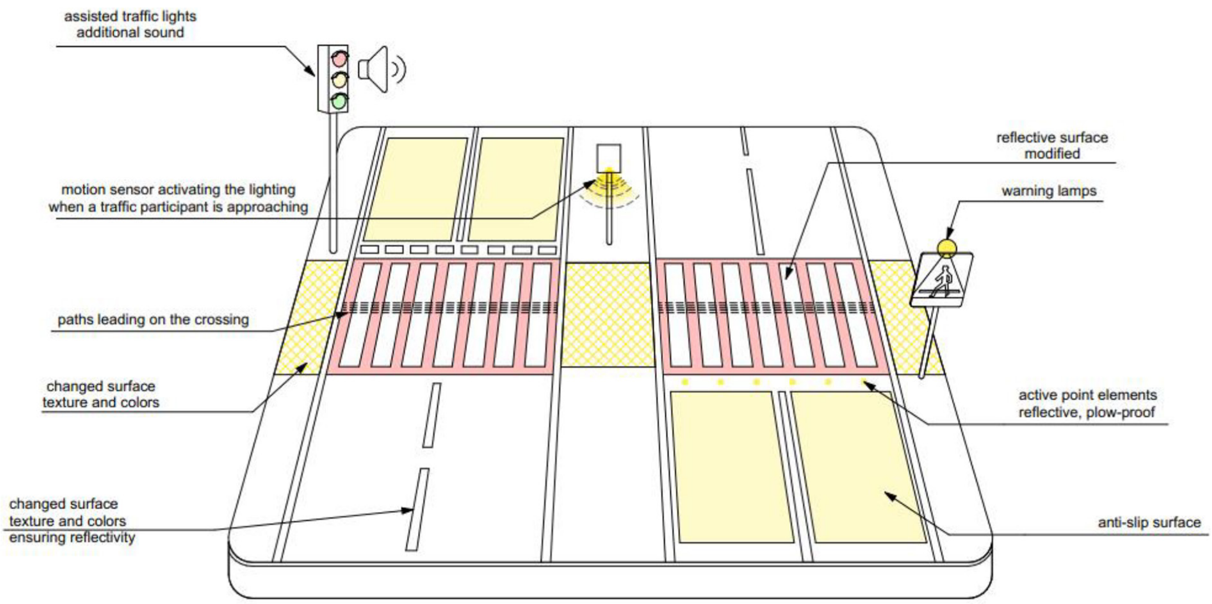

Figure 20. Diagram of an active crosswalk with architectural barrier mitigation elements

crossings. In contrast, darker aggregates such as basalt, amphibolite, and melaphyre absorb more light, reducing surface contrast and pedestrian visibility, especially under low-light conditions.

Bright road surfaces significantly enhance both daytime and nighttime safety. High-luminance aggregates improve visibility for both drivers and pedestrians by increasing the contrast between the road surface and pedestrians. Moreover, these materials help reduce road glare and lower surface temperatures, mitigating the risk of excessive heat absorption in warmer climates. The surface texture and aggregate fraction size further influence luminance performance. Smaller aggregate fractions (0/2 mm, 2/5 mm) generally provide higher luminance and retroreflection values compared to larger fractions, thereby enhancing the durability and visibility of road markings. In addition, surface roughness influences skid resistance, making it necessary to balance optimal reflectivity with adequate traction.

Universal design elements complement the use of high-luminance surfaces. The integration of textured surfaces, guiding pathways, and active pedestrian crossings equipped with pulsating signals and audible cues greatly enhances accessibility for individuals with disabilities and improves overall pedestrian safety. Lowered curbs and contrasting textures further facilitate navigation, particularly for visually impaired pedestrians. Active pedestrian crossings equipped with technologies such as motion-activated lighting and Bluetooth-based warning systems improve pedestrian detection, providing drivers with additional reaction time. The use of high-luminance materials within 50 meters of pedestrian crossings significantly enhances early hazard recognition, thereby reducing braking distances and accident rates.

In addition to safety benefits, the use of high-luminance materials also offers economic and environmental advantages. Bright road surfaces reduce the need for additional lighting infrastructure, resulting in lower energy consumption and maintenance costs. Durable materials such as granite and quartzite offer long service lives, minimizing the frequency of resurfacing and repainting of road markings.

In light of these findings, it is recommended to adopt high-luminance materials, such as quartzite, granite, and Devonian limestones, for pedestrian crossings in order to enhance visibility and contrast. Moreover, the standardization of universal design elements, including tactile paving, contrasting textures, and active pedestrian crossing technologies, is essential to improving accessibility for all users. The implementation of high-luminance wearing courses in high-risk pedestrian zones can ensure long-term safety benefits without excessive maintenance requirements. Further research on the long-term durability and cost-effectiveness of various aggregate types is needed to optimize material selection for urban infrastructure projects.

The integration of the optical properties of pavement materials with universal design strategies presents an innovative and cost-effective approach to enhancing pedestrian safety and accessibility. By adopting these recommendations, cities can foster smarter, safer, and more sustainable urban environments that benefit all road users.

REFERENCES

1. Rozporządzenie Ministra Spraw Wewnętrznych i Administracji z dnia 17 września 2022 r. w sprawie ewidencji kierujących pojazdami naruszających przepisy ruchu drogowego.
2. Police Database SEWIK – Accident and Collision Register, 2024
3. Jamroz, K., et al. Ochrona pieszych. Podręcznik dla organizatorów ruchu pieszego. 2014, Krajowa Rada Bezpieczeństwa Ruchu Drogowego, Gdańsk, Kraków, Warszawa.
4. Jaździk-Osmolska, A. Wycena kosztów wypadków i kolizji drogowych na sieci dróg w Polsce na koniec roku 2015, z wyodrębnieniem średnich kosztów społeczno-ekonomicznych wypadków na transeuropejskiej sieci transportowej. 2016, Krajowa Rada Bezpieczeństwa Ruchu Drogowego, Warszawa.
5. Strbac-Hadzibegovic, N.; Strbac-Savic, S.; Kostic, M. A New Procedure for Determining the Road Surface Reduced Luminance Coefficient Table by On-Site Measurements. Light. Res. Technol. 2019; 51: 65–81.
6. Bodmann, H.W., Schmidt, H.J. Road surface reflection and road lighting: field investigations. Light. Res. Technol. 1989; 21: 159–170.
7. Qin, L.; He, S.; Yang, D.; Leon, A.S. Proposal for a calculation model of perceived luminance in road tunnel interior environment: A case study of a tunnel in China. Photonics 2022; 9: 870.
8. Kowalik, R.; Widłak, M.; Widłak, A. Sorption of heavy metals by sewage sludge and its mixtures with soil from wastewater treatment plants operating in MBR and INR Technology. Membranes 2021; 11: 706. https://doi.org/10.3390/membranes11090706

9. PN-EN 13201-2: 2016 – Oświetlenie dróg. Część 2: Wymagania eksploatacyjne.
10. PN-EN 13201-3: 2016 – Oświetlenie dróg. Część 3: Obliczenia parametrów oświetleniowych.
11. PN-EN 13201-4: 2016 – Oświetlenie dróg. Część 4: Metody pomiaru efektywności oświetlenia.
12. PN-EN 13201-5: 2016 – Oświetlenie dróg. Część 5: Wskaźnik efektywności energetycznej.
13. van Bommel, W.J.M.; de Boer, J.B. Road Lighting; Palgrave Macmillan: London, UK, 1980; ISBN 978-1-349-05802-0.
14. Serkan Üncü, I.; Kayakus, M. Analysis of visibility level in road lighting using image processing techniques. Sci. Res. Essays 2010; 5: 2279–2785.
15. Sørensen, K. Performance of road markings and road surfaces 2011. Available online: https://nmfv.dk/wp-content/uploads/2012/03/Performance-of-road-markings-and-road-surfaces.pdf (accessed on 01 March 2025).
16. Hu, J.; Guan, Y.; Wang, R.; Cao, Q.; Guo, Y.; Hu, Q. investigating the daytime visibility requirements of pavement marking considering the influence of CCT and illuminance of natural light. Int. J. Environ. Res. Public Health 2022; 19: 3051. https://doi.org/10.3390/ijerph19053051
17. Bąk-Patyna, P., Mazurek, G., Podsiało, M., Ludwikowska-Kęzia, M., Ramiączek, P., &Patyna, H. Luminancja kruszyw drogowych w ujęciu petrograficznym. Poszerzamy Horyzonty. 2023; XL, Słupsk.
18. Mazurek, G.; Bąk-Patyna, P.; Ludwikowska-Kędzia, M. Modelling of the luminance coefficient in the light scattered by a mineral mixture using machine learning techniques. Appl. Sci. 2024; 14: 5458. https://doi.org/10.3390/app14135458
19. Mazurek, G.; Bąk-Patyna, P. Application of data mining techniques to predict luminance of pavement aggregate. Appl. Sci. 2023; 13: 4116. https://doi.org/10.3390/app13074116
20. Dumont, E.; Paumier, J.L.; Ledoux, V. Are standard R-Tables still representative of road surface photometric characteristics in France? In Proceedings of the CIE International Symposium on Road Surface Photometric Characteristics, Année, France, 9 July 2008; 8.
21. Wang, J.H.; Cao, Y. Effects of road marking luminance contrast on driving safety; Rhode Island Department of Transportation: Providence, RI, USA, 2004.
22. Zhang, X.Q.; Hu, J.B.; Wang, M.; Gao, X.J. Road surface luminance of tunnel interior zone based on the driving visual cognition demand. J. Beijing Univ. Technol. 2016; 42: 770–772.
23. Heng, T.; Wen, H.; Xu, T.W. An experimental study of the relationship between landmark backgrounds and drivers' identification power under different conditions of luminance and color temperatures. J. Wuyi Univ. 2019; 33: 35–42.
24. Zwahlen, H.T. Conspicuity of suprathreshold reflective targets in a driver's peripheral visual field at night. Transp. Res. Rec. 1989; 1213: 35–46.
25. PKN-CEN/TR 13201-1: 2016-02 – Road Lighting – Part 1: Guidelines for the Selection of Lighting Classes, Polish Committee for Standardization, Warsaw, Poland. 2016. Available online: https://sklep.pkn.pl/pkn-cen-tr-13201-1-2016-02e.html (accessed on 19 February 2025).
26. Boyce, P.R. Human factors in lighting; CRC Press: Boca Raton, FL, USA, 2003; ISBN 978-0-429-22113-2.
27. LUMI SYSTEM FON. Fakturowe Oznaczenie Nawierzchnie chodnikowe, 2018, Katalog. ARTBAU Sp. z o.o., Mszczonów.
28. PN-EN 1436:2000 (współczynnik luminancji w świetle rozproszonym, powierzchniowy współczynnik odblasku).
29. PN-EN 1436:2007 + 2018 – (odblask w świetle reflektorów samochodowych, metody badań i warunki). Prawo o ruchu drogowym (Dz.U. z 2020 r. poz. 110).
30. Kuryłowicz, E. Projektowanie uniwersalne: udostępnianie otoczenia osobom niepełnosprawnym. Centrum Badawczo-Rozwojowe Rehabilitacji Osób Niepełnosprawnych, 1996, Warszawa.
31. Kalabińska, M., Piłat, J., & Radziszewski, P. Technologia materiałów i nawierzchni drogowych. 2015, Politechnika Warszawska.
32. Sørensen, K. Performance of Road Markings and Road Surfaces 2011. Available online: https://nmfv.dk/wp-content/uploads/2012/03/Performance-of-road-markings-and-road-surfaces.pdf (accessed on 21 February 2025).
33. Numan, M.; Khan, Q.S.; Qazi, A.U.; Kazmi, S.M.S.; Munir, M.J. Development of cement-less recycled aggregate concrete mixes: a step towards sustainable construction. Sustainability 2025; 17: 2371. https://doi.org/10.3390/su17062371
34. Janaszek, A.; Silva, A.F.d.; Jurišević, N.; Kanuchova, M.; Kozáková, Ľ.; Kowalik, R. The assessment of sewage sludge utilization in closed-loop economy from an environmental perspective. Water 2024; 16: 383. https://doi.org/10.3390/w16030383
35. Nešović A, Kowalik R, Bojović M, Janaszek A, Adamczak S. Elevational Earth-Sheltered Buildings with Horizontal Overhang Photovoltaic-Integrated Panels – New Energy-Plus Building Concept in the Territory of Serbia. *Energies*. 2024; 17(9): 2100
36. Szopińska, K.; Cienciała, A.; Bieda, A.; Kwiecień, J.; Kulesza, Ł.; Parzych, P. Verification of the perception of the local community concerning air quality using ADMS-Roads modeling. Int. J. Environ. Res. Public Health 2022; 19: 10908.
37. Nartowska E, Podlasek A, Vaverková MD, Koda E, Jakimiuk A, Kowalik R, Kozłowski T. Mobility of

Zn and Cu in bentonites: implications for environmental remediation. Materials. 2024; 17(12): 2957. https://doi.org/10.3390/ma17122957

38. Grzegorzek, M.; Wartalska, K.; Kowalik, R. Occurrence and sources of hormones in water resources – environmental and health impact. Environ Sci Pollut Res, 2024; 31: 37907–37922, 2024. https://doi.org/10.1007/s11356-024-33713-z
39. Widłak, M,; Kowalik, R.; Sobura, S. Quality of the soil and water environment in the immediate vicinity of the Barania Gora forest reserve. Desalination and Water Treatment, 2021; 232: 404–413. https://doi.org/10.5004/dwt.2021.27604.
40. Kozlowski, T.; Ludynia, A. Permeability Coefficient of Low Permeable Soils as a Single-Variable Function of Soil Parameter. Water 2019; 11: 2500. https://doi.org/10.3390/w11122500
41. Stempkowska, A.; Gawenda, T.; Chajec, A.; Sadowski, Ł. Effect of Granite Powder Grain Size and Grinding Time of the Properties of Cementitious Composites. Materials 2022; 15: 8837. https://doi.org/10.3390/ma15248837
42. Tadej, M., Tadej, M., Czech, P., Gustof, P., Hornik, A., Jędrusik, D., Wpływ działania układu ABS na osiąganą wartość opóźnienia hamowania samochodu osobowego. 2016, Bezpieczeństwo i ekologia, AUTOBUSY, 2016; 12: 447-45
43. Filipczyk, Z., &Kukielska, M. Badania nad jasnością nawierzchni drogowych. Journal of Road Engineering, 2016; 12*(3): 145–158.
44. Jurkowska, A. Idea projektowania uniwersalnego w planowaniu przestrzennym. 2002, Planning Review, 2002; 18(1): 32–45.
45. Brutkowski, M., et al. Standardy dostępności budynków dla osób z niepełnosprawnościami, uwzględniając koncepcję uniwersalnego projektowania – poradnik. Ministerstwo Infrastruktury i Budownictwa, 2017, Warszawa. Ergänzende Festlegungen Asphalt.2013, Hessen.
46. Jackett, M. Quantifying the Impact of Road Lighting on Road Safety. 2013, A New Zealand Study. IATSS Research, 2013; 36: 139–145.
47. Rozporządzenie Ministra Spraw Wewnętrznych i Administracji z dnia 17 września 2022 r. w sprawie ewidencji kierujących pojazdami naruszających przepisy ruchu drogowego.
48. Kuryłowicz, E. Projektowanie uniwersalne: udostępnianie otoczenia osobom niepełnosprawnym. Centrum Badawczo-Rozwojowe Rehabilitacji Osób Niepełnosprawnych, 1996, Warszawa.