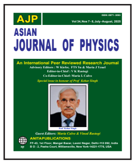

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Directional reflectance characterization of asphalt mixtures for pavements

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Dedicated to Prof Kehar Singh on the occasion of his 84th Birth Day on July 3, 2025

The optical properties of pavement surfaces play a critical role in their thermal and visual performance in urban environments. This study investigates the spectral and directional reflectance of bituminous mixtures designed with different aggregate types, binder formulations, and pigment compositions. A total of 18 ultra-thin asphalt mixtures (AUTL 8) were fabricated using limestone, granite, or porphyry aggregates combined with conventional or synthetic pigmentable binders. Additional mixtures of open-graded (BBTM 8A) and dense asphalt concrete (AC 16S) types were produced to assess the influence of surface texture.

Directional reflectance −including quasi-retroreflective behaviour− was evaluated using a spectroradiometer under varying entrance and observation angles. Mixtures with light-coloured aggregates and white pigments (TiO_2) showed high reflectance in the visible spectrum, whereas black mixtures exhibited consistently low reflectance due to their dark pigmentation. Directional measurements revealed higher reflectance when the detection angle was close to the incident direction, indicating quasi-retroreflective behaviour, particularly in textured, light-coloured mixtures.

Although not retroreflective in the strict optical sense, certain asphalt surfaces exhibited enhanced backscattering under specific geometries. Reflectance also increased with entrance angle due to surface roughness effects. These results highlight the potential of tailored asphalt mixtures to mitigate solar heat gain and improve environmental comfort, supporting their integration in climate-adaptive pavement design. © Anita Publications. All rights reserved.

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1 Introduction

The temperature increase is more pronounced in urban areas due to the phenomenon known as the urban heat island effect [1,2], with temperature differences between urban and rural areas observed to range from 1 to 14 ºC [3-5]. This effect is intensified by several factors. High heat emissions result from concentrated human activity. Additionally, lower levels of vegetation and a high concentration of materials such as asphalt mixtures, concrete, and bricks contribute to this effect. These materials absorb solar radiation, causing their temperatures to rise [6,7]. They are characterized by a high thermal storage capacity and low solar reflectance. As a consequence, their surface temperature increases during the day and releases the absorbed heat at night, keeping temperatures high. Tackling the urban heat island effect problem is essential for improving the habitability and sustainability of cities in the context of global climate change.

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This work aims to evaluate the directional reflectance properties of various bituminous mixtures, differing in aggregate type, binder, pigment and surface texture. Using spectroradiometric techniques under controlled angular configurations, we explore how mixture composition and light incident angle affect the reflectance of asphalt surfaces. The ultimate goal is to assess their suitability for urban deployment in the context of climate-adaptative infrastructure.

2 Theoretical background

The optical performance of pavement surfaces plays a significant role in their contribution to urban thermal dynamics and visibility [1,2]. Among the key parameters describing optical behaviour, reflectance ─defined as the fraction of incident radiation reflected by a surface─ depends on several factors including wavelength, surface roughness, material composition, and the angular configuration of both incidence and observation [8].

In this context, spectral reflectance refers to the wavelength-dependent behaviour of the surface, which provides information about how different materials interact with solar radiation across the ultraviolet (UV), visible (VIS) and near-infrared (NIR) ranges. For materials such as asphalt mixtures, the spectral behaviour is relevant, as their thermal and visual impacts vary substantially across the spectrum. Lighter-coloured mixtures, for instance, tend to reflect more energy in the visible and NIR bands, contributing to lower surface temperatures.

Although total reflectance accounts for the reflected energy integrated over all directions, it provides limited information about the angular distribution of the reflected light. This is particularly relevant for non-Lambertian surfaces, such as bituminous pavements, whose reflectance is highly anisotropic due to their roughness, granular composition and textured surfaces. Consequently, an understanding of directional reflectance becomes essential, especially in applications where visual comfort, safety, or radiative exchange with the environment are relevant considerations.

In contrast to conventional reflectance, retroreflectance describes a specific optical phenomenon where incident light is reflected predominantly back in the direction of the source. This property is well-established in engineering materials, such as vehicle retroreflectors, road signs, and optical tapes, which are designed to maximize return light at specific entrance angles using microprismatics or spherical elements [8].

However, bituminous materials do not contain retroreflective elements in a strict optical sense. Their observed directional behaviour ─where reflected light intensity increases along certain near-specular or backscatter directions─ can resemble retroreflection under certain conditions. This behaviour, observed in our experimental data, is likely a result of the microstructure and scattering characteristics of the surface, especially for lighter mixtures and higher incident angles. Yet, such directional enhancement should be interpreted cautiously, since it does not equate to true retroreflectance as defined in photometric standards, but may still offer functional advantages in terms of reduced glare and localized radiative transfer.

Thus, in this study, we consider quasi-retroreflective behaviour in the context of directional reflectance, acknowledging the optical complexity of real asphalt surfaces. This paper details the measurement configurations used for experiments on pavement samples in an optical laboratory. By characterizing reflectance across a range of angles and wavelengths, we aim to understand how composition and texture influence the overall optical response of bituminous mixtures.

3 Materials: asphalt mixtures

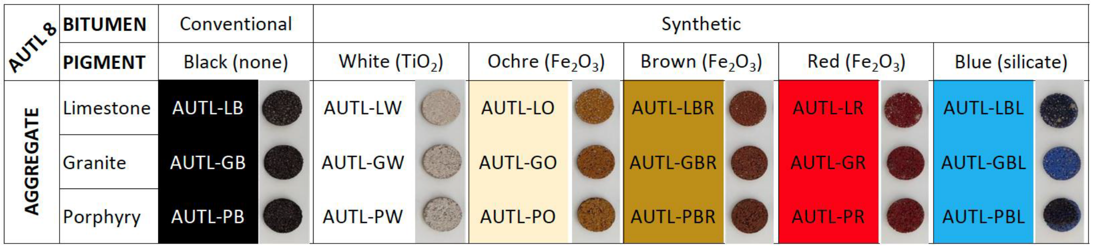
This study considered a broad range of bituminous mixtures with variations in aggregate type, binder formulation, and pigmentation, aiming to explore the influence of material composition on the optical reflectance properties of asphalt surfaces. Further details on the mixtures are provided elsewhere [9].

Three types of aggregates were selected based on their colour and mineral composition: limestone (light-coloured), granite (intermediate grey) and porphyry (dark-coloured). These aggregates exhibit different emissive and reflective properties due to their intrinsic albedo and surface characteristics.

Two types of bitumen were used: conventional 50/70 penetration-grade bitumen, and a polymer-modified colourless binder with similar penetration characteristics. The synthetic binder served as the matrix for pigmented mixtures, enabling a wide range of colour customization without compromising mechanical properties.

Colour was introduced into the synthetic binder using inorganic pigments: titanium dioxide (TiO_2) for white mixtures, iron oxides for ochre, brown and red shades, and a mixed silicate compound (silica, sulfur, aluminium, sodium) for blue shades. The reflectance of the resulting mixtures was strongly influenced by pigment type, with white and ochre formulations showing the highest optical performance. No pigment was added to the 50/70 conventional binder, which yielded a black surface used as a reference.

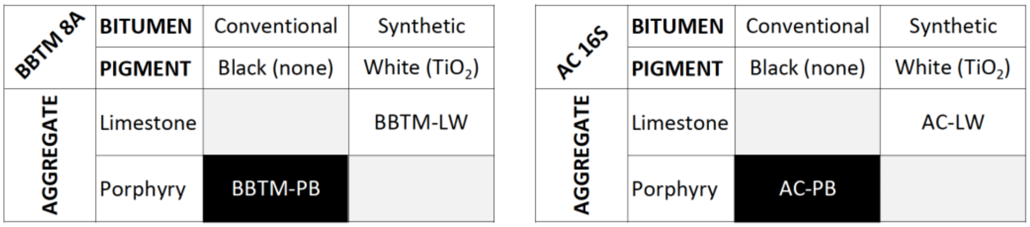
The resulting combinations were used to fabricate ultra-thin asphalt layers (AUTL 8), producing a total of 18 coloured mixtures that covered a broad spectrum of albedos and spectral profiles (Fig 1).



AUTL 8	BITUMEN	Conventional	Synthetic				
	PIGMENT	Black (none)	White (TiO_2)	Ochre (Fe_2O_3)	Brown (Fe_2O_3)	Red (Fe_2O_3)	Blue (silicate)
AGGREGATE	Limestone	AUTL-LB	AUTL-LW	AUTL-LO	AUTL-LBR	AUTL-LR	AUTL-LBL
	Granite	AUTL-GB	AUTL-GW	AUTL-GO	AUTL-GBR	AUTL-GR	AUTL-GBL
	Porphyry	AUTL-PB	AUTL-PW	AUTL-PO	AUTL-PBR	AUTL-PR	AUTL-PBL

Fig 1. Studied AUTL mixtures, according to the type of aggregate, binder and pigment used for their manufacturing.

To specifically assess the influence of surface texture, a second, more limited set of mixtures was produced using BBTM 8A (open-graded) and AC 16S (dense) gradations. In these cases, only the two extreme-colour formulations −white and black− were selected, in order to isolate texture-related effects, using limestone and porphyry aggregates, respectively (Fig 2).



BBTM 8A	BITUMEN	Conventional	Synthetic
	PIGMENT	Black (none)	White (TiO_2)
AGGREGATE	Limestone		BBTM-LW
	Porphyry	BBTM-PB	

AC 16S	BITUMEN	Conventional	Synthetic
	PIGMENT	Black (none)	White (TiO_2)
AGGREGATE	Limestone		AC-LW
	Porphyry	AC-PB	

Fig 2. Studied BBTM and AC bituminous mixtures.

4 Optical measurement methodology

To evaluate the directional reflectance properties of the asphalt mixtures, a spectroradiometer was used to measure reflectance in a specified observation direction within a controlled experimental setup. The setup allowed independent control of the relative orientation of the sample, the illumination source, and the spectroradiometer, enabling variation of both the incident light direction and the observation direction. As a result, the measurements were sensitive to surface texture effects.This approach allowed for a detailed characterization of the spectral and angular behaviour of the materials, particularly within the visible range.

Directional reflectance was measured using a PR-715 SpectraScan spectroradiometer (PhotoResearch®, USA), sensitive in the visible range (400-700 nm) (Fig 3). Samples were placed inside a VeriVide CAC 120 H4 colour assessment booth with D65 standard illumination and diffusely reflective gray walls to minimize ambient reflections.

The characterization of directional reflectance and the estimation of retroreflective behaviour require precise control of the angular configuration of illumination and observation relative to the surface. Figure 4 provides a schematic diagram of the angular configuration used throughout the study, which adheres to the standard angle definitions for reflectance measurements [10]: β is the entrance angle of the light beam with respect to the surface normal, and θ is the observation angle between the detector and the direction of the incident light.

Fig 3. Directional reflectance measurement setup: (1) spectroradiometer; (2) measurement booth; (3) tested sample; and (4) laptop to register the results.

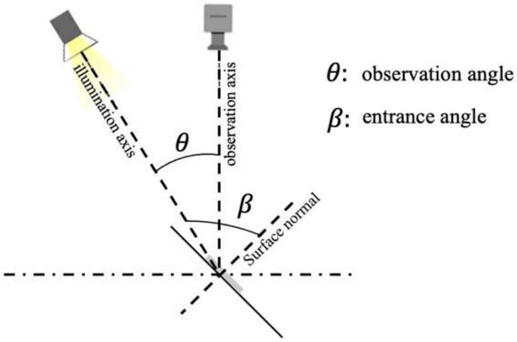


Fig 4. Schematic of illumination and observation angles used in reflectance measurements.

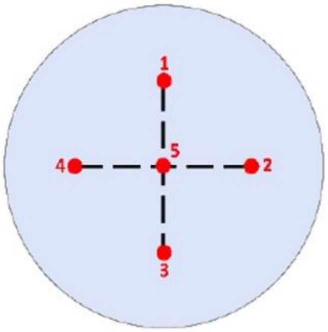


Fig 5. Diagram of the measurement points taken in every sample.

The spectral power distribution of the lamp was measured, yielding a correlated colour temperature of 6438 K (10º observer). To exclude potential external light sources from influencing the results, the room was darkened during the reflectance measurements, ensuring that the booth lamp was the sole source of illumination. A calibrated PTFE white standard (Photo Research Reflectance Standard, Model SRS-3) was employed as the reference. Multiple measurements were collected across the specimen surfaces following the positional scheme (1 - 5) illustrated in Fig 5. During acquisition, the sample was repositioned and rotated so that the measured area remained in the same relative position with respect to the equipment. The spectroradiometer was limited to the visible domain.

To assess quasi-retroreflective behaviour, the spectroradiometer was configured with the light source and detector aligned to simulate near-zero observation angles ($\theta \simeq 0º$). This configuration was intended to evaluate the proportion of reflected light returning along the direction of incidence (Fig 6).

Three entrance angles (β) were tested: 0º, 45º, and 60º, by tilting the samples accordingly while maintaining the source-detector alignment. These measurements aimed to investigate the influence of surface texture and material colour on directionally reflected light.

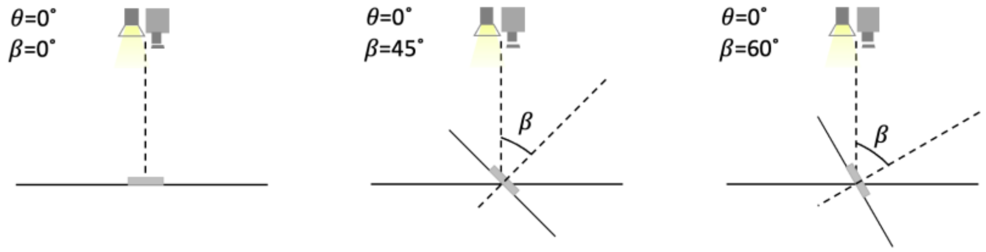


Fig 6. Schematic of illumination and observation angles for the quasi-retroreflectance evaluation.

5 Results and discussion

This section presents the results of the directional reflectance measurements, with special attention to their dependence on material composition and illumination geometry.

5.1 Directional Reflectance of AUTL mixtures

Table 1 provides the mean and standard deviation values of the measured reflectance in the visible spectrum (400-700 nm) for the 18 AUTL-type bituminous mixtures. The directional reflectance was specifically at 45º relative to the incident light ($\beta = \theta = 45º$ in Fig 4).

Table 1. Directional reflectance values in the visible range for the AUTL samples ($\beta = \Theta = 45^o$)

Bituminous Mixture	Directional Reflectance (%)	
	Mean	Std. Dev.
AUTL-LW	67.8	2.5
AUTL-GW	58.8	2.4
AUTL-PW	40.3	8.3
AUTL-LO	23.6	1.1
AUTL-GO	19.5	1.4
AUTL-PO	19.0	1.0
AUTL-LBR	19.2	1.6
AUTL-GBR	15.3	1.8
AUTL-PBR	14.5	1.1
AUTL-LR	15.2	1.1
AUTL-GR	13.3	1.0
AUTL-PR	12.0	1.0
AUTL-LBL	10.6	0.6
AUTL-GBL	10.3	1.6
AUTL-PBL	9.7	2.5
AUTL-LB	5.1	0.8
AUTL-GB	5.1	0.6
AUTL-PB	4.9	1.1

Regarding colour appearance, these results confirm that lighter mixtures reflect significantly more light, while darker mixtures absorb most of the visible radiation, and convert it into heat. The use of synthetic binders and high-albedo pigments (e.g., titanium dioxide, TiO_2) notably enhance reflectance.

Aggregate type affects spectral reflectance. Mixtures incorporating limestone aggregates, which are lighter in colour, show higher spectral reflectance values than those cointaining granite or porphyry, with more pronounced differences for the lighter shades of the mixture (white, ochre or brown). For darker samples (red, blue or black), the differences between mixtures with different aggregates are minimal.

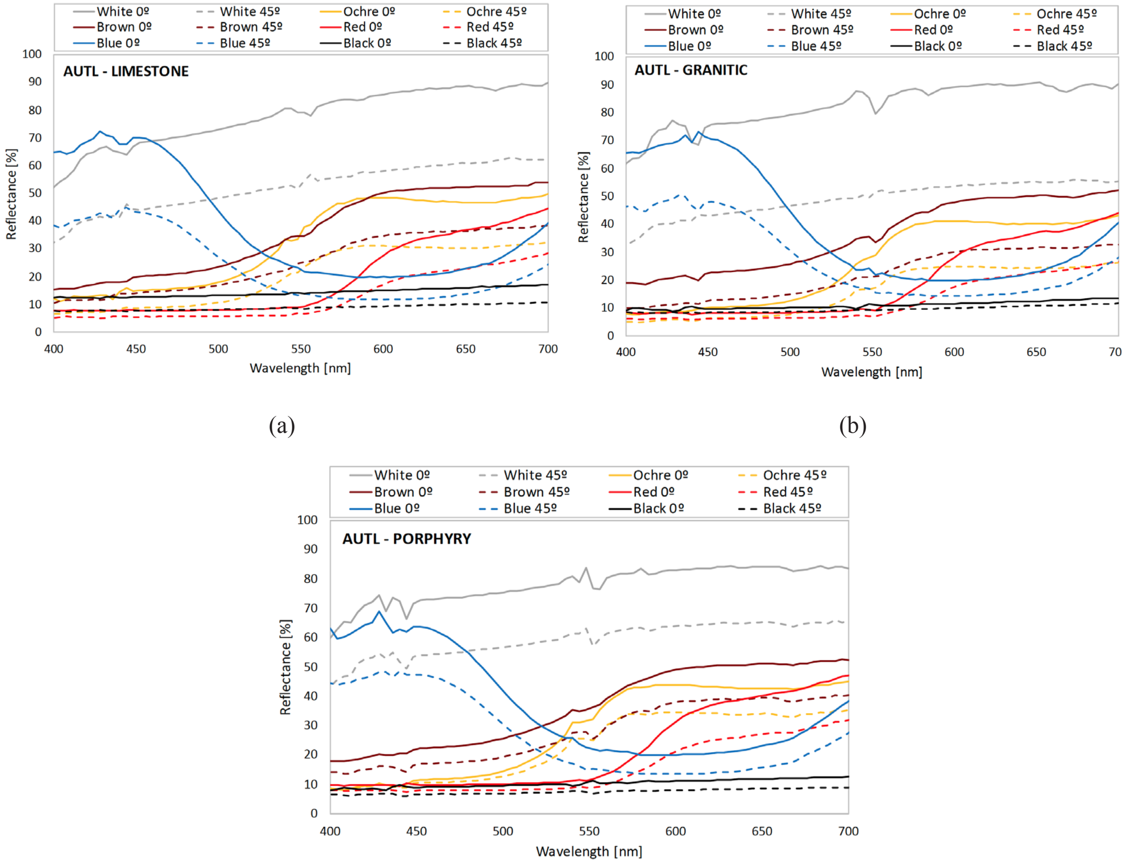
5.2 Influence of observation geometry

Figure 7 shows the variation in reflectance when varying the observation angle θ between the direction of the incident light source and the measurement direction of the reflectance. The entrance angle β of the illumination beam is kept to 45º. The mean value and standard deviation of the reflectance measurements are provided in Table 2.

When the observation angle was reduced to approximately 0º −simulating a quasi-retroreflective configuration− an increase in reflectance was observed for all mixtures. The enhancement was more pronounced in lighter mixtures, suggesting some degree of preferential backscattering due to surface roughness and material composition.

Table 2. Reflectance values in the visible spectrum for the AUTL samples when varying the observation angle (θ = 0º, 45º). The entrance angle is kept to β = 45º .

Bituminous Mixture	**Reflectance (%)**			
	θ = 45º		θ = 0º	
	Mean	Std. Dev.	Mean	Std. Dev.
AUTL-LW	52.4	2.3	78.0	9.7
AUTL-GW	49.1	2.6	82.7	11.6
AUTL-PW	59.5	10.2	78.2	10.9
AUTL-LO	20.5	1.5	32.4	5.8
AUTL-GO	16.0	2.5	26.4	4.3
AUTL-PO	23.3	2.4	28.7	9.1
AUTL-LBR	25.2	2.2	35.9	2.1
AUTL-GBR	21.9	2.3	36.1	1.6
AUTL-PBR	27.9	2.0	36.5	4.2
AUTL-LR	12.4	1.6	19.1	1.9
AUTL-GR	12.6	2.0	19.4	2.4
AUTL-PR	15.5	2.3	21.9	3.1
AUTL-LBL	23.4	1.6	38.4	2.1
AUTL-GBL	27.0	2.4	38.9	2.1
AUTL-PBL	26.4	1.3	36.9	8.5
AUTL-LB	8.9	0.6	14.3	2.7
AUTL-GB	9.5	1.4	11.0	3.1
AUTL-PB	7.6	2.7	10.4	2.2



(a)

(b)

(c)

Fig 7. Reflectance values of the different AUTL-type mixtures, obtained by using the spectroradiometer at entrance angle $\beta = 45º$ and observation angles $\theta = 0º, 45º$. Results for mixtures made with (a) limestone, (b) granitic, and (c) porphyry aggregates.

When the observation angle was reduced to approximately 0º −simulating a quasi-retroreflective configuration− an increase in reflectance was observed for all mixtures. The enhancement was more pronounced in lighter mixtures, suggesting some degree of preferential backscattering due to surface roughness and material composition.

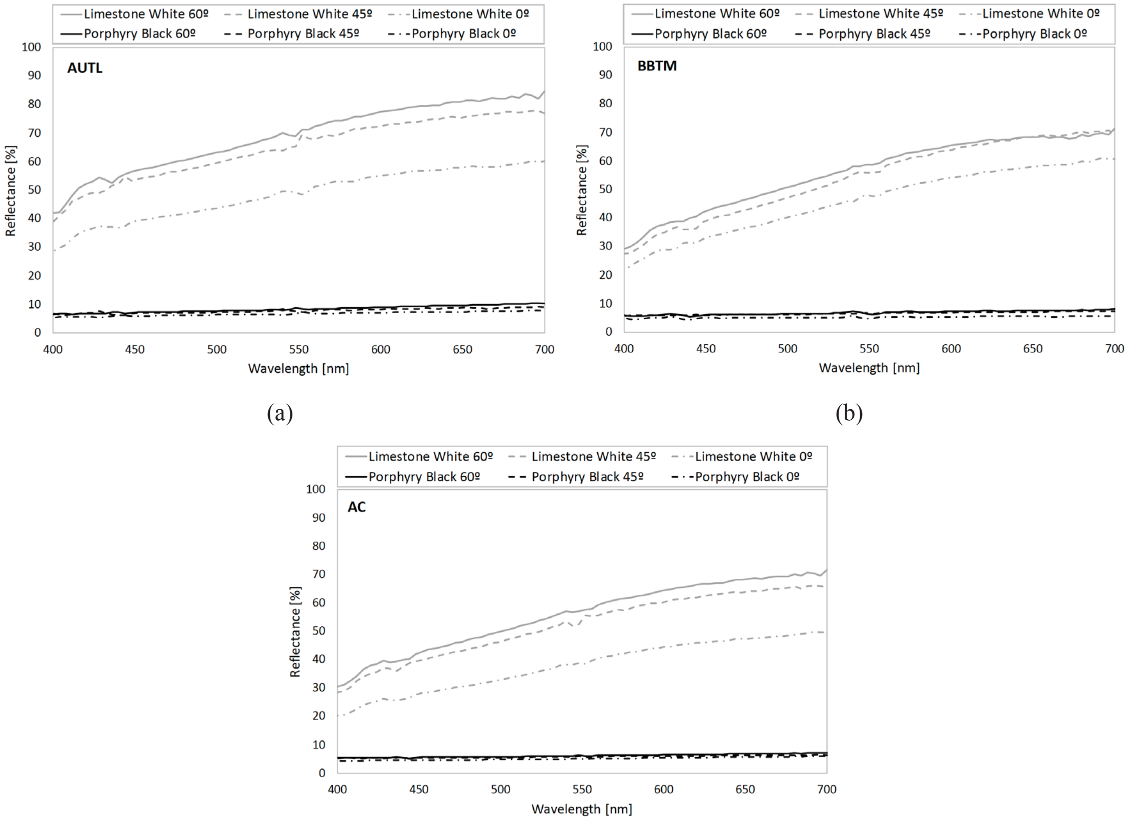
For example, AUTL-GW (white granite) increased from 49.1% at 45º to 82.7% at 0º, while AUTL-PB (black porphyry) increased only modestly from 7.6% to 10.4%. This directional dependence demonstrates that some asphalt mixtures exhibit behaviour qualitatively similar to retroreflective materials, despite lacking engineered microstructures.

It should be noted that the samples analysed at this stage, although measured at the same entrance angle (45º), differ from those used for the same angle in the previous section. In this second stage of the study, the samples have been exposed to solar radiation for a long period of time. This has caused the lighter samples to be slightly darker than the original ones, while the darker mixtures appear slightly lighter. Consequently, reflectance values can only be directly compared within each stage of the study, and not between Sections 5.1 and 5.2. Nevertheless, consistent with the results presented in Section 5.1, the aggregate type influences only the lightest mixtures (white and ochre), among which the limestone aggregate exhibited slightly higher values in general.

It must be remembered that all the measurements with the spectroradiometer were conducted with the same light entrance angle with the surface normal ($\beta = 45^{\circ}$). In the following subsection, the effect of the entrance angle on the retroreflectance values is analyzed. A priori, it could be thought that the texture of the mixture will also influence the measurements obtained; therefore, in addition to the AUTL-type mixtures, two further types of mixtures have been considered, a BBTM 8A and an AC 16S, both with different textures.

5.3 Influence of light entrance angle

Figure 8 shows the reflectance of selected mixtures (white and black in AUTL, BBTM and AC types) as a function of entrance angle. Measurements were performed at an observation angle of 0º, while the entrance angle was set to 60º, 45º, and 0º. Mean values and standard deviations for the obtained reflectance spectra are shown in Table 3.



(a)

(b)

(c)

Fig 8. Reflectance as a function of light entrance angle ($\beta = 60^{\circ}$, 45°, and 0°), measured at a fixed observation angle of $\theta = 0^{\circ}$. Results are shown for (a) AUTL 8, (b) BBTM 8A, and (c) AC 16S mixtures.

For all surface textures, reflectance increased with increasing entrance angle β, corresponding to more grazing illumination conditions. This trend can be attributed to the roughness of the surface topography: at normal incidence, a larger fraction of the radiation is absorbed within the surface cavities, which occupy a substantial portion of the sample area. Conversely, at steeper angles, the cavities appear smaller, and more light is reflected from the upper facets of the texture (see Fig 9).

Table 3. Reflectance values in the visible spectrum for white and black AUTL, BBTM and AC samples measured at an observation angle of $\theta = 0^\circ$, for illumination entrance angles of $\beta = 60^\circ$, 45º and 0º

Bituminous Mixture	**Reflectance (%)**					
	$\beta = 60^\circ$		$\beta = 45^\circ$		$\beta = 0^\circ$	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
AUTL-LW	68.9	4.5	64.7	6.8	48.5	6.3
AUTL-PB	8.4	1.6	7.7	1.8	6.7	0.8
BBTM-LW	56.0	2.5	54.1	3.6	45.9	5.7
BBTM-PB	6.8	2.4	6.5	1.3	5.2	2.1
AC-LW	55.8	1.9	52.2	3.6	37.9	2.7
AC-PB	6.2	2.4	5.8	1.5	5.1	1.2

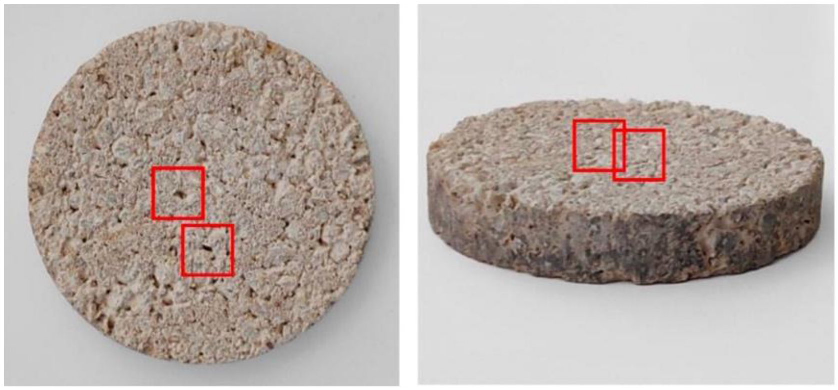


Fig 9. Surface views illustrating the perception of surface cavities under different illumination geometries: top view at normal incidence ($\beta = 0^\circ$, left) and side view at grazing incidence ($\beta = 60^\circ$, right).

The shade of the samples also exerts a significant influence. The increase in reflectance with entrance angle was particularly pronounced in lighter mixtures (e.g., AUTL-LW: 48.5% at 0º, 68.9% at 60º), whereas black mixtures exhibited minimal angular sensitivity due to their low reflectance values (e.g., AUTL-PB: 6.7% to 8.4%).

With respect to texture, the AUTL mixtures have reflectance values similar to, or slightly higher than, those of the BBTM mixtures. Both types of samples showed higher values than the AC mixtures for all considered entrance angles. This trend, however, was only evident for light shades, as the reflectance values of dark samples were very similar for all types of mixture.

6 Conclusions

This study evaluated the optical behaviour of various bituminous mixtures by analyzing their spectral and directional reflectance properties under controlled laboratory conditions. Based on the results, the following conclusions can be drawn:

1. Reflectance was strongly influenced by aggregate type, binder formulation and pigmentation. Mixtures containing light-coloured aggregates (e.g., limestone) and white pigments (TiO_2) exhibited the highest reflectance across the visible spectrum. In contrast, black mixtures formulated with dark aggregates and conventional bitumen showed very low reflectance and minimal angular variation.

2. The directional reflectance analysis revealed that light-coloured mixtures not only reflected more energy overall, but also demonstrated enhanced reflectance when the detection axis approached the illumination axis ($\theta = 0°$). This behaviour partially mimics that of retroreflective materials, despite the absence of dedicated retroreflective elements in asphalt.
3. Reflectance increases with grazing light incidence (higher entrance angles). This effect was more pronounced in rough-textured mixtures and for lighter colours, indicating a texture-dependent response in directional reflectance. Surfaces with higher roughness, such as AUTL and BBTM mixtures, exhibited greater angular variation, with higher reflectance at steeper entrance angles. This may be attributed to cavity effects, which trap radiation more effectively at normal incidence but reflect more light when illuminated at shallow angles.

In summary, the combination of light pigmentation, high-albedo aggregates, and optimized surface texture can significantly enhance the optical reflectance of asphalt mixtures, contributing to urban heat island mitigation and improved radiative behaviour of pavements. However, these optical benefits must be evaluated alongside, durability, aging and skid resistance requirements. Pigmented mixtures may degrade under UV exposure or wear, and increased smoothness aimed at improving reflectance may compromise friction performance. Therefore, an integrated design approach is needed to balance thermal, optical and mechanical performance requirements.

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