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Original Article

Development of Asphalt Pavements with Photoluminescent Stones to Improve Nighttime Road Safety in High-Andean Regions

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Abstract *- High Andean regions present specific challenges that are particularly related to poor visibility at night time and a high incidence of road accidents, which are intensified by the limited availability of public lighting infrastructure. This present study proposes the development of hot-mix asphalt incorporating photoluminescent stones (COLORCEM LUX) as a partial substitution for conventional coarse aggregate, with the purpose to improve road safety during nighttime conditions. Briquettes were designed through the Marshall approach with PEN 60/70 asphalt cement in portions of of 4.5%, 5.0%, 5.5%, and 6.0%, keeping the photoluminescent aggregate content constant at 60.9%. The results obtained indicate that the optimal asphalt cement content is of 5.5% with a Marshall stability with a maximum value of 12.3 kN, as well as a density of 2.35 g/cm³. In terms of luminous performance, the same dosage showed an initial illuminance of 210 lux and still maintained 85 lux after 60 minutes of darkness. Therefore, the outcomes suggest that the controlled incorporation of photoluminescent material does not compromise the mechanical performance of the asphalt mixture and represents a sustainable solution for improving nighttime visibility on access roads serving High Andean communities.*

Keywords *- Asphalt pavement, Photoluminescent stones, Road safety, Marshall method, High Andean Regions, Night visibility, Colorcem lux.*

1. Introduction

Guaranteeing road safety during night-time represents a critical challenge in countries with rugged geography like Peru, which is located in the High Andean regions. Its government struggles to guarantee road safety. Peru has a very limited public lighting coverage in main roads and highways, which limits visibility during night-time and increases the risk of traffic accidents [1]. The main threat to public safety in this case is the combined presence of typical flexible pavement failures (like aggregate raveling and cracking) and low lighting areas, both key factors that have a significant impact on the occurrence of road crashes. According to the Ministry of Transport and Communications (MTC), a significant proportion of accidents occurs during nighttime hours, especially on rural roads [2]. This issue is a national-level threat since it is widespread in almost all national roads due to insufficient lighting infrastructure [3].

In this context, photoluminescent materials constitute a technological alternative to improve nighttime visibility without relying on artificial lighting systems. The ability of these materials to absorb energy during the day and emit it in darkness has been applied in road infrastructure and signage [4], contributing to better identification of hazards on the road [4], contributing to a better identification of risks on the road [5].

Nonetheless, the challenge to adapt these technologies to local conditions persists because factors like the weather, availability and material transit in the Peruvian context have to be considered [6]. In this sense, the incorporation of photoluminiscent material in on the asphalt is presented as a passive and durable solution that can be easily implemented [7].

From this integral approach, this proposal contributes to the road safety because it improves nighttime visibility [8, 9], and sustainability since it reduces the dependence on artificial light. Likewise, it is necessary to verify that the incorporation of this solution does not negatively affect the mechanical performance of the pavement.

In this context, the current study has the objective to determine the optimal content of asphalt cement in hot asphalt mixtures modified with photoluminescent stones as a partial substitution of the of the coarse aggregate, while also evaluating its mechanical behavior and its luminescent properties.

However, most previous applications of photoluminescent technologies in road infrastructure have focused on surface coatings, paints, mortars, road markings or pedestrian facilities [10-12], while limited evidence is available regarding the incorporation of photoluminescent stones as partial coarse aggregate replacement in hot-mix asphalt, with only a few studies investigating self-luminous asphalt mixtures containing luminescent aggregates [13, 14]. Furthermore, the performance of these systems under High-Andean Road conditions remains insufficiently discussed, particularly considering limited public lighting, intense solar radiation, low nighttime temperatures, freeze–thaw exposure and rural maintenance constraints. Therefore, the research gap addressed in this study is the lack of experimental evidence on the mechanical and luminous feasibility of photoluminescent asphalt mixtures designed for nighttime visibility improvement in High-Andean rural roads.

The originality of this study lies in the laboratory development of a hot-mix asphalt incorporating COLORCEM LUX photoluminescent stones as a functional aggregate, with the purpose of combining mechanical pavement performance and passive nighttime visibility. Even though there are previous studies that investigated self-luminous asphalt systems and the incorporation of luminescent aggregates in the mixture [14, 15], the proposed approach in this study uses commercially available COLORCEM LUX stones as a partial coarse aggregate replacement in a conventional hot-mix asphalt. This is proposed in terms of feasibility, low cost, and functionality. The COLORCEM LUX aggregate was designed specifically for High-Andean rural roads, which, unlike conventional reflective markings or surface-applied luminous coatings, this photoluminescent material is directly poured and integrated into the asphalt mixture itself, which contributes to its durability. What this research looks for is to do a contribution to the scholar literature by doing two things: first, through the determination of the optimal asphalt cement content by utilizing the Marshall method; second, through the evaluation of the luminous intensity decay over time; and third, through the identification of the dosage ratio that permits to get the structural balance, stability, density, and photoluminescent performance for its potential application in High-Andean access roads.

2. Materials and Methods

We've adopted, in this article, an experimental approach to evaluate the performance of both the mechanical properties and luminosity of asphalt mixtures that include photoluminescent aggregates. Parameters like 1) the Marshal stability; 2) flow index; 3) density; 4) air voids; and 5) luminosity intensity (lux) were analyzed according to the technical guidelines stablished by the Peruvian Ministry of Communications and Transportation [16].

The experimental design of this study was structured for the evaluation of the effect of asphalt cement content on the mechanical and photoluminescent behavior of hot-mix asphalt containing a constant 60.9% proportion of photoluminescent stones. In comparison, the cement content in asphalt was varied at 4.5%, 5.0%, 5.5% and 6.0%, enabling for the identification of binder content that provides the best balance between Marshall stability, volumetric behavior and luminous intensity decay; this approach was inspired by an experimental strategy, commonly adopted for optimizing modified asphalt mixtures through Marshall mix design [17, 18].

Since the tests were focused on the optimization of the modified photoluminescent asphalt mixture, conventional hot-mix asphalts without photoluminescent aggregate weren't physically tested in this phase, so the control criterion was established through comparison with conventional Marshall design requirements, technical standards and reference values reported in previous studies. With regards this constrain, it is clearly acknowledge in the discussion section of this investigation, as a consequence, the integration of standardized control mixtures is strongly advised for its validation in the future.

2.1. Materials

2.1.1. Fine Aggregate

According to the ASTM D1073, the fine aggregate needed to present a continuous and uniform distribution of particles according to their size, that went from medium to coarse particles. This classification improves the structural strength of the mixture, it also guarantees an adequate workability and stability during the mixing and compaction process [19].

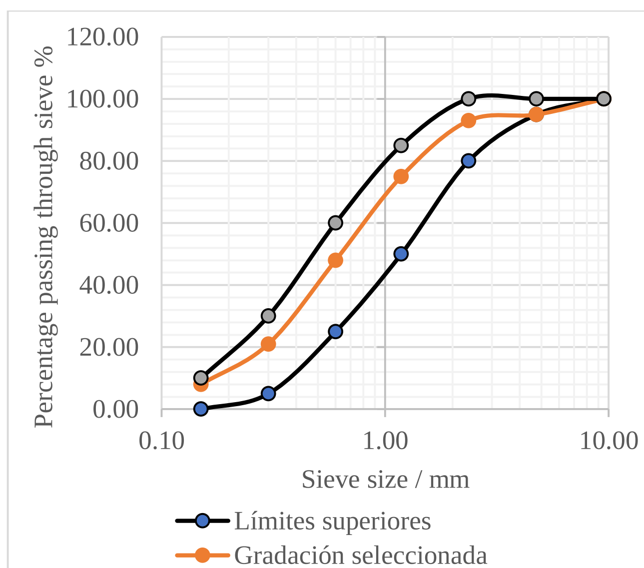


Fig. 1 Fine Aggregate gradation

The gradation of the fine aggregate complies with the ranges established by the current standard, as shown in Figure 1. The proper gradation of the fine material forms part of the "granular skeleton," which is a key in determining the stiffness and bearing capacity of the mixture [20].

2.1.2. Coarse Aggregate

We partially replaced the conventional coarse aggregate with COLORCEM LUX photoluminescent stones. These are commercial mineral-based aggregates with light-storage capacity (therefore capable of absorbing solar or artificial light during an excitation period, subsequently being able to emit visible light under dark conditions for approximately 8 to 10 hours) [21]. Moreover, this material has two purposes within the asphalt mixture. First, it becomes part of the granular skeleton (contributing to the mixture's physical integrity). Second, this material also acts as a functional component that improves its passive night-time visibility.

As shown in Figure 2, the COLORCEM LUX aggregate used in this study had a particle size ranging from 10 to 20 mm. This aggregate partially replaced the conventional coarse aggregate with no significant modifications of the overall gradation of the asphalt mixture. The photoluminescent aggregate content ratio was constant at 60.9% in all modified mixtures. However, the asphalt cement content ratio was varied. There were samples that contained a ratio of 4.5%, 5.0%, 5.5%, and 6.0%. As a consequence, the design of this experiment permitted to do the evaluation of how the binder dosage affects or influences in the mechanical performance, the volumetric characteristics, and the photoluminescent behavior of the mixtures.

With the aim to ensure the effectiveness of the photoluminescent aggregate, there must be adequate exposure of it within the asphalt matrix because an excessive amount of asphalt cement could encapsulate the surface area of the photoluminescent stones. This could reduce their capability to absorb and emit light passively. On the contrary, when the content of binder is not enough, it causes the cohesion of the mixture to decrease, this situation definitely compromises its mechanical stability. As a result, the integration process was controlled by maintaining a constant proportion of photoluminescent aggregate while varying the asphalt cement content. This approach enabled to identify the optimal dosage that assures the balance between Marshall stability, density, air voids, and luminous intensity decay.

During the preparation of the mix, the photoluminescent stones were blended together with other heated aggregates prior to the mixture with the asphalt binder. This ensured that COLORCEM LUX stones were distributed uniformly in the asphalt matrix. All samples were prepared under identical mixing to guarantee compaction and to eliminate the possibility of cofounding variables (minimizing variability among mixtures that could cause changes in the mixture's behavior). The main physical and functional properties of the COLORCEM LUX photoluminescent aggregate are summarized in Table 1, while its nighttime light-emission behavior is illustrated in Figure 3.

Table 1. Properties of coarse aggregate (COLORCEM LUX) [21]

Property	Description / Value
Type of material	Photoluminescent mineral aggregate
Main function	Light absorption and visible emission under dark conditions
Role in asphalt mixture	Partial replacement of conventional coarse aggregate and passive nighttime visibility component
Particle shape	Irregular gravel/stone type
Nominal particle size	10–20 mm
Color under daylight	Green or blue
Color in darkness	Greenish/bluish light emission
Activation source	Sunlight or artificial light
Approximate luminescence duration	8–10 hours in total darkness
Recommended use	Pavements, bike lanes, signage, decorative surfaces, and visibility applications
Visibility condition	Better performance in low-light or dark environments
Environmental resistance	Suitable for outdoor exposure according to the manufacturer
Integration criterion in this study	Constant photoluminescent aggregate content of 60.9% in all modified asphalt mixtures
Main technical limitation	Possible reduction of luminous efficiency when particles are excessively coated by asphalt binder

Fig. 2 COLORCEM LUX aggregate

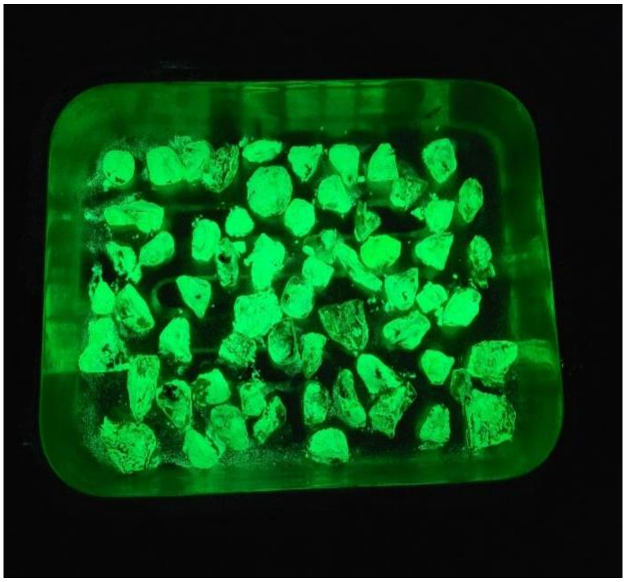


Fig. 3 Aggregate emitting photoluminescent light

Fig. 4 Asphalt cement used as binder

2.1.3. Asphalt Cement

The asphalt cement used corresponds to PEN 60/70, which is widely used in Peru due to it being suitably consistent in the occurrence of climatic variations (considering the varied amount of different climatic phenomena that occur in the totality of the national territory), high cohesion, and durability, as shown in Figure 4. This binder option is compliant with the technical specifications required for medium-to-heavy-traffic pavements [21].

2.2. Mix Design

The design of the asphalt mix was performed by means of the Marshall method. This is done by keeping the aggregate proportions constant and varying the asphalt cement content (AC), testing the same amount of aggregate in different densities of binder. Said different AC samples were: 4.5%, 5.0%, 5.5%, and 6.0%. The constant ratio of COLORCEM LUX aggregate was 60.9%. The dosage and weight of the briquettes are shown in Table 2.

Table 2. Briquette dosage according to AC percentage

Mixture code	Photoluminescent aggregate content	Asphalt cement content	Function in the study
MAF-4.5%	60.9%	4.5%	Modified mixture, low binder content
MAF-5.0%	60.9%	5.0%	Modified mixture, intermediate binder content
MAF-5.5%	60.9%	5.5%	Modified mixture, optimum observed dosage
MAF-6.0%	60.9%	6.0%	Modified mixture, high binder content
Conventional HMA / reference criterion	0%	According to Marshall design	Reference/control criterion based on standards and literature

For each dosage, three specimens were prepared (n = 3) in order to ensure the repeatability of the results.

2.3. Preparation of the Sample

The materials were heated between 150 °C and 160 °C, while compaction was carried out at approximately 140 °C. The briquettes were compacted with 75 blows per face, in accordance with MTC E 504 [16].

After this, the specimens were removed from the molds and cooled for 24 hours before putting them under tests, as depicted in Figure 5.

Fig. 5 Asphalt mix specimens

2.4. Marshall Test

The Marshall test was executed in accordance with MTC E 504 [1] and ASTM D6927 [2] guidelines. The stability and flow of the mixture were evaluated, as well as the volumetric parameters, which are the following: Air Voids (Va), Voids in the Mineral Aggregate (VMA), and Voids Filled with Asphalt (VFA).

These parameters make it possible to determine the optimum asphalt content, seeking a balance among mechanical strength, density, and pavement durability, as shown in Figure 6.

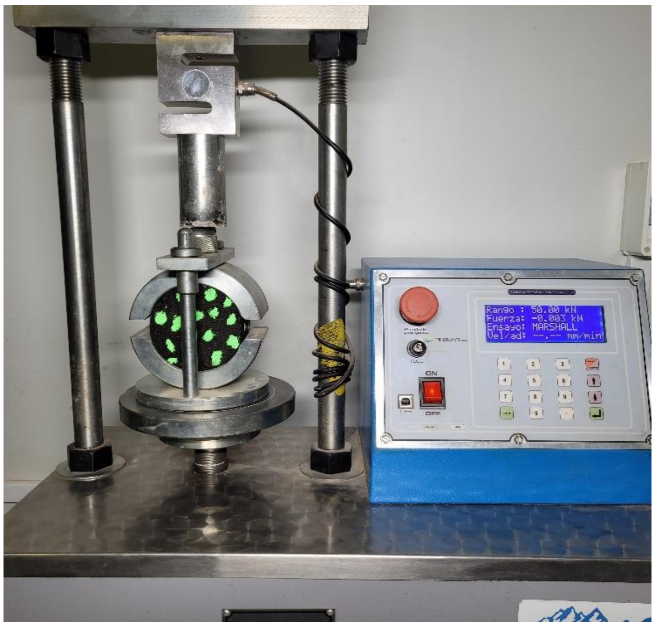


Fig. 6 Briquette subjected to the Marshall test

2.5. Dimensional Verification of Briquettes

The dimensions of the briquettes were verified in accordance with I.N.V. E-748, ensuring the uniformity of the specimens, according to Reyes and Camacho [20]. The results of the dimensional control are shown in Table 3.

Table 3. Dimensional verification of briquettes

Ítem	Briquette Verification	Adjusted Weight
MAF-4.5%	6.35	1200.00
MAF-5.0%	6.40	1250.16
MAF-5.5%	6.45	1246.37
MAF-6.0%	6.50	1242.65

2.6. Luminescence Test

The evaluation of luminescence is based on the ability of the photoluminescent material to absorb light energy and re-emit it under dark conditions, in accordance with ASTM E 1819-03 [22] and Grau et al. [23].

The briquettes were subjected to an excitation phase using ultraviolet light or white light for an interval of 10 to 30 minutes. Then, the luminous intensity was measured with a lux meter at defined time intervals: 0, 10, 30, and 60 minutes, as shown in Figure 7.

The behavior of the light emission is modeled by:

$$Luminance = P_0 * t^{-\alpha}$$

Where P_0 is the initial intensity, t is time, and α is the decay coefficient.

Likewise, illuminance is expressed as:

$$E = \frac{\Phi}{S}$$

Where Φ is the luminous flux, and S is the measurement area [24].

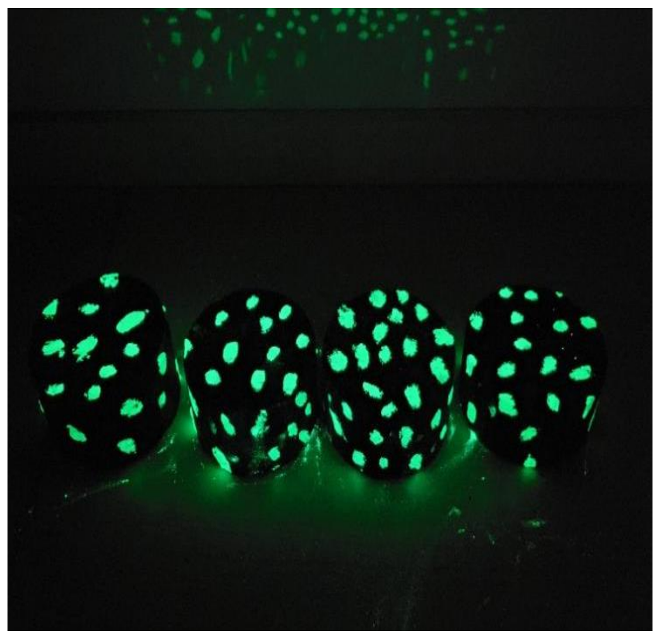


Fig. 7 Briquettes with luminescence intensity

3. Results and Discussion

3.1. Marshall Test

Marshall stability showed a progressive increase from 9.2 kN at 4.5% to 12.3 kN at 5.5%, which indicates an improvement in the internal cohesion of the mixture and in its capacity to resist loads. This behavior is due to the fact that the increase in binder content favors adhesion between particles and improves stress transfer within the granular system, as shown in Figure 8. However, when the asphalt content increases to 6.0%, stability decreases to 10.8 kN, which indicates the presence of excess binder that reduces internal friction and produces a lubricating effect between the aggregates [25], as it is depicted on the following Figure 9.

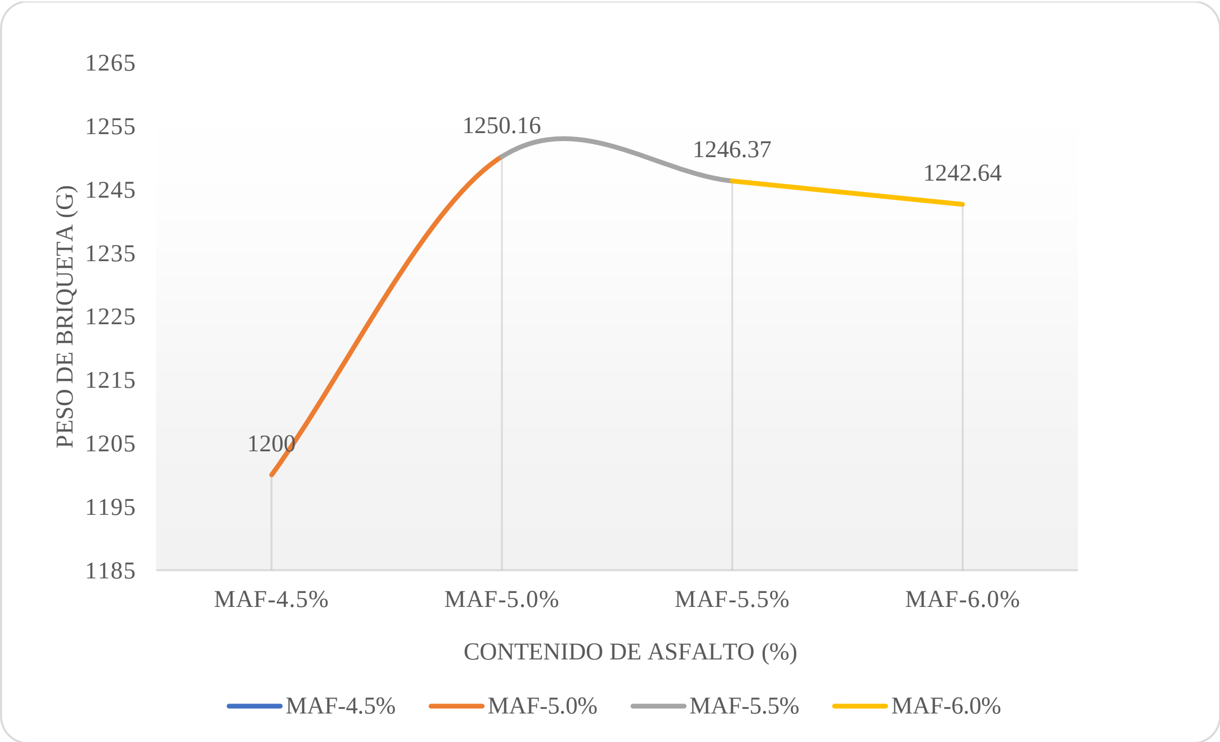


Fig. 8 Briquette weight vs. Asphalt content

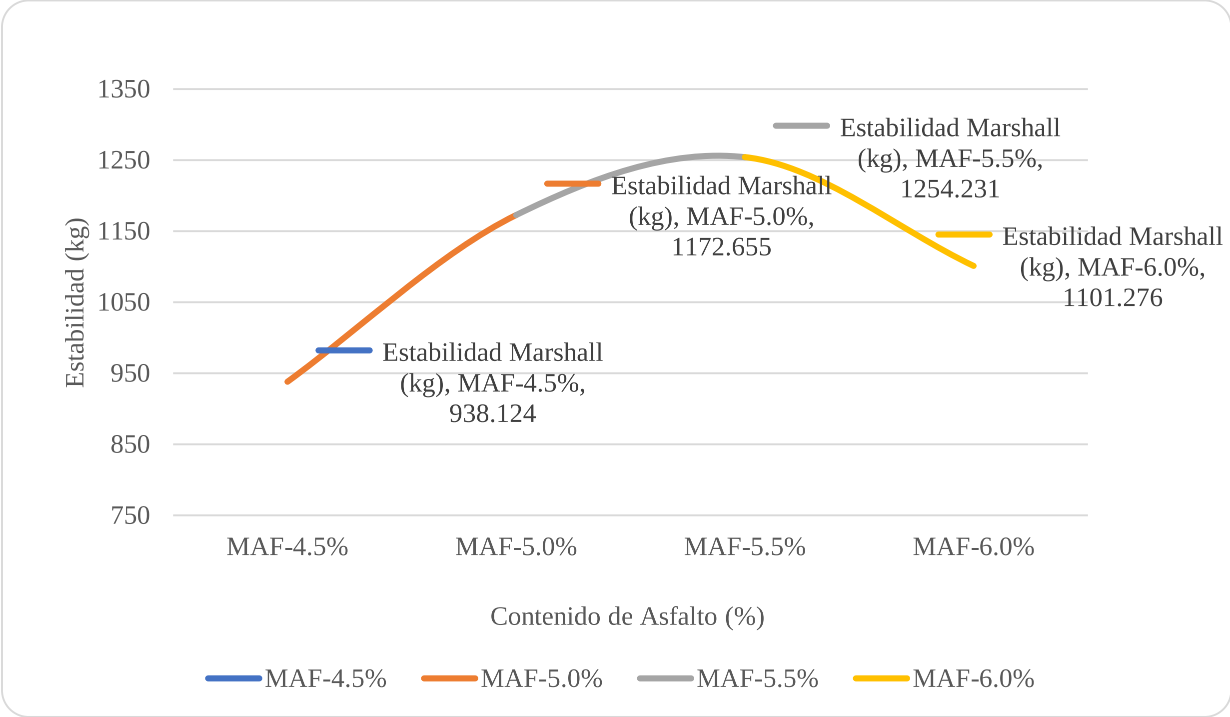


Fig. 9 Marshall stability vs. Asphalt content

Correlation between the continuous increase of flow from 2.1 mm to 4.2 mm and the increase of asphalt content is noted. This behavior indicates that, as the viscous phase increases, the mixture becomes more deformable. Although this may improve pavement flexibility, high values (such as those recorded at 6.0%) may lead to greater susceptibility to permanent deformation under repeated loads, especially under service conditions [26], as exhibited on the following Figure 10.

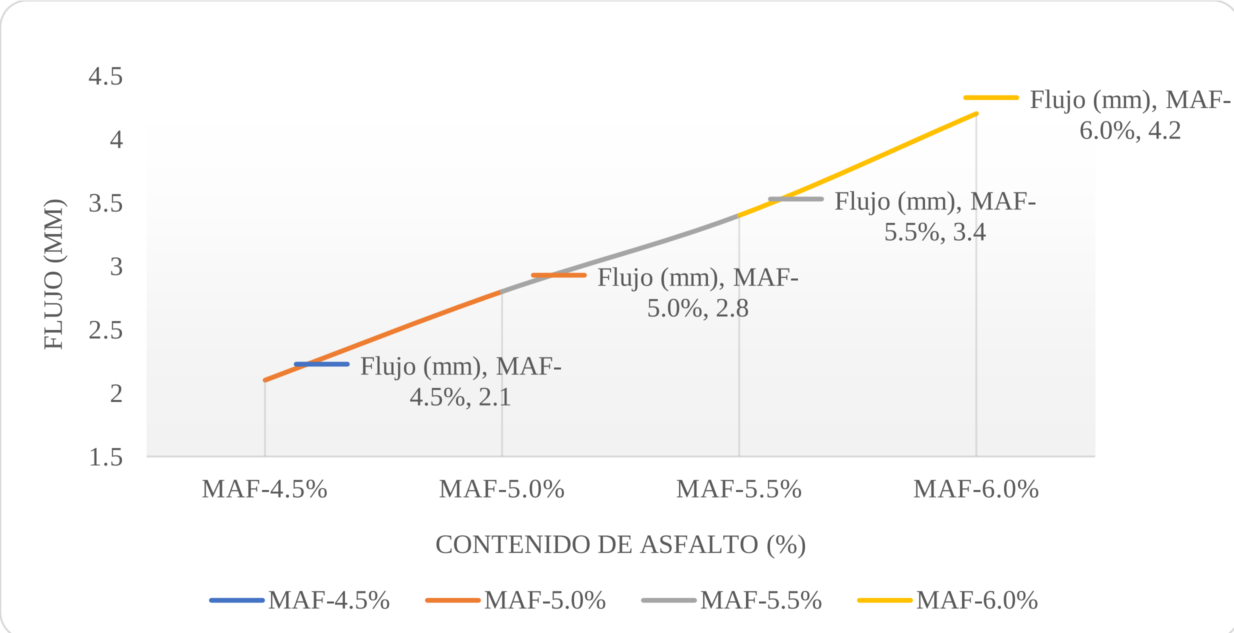


Fig. 10 Flow vs. Asphalt content

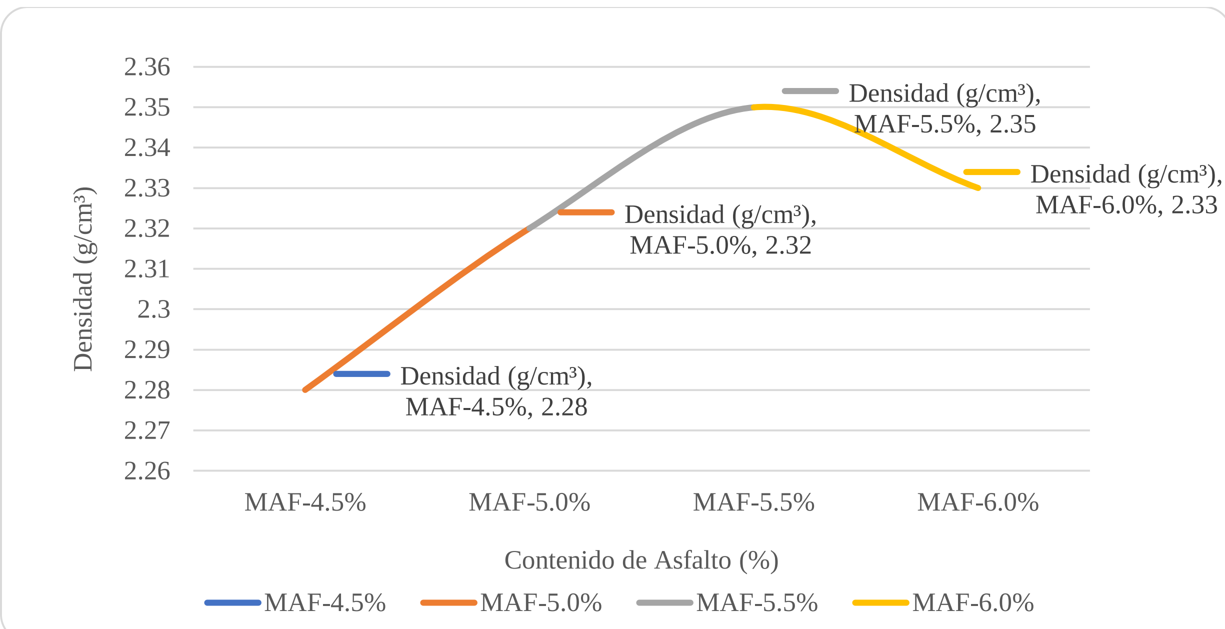


Fig. 11 Density vs. Asphalt content

A density increment is noticed, which goes from 2.28 g/cm³ to a maximum value of 2.35 g/cm³ at the 5.5% dosage. When the dosage is 6.0%, a minor reduction in the density can be perceived. From this, it appears that the compaction level in 5.5% reaches an optimal point, and this optimal point balances the binder content and structure of the granular skeleton. Hence, the mixture with a 5.5% dosage permits to have a better distribution of voids and greater structural stability [27], Figure 11 displays this. This result is consistent with studies that asseverate that there is a strong dependency between the volumetric properties of asphalt mixtures and gradation, absorption, and particle redistribution during the mixing and compaction processes, directly influencing the final density of the mixture [28], as shown in Figure 12. Also, surges in density have been reported in scenarios in which air void content decreases, therefore proving an inverse-proportion relationship between both parameters. In this sense, this proves the relevance of measuring compaction in HMA performance, since mixtures with higher density present better mechanical properties, such as higher resilient modulus and stability, due to a denser and more efficient internal structure [29].

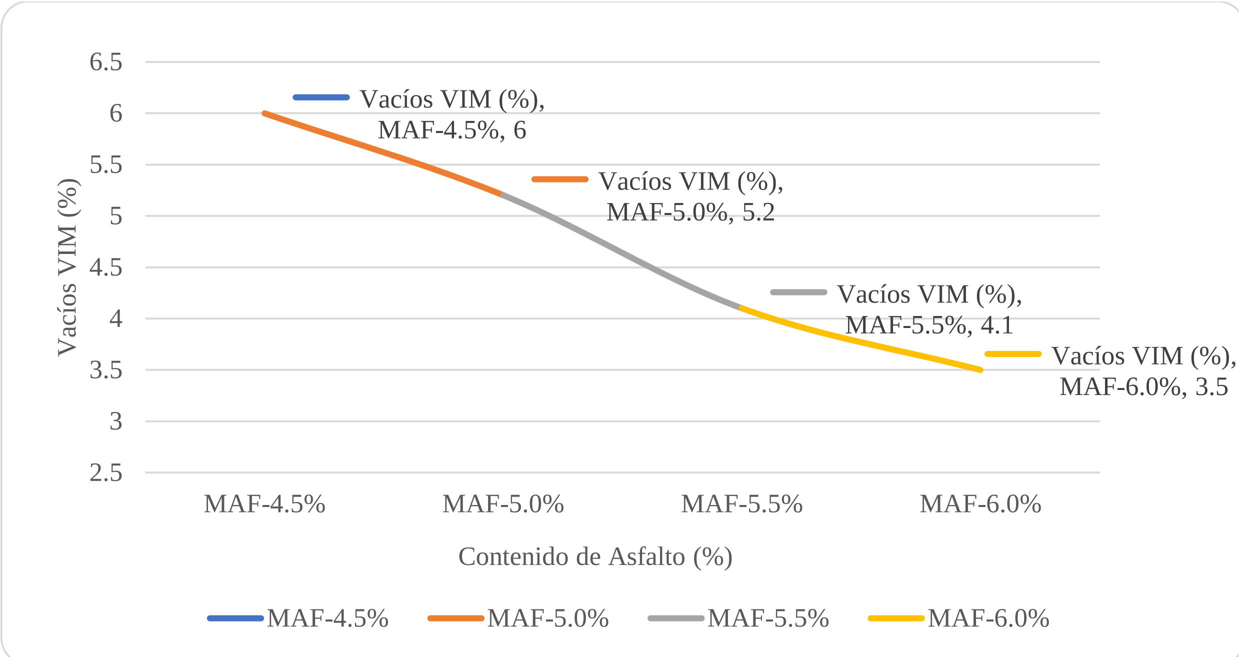
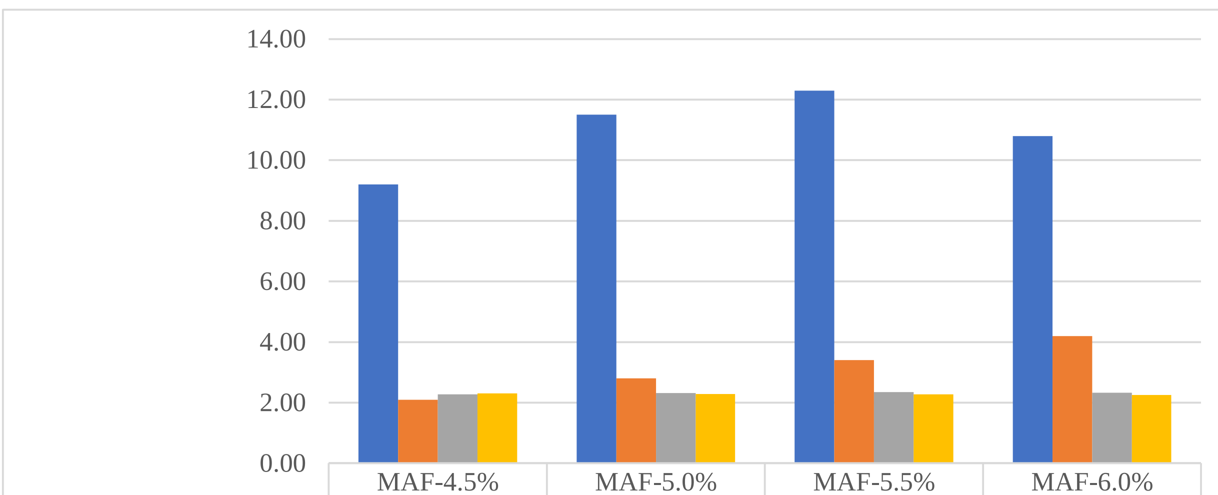


Fig. 12 VIM voids vs. Asphalt content

Overall, the analysis of the Marshall parameters indicates that the 5.5% asphalt cement dosage presents the best overall performance, as it achieves an adequate balance among stability, deformability, density, and void content, as shown in Figure 13, where the convergence of the design criteria toward this optimum content can be observed. This result is consistent with previous studies indicating that the optimum binder content is determined from the balance between the volumetric and mechanical properties of the mixture, such as air voids, stability, and flow. However, recent studies have shown that this value may vary depending on the design method used; for example, optimum contents of 4.3% and 4.4% have been reported using the Marshall and Superpave methodologies, respectively, and even lower values of 3.5% when Binder Film Thickness (BFT) is used as a design criterion, showing that performance optimization depends on the adopted approach [30].



	MAF-4.5%	MAF-5.0%	MAF-5.5%	MAF-6.0%
Estabilidad (kN)	9.20	11.50	12.30	10.80
Flujo (mm)	2.1	2.8	3.4	4.2
Densidada (gr/cm3)	2.28	2.32	2.35	2.33
Peso Unitario (gr/cm3)	2.31	2.29	2.27	2.25

Fig. 13 Values obtained from the Marshall design

3.2. Luminous Intensity Test

The results of the luminescent evaluation are shown in Table 4, where the variation in luminous intensity over time for each evaluated dosage can be observed.

The MAF-5.5% sample mixture presented both the highest luminous intensity values and the longest duration of emission among all samples, reaching 210 lux at the initial time and maintaining 85 lux at 60 minutes. This behavior implies that this mix has greater relative efficiency in absorbing and releasing light, meaning that this mix's ratio of aggregate-binder is adequately distributed. This could be explained by the fact that there is less interference from the binder in the aggregate's emission capacity. This agrees with what was reported in the literature, where it's demonstrated and concluded that constant light emission relies on the material's capacity to store energy in electronic traps and release it progressively through emission centers [31].

In contrast, the mixture with 4.5% showed the lowest luminescence values and a higher decay rate, therefore meaning that this mixture has lower cohesion and a likely uneven distribution of the photoluminescent material.

The latter phenomenon has been reported in composite systems that have inadequate particle dispersion, since this generates aggregate agglomerations that reduce the overall performance of the photoluminescent material [32]. Additionally, even though the 6.0% dosage presents the absolute highest initial luminous intensity value, a slight reduction is observed compared with the 5.5% dosage.

This implies that an increase in binder density from 5.5% ends up coating the luminescent aggregate, hindering its luminous efficiency by causing an encapsulation effect, as shown in Figure 14.

Table 4. Intensity vs Time

Data Used for Lux vs. Time				
Ítem	**0 mín.**	**10 mín.**	**30 mín.**	**60 mín.**
MAF-4.5%	160.00	110.00	70.00	40.00
MAF-5.0%	190.00	140.00	95.00	60.00
MAF-5.5%	210.00	165.00	130.00	85.00
MAF-6.0%	200.00	150.00	115.00	75.00

Fig. 14 Aggregates encapsulated by Asphalt cement

Likewise, it was observed that, with a higher excitation intensity of 46,320 lux, luminous emission increased in all dosages. However, this increase is not proportional, which shows a saturation phenomenon in the material, where a limit is reached in its energy storage capacity, in agreement with [33].

Finally, these results are consistent with what was reported by [34], who indicate that luminous intensity and persistence depend largely on the proper dispersion of the photoluminescent particles and on the transparency of the medium surrounding them, factors that directly influence the efficiency of the light absorption and emission process.

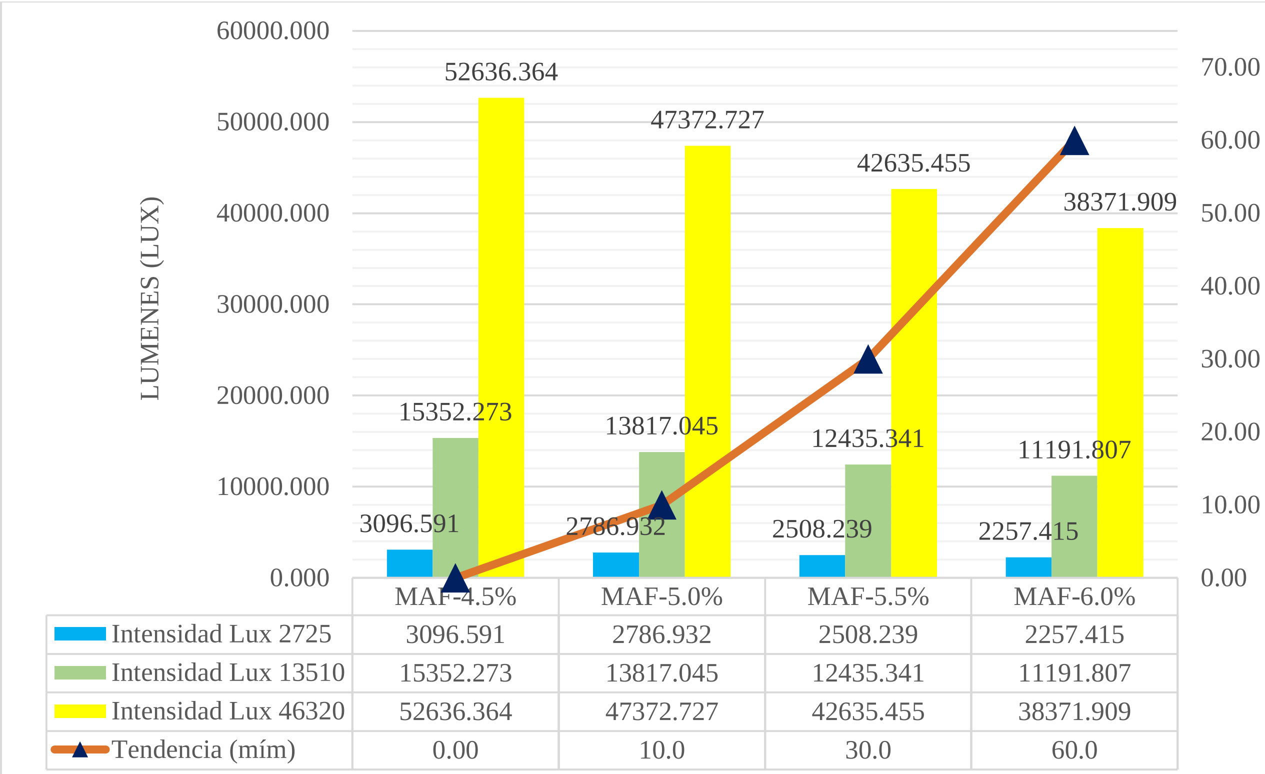


Fig. 15 Luminescence vs. Time

The reduction in luminosity is evidenced from the 4.5% asphalt cement content, where greater luminosity capture is recorded at each lux intensity, in contrast with the 6.0% content, where it decreases, as shown in Figure 15.

This witnessed behavior is directly related to the asphalt content in the briquettes because a higher percentage of binder reduces the amount of voids or pores in the asphalt mixture, which generates a denser and less textured surface that decreases light reflectance. This outcome is consistent with previous studies that display an inverse relationship between density and air voids, as well as the influence of these two characteristics on the surface and mechanical properties of asphalt mixtures [29, 30].

3.3. Study Limitations and Future Research Directions

This study represents an initial laboratory-stage evaluation of photoluminescent asphalt mixtures. Therefore, field validation, long-term aging, traffic abrasion, moisture damage and freeze–thaw resistance were not fully addressed in the present phase. Although previous studies have investigated selected aspects of the mechanical performance, moisture resistance and luminescent behavior of self-luminous asphalt systems under laboratory conditions [6, 15], these aspects require further evaluation under real service environments. Accordingly, future implementation should be supported through pilot road sections, accelerated environmental conditioning and in-situ monitoring under High-Andean service conditions.

Table 5. Comparison with existing technologies

Technology	Main function	Advantages	Limitations	Relevance to High-Andean roads
Conventional asphalt	Structural pavement	Known performance, standard construction	No passive nighttime visibility	Requires external lighting or markings
Retroreflective road markings	Visibility with headlights	Low cost, standardized	Depends on vehicle headlights and maintenance	Useful but limited in fog/rain/poor markings
Photoluminescent coatings	Passive light emission	Easy surface application	Possible wear, adhesion and durability issues	Useful for curves, crossings, edges
Photoluminescent asphalt mixture	Structural + luminous function	Integrates luminous material into pavement	Requires mix design control and durability validation	Potentially suitable for rural roads without lighting

3.4. High-Andean Environmental Conditions, Durability and Comparative Assessment

Compared with surface-applied photoluminescent coatings and road markings [35-37], the proposed mixture offers the potential advantage of integrating the luminous component into the pavement material rather than relying only on a superficial layer. Nevertheless, coatings and markings may provide easier installation and maintenance [37], while asphalt-integrated photoluminescent aggregates require careful control of binder content to avoid particle encapsulation and loss of luminous efficiency. As perceived in the present study's results, the 5.5% asphalt cement content contains the ideal balance between Marshall stability and light emission. Further comparison with conventional asphalt, retroreflective markings and full-scale photoluminescent systems is required in order to expand the present field.

3.5. Statistical Treatment and Presentation of Experimental Results

To ensure that the results of the experiments are analytically rigorous, descriptive statistical indicators to reorganize the Marshall and luminescence data were utilized. Three specimens (n = 3) for each asphalt cement content ratio sample were considered, which allowed to calculate mean values, standard deviation and the variation coefficient for main response variables (Marshall stability, flow, density, air voids and luminous intensity). The presentation of the results was done by using figures and tabular data, including applicable error indicators. For the luminescence test, the light decay was interpreted through the power-law model, considering the decay coefficient as a comparative parameter among mixtures. This statistical and graphical treatment analysis permits to attain a more robust framework for the identification of the optimal cement content (dosage) through the evaluation of the interaction among the mechanical stability, the volumetric behavior and the persistence of luminous intensity between all samples. As a result of these measurements, we've found that the optimal dosage is 5.5% because it ideally balances the abovementioned factors.

3.6. Field Validation, Safety and Implementation Guidelines

Field validation and pilot-scale application were not performed in this phase because this study corresponds to an initial laboratory-scale evaluation. Notwithstanding, future studies that measure the use of photoluminescent asphalt mixtures in High-Andean roads should include a pilot road section under real service conditions in order to test the mix's operational performance. For that matter, we propose to recommend a validation protocol that considers mechanical, environmental and functional monitoring mechanisms (traffic abrasion, moisture damage, freeze–thaw cycles, ultraviolet exposure, rutting, cracking, surface texture, skid resistance and luminous intensity decay over time are ought to be measured). Additionally, we suggest that the material's safety performance must be evaluated by measuring nighttime visibility indicators, such as detection distance, visual contrast, driver perception and compliance with road safety standards. For this technology to be implemented, its use in rural road sections with limited public lighting, such as curves, pedestrian crossings, road edges, access roads to High-Andean communities and critical areas with recurrent nighttime visibility problems should be prioritized. We also recommend to monitor the integrity of these mixtures at 3, 6 and 12 months. This must be done to determine the durability, luminous persistence and operational feasibility of the proposed mixture under real, high-risk conditions.

4. Conclusion

This study's findings demonstrate that a higher content of asphalt cement improves the mixture's stability until a 5.5% ratio, improving mixture cohesion and structural capacity. If the presence of asphalt cement increases over this limit, as shown in the 6.0% sample, stability decreases due to the lubricating (and softening) effect of the excess binder. In this sense, we conclude that the optimal asphalt content ratio is 5.5%, since it maximizes mechanical strength without compromising the other critical factors.

We've also perceived a progressive increase in flow when asphalt content rises, since asphalt is a highly viscous binder. This proportionally brings more deformability and flexibility to the mixture, although, in excessive amounts (like the ones obtained at 6.0%), it might make the mixture susceptible to permanent deformation.

Regarding density and compaction, the optimal value is, as we've mentioned, achieved at the 5.5% ratio, with an adequate distribution of voids. Excess presence of asphalt beyond this ratio causes a slight decline. A reduction in the voids is observed when the asphalt content increases, indicating that an increase in the mixture's viscosity causes the progressive filling of its gaps and the reduction of surface texture, whereas excessive contents may cause negative implications in durability and behavior under heavy loading and high transit periods. This increase in viscosity enhances binder density but decreases light reflectance, which explains why mixtures with a higher asphalt percentage, such as 6.0%, show a lower luminous efficiency despite having good structural cohesion.

We conclude that the 5.5% asphalt cement mixture shows the best luminescent performance, backed by its higher initial luminous intensity and better persistence over time, indicating an adequate dispersion of the aggregate and less binder content interference. Higher or lower binder contents leads to the reduction of luminous efficiency (due to a poor distribution) or the encapsulation of luminous particles, in both cases negatively impacting the mixture's performance.

Regarding luminescence, all mixtures show decaying in luminosity, since the COLORCEM LUX aggregate is not constantly powered, but only emits light by storing it during the day. Despite of this decay, the optimal 5.5% mixture is still the one that maintains the highest lighting levels and shows a better capacity for energy storage and release.

The results show that the sample that contains 5.5% ratio of asphalt cement is the most suitable, since this mixture achieves an optimal balance of the mixture's mechanical, volumetric, and functional properties. In addition, this mixture ratio guarantees a higher rate of stability, density, and structural performance without compromising pavement strength, while ensuring both the optimization of the aggregate's luminescent capacity and the night-time visibility. We conclude that it is technically feasible and beneficial to use COLORCEM LUX aggregate, only if it's incorporated in controlled proportions, allowing to improve road safety through passive lighting and to maintain adequate structural performance if the optimal binder/aggregate ratio is respected.

References

[1] Nelve Núñez Bustamante, Krantz Pelaez, and Aler Rafael, "Flexible Pavement Maintenance Management Based on PCI: Assessment and Prioritization on the PE-08A Road (Cajamarca, Peru)," *Technology Rain Journal*, vol. 5, no. 1, 2026. [CrossRef] [Google Scholar] [Publisher Link]

[2] MTC Conducts Preventative Operation on the Pan-American Highway South to Prevent Road Accidents due to Poor Visibility, Ministry of Transport and Communications, 2024. [Online]. Available: https://www.gob.pe/institucion/mtc/noticias/941204-mtc-realiza-operativo-preventivo-en-la-panamericana-sur-para-prevenir-siniestros-viales-por-poca-visibilidad

[3] Lin Chomba, This is the Region with the Most Fatal Traffic Accidents in Peru, According to the PNP: it has Almost 30 Accidents per Month, La Republic, 2024. [Online]. Available: https://larepublica.pe/sociedad/2024/11/19/esta-es-la-region-con-mas-accidentes-fatales-de-transito-en-peru-segun-pnp-tiene-casi-30-siniestros-por-mes-791445

[4] Peru and Korea Promote Road Modernization with Smart Technology, Ministry of Transport and Communications, 2025. [Online]. Available: https://www.gob.pe/institucion/mtc/noticias/1192652-peru-y-corea-impulsan-modernizacion-vial-con-tecnologia-inteligente

[5] Technological Advances in Road Infrastructure - Innovative Improvements for the Roads of the Future - Construction Technology Centre of the Region of Murcia, 2026. [Online]. Available: https://ctcon-rm.com/es/avances-tecnologicos-en-infraestructura-vial-mejoras-innovadoras-para-carreteras-del-futuro/

[6] Wei Jiang et al., "Development and Performance of Pouring Self-Luminescent Asphalt Mixture," *Journal of Cleaner Production*, vol. 414, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[7] Ricard Puig Salas, "*Luminescent Applications for Road Infrastructure Road Surfaces*," Master Thesis, University Master's Degree in Civil Engineering, Canals and Ports, 2023. [Google Scholar] [Publisher Link]

[8] Helder Guillermo Aldas Arco et al., "Descriptive Analysis of Psychomotor Skills and Road Safety Education in Public and Private Preschool Institutions in Ecuador," *Sportis. Scientific Journal of School Sport, Physical Education and Psychomotricity*, vol. 12, no. 1, pp. 1-20, 2026. [CrossRef] [Google Scholar] [Publisher Link]

[9] Suha Falih Mahdi Alazawya, Rouwaida Ali, and Roaa Falih Mahdi, "Enhancing Road Safety: A Comprehensive Examination of Critical Factors," *DYNA*, vol. 92, no. 237, pp. 89-95, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[10] Wentong Wang et al., "Cement Filled With Phosphorescent Materials for Pavement: Afterglow Decay Mechanism and Properties," *Construction and Building Materials*, vol. 284, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[11] Wangjie Wu, Zhiyu Fu, and Wei Jiang, "Developing a Novel Sustainable and Durable Self-Luminous Pavement Material with Solar Energy Absorption Capability," *Construction and Building Materials*, vol. 445, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[12] Yinzhang He et al., "Eco-Friendly Waterborne $SrAl_2O_4:Eu^{2+}$, Dy^{3+} Luminous Road Markings: Preparation Method with Enhanced Durability," *Transportation Research Part D: Transport and Environment*, vol. 143, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[13] Runhua Guo, and Siquan Liu, "Design and Experiment of Self-Luminescent Asphalt-Based Pavement Materials," *Construction and Building Materials*, vol. 342, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[14] Chengjia Han, and Shu Yang, "Design of Optical Performance for Self-Luminous Pavement Materials," *Construction and Building Materials*, vol. 449, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[15] Wenliang Jin et al., "Study on Mechanical Properties and Luminescence Function of Pouring Energy-Storage Luminescent Asphalt Mixture," *Frontiers in Materials*, vol. 12, pp. 1-10, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[16] Ministry of Transport and Communications, "*Director's Resolution No. 18-2016-MTC/14*," gob.pe, 2016. [Publisher Link]

[17] Nabanita Datta, Sayantan Sasmal, and Ambika Kuity, "Performance Evaluation of Composite Bio-Asphalt using Treated Rubber Seed Oil and Crumb Rubber," *Innovative Infrastructure Solutions*, vol. 11, no. 6, 2026. [CrossRef] [Google Scholar] [Publisher Link]

[18] Ceren Beyza İnce, "Performance Evaluation of Hot Mix Asphalt Modified with Biomass-Based Waste Chestnut Shells as Filler Replacement," *Materials*, vol. 19, no. 3, pp. 1-23, 2026. [CrossRef] [Google Scholar] [Publisher Link]

[19] "*ASTM D1073-16(2022), Standard Specification for Fine Aggregate for Asphalt Paving Mixtures*," Advancing Standards Transforming Markets, pp. 1-3, 2022. [CrossRef] [Publisher Link]

[20] Oscar J. Reyes-Ortiz, and Javier Camacho-Tauta, "Influence of Particle Size Distribution on the Rutting Resistance of Asphalt Mixtures," *Engineering and Development*, pp. 26-42, 2008. [Google Scholar] [Publisher Link]

[21] Luminous Stones for Decoration, Luminescent Stones for Floors and Walls of Concrete or Mortar with Exposed Aggregate, Morteros Henares, 2023. [Online]. Available: https://www.morteroshenares.com/morteros/piedras-luminiscentes

[22] "*ASTM Standard E1918-06 Measurement of Solar Reflectance*," Pdfcoffee, 2021. [Publisher Link]

[23] José Simón Grau et al., Reflective Asphalt Pavements, Experimental Sections, [Online]. Available: https://asefma.es/wp-content/uploads/2020/11/6-CHM-Comunicacion-Asefma-2020.pdf

[24] Everything about Luminous Intensity, Luminous Flux, and Illuminance, Auer Signal. [Online]. Available: https://www.auersignal.com/es/datos-tecnicos/indicacion-luminos/intensidad-luminosa/

[25] Fatemeh Shahrajabian, and Kiachehr Behfarnia, "The Effects of Nano Particles on Freeze and Thaw Resistance of Alkali-Activated Slag Concrete," *Construction and Building Materials*, vol. 176, pp. 172-178, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[26] Hussain Arshad, and Yan Jun Qiu, "Evaluation of Asphalt Mixes Containing Reclaimed Asphalt Pavement," *Applied Mechanics and Materials*, vol. 178-181, pp. 1522-1525, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[27] Kawther Y. H. Al-Soudany et al., "Experimental Study of the Effect of Crumb Rubber on Properties of Asphalt Mix by Wet Process," *E3S Web Conference*, vol. 427, pp. 1-7, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[28] Abbaas I. Kareem et al., "Effects of Breakage of Construction and Demolition Waste Materials (C&DWMs) at Asphalt Mixtures," *Al-Qadisiyah Journal for Engineering Sciences*, vol. 18, no. 1, pp. 54-64, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[29] Mutahar Abdul Salam Al-ammari et al., "The Effect of Aggregate and Compaction Method on the Physical Properties of Hot Mix Asphalt," *IOP Conference Series: Materials Science and Engineering*, vol. 512, pp. 1-12, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[30] Muhammad Adeel Khan et al., "Performance Optimization of Asphalt Pavements using Binder Film Thickness as a Criterion in Innovative Mix Design Compared to Marshall and Superpave Methods," *Frontiers in Materials*, vol. 11, pp. 1-18, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[31] Maria S. Batista et al., "Optical Studies in Red/NIR Persistent Luminescent Cr-Doped Zinc Gallogermanate (ZGGO:Cr)," *Applied Sciences*, vol. 12, no. 4, pp. 1-19, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[32] Farooq Muhammad, and Shawnam Jalal, "An Overview of the Effect of Stirrer Design on the Mechanical Properties of Aluminium Alloy Matrix Composites Fabricated by Stir Casting," *Zanco Journal of Pure and Applied Sciences*, vol. 34, no. 1, pp. 18-35, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[33] Parvej Alam et al., "Organic Long-Persistent Luminescence from a Single-Component Aggregate," *Journal of the American Chemical Society*, vol. 144, no. 7, pp. 3050-3062, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[34] Guojun Li et al., "Preparation of Long Afterglow Luminescent Road Marking Coatings and its Applicability Simulation," *PLoS One*, vol. 20, no. 9, pp. 1-23, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[35] Yan Zhang et al., "Exploitation and Comprehensive Performance Evaluation of Long-Afterglow Luminescent Road Marking Coatings Based on Combined Weighting–VIKOR Method," *Luminescence*, vol. 40, no. 8, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[36] Yinzhang He, "Innovative Preparation of $SrAl_2O_4:Eu^{2+}$, Dy^{3+} Coatings for Durable Luminescent Road Markings," *Case Studies in Construction Materials*, vol. 22, pp. 1-16, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[37] Lisha Zhao, Liqun Hu, and Zheng Yang, "Design and Performance Evaluation of a Durable Self-Luminous Composite Coating for Pavement Applications," *International Journal of Pavement Engineering*, vol. 27, no. 1, 2026. [CrossRef] [Google Scholar] [Publisher Link]