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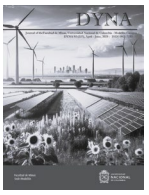

UNIVERSIDAD NACIONAL DE COLOMBIA

Contribution of an asphalt pavement modified with TiO_2 to the moderation of the Urban Heat Island (UHI)

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Abstract
Urban pavements, covering up to 40% of cities, intensify the Urban Heat Island (UHI) phenomenon by impeding rainwater infiltration and absorbing solar radiation. High pavement temperatures increase urban energy demand and pollution. One important factor affecting pavement temperature is albedo. The higher the albedo, the less solar irradiation the pavement absorbs, and the cooler it remains. This study evaluates TiO_2 incorporated into asphalt to enhance albedo. The thermal response of conventional and TiO_2-modified pavements was monitored under natural sunlight. Opto-thermal properties were measured initially and after twelve months of outdoor exposure. An energy balance quantified the heat amount released to the environment for both pavements. Results demonstrate TiO_2 effectiveness in reducing heat storage and improving radiative cooling over time. Additionally, the mechanical and rheological impacts of TiO_2 on asphalt binders were analyzed. Cool pavements with TiO_2 emerge as a viable UHI mitigation strategy, offering energy savings and enhanced urban sustainability.

Keywords: modified asphalt pavements; TiO_2; urban heat island; albedo; aging; released energy.

Contribución de un pavimento asfáltico modificado con TiO_2 a la moderación de la Isla de Calor Urbana (ICU)

Resumen
Los pavimentos urbanos, que cubren hasta el 40% de las ciudades, intensifican el fenómeno de la Isla de Calor Urbana (ICU) al impedir la infiltración de agua de lluvia y absorber la radiación solar. Las altas temperaturas del pavimento aumentan la demanda energética urbana y la contaminación. Un factor importante que afecta la temperatura del pavimento es el albedo. Cuanto mayor es el albedo, menor es la radiación solar que absorbe el pavimento y más frío se mantiene. Este estudio evalúa el TiO_2 incorporado al asfalto para mejorar el albedo. Se monitoreó la respuesta térmica de los pavimentos convencionales y modificados con TiO_2 bajo la luz solar natural. Se midieron las propiedades opto-térmicas inicialmente y después de doce meses de exposición al aire libre. Un balance energético cuantificó la cantidad de calor liberado al ambiente para ambos pavimentos. Los resultados demuestran la eficacia del TiO_2 para reducir el almacenamiento de calor y mejorar el enfriamiento radiativo con el tiempo. Además, se analizaron los impactos mecánicos y reológicos del TiO_2 en los ligantes asfálticos. Los pavimentos fríos con TiO_2 surgen como una estrategia viable de mitigación de UHI, que ofrece ahorros de energía y una mayor sostenibilidad urbana.

Palabras clave: pavimentos de asfalto modificados; TiO_2; isla de calor urbana; albedo; microclima.

1. Introduction

In recent decades, large-scale production of goods and industrial activities have caused an increase in the number of residents living in cities near production centers. The population density in cities is continuously growing and it is estimated that by 2050, nearly 70% of the world's population will live in megacities.

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To accommodate this ever-growing urban population, a housing and communication infrastructure that causes significant environmental changes has been implemented: there is an increasing replacement of natural soil with impermeable soil, and materials with inadequate opto-thermal properties are used in construction [1,2].

At present, almost half of urban land has been replaced by asphalt pavement. During the day, due to the incidence of solar irradiation, these pavements heat up and afterward release heat to the environment. Asphalt pavements are dark, so as a black body, they absorb a significant portion of the incident solar irradiation as heat, reaching surface temperatures close to 70ºC in some geographic regions during the summer. Higher pavement surface temperatures are one of the causes of the urban heat island effect, UHI, with air temperatures higher in the city than in the surrounding suburbs and rural areas [3].

A conventional asphalt pavement transfers heat to its interior, stores it during sunlight hours, and releases it into the air during the evening and night hours, causing thermal discomfort for city dwellers [4-9].

There is a huge consumption of fossil energy to cool premises and residences and air pollution occurs in large cities. In addition, due to the viscoelastic nature of asphalt, the load resistance of the pavement decreases as the temperature increases and rutting occurs on the surface, reducing the service life of the pavement. During the life of the pavement, changes occur in the composition of the asphalt binder. The laboratory-aging test reveals that the asphalt became stiffer and more prone to cracking by losing its viscous component due to temperature, humidity and the incidence of the ultraviolet (UV) component of solar radiation, among other environmental factors to which an outdoor pavement is subjected. The pavement undergoes modifications in its structure and cracks and rut appear on the surface [10-13]. Many studies have identified permanent deformation induced by high temperatures as one of the main problems in asphalt pavements in the current climate change situation.

To mitigate the UHI (Urban Heat Island) effect, among other possible solutions, it is recommended to use paving materials with higher albedo, which is defined as the ratio between reflected solar irradiation and the total solar irradiation incident on the surface [3]. The higher the albedo value is, the less solar irradiation the pavement absorbs, and the cooler it remains. The most common comparison between asphalt and concrete pavements shows that the latter has a cooler surface due to its lighter color [4,14] Various strategies have been proposed to reduce the amount of heat absorbed and stored by pavement, including the incorporation of pigments into asphalt mixtures to achieve a lighter surface color, particularly on the top layer [15]. Chen et al. affirm that incorporating TiO_2 fillers at varying percentages into a transparent resin, which is subsequently applied as a coating on different asphalt mixtures, significantly enhances the albedo value, depending on the size and concentration of the fillers [16].

Zhong has demonstrated that modifying an asphalt emulsion with varying percentages of TiO_2 and applying it as a surface coating reduces the pavement's surface temperature by approximately 5°C [17]. Cool pavements can be implemented in urban areas as a strategy to mitigate the adverse effects of urban heat islands. By preventing pavement overheating, energy savings are achieved, and the urban microclimate is improved.

It is noteworthy that asphalt pavements, initially dark in color, lighten over time, slightly increasing their albedo and reducing heat absorption as they age in service. This outdoor color variation is attributed to irreversible physicochemical modifications of the asphalt (aging), caused by a complex oxidation process of its organic compounds under the influence of environmental factors such as rainfall, temperature fluctuations, and UV component of incident solar irradiation, which photo-catalyzes the degradation [11].

This study analyzes the optothermal response of dense asphalt pavement specimens, before and after the incorporation of TiO_2 microparticles (average size 0.5 μm) as fillers in the asphalt mixture.

The surface temperature, albedo, and emissivity of the exposed samples were measured, and the effect of prolonged outdoor exposure on their thermal behavior was evaluated. Additionally, using an energy balance approach, the heat released by the samples into the environment was calculated both initially and after 12 months of outdoor exposure. The effect of TiO_2 microparticles on the physical properties of asphalt, high-temperature performance grade, and fatigue damage tolerance were also investigated using a dynamic shear rheometer (DSR).

2. Experimental

Two representative types of dense-graded asphalt mixtures were prepared. The first type utilized an asphalt binder CA-30, stone aggregates with commercial designations of 6:12 (coarse aggregate) and 0:6 (fine aggregate), and combined fillers (lime + all particles smaller than the #200 sieve from the coarse and fine aggregates). This mixture was used to fabricate reference specimens. The second asphalt mixture was prepared by removing the combined fillers, and incorporating 5% of TiO2, a powdered pigment that meets the specifications of ASTM C979. The TiO2-modified specimens analyzed in this study were fabricated with this modified asphalt mixture. All specimens were 0.3 m × 0.3 m × 0.05 m. In this paper 'specimen' denote asphalt pavement mixture, and 'sample' denote asphalt binder.

Thermal measurements were conducted by placing the specimens on a polystyrene foam (EPS) sheet 0,1 m thick, which exhibits negligible thermal conductivity (ca. 0.032 W.m-1K-1).

The albedo value of each specimen (reference and TiO_2-modified) was measured following the ASTM E1918A standard modified by Akbari et al. [18], during clear-sky days in January 2024 and January 2025, on the rooftop of the Universidad Tecnológica Nacional, Facultad Regional La Plata (National Technological University, La Plata Regional Faculty). The instrumentation included a calibrated Kipp & Zonen CMP-3 pyranometer coupled to a Campbell Scientific CR300 datalogger.

The thermal behavior of samples exposed to direct solar irradiation was evaluated using K-type thermocouples connected to Testo data-loggers. The surface temperatures of the specimens were recorded continuously every ten seconds over five consecutive days in January 2024, with the measurements repeated under similar conditions in January 2025.

Additionally, a Testo 865 thermal imaging camera was employed to estimate the emissivity (ε) of each sample, following the guidelines outlined in ASTM E1933-99a [19]. The camera, with an infrared resolution of 320 × 240 pixels and a thermal sensitivity of 0.1 °C, also enabled visual analysis of surface temperature differences between the samples, complementing the data recorded by the thermocouples.

A simplified model was employed accounting for the heat fluxes occurring between the pavement and its surrounding environment, incorporating the primary energy transfer mechanisms. The model includes: the incident solar irradiation, the portion of it absorbed by the pavement, the heat transferred to the pavement by thermal conduction, the energy released to the environment by convection (sensible heat), and the longwave radiation emitted from the hot pavement surface to the air. Using this framework, the total energy released to the environment by the two types of asphalt pavement was quantified.

To analyze the influence of TiO_2 microparticles on the asphalt binder, physical properties such as penetration (ASTM D5/D5M) [20] and softening point (ASTM D36/D36M) [21] were determined. Additionally, the high and intermediate temperature performance grades (AASHTO M320) [22] were evaluated using a dynamic shear rheometer.

The effect of TiO_2 on the physical and rheological properties of the asphalt binder was evaluated before and after subjecting the samples to thin-film oven aging (RTFOT) following AASHTO T240 [23].

3. Results

3.1 Color variation of asphalt mixtures under outdoor exposure

Fig. 1 shows images depicting the color of reference and 5% TiO_2-modified asphalt pavement specimens, both initially and after one year of outdoor exposure.

Initially, the reference specimen exhibits a characteristic black color, whereas the TiO_2-modified specimen displays a brown coloration [27]. This suggests that TiO_2 may have catalyzed a chemical transformation in the asphalt from the beginning of the experiment [24-25]. After 12 months of outdoor exposure, the reference specimen developed a dark gray coloration, while the TiO_2-modified sample exhibited a light gray tone. It can be concluded that prolonged outdoor exposure has caused surface color variations in both analyzed samples.

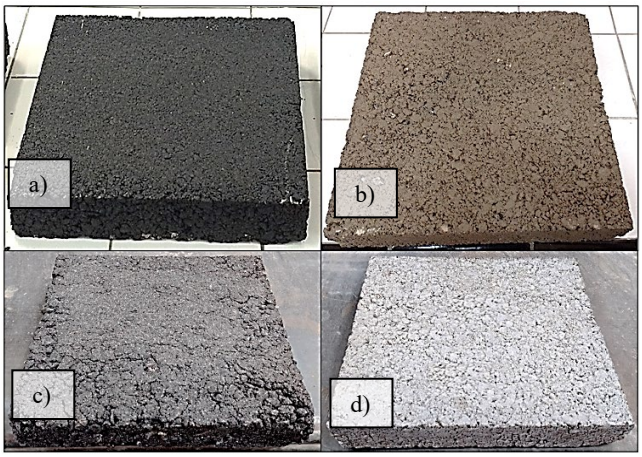

Figure 1. Images of the samples: a) reference asphalt pavement and b) TiO_2-modified asphalt pavement, at month 1; c) reference asphalt pavement and d) TiO_2-modified asphalt pavement, after 12 months of outdoor exposure.
Source: Authors' own work.

The observed color change in both specimens is attributed to the oxidation process of the asphalt due to a prolonged stay in open air (UV radiation, rainfall, oxygen, etc), a process catalyzed by TiO_2 in the modified specimen [26].

A cross-sectional cut was performed on the reference and TiO_2-modified samples exposed to outdoor conditions for 12 months to determine whether the color change was superficial or occurred throughout the whole specimen's volume. Fig. 2 shows images of the cross-sectional cuts of the (a) reference and (b) TiO_2-modified specimens. In both cases, a color difference is observed between the air-exposed surface and the sample's interior, which can be attributed to a greater aging of the surface due to UV radiation exposure. The cross-section of the TiO_2-modified specimen exhibits a marked color difference between the surface and the interior of the modified asphalt mixture. It is possible that the presence of TiO_2 catalyzes the reaction between asphalt and oxygen under UV radiation, resulting in a noticeable surface color change in the TiO_2-modified sample compared to the surface color change observed in the reference specimen for the same reaction.

3.2 Albedo values determined at solar noon on a summer day

The variation in albedo of the pavement specimens before and after being exposed to outdoor conditions for 12 months is shown in Fig. 3. The albedo measurement of each specimen was repeated six times and the standard deviation obtained was ± 0.3%.

It is confirmed that the incorporation of TiO_2 into the asphalt mixture increased the albedo at the start of the experiment.

Figure 2. Cross-sectional cut in a) the reference specimen and b) the TiO_2-modified specimen exposed to outdoor conditions for 12 months.
Source: Authors' own work.

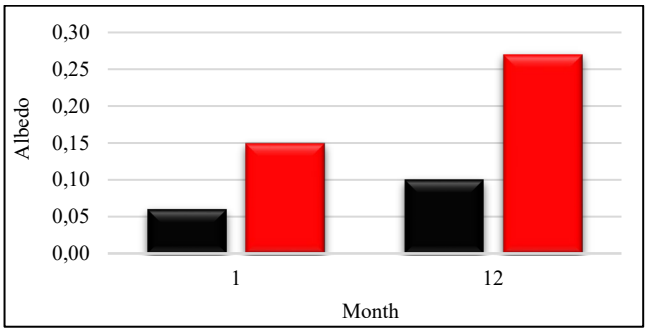

Figure 3. Albedo values for reference specimen (black) and TiO_2-modified specimen (red) at month 1 and after 12 months of outdoor exposure.
Source: Authors' own work.

After 12 months of outdoor exposure, both pavements exhibit an increase in their albedo values, with the TiO2-modified specimen showing a particularly significant rise. An increase in albedo implies a lower surface temperature of the asphalt pavement exposed to solar irradiation [28-29].

3.3 Variation in surface temperature of samples exposed to outdoor conditions

Figs. 4a and 4b illustrate the surface temperature variations of the reference and TiO_2-modified asphalt pavement specimens over a five-day period a) at the start of outdoor exposure and b) after 12 months of outdoor exposure.

Fig. 4a shows that, at the start of outdoor exposure, the TiO_2-modified asphalt pavement specimen exhibits a decrease of approximately 4°C in its surface temperature value particularly when the Sun is at its zenith. After 12 months of outdoor exposure, Fig. 4b reveals that the TiO_2-modified sample displays a more pronounced decrease in surface temperature, approximately 10°C, compared to the value recorded in the reference sample, especially during solar zenith. The observed decrease in temperature correlates with the higher albedo values measured in the specimen after 12 months of outdoor exposure. Similar behavior of the pavement superficial temperature during the solar day has been shown in [17].

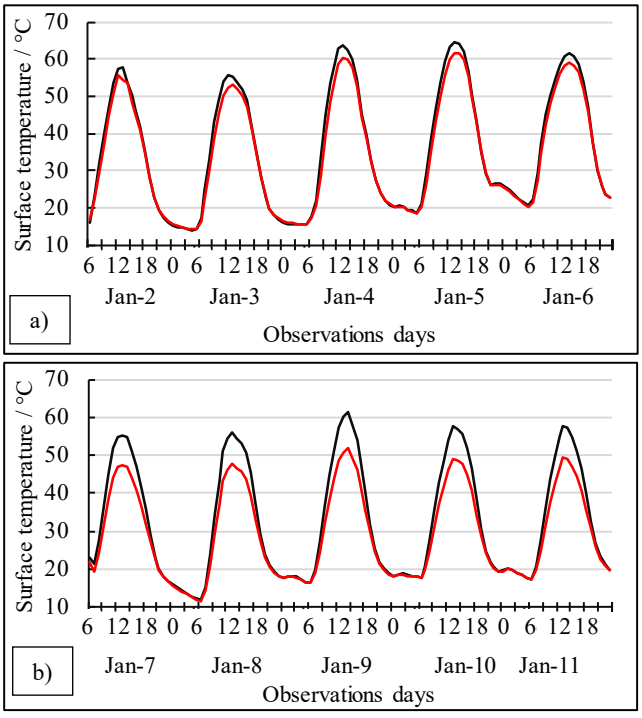

Figure 4. Surface temperature variation over five studied days, due to daily solar irradiation on the reference asphalt pavement specimen (black line) and on the TiO2-modified pavement specimen (red line): a) at month 1 and b) after 12 months of outdoor exposure.
Source: Authors' own work.

3.4 Thermographic Images

The change in surface temperature of the analyzed specimens can be qualitatively observed in the thermographic images shown in Fig. 5. The color scale illustrates that both samples (reference and TiO_2-modified asphalt pavement) at the start and after one year of outdoor exposure, exhibit lower surface temperatures, with this cooling effect being more pronounced in the TiO_2-modified specimen.

Using thermographic images and data recorded with thermocouples, the emissivity (ε) of each analyzed surface was determined. The emissivity values (ε), both at month 1 and month 12, were 0.91 for the reference specimen and 0.97 for the TiO_2-modified specimen.

3.5 Variation of Heat Released to the Environment for Each Analyzed Pavement

The thermal balance of a pavement exposed to solar irradiation must account for:

- The amount of solar irradiation absorbed by the pavement,
- The heat flux transferred by conduction (Qcond) into the pavement's interior,
- The infrared radiation (Qrad) emitted by the surface of the heated body,
- The heat flux, transferred by convection (Qconv), from the hot surface to the air.

According to the Bentz model [30] and following the analyses by Asaeda [31] Qin et al and Xu et al. [32,33], the energy balance at the surface of a dry pavement is:

$$I.(1-albedo) = h_c.(T_S - T_{amb}) + \varepsilon.\sigma.(T_S^4 - T_C^4) - k.(dT/dz) \quad (1)$$

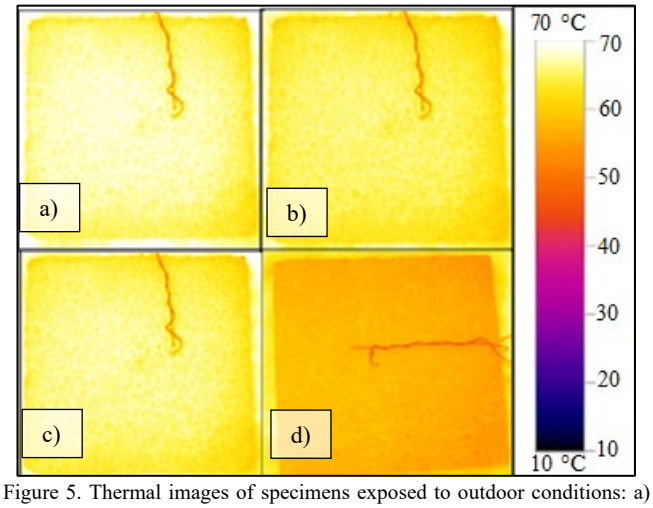

Figure 5. Thermal images of specimens exposed to outdoor conditions: a) and b) reference asphalt pavement and TiO_2-modified asphalt pavement at month 1, respectively; c) and d) reference asphalt pavement and TiO_2-modified asphalt pavement after 12 months of outdoor exposure, respectively.
Source: Authors' own work.

where I is the incident solar irradiation on the sample surfaces; h_c [$W.m^{-2}.K^{-1}$] is the convective coefficient, dependent on wind speed; T_S [K] is the pavement surface temperature; T_{amb} is the ambient temperature [K]; σ is the Stefan-Boltzmann constant (5.67×10^{-8} [$W.m^{-2}.K^{-4}$]); ε is the emissivity of the pavement (dimensionless, ranging between 0 and 1); T_C[1] [K] is the sky temperature; k [$W.m^{-1}.K^{-1}$] is the material's thermal conductivity; and dT/dz [$K.m^{-1}$] is the thermal gradient into the pavement's interior.

The portion of solar energy that is not reflected by the surface is absorbed by the pavement. The absorbed energy is partially transferred throughout the pavement's volume via conduction, increasing its temperature. Additionally, a heated body emits radiation in the infrared (IR) region of the electromagnetic spectrum. This radiative heat transfer depends on the surface temperature value and the emissivity of the composite material. Furthermore, when the pavement's surface temperature exceeds the temperature of the air above it, part of the absorbed energy begins to be transferred from the pavement surface to the air via convection (sensible heat). Convective heat transfer to the environment depends on the surface temperature of the heated sample, the surrounding air temperature, and the wind speed over the analyzed surface.

Using the surface temperature data shown in Fig. 4a and 4b, considering the thermal balance, and accounting for the variation in the optical properties that the samples undergo after being exposed to the outdoors for 12 months, the energy released into the environment as sensible heat and longwave radiation is calculated over a five-day period using eq (1).

Fig. 6 shows the behavior of each component of the energy balance (at month 1 and after 12 months) for the reference sample and the TiO2-modified sample of outdoor exposure, both over five consecutive days.

It is confirmed that the TiO2-modified sample absorbs less energy than the reference sample, which is directly reflected in the amount of energy the sample releases to the air adjacent to the surface. This effect is more pronounced when the samples have been exposed to outdoor conditions for 12 months. The amounts of energy flux released to the environment by the samples over the five studied days during both daytime and nighttime periods were calculated.

Table 1 presents the energy flux released to the environment (Q_{rel}) between 06:00 and 20:00 hours, calculated as the sum of sensible and radiative heat, for reference and the TiO_2-modified samples, both over the five studied days, at month 1 and after 12 months of exposure to outdoor conditions.

Table 1 demonstrates that, during daytime hours, the majority of energy flux released to the environment by both specimens occurs as sensible heat (Q_{conv}), with the reference sample exhibiting a higher Q_{conv} value than the TiO_2-modified specimen.

In contrast, during nighttime (Table 2), the total amount of energy released is lower than the one released during the daytime, and it is primarily attributed to long-wave radiation, Q_{rad}, the lower emission value is again for the TiO_2- modified specimen.

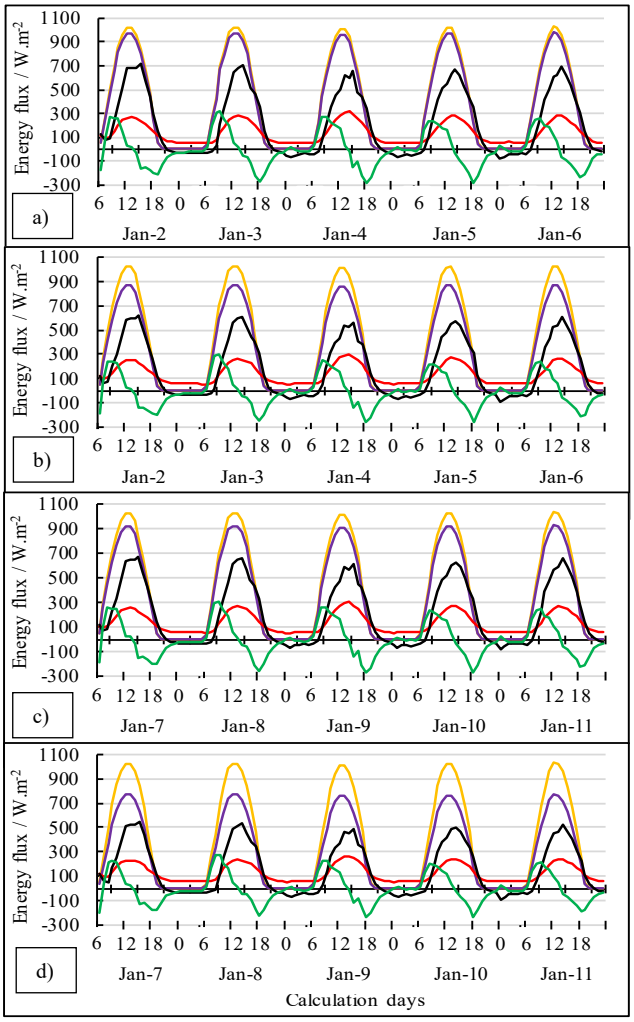

Figure 6. Energy flux components calculated over five days period of: a) reference specimen and b) TiO_2-modified specimen with optical properties of month 1; c) reference asphalt specimen and d) TiO_2-modified asphalt specimen with optical properties of month 12. Lines: *yellow*: incident solar irradiation; *purple*: absorbed solar energy; *black*: energy transferred to the environment via convection; *green*: long-wave IR energy emitted to the environment; *red*: heat flux between the pavement surface and its interior. Source: Authors' own work.

Table 1.
Energy flux released to the environment (Qrel) over the five studied days, by the reference and TiO_2-modified asphalt pavement specimens, between 06:00 and 20:00 hours, before and after 12 months of outdoor exposure.

Month	Reference Specimen		TiO_2 Modified Specimen	
	Q_{Rel} / $Wh.m^{-2}$		Q_{Rel} / $Wh.m^{-2}$	
1	Q_{Rad} / $Wh.m^{-2}$	Q_{Conv} / $Wh.m^{-2}$	Q_{Rad} / $Wh.m^{-2}$	Q_{Conv} / $Wh.m^{-2}$
	12008.8	26443.4	11503.5	22807.3
	38452.2		34310.9	
	Q_{Rel} / $Wh.m^{-2}$		Q_{Rel} / $Wh.m^{-2}$	
12	Q_{Rad} / $Wh.m^{-2}$	Q_{Conv} / $Wh.m^{-2}$	Q_{Rad} / $Wh.m^{-2}$	Q_{Conv} / $Wh.m^{-2}$
	11483.1	24889.1	10430.7	19718.4
	36372.2		30149.1	

Source: Authors' own work.

[1] The sky temperature, T_C, is the average temperature derived from the ground surface under study and the temperature in the upper troposphere, where water vapor content is minimal.

Table 2.
Energy flux released to the environment (Q_{rel}) by the reference and TiO_2-modified asphalt pavement specimens, over the five studied days, between 20:00 and 06:00 hours, before and after 12 months of outdoor exposure.

Month	Reference Specimen		TiO_2 Modified Specimen	
	Q_{Rel} / Wh.m^{-2}		Q_{Rel} / Wh.m^{-2}	
1	Q_{Rad} / Wh.m^{-2}	Q_{Conv} / Wh.m^{-2}	Q_{Rad} / Wh.m^{-2}	Q_{Conv} / Wh.m^{-2}
	2859.2	-740.7	2978.2	-958.5
	2118.5		2019.8	
	Q_{Rel} / Wh.m^{-2}		Q_{Rel} / Wh.m^{-2}	
12	Q_{Rad} / Wh.m^{-2}	Q_{Conv} / Wh.m^{-2}	Q_{Rad} / Wh.m^{-2}	Q_{Conv} / Wh.m^{-2}
	2848.9	-773.4	2957.1	-1021.1
	2075.5		1936.1	

Source: Authors' own work.

In contrast, during nighttime (Table 2), the total amount of energy released is lower than the one released during the daytime, and it is primarily attributed to long-wave radiation, Q_{rad}, the lower emission value is again for the TiO_2- modified specimen.

It is observed that the greatest energy flux released from the samples to the environment occurs during the sunlight period. Notably, when comparing the TiO_2-modified sample energy flux released with that of the reference sample, it is noticed a reduction in the energy flux transferred to the environment by the TiO_2-modified sample, both initially and after 12 months of outdoor exposure. The TiO_2-modified pavement, being lighter in color, absorbs less solar heat and lowers its surface temperature, thereby contributing to an improved urban microclimate [5,7].

3.6 Influence of TiO_2 on the physical properties of asphalt CA-30

The effect of TiO_2 on the physical properties of the asphalt binder was evaluated before (virgin) and after subjecting the samples to thin-film oven aging (aged) (RTFOT) following AASHTO T240.

In Table 3, the penetration and softening point values before and after subjecting the samples to thin-film oven aging (RTFOT): i) asphalt CA-30, ii) asphalt CA-30 + combined fillers, and iii) asphalt CA-30 + TiO_2 filler, at the proportions used in the mixture.

Table 3 shows that asphalt with combined fillers has the lowest penetration value and the highest softening point, a behavior like to that of asphalt with only TiO_2 as a filler, both, before and after aging. This behavior derives from the filler/asphalt weight ratios, being 1.1 for CA-30 asphalt with combined fillers and 1 for CA-30 with TiO_2 filler.

Table 3.
Properties of asphalt CA-30 and fillers modified asphalt CA-30 before and after subjecting the samples to thin-film oven aging (RTFOT).

Samples	Properties	
	Penetration	Softening Point
Virgin asphalt	46 x 10^{-1} mm	54 °C
Aged asphalt (RTFOT)	29 x 10^{-1} mm	59 °C
Virgin Asphalt + combined fillers	20 x 10^{-1} mm	63 °C
Aged Asphalt + combined fillers (RTFOT)	15 x 10^{-1} mm	68 °C
Virgin Asphalt + TiO_2 filler	27 x 10^{-1} mm	60 °C
Aged Asphalt + TiO_2 filler (RTFOT)	17 x 10^{-1}mm	65 °C

Source: Authors' own work.

This indicates that asphalts with fillers (combined or with only TiO_2) have low thermal susceptibility, and therefore, in both cases, the viscosity resists creep changes with increasing temperature [34,35].

3.7 High-Temperature Performance Grade (PG)

To evaluate the high-temperature performance grade of the analyzed asphalt binder (virgin and RTFO-aged) according to AASHTO M320, the rutting parameter (G*/sinδ) was determined for asphalt CA-30, asphalt CA-30 + combined fillers, and asphalt CA-30 + TiO_2 filler. Here, G* (complex modulus) represents a measure of the material's dynamic mechanical properties, and δ (phase angle) corresponds to a measure of its elastic and viscous properties [36,37].

From the G*/sinδ vs. temperature relationship, it was determined that by incorporating TiO_2 into CA-30 asphalt, the rutting failure temperature changed from 64°C for CA-30 asphalt to 76°C for CA-30 asphalt + TiO_2 filler, and 82°C for CA-30 asphalt + combined fillers.

The data reveals an improved performance grade in the asphalt CA-30 modified with combined fillers concerning rutting resistance (G*/sinδ) compared to the sample asphalt CA-30 + TiO_2 filler.

However, regarding surface temperatures recorded in specimens shown in Fig. 4a, a contrasting performance is noticed: the TiO_2-modified specimen exhibits higher albedo, which reduces its surface temperature under the same solar irradiation conditions as those experimented by the reference specimen.

This behavior suggests that, under real-world exposure conditions, the sample prepared with CA-30 asphalt + TiO_2 filler could compensate for its lower intrinsic rutting resistance through its enhanced heat-reflective capacity. Studies by Saleh and Trad, as well by Hashema et al. [38,39], show that, according to the SUPERPAVE and LTPP programs (integrated in the AASHTO M 320 standard), the geographic PG (Performance Grade) predicts the surface temperature of black pavements based on regional climatic conditions. Thus, the determination of the geographic PG is affected not only by climatic data but also by the pavement albedo value, an optical property of the pavement surface nature.

The maximum surface temperatures, shown in Fig. 4a, reached 64 °C for the reference specimen, compared to 61 °C for the TiO_2-modified specimen. Indicating that the TiO_2 modified pavement will be under lower thermal loads. Consequently, by operating at a lower surface temperature, the TiO_2-modified sample exhibits a mechanical response to rutting that could match or surpass that of the CA-30 asphalt + conventional fillers. To validate this hypothesis, we quantified the rutting rheological parameters (G*/sinδ) at the specific temperatures attained by each sample under real environmental conditions (Table 4), derived from temperature sweeps conducted via DSR rheometer.

The values shown in Table 4 indicate that the specimen incorporating CA-30 + TiO_2 asphalt filler, which has the highest albedo and lowest surface temperature, shows improved rutting resistance under these conditions.

Table 4.
G*/sinδ values obtained with samples, at the surface temperatures reached by the respective specimens under identical solar irradiation conditions.

Sample	G*/sinδ	Surface temperature / °C
Asphalt CA-30 + combined fillers	9.1	64
Asphalt CA-30 + TiO_2 filler	9.9	61

Source: Authors' own work.

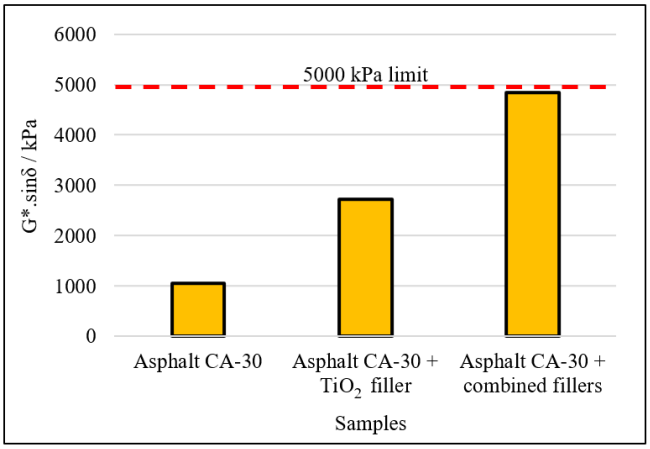

Figure 7. Fatigue parameters obtained at 30°C for the three analyzed samples: a) asphalt CA-30, b) asphalt CA-30 + TiO_2 filler, and c) asphalt CA-30 + combined fillers.
Source: Authors' own work.

3.8 Fatigue damage tolerance

The fatigue parameter G*.sin δ was assessed following the SHRP SUPERPAVE methodology [34], with the limiting value of G*.sin δ defined as 5000 kPa. The values obtained at an intermediate temperature (30°C) for the asphalt CA-30, asphalt CA-30 + combined fillers, and asphalt CA-30 + TiO_2 fillers (shown in Fig. 7) illustrate that the asphalt CA-30 + combined fillers will be the first to fail under fatigue conditions. Therefore, the asphalt CA-30 + TiO_2-filler presents a superior intermediate-temperature performance.

4. Conclusions

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It was possible to prepare two different specimens employing CA-30 binder: reference specimen with combined fillers and a modified specimen with TiO_2 filler. To evaluate the physical and rheological properties, samples of the CA-30 asphalt + combined fillers and CA-30 asphalt + TiO_2 fillers were studied. The thermal behaviors of the specimens were also evaluated before and after outdoor exposure for twelve months.

The most relevant conclusions are:

1. **Initial Albedo:** The TiO_2-modified asphalt mixture pavement exhibits a higher initial albedo compared to the reference pavement.
2. **Albedo Increase Over Time**: After 12 months of outdoor exposure, both the reference and TiO_2-modified asphalt pavements showed increased albedo values, with their coloration becoming lighter compared to the experiment's initial state.
3. **Photocatalytic Effect**: TiO_2 acts as a photocatalyst of a process which explains its more effective bleaching (decolorizing) action.
4. **Thermal Impact Reduction**: The addition of TiO_2 into the asphalt mixture helps to reduce heat transfer from the pavement surface to the surrounding air.
5. **High-Temperature Performance Enhancement**: Although the asphalt CA-30 + combined fillers exhibit the highest rutting resistance, the superior albedo of the asphalt CA-30 + TiO_2 filler specimen, which results in lower surface temperatures under equivalent solar irradiation, enhances the high-temperature performance grade of the latter.
6. **Fatigue Damage Tolerance**: At intermediate temperatures, the asphalt CA-30 + TiO_2 filler exhibits higher fatigue damage tolerance.

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