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OPTIMIZING NIGHTTIME VISIBILITY AND ROAD SAFETY THROUGH THE USE OF PHOTOLUMINESCENT MATERIALS IN URBAN INFRASTRUCTURE

BY

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Abstract. The article explores the use of two-component epoxy resin and phosphorescent pigments as an innovative solution to enhance nighttime visibility and improve road and pedestrian safety. The study focuses on photoluminescent materials, which absorb and store light energy during the day and gradually release it in darkness, thereby increasing the visibility of sidewalks, curbs, and road markings. The implementation of these materials is particularly advantageous in poorly lit areas or locations prone to frequent power outages. Experimental results indicate that epoxy resin and phosphorescent pigment mixtures maintain a high level of brightness for up to six hours, offering a durable and sustainable alternative to conventional lighting. Additionally, these materials contribute to reducing energy consumption and minimizing light pollution. The study's conclusions validate the applicability of photoluminescent technology in road safety while emphasizing the need for further testing to optimize performance under diverse traffic and climatic conditions.

Keywords: photoluminescence, epoxy resin, road safety, phosphorescent pigments, nighttime visibility.

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1. Introduction

Although only about a quarter of total vehicle travel takes place after dark, nighttime conditions account for nearly half of all road-traffic deaths. Consequently, the probability of a fatal outcome per unit distance travelled is approximately three times greater at night than during daytime. Because drivers' visual perception after dark depends largely on pavement luminance, enhancing the nighttime visibility of roads and road markings remains a primary objective of road-safety engineering.

The conventional response combines street lighting with retroreflective markings, but both have limits. Street lighting alone can account for up to 40% of municipal electricity bills, contributing to 15% of global power consumption (Pasolini *et al*., 2024), and is frequently absent from rural and secondary road networks. Furthermore, retroreflective markings experience a substantial reduction in performance on wet pavements: the water film over the embedded glass beads changes the bead-to-medium refractive-index ratio, so that a refractive index of approximately 1.9, which is known to maximize retroreflectance under dry conditions, actually exhibits much poorer retroreflectance under wet conditions (Shin *et al*., 2019). As a result, increasing attention has been directed toward autonomous photoluminescent technologies that can provide nighttime guidance without external energy input.

Photoluminescent ("glow-in-the-dark") materials offer an attractive solution to these limitations because they absorb and store light energy during daylight and gradually release it as visible light after dark, without requiring any external power source. Their operation is based on a persistent luminescence mechanism in which excitation elevates the activator ions to higher energy states, while defect-related traps within the crystal lattice capture a portion of the generated charge carriers. The gradual thermal release of these trapped carriers sustains light emission for several hours after the excitation source has been removed. A major breakthrough in this field was reported in the mid-1990s when in 1996, Matsuzawa et al. reported on the extremely long-lasting afterglow of $SrAl_2O_4:Eu^{2+}$ codoped with Dy^{3+} ions, which was more than 10-times brighter than the previously widely used ZnS:Cu,Co. (Van den Eeckhout *et al*., 2010). Since then, strontium aluminate-based phosphors have largely replaced traditional zinc sulfide systems in high-performance applications. Of the two principal pigment families, copper-doped zinc sulfide (ZnS:Cu) is chemically stable but exhibits relatively low luminance and short afterglow duration, whereas europium - and dysprosium-doped strontium aluminate ($SrAl_2O_4:Eu^{2+},Dy^{3+}$) emits intense green light around 520 nm - close to the peak sensitivity of human scotopic vision - with approximately an order of magnitude greater brightness and significantly longer persistence. Its primary limitation remains its sensitivity to moisture and hydrolytic degradation.

Recent studies have incorporated strontium-aluminate phosphors into pavement coatings, with epoxy- and acrylic-based systems reaching afterglow durations of nine to eleven hours and converging on a phosphor loading of about 30% by weight as the practical optimum. The binder is decisive, as it governs adhesion, abrasion resistance, and protection of the moisture-sensitive phosphor.

Epoxy resins have attracted considerable interest as binder systems for photoluminescent coatings because of their excellent adhesion, chemical resistance, and mechanical durability. Previous research demonstrated that the luminous coating prepared with epoxy resin as the matrix material had good luminous performance and fatigue resistance (Pan *et al*., 2023). Despite these promising results, relatively few studies have directly compared the performance of the main commercial photoluminescent pigments within the same well-defined polymer matrix under identical experimental conditions.

To address this gap, the present study evaluates three photoluminescent pigments - a strontium-aluminate phosphor, a water-based zinc sulfide pigment, and a solvent-based strontium-aluminate pigment - incorporated into a two-component DGEBA epoxy resin at five mass fractions ranging from 10% to 50%. The objectives are to: (i) compare afterglow duration and perceived brightness as a function of pigment loading; (ii) identify the formulation that provides the best compromise between optical performance and mechanical integrity; and (iii) position the most promising candidate within a standardized characterization framework for subsequent photometric and durability assessment.

2. Road lighting: importance, challenges and technological solutions

Nearly half of all traffic fatalities occur at night, even though only about one-quarter of travel takes place after dark (United States Department of Transportation, 2016). To improve safety, artificial road lighting must provide road users with optimal visibility and visual comfort. A driver's nighttime visibility is directly influenced by the luminance of the road surface, since luminance is the only photometric quantity actively perceived by the human eye (NP 062:2002/AC:2022). The presence of electric road lighting can increase traffic speeds and improve traffic flow at night, while simultaneously reducing accident risk. Nonetheless, many roads outside of urban areas lack any artificial lighting, which makes it a major challenge to provide effective street lighting for safe travel at night. Street lighting also entails significant energy consumption on a global scale. Globally around 2.3% of electricity generated is utilized for street lighting purposes (Saleem and Hosoda, 2021). Additionally, the transport sector accounts for almost 37% of the world's energy is consumed in the transport sector, and around 15-20% of which is consumed in illumining the roads and highways (Kostic *et al*., 2009).

Over the years, a variety of solutions have been explored to improve nighttime visibility, including the use of glass beads, high-visibility paint

markings, LEDs, pavement reflectors, and other strategies. No single solution has gained universal acceptance, as each offers its own advantages and disadvantages. As a result, when lighting is inadequate, drivers struggle to detect obstacles, road signs, and road markings, which can lead to collisions or vehicles veering off the roadway.

2.1. Visual perception and road lighting

Vision is the primary sense by which drivers orient themselves in traffic, and its effectiveness depends on perceiving the shape, color, size, and luminance of objects. Visual acuity is divided into:

- Static visual acuity, for observing stationary objects;
- Dynamic visual acuity, required in traffic for the rapid recognition of moving objects and road signs.

Adaptation of the eye to low light is enabled by rod cells and rhodopsin, a pigment essential for night vision; vitamin A deficiency can impair this process. Cone cells, specialized for color perception, respond to different wavelengths (red, green, blue).

Therefore, artificial road lighting should be designed in accordance with human visual physiology to support visual comfort and safety under low-light conditions.

2.2. Factors of visual comfort in roadway lighting

Effective road lighting must ensure visual comfort by controlling glare and maintaining uniform illumination. Glare, either disability (from very bright sources) or discomfort (from uneven brightness) impairs visibility and slows driver reaction, so it must be minimized.

Lighting quality is judged by *objective metrics* – adequate luminance/illuminance and good uniformity, and *subjective aspects* – appropriate light color and color rendering, minimal light pollution, and clear visual guidance for drivers. High-quality installations meet photometric targets, limit glare and spill, and provide clear cues that support safe, comfortable night driving.

2.3. Retroreflection and the importance of road markings

At night or in poor light, retroreflective pavement markings are essential for driver guidance. Recent peer-reviewed work emphasises that road markings delineate the traffic surface by using lines, text, and symbols to provide visual guidance information for road users (Babić *et al*., 2020), conveying the same kind of directional information as traffic signs - lane edges, centrelines, no-passing zones without forcing drivers to look away from the roadway. These markings are typically made of paints, thermoplastic materials, or preformed tapes

embedded with tiny glass beads or prismatic optics, so that headlight beams are returned toward the driver and the marking remains visible at night. The strategic role of this in-lane guidance is well documented in the systematic-review literature, which notes that road markings have become an important and inseparable part of road infrastructure and one of the common safety elements around the world (Babić *et al*., 2020).

Because the glass beads redirect the beam back to its source, retroreflective markings dramatically improve nighttime visibility and lane-keeping. Drivers of all ages consistently prefer brighter, more reflective lane lines and consider them important for safety. Indeed, studies show that increasing pavement marking retroreflectivity can significantly reduce night-time crashes. For example, a large FHWA/TTI evaluation found roughly 30-50% fewer wet-night crashes and fatalities on highways after installing enhanced high-visibility markings. Overall, such high-retroreflection markings help maintain traffic flow and prevent lane-departure accidents, thereby enhancing road safety.

However, ordinary bead-based paint can become ineffective in wet weather. A thin film of water over the beads (with refractive index ≈ 1.33) causes most of the headlight light to refract into the water rather than return to the driver. Figure 1 shows the diffuse reflectivity of glass beads in a road marking under wet conditions. Diffuse reflectivity is the property of light hitting a glass bead to scatter in multiple directions, which helps to maintain the visibility of the road marking in rainy or wet conditions (Zhang *et al*., 2024)

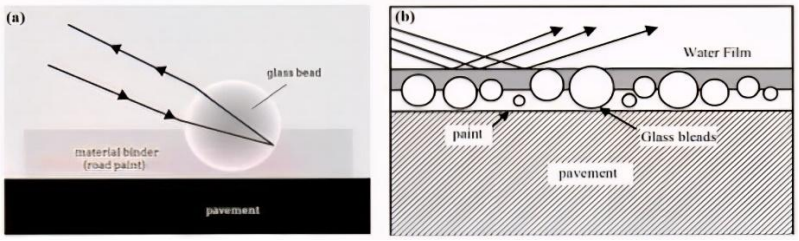


Fig. 1 – Retroreflection of glass bead in road markings: (a) dry retroreflectivity; (b) wet diffused reflectivity (Zhang *et al*., 2024).

In practice, this makes painted lane lines nearly invisible when it rains. Some solutions (such as special “wet-weather” beads or separate reflective tapes on the pavement) can help restore visibility, but they have trade-offs. For instance, raised or embedded reflective strips on the road can improve wet-night guidance, yet in snowy regions these strips are often scraped off by snowplows.

By design, retroreflection lets headlights illuminate the way even in total darkness. This makes well-maintained lane markings just as vital as signs at night: they continuously show the road’s alignment and permissible maneuvers, keeping drivers oriented and alert on the roadway.

2.4. Photoluminescent materials: an innovative solution

An emerging research field focuses on the application of photoluminescent paint for road markings. Photoluminescent materials, also known as "glow-in-the-dark" materials, represent an innovative solution for improving nighttime visibility.

These materials function based on the principle of phosphorescence, a process in which absorbed light is gradually released in the form of visible illumination. The energy required for this process can come from artificial sources, such as vehicle headlights or street lighting, as well as from solar radiation accumulated throughout the day.

In this regard, glow-in-the-dark (GiD) materials offer a unique opportunity to researchers and engineers seeking innovation in materials to improve the performance capabilities of existing design of raised pavement markers (Saleem and Hosoda, 2021).

2.4.1. Physico-chemical fundamentals of persistent phosphors

From a fundamental perspective, the long-lasting phosphorescence used in modern road-marking systems originates from a class of ceramic compounds known as persistent phosphors, typically activated with rare-earth ions. Among these materials, europium-activated and dysprosium-codoped strontium aluminate ($SrAl_2O_4:Eu^{2+},Dy^{3+}$) emerged in the mid-1990s as a high-performance alternative to traditional copper-doped zinc sulfide (ZnS:Cu) phosphors and has since become the most studied material in this class (Rojas-Hernandez *et al*., 2018).

Compared with ZnS:Cu, which generally exhibits limited afterglow duration and lower resistance to moisture and ultraviolet degradation, $SrAl_2O_4:Eu^{2+},Dy^{3+}$ delivers substantially improved optical performance. Its persistent luminescence is characterized by both a far higher initial intensity and a much longer lifetime (Van den Eeckhout *et al*., 2010), making it particularly suitable for outdoor and roadway applications. Owing to its efficient energy-storage capability, prolonged emission, and superior luminance, $SrAl_2O_4:Eu^{2+},Dy^{3+}$ has become the reference material for the development of modern persistent phosphor technologies used in nighttime visibility and road-safety systems.

The optical behaviour of $SrAl_2O_4:Eu^{2+},Dy^{3+}$ phosphors rests on the generation of migrating charge carriers during excitation that are localised in trapping centres (Vitola *et al*., 2019). Under ultraviolet or blue excitation ($\approx$ 320 - 450 nm), Eu^{2+} ions are promoted to a higher electronic state through their characteristic $4f^7 5d^1$ - $4f^8$ line transition, and some of the resulting electrons are captured at trap levels introduced by the Dy^{3+} co-dopant and by intrinsic lattice defects. Once the excitation source is removed, the cause of the persistent

afterglow is thermally stimulated gradual charge release from trapping centres with resultant recombination at the Eu^{2+} luminescence centres (Vitola *et al*., 2019). The resulting emission maximum, near 510 - 520 nm, sits close to the peak sensitivity of human scotopic vision, which is why these pigments perform particularly well for nighttime visibility applications.

Experimental studies have shown that the presence of a broad trap depth distribution in $SrAl_2O_4$:Eu,Dy is beneficial to cover the longer and colder winter nights under realistic outdoor conditions (Botterman *et al*., 2015). Co-doping with additional trivalent ions provides a further route for tuning these traps. The introduction of Gd^{3+} into the $SrAl_2O_4:Eu^{2+},Dy^{3+}$ host has been reported to lengthen the afterglow without changing the emission band: the fluorescence lifetime, luminous intensity, and afterglow time gradually increased with co-doping, although the quantum yield decreased (Gao *et al*., 2023a). Synthesis route also matters. By tuning the oxidizer/fuel ratio in a perchlorate-assisted combustion process, glycine-rich recipes were shown to outperform the stoichiometric reference, with the best results in terms of emission intensity and decay time were obtained in the case of 100% glycine excess, demonstrating a cost-effective route to phosphors for developing glow-in-the-dark safety markings (Lazău *et al*., 2023).

2.4.2. Optical performance and integration into binders

The performance of photoluminescent road markings is generally assessed through a small set of indicators: the initial luminance (in mcd/m^2), the temporal decay profile (afterglow curve), and the time required to reach the conventional visibility threshold, defined by ISO 17398 as the moment when the luminous brightness drops to 0.32 mcd/m^2 (Li *et al*., 2025). Spectral sensitivity to excitation is also relevant, since the afterglow is recharged each day by ambient daylight. The principal review on aluminate road markings highlights that this class of materials, especially $SrAl_2O_4:Eu^{2+},Dy^{3+}$, is favoured due to their long afterglow period, high brightness, and non-radioactivity, while their main practical limitations are hydrolysis upon contact with water and damage to the crystal structure under elevated surface temperatures (Zhang *et al*., 2024).

An epoxy-based formulation combining strontium-aluminate luminescent powder with reflective filler has been reported to achieve the afterglow time was more than 11 h at night in laboratory test, with the optimal mass proportions of epoxy resin, toughening agent, curing agent, curing accelerator, luminous powder, reflective powder, glass bead, and glass powder set at 1.0:0.1:0.3:0.006:0.4:0.3:0.25:0.55 (Pan *et al*., 2023).

The binder matrix governs light transmission, adhesion to the pavement surface, and long-term mechanical durability. Commonly used systems include epoxy, polyurethane, acrylic, thermoplastic, and water-based resins. For polyurethane-based self-luminous pavement coatings, a particle-size

optimisation study reported that the 50-mesh LP has the optimal overall performance, with initial luminance values for the 50-, 100-, and 400-mesh phosphors of 15.26 cd/m^2, 13.65 cd/m^2, and 12.13 cd/m^2, respectively - confirming that coarser phosphor particles yield higher initial luminance than finer ones (Lu *et al*., 2024).

One of the principal limitations of $SrAl_2O_4$-based phosphors is their sensitivity to moisture and water exposure, which can accelerate hydrolysis and reduce luminescent efficiency. To address this issue, researchers have proposed encapsulation methods involving nanometric SiO_2 coatings or hydrophobic polymers such as fluorinated resins and polydimethylsiloxanes (Lin *et al*., 2023). When combined with hydrophobic binders such as epoxy or polyurethane, these protective treatments significantly enhance environmental stability and long-term durability.

2.4.3. Durability under traffic and environmental degradation

The long-term performance of photoluminescent road markings is strongly affected by several environmental and mechanical stress factors, including abrasion, thermal fatigue, ultraviolet exposure, and freeze-thaw cycling. Laboratory work on glow-in-the-dark (GiD) concrete-based raised pavement markers containing 5–15% luminescent powder showed a clearly diminishing return with loading, while the higher dosage simultaneously retained the mechanical performance required under traffic. The technological appeal of these markers is straightforward, given that conventional retroreflective devices currently used on the road infrastructure come in a large variety of shapes and sizes, however, all of them fall under the category of retroreflectivity since they depend on vehicle lights to provide reflection (Saleem and Hosoda, 2021); in contrast, GiD-based markers act as autonomous light sources at night and can be used for lane separation and edge detection without relying on vehicle headlamps (Saleem and Hosoda, 2021).

Environmental exposure remains the principal limitation of photoluminescent road markings, particularly under hot and humid conditions. Reliability testing of $SrAl_2O_4:Eu^{2+},Dy^{3+}$ phosphors has shown that $SrAl_2O_4$ easily undergoes hydrolysis in the presence of atmospheric moisture (Wang *et al*., 2020). Under combined high-temperature and high-humidity exposure, X-ray diffraction analysis confirmed that the $SrAl_2O_4$ phase transformed into the $Sr_3Al_2(OH)_{12}$ phase with $SrAl_3O_5(OH)$ by-products, accompanied by a marked drop in photoluminescence intensity in unprotected films; the same study further reported that the developed flexible films are excellent candidates for temperature sensing because they exhibit temperature-dependent PL intensity and are highly sensitive to surrounding temperature variation 300-420 K (Wang *et al*., 2020), a sensitivity range that fully overlaps with real pavement-surface temperatures. These observations indicate that, in tropical climates where humidity, elevated

temperatures, and intense ultraviolet radiation act simultaneously, hydrolytic conversion of the host lattice and photoinduced ageing can be expected to dominate the loss of optical performance, justifying both encapsulation of the phosphor and the use of low-permeability binders for practical roadway service.

A further degradation route is intrinsic to the activator chemistry. Recent photoluminescence studies on $SrAl_2O_4:Eu^{2+},Dy^{3+}$ have observed a red-region emission peak associated with Eu^{3+}, suggesting partial oxidation of Eu ions even during synthesis (Kalkal *et al*., 2025). Because this valence shift converts a fraction of the green-emitting Eu^{2+} centres into non-luminescent Eu^{3+} species, prolonged exposure to oxidative conditions - particularly oxygen diffusion through the binder layer - is expected to drive the same conversion in service. This motivates the practical preference for binders with low permeability to oxygen and water vapour in long-life roadway applications.

2.4.4. Pilot implementations and international case studies

The academic record on photoluminescent road markings is dominated by a small set of peer-reviewed laboratory-to-roadway studies that have characterised real-scale materials under realistic service conditions. Recent work has emphasised that GiD concrete based markers can be used for visible light instead of retroreflectivity in addition to acting as a driver alertness tool (Saleem and Hosoda, 2021), making them a credible substitute for retroreflective devices on unlit corridors. Although several widely publicised demonstrations have taken place in Europe and Asia, only a handful of these have been documented in the peer-reviewed literature with quantitative performance data, providing the basis on which subsequent deployments and standardisation efforts are being designed.

The most detailed peer-reviewed deployment to date evaluated resin-based photoluminescent pedestrian crossings under urban traffic conditions in Spain. The field characterisation confirmed that after 20 min, luminance values peaked at 68 mcd/m², surpassing standard vehicle headlights at 100 m (Mateo Sanguino *et al*., 2024) and that the material exhibited noteworthy mechanical properties, displaying consistent tensile strength, load capacity, and strain values with a remarkable Shore A hardness (Mateo Sanguino *et al*., 2024). A subsequent study by the same group extended the structural characterisation to typical traffic-loading conditions, reporting a vertical displacement of always less than 2 mm in vehicles with a wheel load of 12.5 kN, reaching a compressive and tensile strength of more than 56 MPa, and confirming that the acoustic vibration test confirmed that the proposed system would provide a very efficient audible warning to pedestrians (Lozano Domínguez *et al*., 2024).

Together, the two articles supply both the optical and structural parameters needed to translate pilot results into standardised crossings on public roads.

Beyond pilot installations, the dependence of optical performance on the asphalt substrate has been examined in laboratory work that links surface texture, binder drain-down, and paint distribution to the effective light-emitting area. Open-graded friction courses, in particular, allow part of the photoluminescent paint to migrate into the surface voids and reduce the area available for emission, while dense-graded layers preserve a more uniform film and better luminance retention. These observations established one of the first systematic frameworks for selecting the appropriate pavement structure for photoluminescent coating applications.

Durability under real environmental and traffic conditions remains, however, the principal limitation reported in the peer-reviewed literature. Recent work on composite-silicon-film coatings for $SrAl_2O_4:Eu^{2+},Dy^{3+}$ developed an integrated organic-inorganic encapsulation that combined the advantages of organic and inorganic coatings without losing the properties of the materials (He *et al*., 2025), showing that the protected powder is suitable for use in waterborne road-marking systems. These findings, together with techno-economic considerations highlighted by laboratory work on glow-in-the-dark concrete markers, suggest that costs and reapplication intervals - not optical performance alone - currently set the principal bound on large-scale deployment. Comparative testing has shown that as the GiD component increases from 5% to 10% the gain in intensity was 13% while 23% gain in intensity was observed for GiD component increase of 10% to 15% (Saleem and Hosoda, 2021), while structural testing confirmed that the resulting markers retained an average compressive strength of 92.42 MPa (Saleem & Hosoda, 2021) - well above the requirements for traffic loading.

Complementary applied research from China has shown that optimised long-afterglow road-marking formulations can sustain visibility over extended nighttime periods under simulated traffic conditions. A recent peer-reviewed study reported that the optimal formulation (30% luminescent powder, 8% glass powder, 4% titanium dioxide) achieved the best luminescence performance and colorimetric characteristics, sustaining light emission for 9 hours with good road performance (Li *et al*., 2025), with Twinmotion and DIALux simulations further showing measurable improvement in nighttime visibility under different ambient-brightness levels.

The need for systematic outdoor validation is increasingly recognised in the lighting-research community, where the performance of photoluminescent paints for road marking have been assessed from calibrated camera measurements during 18 months in outdoor conditions (Villa *et al*., 2024), with the authors concluding that they can provide some cues and a methodology for future regulations of these innovative products (Villa *et al*., 2024) that allows the yearly luminescence performance to be forecast for a given site. Taken together with the European and Asian peer-reviewed studies cited above, these international results document a coherent body of evidence supporting the technical feasibility of

photoluminescent road markings for unlit urban and rural corridors, while pointing to encapsulation, binder selection, and standardised characterisation as the principal areas where further engineering work is still needed.

2.4.5. Economic aspects and sustainability

The relatively high cost of rare-earth-based phosphors remains a key barrier to the wider adoption of photoluminescent road markings. On roads without public lighting, however, life-cycle analyses suggest that these systems can become economically competitive over time, since removing lighting poles, electricity consumption, and maintenance partly offsets the higher initial outlay, while reduced light pollution adds further environmental benefit. The principal review in this field has explicitly identified the luminescence performance, long-term durability, and economic cost (Lin *et al*., 2023) as the three coupled limitations that future research on active luminous road markings must address simultaneously. Beyond the strictly economic dimension, broader ecological assessments stress the importance of limiting artificial nighttime lighting because of its substantial impact on natural ecosystems. As argued in the principal review on the topic, the erosion of night-time by the introduction of artificial lighting constitutes a profound pressure on the natural environment, with impacts ranging from changes in gene expression to ecosystem processes, and emissions from vehicle headlights need to be considered as a major and growing, source of ecological impacts of artificial night-time lighting (Gaston *et al*., 2018).

Advances in synthesis are progressively reducing manufacturing costs of persistent phosphors. Combustion synthesis, sol-gel processing, hydrothermal synthesis, and related routes have been identified as promising alternatives for improving scalability and sustainability. In particular, the most cited recent review explicitly characterises $SrAl_2O_4$:Eu, Dy as the most studied material (Rojas-Hernandez *et al*., 2018) in this class, owing to its favourable balance between photoluminescent efficiency, chemical stability, and relatively low toxicity compared with earlier sulphide phosphors. The same review emphasises that ongoing efforts are directed at developing new strategies to obtain sub-micrometric particles, avoiding stringent, intricate, tedious, costly, or inefficient preparation steps (Rojas-Hernandez *et al*., 2018), which represents the principal pathway towards industrial-scale viability.

From a sustainability standpoint, photoluminescent road markings are increasingly viewed as autonomous and renewable alternatives to traditional roadway lighting. Because they operate without external electrical energy (Lin *et al*., 2023), they are particularly suitable for rural roads, bicycle paths, and environmentally sensitive areas, where the installation of conventional lighting infrastructure would be technically difficult or economically disproportionate. Within this context, the central engineering challenge identified by the peer-reviewed literature is no longer optical performance but rather the simultaneous

mitigation of moisture sensitivity, mechanical wear, and ultraviolet ageing of the phosphor during prolonged service.

At the same time, sustainability also depends on improving long-term durability and environmental resistance. Recent research on protective coatings and encapsulation has shown that silica- and polymer-based surface treatments can substantially improve the water resistance of $SrAl_2O_4:Eu^{2+},Dy^{3+}$ phosphors while preserving their luminescent performance. A dedicated study demonstrated outstanding durable properties of $SrAl_2O_4:Eu^{2+},Dy^{3+}$ persistent phosphors coated with silica–polymer hybrid shell, prepared as the first step to achieve the durable luminescent road surface marking (Lyu *et al*., 2020). Such developments are considered essential for extending service life and reducing the reapplication frequency required in real roadway applications.

2.4.6. Road safety performance

A growing body of peer-reviewed research, combining laboratory characterisation, full-scale mock-ups, and driving-simulator studies, supports the view that photoluminescent road markings can improve nighttime orientation and visual guidance. Laboratory measurements combined with visibility computations based on the COST 331 model showed that luminescent road markings could strengthen the visual guidance of drivers on the road with traffic by increasing the visibility distance beyond the headlamp beams during the first few hours of the night, and in unlit areas such as bicycle paths, but the performance depends on the night-time illumination level (Brémond *et al*., 2022). The same study emphasised that ambient nighttime illumination, rather than the phosphor performance alone, ultimately governs the usable visibility distance.

More recent driving-simulator research has examined the effect of photoluminescent markings on driver behaviour along horizontal curves. A controlled experiment using a 3 × 2 × 2 within-subjects design with green and red photoluminescent road markings (PRMs) of conventional and wide profile demonstrated measurable changes in transversal and longitudinal driving indices on simulated rural curves at night, characterising PRMs as a potentially useful visual guidance technology for improving road safety in low-visibility conditions (Angioi *et al*., 2025). The same study noted that road infrastructure regulations lack guidelines for PRMs design (Angioi *et al*., 2025), identifying this as one of the key obstacles to large-scale adoption.

Additional evidence on pedestrian safety came from urban-scale evaluations of photoluminescent crossings. Field measurements in Spain confirmed a luminance of 68 mcd/m^2 at 20 min was confirmed, which would allow, by a wide margin, a pedestrian crossing to be observed in a vehicle more than 100 m away (Lozano Domínguez *et al*., 2024), with estimated reductions in mortality and injury rates through the combined effect of vehicle-speed reduction and improved nighttime visibility. The same study reported lower average vehicle

speeds and improved driver awareness near the photoluminescent crossings, supporting their value in urban environments where pedestrian–vehicle interaction is the principal safety concern.

Overall, the recent peer-reviewed literature supports the conclusion that photoluminescent road markings can contribute positively to nighttime road safety by extending visual guidance distances, improving lane perception on curves, and increasing pedestrian conspicuity in poorly illuminated areas. Their effectiveness, however, remains conditioned by ambient lighting, charging efficiency, and the photometric properties of the luminescent system, and depends critically on the standardised characterisation frameworks that the lighting-research community is still in the process of building. Recent outdoor measurements have confirmed the dominant role of ambient nighttime illumination on the performance of luminescent road markings; based on this model, a method is proposed to predict the luminescence performance over a year in a given place as a function of the yearly distribution of horizontal illuminance averaged during the night (Villa *et al*., 2024), offering a site-specific predictive framework for evaluating glow-in-the-dark markings under real outdoor conditions.

2.4.7. Limitations

Despite the promising results reported in recent studies, photoluminescent road marking technologies still present several important technical and operational limitations. One of the most significant constraints is the charging efficiency of the phosphorescent materials, since the optical output depends directly on the quantity and duration of absorbed light energy and on the ambient thermal conditions. Outdoor studies on $SrAl_2O_4$:Eu,Dy demonstrated that the light output profile is hardly influenced by the ambient temperature in a wide range as a result of the presence of a broad trap depth distribution, which is beneficial to cover the longer and colder winter nights (Botterman *et al*., 2015). Even so, during winter periods or successive cloudy days, the cumulative excitation may become insufficient, causing the emitted luminance to fall below the human perceptibility threshold much faster than under summer conditions.

Another major limitation concerns the restricted chromatic range of high-efficiency persistent phosphors. Current long-afterglow materials reach their best photoluminescent performance within the green-yellow spectral domain, while red and blue phosphors generally exhibit significantly lower quantum yields and shorter afterglow durations. Experimental work on $SrAl_2O_4:Eu^{2+},Dy^{3+}$ confirmed a broad green emission with a central wavelength of 508 nm, which was attributed to the characteristic $4f^65d^1$ to $4f^7$ electronic dipole of the Eu^{2+} ion, with measured quantum yields up to 65.87% for the $SrAl_2O_4:Eu^{2+}$ system (Gao *et al*., 2023a). This dominance of the green channel restricts the design of multi-colour signalling systems with comparable optical efficiency.

Moisture sensitivity remains one of the most critical durability challenges for strontium aluminate phosphors. Even when encapsulation and hydrophobic surface treatments are applied, hydrolysis still constitutes a major degradation pathway under humid outdoor conditions, progressively reducing luminance intensity and afterglow duration. Studies dedicated to road-marking applications have shown that unprotected $SrAl_2O_4:Eu^{2+},Dy^{3+}$ phosphors lose poor visibility at night behaviour primarily because the existing road surface marking with poor visibility at night results in traffic safety hazards in insufficient lighting roads, motivating the development of silica–polymer hybrid shell coatings as a first step towards durable luminescent road markings (Lyu *et al*., 2020).

Economic limitations remain equally important for large-scale implementation. The cost of rare-earth-based phosphors, combined with specialised binders and protective encapsulation, still exceeds that of conventional thermoplastic road markings with retroreflective glass beads. As a result, current implementations are generally limited to high-risk zones, bicycle paths, pedestrian crossings, tunnels, or road sections without public lighting infrastructure. Experimental work on glow-in-the-dark concrete pavement markers concluded that GiD component larger than 20% has negligible performance gains as compared to cost increase, defining a clear techno-economic optimum but also confirming that the application of GiD material in the form of paint coating can have poor durability with paint application eroding in 0.7–2.5 years, depending on traffic volume and location (Saleem and Hosoda, 2021).

Overall, although photoluminescent markings offer considerable potential for improving nighttime road safety and reducing energy consumption, current limitations related to charging dependency, chromatic efficiency, environmental durability, and economic viability still restrict their widespread deployment in conventional roadway infrastructure.

2.4.8. Comparison with recent scientific literature

Recent peer-reviewed studies have shifted the focus of glow-in-the-dark pavement research from feasibility demonstrations toward engineered phosphor-binder systems, accelerated durability protocols, and predictive visibility modelling. Comprehensive reviews now identify aluminate long-afterglow materials as the most promising candidates for self-illuminating road markings, since these materials absorb light energy during the day and continue to emit light at night, providing an illumination solution for road surfaces that does not require an external power source, significantly improving nighttime driving safety (Zhang *et al*., 2024). The same body of work converges on the conclusion that simultaneous mitigation of hydrolysis, thermal degradation, and luminance loss is the principal engineering challenge constraining outdoor deployment.

On the binder side, optimised epoxy-based formulations have provided reference compositions for further work. A self-luminous pavement marking study established a balanced epoxy system and showed that it is feasible to prepare different colors of the SLPM according to the RGP principle and that the afterglow color and luminous intensity of SLPM strongly depend on the luminous material and its proportions (Pan *et al*., 2023), providing a structured framework for adjusting colour, brightness, and durability through controlled changes in the proportions of phosphor, reflective powder, and glass beads. Complementary work on long-afterglow flexible films noted that epoxy resins are important optical material, which have high chemical resistance, excellent weather resistance, low cost-effectiveness and low toxicity, and excellent transparency (Wang *et al*., 2020), properties that make epoxy systems particularly attractive as host matrices for $SrAl_2O_4:Eu^{2+},Dy^{3+}$ phosphors in road-marking applications.

Encapsulation strategies have evolved into well-defined multilayer architectures. Studies on silica-polymer hybrid shells designed specifically as photoluminescent pigments in waterborne UV acrylic systems confirmed that the coating process did not cause damage to the phosphor crystal (Wu e*t al*., 2021), an essential condition for any protective treatment to remain viable as a road-marking pigment. More recent composite-silicon film schemes designed specifically for road-marking applications reported that the proposed dual-layer coating effectively improve the durability and organic compatibility of SA, with its hydrolysis resistance improved by about 87.48%, while the encapsulated phosphor displayed compact surface morphology and good thermal stability (the mass loss rate was less than 0.5% at 210ºC) (He *et al*., 2025), simultaneously addressing the two main limitations of bare aluminate phosphors. Comparable durability gains have been obtained through additive optimisation within the coating itself: after 120 h of water immersion, the afterglow intensity of the coating decreases to 76% of the original, showing good water resistance, and after daylight excitation in different weather conditions (cloudy, sunny, rainy), the afterglow can reach more than 5 h (Zheng *et al*., 2023), supporting practical deployment under variable outdoor lighting and humidity.

A clearer durability envelope is now emerging from laboratory work on long-afterglow coatings designed for in-service evaluation. A recent study acknowledged that many existing luminescent coatings still suffer from low brightness, short afterglow duration, and limited durability, and most studies remain limited to laboratory tests, without evaluating their actual night-time visibility (Feng *et al*., 2026), and reported, for an optimised formulation, that the abrasion value of the marking coating is 3 mg, which is almost no abrasion and meets the specification requirements (Feng *et al*., 2026), with cumulative colour drift after 12 ageing cycles remaining well below the perceptible threshold for human vision.

In parallel, surface-modification work on PLA-based composites confirmed that organofunctional silane treatments improve dispersion and matrix

compatibility, since the SAO particles should have a variety of excellent characteristics in the PLA matrix, among which dispersibility and compatibility are particularly important; so, they can be modified by 3-aminopropyltriethoxysilane (APS) to achieve the target characteristics (Ni *et al*., 2021), while multifunctional core–shell architectures such as a novel self-luminous wood coating with carbon dots (CDs)/titanium dioxide (TiO_2) nanomaterial coated $SrAl_2O_4:Eu^{2+},Dy^{3+}$ (CDs/TiO_2@SAO) composite (Zhang *et al*., 2023) illustrate how modern shells move beyond simple barriers towards combined protective and active functionality.

On the visibility side, predictive and simulation-based studies have provided quantitative frameworks for evaluating glow-in-the-dark markings in real traffic environments. Outdoor measurements over 18 months have quantified performance through a clearly defined operational indicator - the cumulative time at night during which the luminance of a photoluminescent marking exceeds that of conventional road marking (Villa *et al*., 2024) -providing an objective basis for comparing competing technologies. Complementary CW-VIKOR-based simulations using Twinmotion and DIALux confirmed that when 3 m of luminescent coating was applied to the sidewalls, the average pavement brightness was improved by 22.3% compared to that when the coating is absent, and highlighted that in the event of power outages and other sudden emergencies, the luminescent coating deployed can be used as emergency lighting to guide people to escape (Li *et al*., 2025). Together, these results confirm that the added value of photoluminescent markings is concentrated in unlit sections such as tunnels and roads outside the direct headlamp envelope, as well as during exceptional events where conventional electrical lighting becomes unavailable.

3. The use of photoluminescent materials in road infrastructure: advantages, challenges, and perspectives for nighttime safety

Road safety is a critical concern in modern infrastructure, especially in areas where illumination is poor. Traditional lighting systems and retroreflective markings often fail under adverse conditions, contributing to accidents. In this context, photoluminescent materials offer a promising alternative. These substances absorb light during the day and then slowly re-emit it as visible luminescence after dark. For example, rare-earth-doped aluminates such as strontium aluminate ($SrAl_2O_4$ doped with Eu^{2+} and Dy^{3+}) can store sunlight and glow for hours, continuously illuminating road markings without external power. By eliminating reliance on lamps or electricity, photoluminescent coatings can maintain visibility at night and in unlit areas (Zhang *et al*., 2024).

Photoluminescent paints for road markings present several advantages over conventional markings. First, once charged by sunlight or ambient light, they emit light autonomously, ensuring nighttime visibility without electricity. Second, they perform reliably in poor weather: unlike glass-bead retroreflective

paints that lose effectiveness when wet, photoluminescent layers continue to glow through rain or fog. Third, because they do not require active lighting, these systems dramatically reduce energy use and operational costs while still guiding drivers in darkness. Finally, properly formulated photoluminescent coatings can be extremely durable. Recent tests show that luminescent road paints can meet standard requirements for abrasion resistance, adhesion, and water resistance under roadway conditions. In fact, field studies comparing long-afterglow markings with standard thermoplastic markings have found that aluminate-based paints can last significantly longer and provide improved nighttime visibility, potentially reducing the need for frequent repainting. In summary, photoluminescent markings can enhance driving safety by glowing independently, working in bad weather, saving energy, and lasting longer (Zhang *et al*., 2024).

Despite these benefits, photoluminescent road paints also have limitations. A key issue is their need for prior light exposure: in regions with very short days or persistent cloud cover, the markings may not fully charge, and their glow will be weaker at night. Moreover, the mechanical wear from heavy traffic and harsh environments can eventually abrade any paint. Although modern formulations aim to resist wear, photoluminescent layers may still fade or require reapplication more often than some traditional paints under intense use. Cost is another factor: high-performance phosphorescent pigments and the binders that hold them (such as specialized resins) tend to be more expensive initially than standard paints. In fact, reviews note that weather resistance and cost-effectiveness remain challenges for self-illuminating road technologies. In practice, these challenges mean that photoluminescent systems must be carefully designed and justified by their safety benefits to justify the higher upfront investment.

Looking forward, the development of photoluminescent road materials continues to advance along several fronts. One area is the integration of luminescent coatings with other visibility-enhancing technologies. For example, hybrid markings that layer photoluminescent paint beneath retroreflective glass beads could ensure visibility under all conditions (charging in daylight and reflecting stray light at night). Researchers are also designing fast-charging pigments with improved trap depths, so that the paint can accumulate energy more quickly (even under weak light) and glow longer after nightfall.

In conclusion, photoluminescent paint offers a sustainable way to brighten roads and pathways when traditional lighting is impractical. As material science advances, these paints are likely to become more efficient, cost-effective, and widely used. By combining photoluminescent pigments with robust binders and possibly retroreflective layers, future road markings could remain highly visible in darkness without external power. Although challenges of charging, wear, and cost exist, early field trials and laboratory studies consistently indicate that long-afterglow markings can significantly enhance nighttime road safety

(Zhang *et al*., 2024). With ongoing innovation, self-illuminating road paints may soon be a common fixture on low-visibility roads and pedestrian zones, supplementing or even replacing some conventional lighting schemes.

3.1. Justification for the use of photoluminescent materials

Road and pedestrian safety is a critical concern in the development of urban and peri-urban infrastructure. In low-visibility conditions or in the absence of street lighting, the risk of accidents significantly increases for both drivers and pedestrians. This study explores the use of photoluminescent materials to enhance the visibility of sidewalks and curbs, providing an innovative, sustainable, and energy-efficient solution.

Photoluminescent materials present a viable alternative with several key advantages:

- Reduced dependence on artificial lighting – Photoluminescent materials emit light without requiring a continuous external energy source.
- Improved user safety – Clear delineation of sidewalks, curbs, and pedestrian routes supports orientation for drivers and walkers alike.
- Durability with minimal maintenance – No electrical feed is required, and the systems exhibit high resistance to environmental stressors.
- Minimal environmental impact – The use of eco-friendly photoluminescent pigments reduces light pollution and resource consumption.

3.2. Component materials used in the study

This study utilized two essential components:

- Epoxy-based bicomponent resin – characteristics and role in application:
- Binding function – Ensures adhesion of phosphorescent pigments to the targeted surfaces.
- High mechanical resistance – Protects pigments from abrasion and environmental exposure.
- Durability and chemical stability – Maintain pigment efficiency over the long term.
- Phosphorescent pigments – characteristics and types used:
- Long-persistence phosphorescent pigments – Release light for over 8-10 hours after exposure to light sources.
- Fast-charging pigments – Absorb and release light energy in shorter cycles.
- Eco-friendly pigments – Water-based, non-toxic, and compliant with environmental protection regulations.

3.3. Operating principle of photoluminescent materials

Photoluminescent materials consist of specialized pigments capable of absorbing and storing light energy from natural or artificial sources and gradually releasing it in darkness. This phenomenon, known as phosphorescence, is governed by electronic transitions within the material's structure, allowing for long-lasting light emission. The process occurs in three main phases:

- Charging phase – The pigments absorb UV radiation and visible light throughout the day.
- Storage phase – The absorbed energy is retained within the molecular structure of the pigments.
- Emission phase – The stored energy is gradually released as visible light in dark conditions.

The duration and intensity of luminescence depend on several factors, including: the type of pigment used, the duration of light exposure prior to emission, the concentration of pigment within the applied material.

3.3.1. Electronic mechanism of persistent luminescence

The persistent luminescence of $SrAl_2O_4:Eu^{2+},Dy^{3+}$ relies on a coupled trapping–release mechanism of charge carriers operating between the activator, the co-dopant and intrinsic lattice defects. Under ultraviolet or blue-light excitation, the introduction of Eu^{2+} into the lattice of the matrix resulted in a broad green emission centred at 508 nm, which is ascribed to the characteristic $4f^65d^1$ to $4f^7$ electronic dipole allowed transition of Eu^{2+} ions (Gao *et al*., 2023b). Part of the electrons generated during this transition do not recombine immediately: Dy^{3+}, as a coactivator, does not emit light itself, but can generate holes to form a trap energy level, which acts as an electron trap center to capture some of the electrons generated by the excitation of Eu^{2+} (Gao *et al*., 2023b). Once the excitation source is removed, these trapped carriers are gradually released by thermal energy and recombine with the activator, producing the characteristic green emission close to the peak sensitivity of the human scotopic vision system.

Trap depth strongly controls afterglow duration. Even in the undoped matrix, thermoluminescence analysis estimated that the trap depth of trap levels in undoped $SrAl_2O_4$ is estimated to be 0.642 eV using Urbach's formula, and density-functional calculations further showed that the green afterglow of undoped $SrAl_2O_4$ originates from the midgap states introduced by oxygen and strontium vacancies (Zhai *et al*., 2021). Shallow traps are responsible for the intense initial emission, whereas deeper traps in the 0.6 eV range release carriers more slowly and sustain long-term luminescence at moderate temperatures, so a broad distribution of trap depths is advantageous because it maintains visible emission across varying environmental conditions. This mechanism explains why

$SrAl_2O_4:Eu^{2+},Dy^{3+}$ performs significantly better than traditional ZnS:Cu phosphors, which exhibit a weaker and shorter afterglow due to a narrower trap distribution.

3.3.2. Microstructure and material characterisation

The luminescent performance of $SrAl_2O_4:Eu^{2+},Dy^{3+}$ is strongly conditioned by its microstructure. The host crystallises in the monoclinic $SrAl_2O_4$ polymorph, whose X-ray diffraction pattern can be matched against the JCPDS reference card no. 34-0379, providing a structural fingerprint for verifying phase purity in synthesised phosphors. Within this lattice, the Sr^{2+} sites accommodate the Eu^{2+} activator and the Dy^{3+} co-dopant, and the characteristic green emission band centred around 515 nm is assigned to the $4f^65d^1 \rightarrow 4f^7$ transition of Eu^{2+} ions. Larger and well-crystallised particles generally produce brighter and longer afterglow, since the photoluminescence intensity decreases with crystallite size reduction, whereas pushing the particle size into the nanometre range typically lowers the photoluminescence response, because in terms of quantum efficiency the main disadvantage of nanosized phosphors is the increasing of defects number due to the larger surface/volume ratio and the absorption of excitation light is decreased by the strong light scattering of nanocrystals and therefore the reduction of the intensity emission (Rojas-Hernandez *et al*., 2017). As a result, despite nano-range particles have been obtained by chemical routes, photoluminescence response decreases and application became unpractical unless dedicated surface engineering - such as core-shell architectures - is used to restore the optical efficiency (Rojas-Hernandez *et al*., 2017).

When incorporated into polymer matrices, pigment dispersion becomes equally important. Agglomeration, sedimentation, or incomplete wetting can generate mechanically weak zones and optically inactive regions, reducing the overall efficiency of the composite. Direct observation supports this dependence: in optimised long-afterglow road-marking coatings, the storage and basic-performance tests confirmed that the long-afterglow coating exhibited good storage stability, showing no aggregation in the container and remaining easy to stir (Feng *et al*., 2026), indicating that uniform dispersion of the phosphor particles in the binder is a prerequisite for stable optical and mechanical behaviour.

A complete material characterisation therefore relies on several complementary techniques applied to the same sample. X-ray diffraction (XRD) is used to identify the crystallographic phase and the appearance of degradation products such as $Sr_3Al_2(OH)_{12}$ during ageing; scanning electron microscopy combined with energy-dispersive X-ray spectroscopy (SEM–EDS) provides information on particle morphology, dispersion quality and the elemental distribution of Sr, Al, Eu, and Dy. In a representative $SrAl_2O_4:Eu^{2+},Dy^{3+}$ powder, the necessary elements of Sr, Al, O, Eu, Dy can be directly recorded in the EDX

spectrum, with measured atomic percentages of about 1.37% [Eu^{2+}] and ... about 0.33% [Dy^{3+}]", providing a direct experimental check of the doping levels (Gao *et al*., 2023b). Fourier-transform infrared spectroscopy (FTIR) is, in turn, particularly useful for monitoring binder cross-linking and detecting degradation products during environmental ageing. Together, these methods provide the structural basis for interpreting the optical behaviour of photoluminescent coatings.

3.3.3. Degradation mechanisms

The long-term durability of photoluminescent road markings is governed by two coupled degradation mechanisms that act simultaneously on the phosphor and on the binder.

The first one is the hydrolysis of strontium-aluminate phosphors. Under humid conditions, uncoated $SrAl_2O_4$:Eu^{2+},Dy^{3+} progressively reacts with water to form hydrated species, so that the originally bright green pigment is transformed into an inactive white powder and the luminance is irreversibly lost. Reliability tests on commercial powders confirm this pathway directly: $SrAl_2O_4$ easily undergoes hydrolysis in the presence of atmospheric moisture", and structural analysis indicates that the $SrAl_2O_4$ phase becoming the $Sr_3Al_2(OH)_{12}$ phase and $SrAl_3O_5(OH)$ [is] generated under HT tests (Wang *et al*., 2020). The luminescent consequence is severe - in the same study the PL intensity of the thin film of SAOED decreased 57.2%, 79.3%, and 98.8% after HT tests, XLG tests for 168 h, and TC tests with 10 repetitions from 233 K to 423 K, respectively- showing that the degradation is not limited to a thin surface layer but progressively destroys the optical functionality of the particle (Wang *et al*., 2020). Because hydrolysis is strongly accelerated by humidity and temperature, unprotected phosphors are essentially unsuitable for outdoor applications, and dedicated protection strategies - silica or silica-polymer shell encapsulation, hydrophobic silane surface treatments - must be applied before incorporating the pigment into the marking system.

The second mechanism is the photo-oxidative ageing of the polymer binder. Under prolonged UV exposure, DGEBA-based epoxy resins undergo chain scission and the formation of chromophoric species responsible for visible yellowing of the matrix. Detailed colorimetric and structural monitoring shows that, after irradiation, the cured epoxy networks evolve through color darkening and accumulation of yellow chromophores, and the global colour shift in the CIE LCh^* system increases rapidly with exposure time - in one of the studied DGEBA systems over 44% of the total color change was measured after the first 100 h and about 87% after 400 h of exposure (Varganici *et al*., 2024). Because this yellowing absorbs light in the same green spectral region emitted by the phosphor, the apparent brightness of the marking gradually decreases even when the phosphor itself remains intact. In addition, traffic abrasion and freeze–thaw

cycles contribute to surface erosion and microcracking, which open new pathways for water ingress and accelerate the hydrolysis described above. Understanding these coupled degradation processes is therefore essential for selecting binder–pigment systems capable of maintaining long-term luminescent performance under real roadway conditions.

3.4. Composition and advantages of two-component epoxy resins in road markings

In this study we used a transparent two-component (bicomponent) epoxy resin binder commonly employed in industrial coatings and infrastructure applications. Such epoxy systems are based on diglycidyl ethers of bisphenol A (DGEBA) – an organic compound (often written as $C_{21}H_{24}O_4$) that, when cured, yields a rigid, cross-linked network with exceptional mechanical strength and chemical stability. In practice, the liquid Component A typically contains DGEBA monomers along with mineral fillers (e.g. silica SiO_2, alumina Al_2O_3 or calcium carbonate $CaCO_3$) and rheology modifiers. These fillers serve several functions: they improve adhesion and toughness of the cured film, and by "bulk displacement" of resin they significantly reduce curing shrinkage. For example, fumed (colloidal) silica (SiO_2) is frequently added to impart thixotropy and control viscosity. Thus Component A may be described as a mixture of DGEBA ($C_{21}H_{24}O_4$) plus extenders that enhance surface wetting, adhesion and dimensional stability.

Component B is the curing agent (hardener), usually a polyamine system. These are often modified aliphatic or cycloaliphatic amines (such as polyethylenepolyamines or cycloaliphatic diamines) that react with the epoxide groups in DGEBA to form the cross-linked network. For example, common hardeners include cycloaliphatic diamines like isophorone diamine ($C_6H_{14}N_2$) or polyetheramines (long-chain amines), which ensure rapid network formation, high glass transition temperature and excellent chemical resistance in the cured resin. Accelerators (catalysts) such as tertiary amines or imidazoles (e.g. 2,4,6-tris(dimethylaminomethyl)phenol, $C_{15}H_{27}N_3O$) may be added to shorten the cure time, allowing the paint to harden quickly at ambient conditions. In sum, Component B (amine hardener plus accelerators) activates epoxide ring-opening to crosslink the polymer, yielding a hard, abrasion-resistant coating.

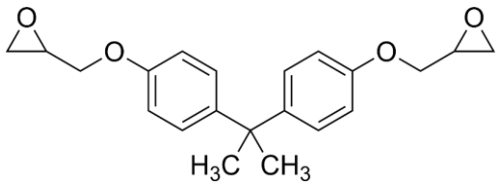


Fig. 2 − Chemical structure of bisphenol A diglycidyl ether (https://en.wikipedia.org/wiki/Bisphenol_A_diglycidyl_ether).

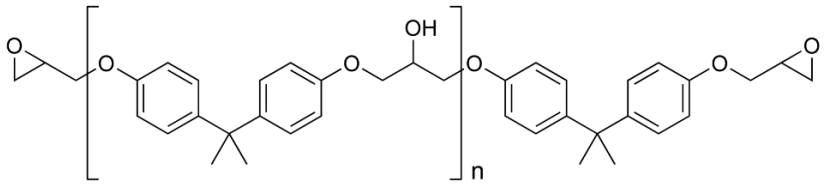


Fig. 3 − Structure of bisphenol-A diglycidyl ether epoxy resin (https://en.wikipedia.org/wiki/Bisphenol_A_diglycidyl_ether).

The choice of a high-performance epoxy binder for road marking paint is justified by several material properties. Epoxy resins are renowned for extremely high adhesion and mechanical durability: in fact, they provide outstanding adhesion, impact- and abrasion-resistance and overall toughness that are "unsurpassed by any other single commercially available resin". Such toughness and cohesion allow the marking to withstand heavy traffic and mechanical wear. Epoxies also have excellent resistance to moisture and chemicals, as required for outdoor pavement: their tightly crosslinked network blocks water ingress and resists oils or deicers, so the paint does not blister or erode under harsh weather. The binder's chemistry is also compatible with phosphorescent (afterglow) pigments: it does not quench their long-lived emission and indeed helps encapsulate and protect them.

Furthermore, epoxies adhere well to the diverse substrates found on roads and sidewalks (concrete, asphalt, metal reflectors, etc.), ensuring the marking does not delaminate under thermal cycling. Epoxy systems can be formulated to resist UV radiation and slow down yellowing – a key benefit since rapid yellowing would otherwise reduce the glow effectiveness. In practice, UV stabilizers or pigmented topcoats are often used to enhance outdoor durability. In summary, the selected DGEBA-based binder ($C_{21}H_{24}O_4$) with amine hardener meets all requirements for a long-lasting, photoluminescent road marking: it binds strongly, cures to a hard chemical-resistant film, and preserves the functional properties of the glow pigments for improved nighttime visibility.

3.4.1. Curing chemistry and network formation

The transformation of liquid DGEBA epoxy resin into a rigid solid occurs through a step-growth polyaddition reaction. During curing, the amine hardeners progressively open the oxirane rings of the resin, building a three-dimensional cross-linked network whose final properties depend strongly on the chosen co-monomers. FTIR spectroscopy provides a direct way of monitoring this process by following the disappearance of the characteristic epoxy ring absorption: in standard DGEBA systems, neat DGEBA epoxy resin is characterized by the

signal of the epoxy ring at 915 cm^{-1} and the signals from 1591 and 1506 cm^{-1} corresponding to skeletal C=C vibrations in aromatic moieties (Varganici *et al*., 2024). The aromatic bands act as internal reference because they remain constant during cross-linking, so the gradual loss of the 915 cm^{-1} absorption gives a quantitative measure of the extent of curing.

The degree of cure directly controls the hardness, glass-transition temperature, and chemical resistance of the final coating. A properly cured network reaches near-complete oxirane conversion and a high cross-link density; residual unreacted epoxide groups soften the matrix and shorten its service life. Beyond a simple kinetic indicator, the same FTIR fingerprint can also be used to detect ageing-induced changes - in aged DGEBA networks, the general decrease in the signals is an indication that photodegradation occurs via chain scission and mass loss (Varganici *et al*., 2024), which is precisely the mechanism implicated in the binder yellowing discussed in the previous section.

3.4.2. Microstructure of the cured binder-pigment composite

In the cured composite, the phosphorescent $SrAl_2O_4:Eu^{2+},Dy^{3+}$ pigment forms a discrete dispersed phase within the continuous epoxy matrix. Mechanical and optical performance depends critically on dispersion quality: well-wetted, uniformly distributed particles maximise both light transmission and stress transfer, whereas agglomeration leaves microvoids and creates stress concentrators that initiate cracks at the particle boundaries.

A key origin of these stresses is the volume shrinkage of the resin itself during cross-linking and cooling. Direct measurements on epoxy-substrate systems confirm that during the curing process, the epoxy resin shrinks when cooled to room temperature, and, where the embedded component has a much lower coefficient of thermal expansion, this mismatch results in the generation of RS at the interface between the epoxy resin and the substrate (Wu *et al*., 2024). Raman mapping in the same study further reveals a strong stress concentration at the interface between the epoxy resin and the silicon wafer (Wu *et al*., 2024)**,** providing a direct experimental analogue for what happens at every pigment–matrix interface inside a luminescent coating.

Scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS) is the standard tool used to assess this microstructure: it reveals particle morphology, size and spatial distribution, interface integrity, and the elemental mapping of Sr, Al, Eu, and Dy in the cured film. In practice, dedicated formulation strategies are used to improve dispersion and mitigate shrinkage stresses. On the pigment side, encapsulating $SrAl_2O_4:Eu^{2+},Dy^{3+}$ particles in a multifunctional shell produces a core-shell CDs/TiO_2@SAO composite coating (Zhang *et al*., 2023) that preserves the phosphor against environmental attack while improving its compatibility with the polymeric host. On the matrix side, the addition of fumed silica nanoparticles further reinforces

the epoxy network: the crosslinking density and T_g of the epoxy/fumed silica composites increased because of the interfacial interaction between the PDMS-treated fumed silica particles and the epoxy matrix, and the flexural strength of the epoxy nanocomposite was very high even at a low silica content because of the strong interactions between the PDMS-treated fillers and the epoxy matrix" (Kim *et al*., 2021). Taken together, these measures reduce voids, relax interfacial stress and preserve the mechanical integrity of the coating, so that its luminescent functionality is maintained over the operating life of the road marking.

3.4.3. Degradation mechanisms of the binder-pigment system

The durability of photoluminescent coatings is mainly controlled by two coupled degradation mechanisms acting simultaneously on the polymer binder and on the strontium-aluminate pigment.

The first one is the photo-oxidative ageing of the epoxy binder. Under prolonged UV exposure, DGEBA-based resins undergo chain scission and the formation of chromophoric species responsible for visible yellowing of the matrix. A systematic comparison of waterborne epoxy coatings cured with different aminic agents confirmed this trend: under accelerated UV ageing, higher aminic values in curing agents degraded faster than lower aminic values (increases of ~3% in delta b and delta E between 5 and 20%), and FTIR and Tg monitoring indicated the resin degradation when using curing agents of unmodified aliphatic amine because of its rapid chemical degradation under a UV environment (Da Silva *et al*., 2024). Because this yellowing absorbs light in the same green spectral region emitted by the phosphor, the apparent brightness of the marking decreases progressively even when the pigment itself remains optically intact. To mitigate this effect, epoxy formulations are typically tailored through the choice of curing agent (cycloaliphatic amines giving better light stability than aromatic or unmodified aliphatic ones) and through the incorporation of UV stabilisers such as hindered amine light stabilisers (HALS) and benzotriazoles. The same comparative study reported that curing agents with aminic values between 200 and 300 KOH/g and the equivalent weight of amine hydrogen higher than 120 g/eq showed the best performance in epoxy coatings and good stability against accelerated aging (Da Silva *et al*., 2024)**,** providing a practical formulation window for outdoor applications.

The second degradation pathway is the hydrolysis of the $SrAl_2O_4:Eu^{2+},Dy^{3+}$ phosphor itself. In humid environments, the pigment progressively reacts with water to form hydrated by-products and loses its luminescent function: strontium aluminate ($SrAl_2O_4$: Eu^{2+}, Dy^{3+})-type rare earth alkali metal aluminate afterglow materials face issues with hydrolysis upon contact with water, leading to a decrease in or disappearance of luminescence, thus necessitating a treatment to make the luminescent powder water-resistant (Zhang *et al*., 2024). The problem is further compounded by thermal stress in real

road environments: asphalt surfaces can reach temperatures of up to 60ºC in summer under direct sunlight, which can also damage the aluminate's crystal structure (Zhang *et al*., 2024), so hydrolysis and thermally induced lattice damage tend to occur in parallel. Epoxy matrices partially limit this process by reducing water penetration to the embedded particles; on top of this barrier effect, the most effective protection is achieved at pigment level, since through the application of organic-inorganic composite coating technology, the water resistance and thermal stability of the materials can be improved, thus enhancing the performance of road markings (Zhang *et al*., 2024). In practice, this means combining silica or silica–polymer shell encapsulation of the phosphor with hydrophobic silane surface treatments before the powder is incorporated into the marking system.

Taken together, photo-oxidation of the binder and hydrolysis of the pigment determine the long-term optical and mechanical stability of photoluminescent road-marking systems under real traffic and weathering conditions, and any meaningful service-life prediction for such coatings must explicitly account for both mechanisms.

3.5. Selection and characterization of photoluminescent pigments used in the experiment

This study evaluates the properties and performance of photoluminescent pigments for their application in road and urban infrastructure. The primary objective is to identify an optimal solution for enhancing visibility in low-light conditions without relying on conventional electric energy sources.

For the experiment, three types of photoluminescent pigments were selected, each with unique characteristics and specific advantages. These pigments were incorporated into a two-component epoxy resin, allowing for an in-depth analysis of: light emission duration and intensity, behavior under various environmental conditions, mechanical and chemical stability in urban infrastructure applications

The selection of pigments was based on efficiency, durability, and compatibility with the materials used. The three pigments chosen for the experiment were:

1) ***High-performance phosphorescent pigments (S-Series)*** - particle size: 30–40 microns. These are strontium-aluminate–based pigments doped with rare-earth ions. A common formula is $SrAl_2O_4:Eu^{2+},Dy^{3+}$, which emits intense green light. Such pigments have very high brightness and long afterglow (often over 12 hours of visibility) and charge quickly under UV/bright light. They are chemically inert and non-flammable, making them durable in varied conditions.

Characteristics:

- These pigments exhibit high brightness and can retain light energy for an extended period (over 12 hours).
- Based on strontium aluminate, they provide high-intensity luminescence with long-lasting performance.
- They charge rapidly when exposed to UV rays or intense artificial light.

Advantages:

- Ideal for applications requiring maximum nighttime visibility.
- Long-lasting light emission without significant intensity loss.
- Good environmental resistance (temperature, humidity).

Limitations:

- Higher cost compared to other types of pigments.
- Require prolonged exposure to intense light for optimal performance.

2) ***Water-based photoluminescent pigments*** - particle size: 5–20 microns. These typically use inorganic glow compounds dispersed in a waterborne binder. A representative chemistry is zinc sulphide doped with copper ($ZnS:Cu^{2+}$), a classic green-emitting pigment. Zinc sulphide pigments glow moderately (on the order of several hours) and are regarded as non-toxic and eco-friendly. They mix readily into water-based paints or resins without degrading chemical stability

Characteristics:

- Eco-friendly and non-toxic, compliant with environmental protection regulations.
- Easily mixes with water-based resins and paints without affecting chemical stability.
- Moderate luminescence, making them suitable for areas with constant light exposure (over 6 hours).

Advantages:

- Sustainable solution – A safe alternative for urban applications and sensitive environments.
- High chemical compatibility – Can be integrated into various formulations without altering the material's mechanical properties.
- Safe handling – Free from toxic solvents or hazardous substances.

Limitations:

- Lower light emission compared to high-performance phosphorescent pigments.
- Sensitive to high humidity, requiring protective coatings for long-term durability.

3) ***Solvent-based photoluminescent pigments*** - particle size: 15–35 microns. These use similar inorganic phosphors but in solventborne (organic) coatings. The pigment contains strontium aluminates ($SrAl_2O_4:Eu^{2+},Dy^{3+}$). In a solvent binder, these pigments withstand harsh chemicals, extreme temperatures, and moisture better

Characteristics:

- These pigments are highly resistant to harsh environmental conditions, including prolonged exposure to humidity, extreme temperatures, and chemicals.
- Suitable for industrial conditions and high-traffic road applications.
- Moderate to high luminescence, depending on the final composition (over 10 hours).

Advantages:

- High chemical resistance – Ideal for industrial environments and abrasion-prone areas.
- Versatile compatibility – Can be integrated into industrial paints, resins, and plastics.
- Extended lifespan – Better resistance to UV degradation.

Limitations:

- Contain volatile solvents, requiring additional safety measures during.
- More challenging to handle than water-based pigments.

In this experiment, the three types of pigments were analysed to determine their performance in specific applications.

High-performance phosphorescent pigments proved to be the most efficient for road markings and applications requiring high nighttime visibility.

Water-based pigments provide an eco-friendly and versatile solution, ideal for urban furniture and pedestrian signage, but with lower light intensity.

Solvent-based pigments are recommended for industrial and harsh environments, offering superior durability and excellent compatibility with industrial paints and resins.

By selecting the appropriate type of pigment based on the application, photoluminescent materials can significantly contribute to enhancing the safety and sustainability of urban and road infrastructure.

Beyond the manufacturer specifications, a rigorous evaluation of such pigments and of their behaviour within the epoxy matrix relies on a set of complementary analytical techniques, which also define the characterisation framework adopted in the present work. X-ray diffraction (XRD) confirms the monoclinic $SrAl_2O_4$ phase and detects hydrated by-products formed during ageing; scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS) characterises particle morphology and size and assesses how

uniformly the pigment is dispersed in the cured film, mapping the distribution of Sr, Al, Eu, and Dy; and Fourier-transform infrared spectroscopy (FTIR) monitors the cross-linking of the binder and the appearance of degradation products such as hydroxylated phases. Dispersion quality is particularly important, because agglomeration or sedimentation of the denser strontium-aluminate particles produces optically inactive regions and mechanical weak points that lower both brightness and durability.

Table 1
Comparative characteristics of the three photoluminescent pigments selected for the study

Property	High-performance (S-Series)	Water-based	Solvent-based
Chemistry	$SrAl_2O_4:Eu^{2+},Dy^{3+}$	$ZnS:Cu^{2+}$	$SrAl_2O_4:Eu^{2+},Dy^{3+}$
Particle size	30–40 µm	5–20 µm	15–35 µm
Emission colour	Green (~520 nm)	Green	Green (~520 nm)
Reported afterglow	> 12 h	> 6 h (moderate)	> 10 h
Main strength	Highest brightness and longest afterglow	Non-toxic, eco-friendly, easy to disperse	Best chemical and UV resistance
Main limitation	Higher cost; moisture-sensitive	Lower intensity; humidity-sensitive	Volatile solvents; harder to handle
Suited to	Road markings; max nighttime visibility	Urban furniture; pedestrian signage	Industrial and high-traffic areas

The durability of each pigment within the coating is governed by the degradation mechanisms discussed in Section 3.3.3: hydrolysis of the strontium-aluminate phase under moisture, and photo-oxidative yellowing of the binder under ultraviolet exposure. These mechanisms explain the comparative ranking adopted here - the solvent-based strontium-aluminate pigment offers the best environmental resistance, the S-Series the highest brightness, and the water-based ZnS:Cu the most favourable environmental and handling profile at the cost of luminous performance. The quantitative confirmation of these qualitative rankings, by luminance-decay measurement under DIN 67510 together with SEM-EDS and FTIR analysis, constitutes the methodological objective of the experimental programme described in the following section.

Of the three pigments evaluated, the high-performance S-Series proved the most effective for road markings and other applications requiring high nighttime visibility; the water-based pigment offers an eco-friendly and versatile solution for urban furniture and pedestrian signage, albeit with lower light intensity; and the solvent-based pigment is preferable for industrial and harsh

environments owing to its superior chemical and UV resistance. Matching the pigment to the application in this way allows photoluminescent materials to make a meaningful contribution to the safety and sustainability of urban and road infrastructure.

3.6. Methodology

To determine the optimal proportion of photoluminescent pigment in epoxy resin–based mixtures, a systematic experimental program was conducted, comprising formulation, application, and comprehensive material testing. The central objective was to establish the ideal composition that maximizes light emission while preserving the physical and mechanical integrity of the composite. The study is framed as a comparative screening of three pigments at five mass fractions; luminous behaviour was assessed qualitatively, by trained-observer ranking, while quantitative evaluation was performed through instrumental colorimetric characterisation.

3.6.1. Materials

The binder was a transparent two-component epoxy system based on the diglycidyl ether of bisphenol A (DGEBA, $C_{21}H_{24}O_4$) cured with an amine hardener of the triethylenetetramine type (TETA, $C_6H_{18}N_4$). The resin and hardener were combined in the manufacturer-specified mass ratio, which was held constant across all formulations to ensure comparability. Three commercial photoluminescent pigments were evaluated: a high-performance solid-state strontium aluminate (S-Series, $SrAl_2O_4:Eu^{2+},Dy^{3+}$, 30–40 μm); a water-based copper-doped zinc sulfide ($ZnS:Cu^{2+}$, 5–20 μm); and a solvent-based strontium aluminate ($SrAl_2O_4:Eu^{2+},Dy^{3+}$, 15–35 μm). Where specific grades, supplier names, and lot numbers are available, they should be reported here to ensure full reproducibility, as recommended by current practice for self-luminous coatings.

3.6.2. Processing difficulties and corrective measures

The final protocol was not established at the first attempt. During its development, several preliminary batches failed, and the difficulties encountered proved as instructive as the successful formulations in defining the working procedure. Reporting these failures explicitly is consistent with the transparency expected of an experimental methodology: rather than presenting an idealised procedure, it documents the empirical basis on which the critical processing parameters were fixed. Three recurring problems were identified, each traceable to a specific physico-chemical cause, and each resolved by a corresponding adjustment of the protocol.

In several early trials, the ambient temperature was not held at the level required for amine-cured epoxy systems - approximately 20ºC - and the mixture failed to harden, remaining tacky or elastic and poorly adherent even after the nominal 48-hour curing period. This outcome reflects the strong temperature dependence of the cross-linking reaction: the ring-opening of the oxirane group by the amine hardener is thermally activated, so that below roughly 20ºC the available thermal energy becomes insufficient for the reaction to reach completion within a practical time. The result is a network arrested at a low degree of conversion, with a depressed glass-transition temperature and markedly inferior mechanical and chemical properties. The corrective measure was to carry out curing in a temperature-controlled enclosure at 23 ± 2ºC; any sample that did not reach a hard, tack-free state within 48 hours was discarded and re-prepared, so that incompletely cured material was never carried forward to testing.

When the pigment was not mixed thoroughly, it remained agglomerated within the resin, producing a visibly uneven, spotty glow and locally weak regions in the cured film. Two factors made the strontium-aluminate pigment particularly prone to this defect: its relatively high density, which promotes sedimentation in the viscous resin before gelation, and the tendency of the fine particles to cluster through interparticle forces during wetting. Such clusters scatter and trap light internally, so that the affected regions emit weakly and non-uniformly, while the resin-poor zones around them become mechanical weak points. This observation led directly to the dispersion procedure described in Section 3.6.4: preconditioning of the pigment by oven-drying and sieving to break up pre-existing agglomerates, gradual addition in small wetted portions, and controlled mechanical homogenisation continued until the dispersion was visually uniform.

The opposite failure arose when the resin was mixed for too long. When stirring continued beyond about 20 minutes, the batch heated up perceptibly and began to thicken, becoming difficult to pour and cast. This behaviour is a direct consequence of the exothermic nature of the amine–epoxy reaction: the heat released by cross-linking accumulates within the batch faster than it can dissipate to the surroundings, raising the temperature, which in turn accelerates the reaction further. Once this self-reinforcing cycle is established, the viscosity rises sharply, gelation sets in prematurely, and the working time collapses. To keep the reaction in a controlled regime, the mixing time was capped below 20 minutes per batch, and small batches were prepared and cast immediately, before the onset of exothermic thickening. Limiting the batch size also increases the surface-to-volume ratio, which helps the reaction heat dissipate and further suppresses self-heating.

These observations are summarised in Table 2.

Table 2
Processing difficulties encountered and the corrective measures adopted

Observed problem	Probable cause	Corrective measure adopted
The mixture failed to cure and remained tacky or soft after 48 h	Ambient temperature fell below the ~20ºC required for amine-epoxy cure, slowing the cross-linking reaction	Curing was carried out in a temperature-controlled enclosure at 23 ± 2ºC; samples that did not reach a hard, tack-free state were discarded and re-prepared
Pigment remained agglomerated, producing uneven, spotty luminescence	Insufficient or non-uniform mixing left particle clusters dispersed unevenly in the resin	The pigment was dried, sieved, and added gradually; mixing was standardised (manual pre-wetting followed by mechanical stirring) until the dispersion was visually uniform
The mixture overheated and thickened, becoming difficult to pour	Mixing the resin for longer than ~20 min triggered the exothermic amine-epoxy reaction, accelerating gelation and raising viscosity	Mixing time was limited to under 20 min per batch; small batches were prepared and cast immediately, before the onset of exothermic thickening

Taken together, these three failures defined the critical control parameters of the procedure. The curing temperature had to be maintained at or above 20ºC - controlled here at 23 ± 2ºC - to ensure complete cross-linking; the quality of pigment dispersion had to be secured through drying, sieving, and gradual addition to obtain a uniform glow and a sound microstructure; and the mixing time had to be kept below 20 minutes to avoid exothermic gelation. Recognising and controlling these three parameters - temperature, dispersion, and mixing time - was the single most important outcome of the preliminary work, and all reported samples were prepared under these fixed conditions.

3.6.3. Determining the optimal pigment proportion

The concentration of photoluminescent pigment directly influences luminescence intensity and material durability. A higher pigment proportion leads to stronger light emission and extended passive illumination duration; however, it may also impact the adhesion and mechanical resistance of the resin.

To evaluate this balance, five different pigment concentrations (10%, 20%, 30%, 40%, and 50% by weight) were prepared and tested. For all formulations, the resin-to-hardener ratio was maintained constant to ensure comparability. Each batch was produced under controlled laboratory conditions to minimize contamination and to guarantee a uniform dispersion of pigment particles throughout the polymer network.

Table 3
Formulation of mixtures

Resin, %	Resin, g	Pigment, %	Pigment, g
90	45	10	5
80	40	20	10
70	35	30	15
60	30	40	20
50	25	50	25

On this basis, five samples were prepared and labelled for each of the three pigment types, giving a total of fifteen specimens. Within each series, the photoluminescent pigment was incorporated into the two-component epoxy resin (component A and component B, mixed in a constant 2:1 mass ratio) at five increasing mass fractions — 10, 20, 30, 40, and 50% by weight — while the corresponding resin fraction decreased from 90 to 50%. Keeping the resin-to-hardener ratio constant across all formulations ensured that any difference in performance could be attributed to the pigment type and loading rather than to the binder. The compositions of the three series are given in Tables 4.

Table 4
Sample identification according to the solvent used

Pigment %	Sample identification Solvent-based pigment	Sample identification Water-based photoluminescent pigment	Sample identification Phosphorescent Gama S
10	S 1.0408	W 6.0408	G 11.0408
20	S 2.0408	W 7.0408	G 12.0408
30	S 3.0408	W 8.0408	G 13.0408
40	S 4.0408	W 9.0408	G 14.0408
50	S 5.0408	W 10.0408	G 15.0408

3.6.4. Preparation and application of mixtures

The experimental methodology was designed to investigate the incorporation of long-afterglow photoluminescent pigments into a two-component epoxy resin system based on diglycidyl ether of bisphenol A (DGEBA, $C_{21}H_{24}O_4$) and an amine-based hardener. The goal was to determine the optimal pigment–resin formulation that provides sustained luminescence, chemical stability, and mechanical durability suitable for road marking applications.

Table 5
Epoxy Resin, Hardener, and Pigments

Epoxy system	Pigment Type	Chemical Formula	Chemical Reactivity
$C_{21}H_{24}O_4$ + $C_6H_{18}N_4$	*High-performance phosphorescent pigments (S-Series)*	$SrAl_2O_4:Eu^{2+},Dy^{3+}$	*Epoxide groups in DGEBA undergo ring-opening crosslinking with amine hardeners; embedded* $SrAl_2O_4:Eu^{2+},Dy^{3+}$ *particles remain inert but act as photoluminescent fillers, stabilized within the polymer matrix.*
$C_{21}H_{24}O_4$ + $C_6H_{18}N_4$	*Water-based photoluminescent pigments*	$ZnS:Cu^{2+}$	*ZnS:*Cu^{2+} *crystals (green-emitting) are physically encapsulated within the epoxy-amine matrix. While chemically stable, their luminescence is humidity-sensitive; epoxy encapsulation reduces degradation and ensures adhesion to waterbor.*
$C_{21}H_{24}O_4$ + $C_6H_{18}N_4$	*Solvent-based photoluminescent pigments*	$SrAl_2O_4:Eu^{2+},Dy^{3+}$	*Similar to the S-Series: epoxy crosslinking with TETA creates a robust polymer matrix, embedding the pigment particles. These solvent-compatible phosphors show excellent afterglow and enhanced resistance to chemical or thermal stress.*

The mixtures were prepared in a controlled environment, ensuring a constant temperature and the absence of contaminants. To achieve a uniform dispersion of the photoluminescent pigment in the resin, a rigorous mixing protocol was followed:

- Preconditioning of pigments – The pigment oven-dried at 110ºC and passed through a 0.063 mm sieve (200 mm diameter) to break up agglomerates before use.
- Gradual addition of pigment – The pigment was introduced gradually into the resin in small quantities, each portion being fully dispersed and wetted before the addition of the next one, in order to prevent particle agglomeration.

– Homogenization of the mixture – A mechanical stirrer equipped with an S 157-01 propeller was used, and the stirring speed was adjusted to 400 rpm, as is shown in Fig. 4. The mixture was homogenized for 3 minutes during each pigment-addition stage and for an additional 10 minutes after the complete amount of pigment had been introduced, in order to ensure complete and uniform dispersion of the pigments within the polymer matrix.

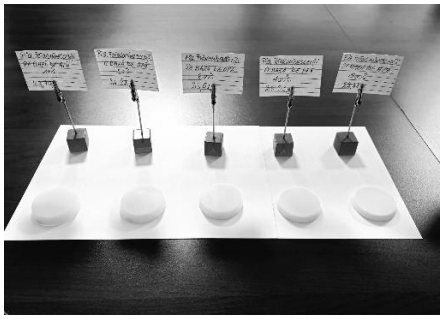
Fig. 4 – Mechanical stirrer S 157-01.

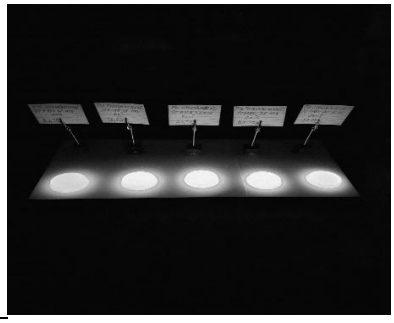
For the experimental tests, the samples were cast into 50 mm silicone molds, chosen for their flexibility and their ability to prevent material adhesion during curing. The layer thickness was maintained uniformly at 10 mm to avoid variations in luminous emission and mechanical strength.

To ensure uniform polymerization and optimal adhesion, the samples were allowed to cure for 48 hours at a controlled temperature of $23^0C \pm 2^0C$.

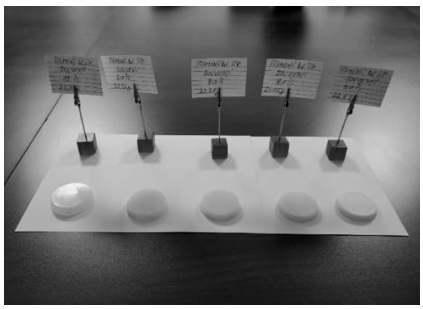
The polymerization process followed three distinct phases:

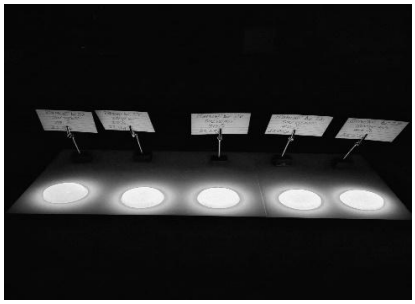
– Initial phase (0-2 hours): the mixture began developing viscosity and maintained its initial shape within the molds.
– Intermediate phase (2-24 hours): The chemical crosslinking process intensified, providing molecular stability to the material.
– Final phase (24-48 hours): The mixture reached full curing, achieving optimal mechanical strength and enhanced optical properties.



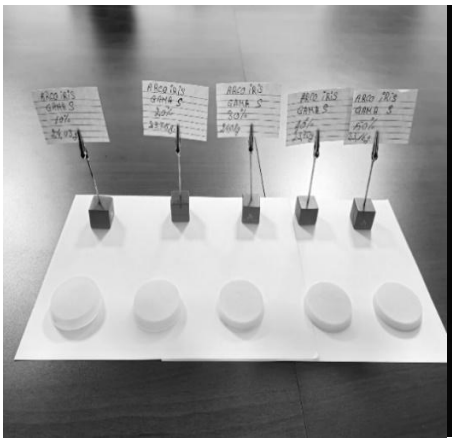


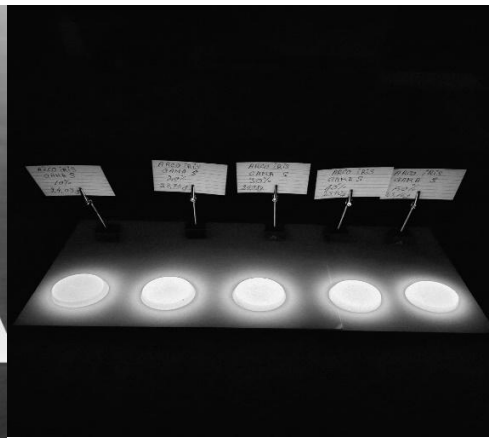
Samples with Water-Based Photoluminescent Pigment
Fig. 5 – Daytime Fig. 6 – Nighttime





Samples with Solvent-Based Photoluminescent Pigment
Fig. 7 – Daytime Fig. 8 – Nighttime





Samples with Solvent-Based High-performance phosphorescent pigments (S-Series)
Fig. 9 – Daytime Fig. 10 – Nighttime

3.6.5. Testing and performance evaluation of materials

The performance of each sample was assessed in two complementary ways: a qualitative evaluation of the persistent luminescence (afterglow), reproducing real-world charging and night-time observation, and a quantitative instrumental characterisation of the cured surfaces by diffuse-reflectance colorimetry. The first establishes how long and how uniformly each formulation glows in darkness; the second provides objective, reproducible numerical descriptors of the surface colour and brightness that govern both daytime appearance and the efficiency with which the green afterglow is transmitted.

3.6.5.1. Afterglow charging and emission test

The photoluminescent performance of each sample was determined through a rigorous experimental method designed to simulate real-world usage conditions.

Fig. 11 – Samples with Photoluminescent Pigment (Daytime).

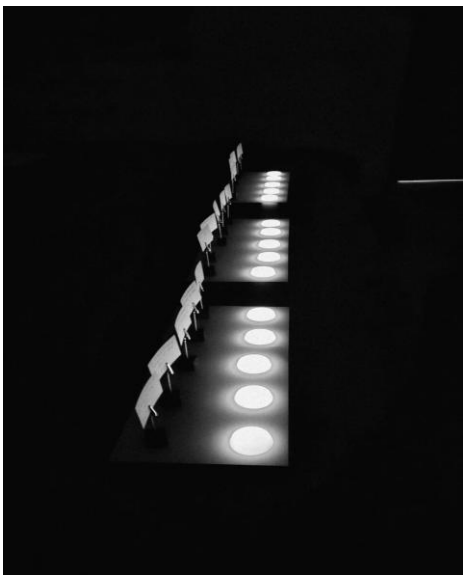


Fig. 12 – Samples with Photoluminescent Pigment (Nighttime).

The evaluation focused on both the light absorption capacity and the duration of emitted light, as follows:

– *Pigment charging:*

To ensure uniform charging of the photoluminescent pigments, each sample was exposed to an artificial light source - a bulb with a spectrum close to natural sunlight - for 30 minutes. This step was intended to replicate daytime exposure

to natural light and optimize pigment charging, allowing for an accurate analysis of their behavior in complete darkness.

– *Evaluation of light emission*

After the charging process, the samples were placed in an optically isolated testing box, eliminating any external light sources. This stage aimed to measure:

– Duration of light emission – the time during which the sample continues to emit visible light in darkness;
– Light intensity – the brightness emitted by the material as a function of the elapsed time since charging;
– Homogeneity of light emission – the uniform distribution of light across the sample's surface to assess potential fluctuations or loss of luminescence.

– *Analysis and interpretation of results*

Measurements were conducted at regular time intervals to observe how each sample gradually lost its light intensity. These data were compared with the optimal parameters of the photoluminescent pigments, allowing for the assessment of the performance of each type of mixture.

Table 6

Comparison of photoluminescent pigment performance

Pigment type	Emission duration	Luminous intensity	Recommended applications
Phosphorescent Gama S	6 hours	High	Road markings, nighttime-visible signs
Solvent-Based Photoluminescent	6-7 hours	Good	Industrial applications, high-traffic areas
Water-Based Photoluminescent	3-5 hours	Moderate	Urban areas, street furniture, pedestrian safety

3.6.5.2. Instrumental colorimetric characterisation

To obtain objective, reproducible descriptors of the cured surfaces, the samples were characterised by diffuse-reflectance spectrophotometry under $d/0^0$ geometry (diffuse illumination, 0^o observation). The measured quantities and their physical meaning are given in Table 7. Because the apparatus accepts samples up to 140 mm in diameter, a small number of specimens cast in larger trays could not be measured owing to geometric constraints.

Table 7
Measured colorimetric parameters and their physical meaning

Parameter	Physical meaning
Rx, Ry, Rz	Diffuse-reflectance tristimulus components in the CIE XYZ colour space (CIE 1931), corresponding approximately to the red, green, and blue channels; Ry, the luminance factor, is the most relevant to the perception of brightness.
R457	Diffuse reflectance measured at 457 nm (blue), the ISO 2470-1 brightness; sensitive to yellowing of the matrix, since yellowing absorbs blue light and lowers R457.
L^*, a^*, b^*	CIELAB coordinates: L^* is lightness (0 = black, 100 = white); a^* is the green-red axis (negative = green); b^* is the blue-yellow axis (positive = yellow).
F	Fluorescence whiteness, obtained as the difference between r457 (with the UV component of the source) and R457 (without it); a measure of surface fluorescence.

This section presents the complete experimental data: the formulation of the mixtures for each pigment type and the per-sample colorimetric measurements obtained by diffuse-reflectance spectrophotometry. These tables may be inserted in the methodology and results sections, or attached as an appendix, as preferred.

The parameters are defined in Table 8, 9, 10: R457 - ISO 2470-1 blue reflectance (brightness); Rx, Ry, Rz - CIE XYZ tristimulus reflectance components (Ry = luminance factor); R∞ - intrinsic reflectance; L^*, a^*, b^* - CIELAB coordinates ($a^* < 0$ = green; $b^* > 0$ = yellow); r457 - blue reflectance including the UV (fluorescence-inducing) component; F - fluorescence whiteness (r457 - R457). Samples cast in trays larger than 140 mm in diameter could not be measured owing to the geometric limit of the instrument.

Table 8
Colorimetric results Solvent-based pigment

Sample identification	R457	Rx	Ry	Rz	R∞	L^*	a^*	b^*	r457	F
Reduced brightness										
S 1.0408	15.56	26.95	26.92	16.83	26.33	58.90	-7.74	18.72	–	–
S 2.0408	18.40	37.72	36.24	19.85	36.26	66.70	-6.38	25.92	–	–
S 3.0408	19.94	44.59	42.91	22.09	42.99	71.49	-7.74	29.95	–	–
S 4.0408	23.19	50.39	48.54	25.34	48.56	75.16	-7.79	30.62	–	–
S 5.0408	24.91	51.78	50.00	26.92	50.00	76.07	-7.92	29.60	–	–
Normal brightness										
S 1.0408	20.77	29.23	28.04	16.55	27.79	59.92	-4.80	21.10	25.89	0
S 1.0408	22.79	37.55	36.32	19.73	35.31	66.76	-7.18	26.26	22.61	0
S 1.0408	24.16	44.63	43.08	21.98	43.02	71.61	-8.20	30.35	23.64	0.52
S 1.0408	27.18	50.40	48.72	25.38	48.66	75.28	-8.43	30.75	26.84	0.28
S 1.0408	28.54	52.37	50.56	26.88	50.59	76.41	-8.11	30.26	28.02	0.52

Table 9

Colorimetric results Water-based photoluminescent pigment

Sample identification	R457	Rx	Ry	Rz	R∞	L^*	a^*	b^*	r457	F
Reduced brightness										
W 6.0408	31.74	48.22	46.82	33.08	47.40	74.07	-4.11	16.98	–	–
W 7.0408	36.22	61.45	59.59	38.29	59.75	81.61	-6.05	23.07	–	–
W 8.0408	38.17	69.07	66.32	40.67	66.79	85.16	-5.86	26.23	–	–
W 9.0408	39.53	71.31	68.78	41.92	68.80	86.40	-6.61	26.86	–	–
W 10.0408	40.20	74.06	71.39	42.80	71.40	87.67	-6.91	28.03	–	–
Normal brightness										
W 6.0408	34.91	48.28	47.66	33.99	48.25	74.61	-5.80	16.65	38.44	0
W 7.0408	38.94	62.16	60.38	38.21	60.45	82.04	-6.55	23.91	38.81	0
W 8.0408	40.83	69.48	66.53	40.40	66.28	85.27	-5.69	26.75	40.70	0
W 9.0408	42.39	71.93	69.40	42.03	69.39	86.70	-6.78	27.26	41.84	0.56
W 10.0408	42.94	74.82	72.11	42.86	72.11	88.02	-7.06	28.55	42.41	0.54

Table 10

Colorimetric results Phosphorescent Gama S

Sample identification	R457	Rx	Ry	Rz	R∞	L^*	a^*	b^*	r457	F
Reduced brightness										
G 11.0408	21.67	33.89	33.24	22.36	33.33	64.35	-5.42	17.15	–	–
G 12.0408	25.55	49.39	48.35	27.76	48.37	75.05	-8.47	26.51	–	–
G 13.0408	26.96	55.65	54.30	29.60	54.23	78.64	-9.20	29.88	–	–
G 14.0408	27.21	57.83	56.31	29.92	56.32	79.79	-9.44	31.39	–	–
G 15.0408	27.52	58.87	57.28	30.29	27.29	80.34	-9.47	31.78	–	–
Normal brightness										
G 11.0408	26.69	34.81	33.46	21.86	34.63	64.53	-3.87	18.37	26.08	0
G 12.0408	29.2	49.56	48.49	27.68	48.55	75.13	-8.50	26.78	28.77	0
G 13.0408	30.43	55.61	54.25	29.26	54.25	78.61	-9.33	30.34	30.62	0.65
G 14.0408	30.78	57.78	56.36	29.90	56.33	79.82	-9.68	61.47	30.58	0.40
G 15.0408	30.87	58.92	57.34	30.03	57.32	80.37	-9.64	32.22	30.61	0.17

While the afterglow test in Section 3.6.5.1 captures how the materials behave in the dark, it relies on the judgement of an observer and cannot, on its own, express performance in numbers. To put the evaluation on a firmer footing, the cured surfaces were also characterised instrumentally, by diffuse-reflectance spectrophotometry under $d/0^0$ geometry (diffuse illumination, observation at 0^0), following the colorimetric conventions of the CIE 1931 system and ISO 2470-1. This technique describes a surface not by how it glows but by how it reflects daylight - its brightness, its colour, and its

tendency to yellow - properties that determine both the daytime appearance of a marking and the efficiency with which the stored green light is later released.

Each of the three pigment series was measured across the five mass fractions (10–50%), and every specimen was read under two illumination levels, described here as reduced and normal brightness, in order to confirm that the colour descriptors do not depend on the measuring light. The complete per-sample results are collected in Tables 8-10. For clarity, the discussion below draws on the normal-brightness values, since the reduced-brightness readings follow the same pattern almost exactly.

1) Brightness rises with pigment content - but with diminishing returns

The clearest message in the data concerns the luminance factor Ry, the parameter most closely tied to perceived brightness. In every series, Ry rises steadily as the pigment fraction increases from 10 to 50%: from 28.0 to 50.6 for the solvent-based pigment, from 33.5 to 57.3 for the phosphorescent Gama S, and most strongly from 47.7 to 72.1 for the water-based pigment. This monotonic increase is exactly what one would expect - more pigment means more reflecting and emitting material at the surface - and it gives an objective, numerical basis for the loading effect that the afterglow test could only suggest qualitatively.

More revealing than the rise itself is its shape. The brightness gained between 10 and 30% is consistently far greater than that gained between 30 and 50%. For the water-based pigment the surface gains 18.9 Ry units over the first interval but only 5.6 over the second; for Gama S the contrast is starker still, a gain of 20.8 units followed by just 3.1. In other words, beyond about 30% each additional increment of pigment buys progressively less brightness. This plateau, taken together with the loss of mechanical integrity observed at the highest loadings, is precisely why a loading of around 30% emerges as the practical optimum: it sits at the point where the optical benefit has very nearly saturated while the coating still cures into a sound, durable film.

2) The green identity of the phosphors survives the matrix

A second consistent finding is that the a^* coordinate is negative for every single sample, across all three series and both illumination levels, ranging from about -3.9 to -9.7. Since a negative a^* denotes a green hue, this confirms that the cured surfaces keep the characteristic green colour of the strontium-aluminate and zinc-sulphide phosphors, and that the transparent epoxy matrix neither masks nor distorts it. The green character is most pronounced for the Gama S series (a^* reaching – 9.7), in keeping with its higher intrinsic emission, and weakest for the water-based pigment at the lowest loading ($a^* \approx$ -3.9 to -5.8), where there is simply less pigment to colour the film. The accompanying positive b* values (roughly 17 to 32) reveal a secondary yellow component that grows hand in hand with Ry; this is unsurprising, because a thicker, denser pigment layer both brightens the surface and deepens its yellow-green body colour.

3) Lightness and whiteness reflect the pigment chemistry

The lightness L^* and the ISO brightness R457 separate the three pigments neatly. The water-based series is the lightest and whitest, reaching $L^* = 88.0$ and R457 = 42.9; the Gama S series is intermediate (L^* up to 80.4); and the solvent-based series is the darkest of the three (L^* up to 76.4, R457 up to 28.5). The fluorescence whiteness F, meanwhile, stays close to zero throughout ($F \approx 0$ – 0.65), which is itself an important result: it tells us that the brightness recorded by the instrument comes almost entirely from ordinary diffuse reflection rather than from any fluorescent emission excited by the ultraviolet content of the source. R457 and Ry can therefore be trusted as honest descriptors of the true body colour of the coatings, uncontaminated by fluorescence artefacts.

4) The measurement is stable across illumination levels

Finally, comparing the reduced- and normal-brightness readings shows differences of at most a fraction of a unit – the brightest water-based sample, for example, gives Ry = 71.4 under reduced and 72.1 under normal illumination. This near-identity confirms that the colorimetric descriptors are robust with respect to the measuring light level and that the ranking of the formulations is a genuine property of the materials, not an artefact of the conditions under which they were read.

5) Placing the indicators against regulatory limits

To judge what these numbers mean for a real marking, each indicator can be set against the thresholds defined by the relevant road-marking standards. One caveat must be stated at the outset: these standards were written for conventional white and yellow retroreflective markings, whereas the material studied here is a green-emitting photoluminescent coating. The comparison therefore serves to locate the material within the existing framework, not to assert formal compliance with classes designed for a different product.

- **Luminance factor β (daytime brightness)**. In EN 1436:2018 the daytime brightness of a marking is expressed by the luminance factor β, numerically the luminance factor Ry on a 0-1 scale ($\beta = Ry/100$). White markings on asphalt must reach $\beta \geqslant 0.30$ (class B2), 0.40 (B3), 0.50 (B4), or 0.60 (B5); yellow markings, $\beta \geqslant 0.20$ (B1) upward. With Ry between 0.28 and 0.72, the present coatings span classes B2 to B5 once the loading reaches 20% or more, matching and at high loading exceeding the daytime brightness demanded of conventional markings - though their green chromaticity means they would not be classed as a white or yellow line.
- **Diffuse luminance coefficient Qd**. EN 1436 also defines Qd, the luminance coefficient under diffuse illumination ($mcd \cdot m^{-2} \cdot lx^{-1}$), with white-on-asphalt classes $Q2 \geq 100$, $Q3 \geqslant 130$, and $Q4 \geqslant 160$. Measuring Qd requires a dedicated reflectometer geometry that was not available in this work; it is therefore deferred to Phase 2. The high Ry values suggest

the material would attain the upper Qd classes, but this must be verified instrumentally before it can be claimed.

- **Chromaticity (x, y).** EN 1436 requires the chromaticity of white and yellow markings to fall inside defined corner-point boxes on the CIE 1931 diagram. The steadily negative a^* of these coatings places them firmly in the green region, deliberately outside those boxes. This is an intended property of a green photoluminescent marking rather than a defect, but it does mean the material lies outside the colour classes defined for conventional lines and would need either a dedicated specification or use alongside a standard white marking.
- **Afterglow luminance**. The night-time performance that is the whole point of a photoluminescent marking is governed not by EN 1436 but by DIN 67510-1, which prescribes the decay of emitted luminance in mcd/m^2 after a standardised excitation - for Class C, 140 mcd/m^2 at 10 minutes and 20 mcd/m^2 at 60 minutes, down to a visibility threshold of roughly 0.32 mcd/m^2. The present study assessed the afterglow only qualitatively; this quantitative measurement is the central objective of the next phase.
- **ISO brightness R457**. R457 is an ISO 2470-1 index conceived for paper and pulp, not for road markings, so no regulatory threshold applies to it here. It is reported because it is acutely sensitive to yellowing - which absorbs blue light and lowers R457 - and so offers a convenient internal benchmark against which the photo-oxidative ageing of the binder can be followed in the planned ISO 4892-3 weathering tests.

In summary, the colorimetric characterisation does three things. It converts the qualitative impression of brightness into a measured quantity, Ry, that rises with loading and plateaus near 30%, giving the optimum a numerical justification. It confirms, through the uniformly negative a^*, that the green identity of the phosphors is preserved in the cured film. And it shows, by comparison with EN 1436, that the daytime luminance of the coatings is already comparable to that of conventional markings.

Performance of phosphorescent Gama S pigments

Mixtures containing 30% phosphorescent pigment maintained a strong luminous emission for 6 hours, providing an optimal balance between brightness and mechanical resistance.

Mixtures with 40% and 50% pigment concentration exhibited higher luminous intensity; however, an increased fragility of the applied layer was observed, which may affect durability under temperature variations.

The optimal concentration for urban and road infrastructure applications is 30% phosphorescent Gama S pigment, ensuring a balance between luminosity and durability.

Performance of solvent-based photoluminescent pigments

Mixtures containing 50% solvent-based photoluminescent pigment exhibited the longest luminous emission duration, maintaining an acceptable level of visibility for up to 6-7 hours.

This type of pigment is suitable for applications in harsh environments where increased resistance to environmental factors is required.

Performance of water-based photoluminescent pigments

Water-based photoluminescent pigments offer an eco-friendly and safe alternative, being non-toxic and compliant with environmental protection regulations. They are ideal for applications in urban areas, street furniture, and pedestrian safety.

Experimental test results showed that these pigments exhibit moderate luminous emission, lasting between 3-5 hours, making them suitable for pedestrian zones and low-traffic areas. They demonstrate excellent compatibility with water-based materials without altering the mechanical properties of the substrate. Additionally, they provide strong adhesion and high chemical stability, preventing peeling or premature degradation.

However, compared to solvent-based pigments, their luminescence is lower, which may limit their applicability in high-traffic conditions or areas with low illumination.

Water-based photoluminescent pigments represent a sustainable solution for eco-friendly applications and pedestrian safety, but they do not offer the same intensity and duration of luminous emission as phosphorescent or solvent-based pigments. The optimal concentration for urban applications is 30-40%, ensuring a balance between brightness, adhesion, and durability.

4. Conclusions

The growing demand for sustainable and energy-efficient road infrastructure underlines the potential of photoluminescent materials as a means of enhancing nighttime visibility. These materials capture and store light during the day and release it gradually after dark, providing a passive, energy-independent source of guidance in places where conventional lighting is absent or unreliable. The present study examined this potential through a comparative screening of three commercial photoluminescent pigments - a phosphorescent Gama S strontium aluminate, a solvent-based strontium aluminate, and a water-based zinc sulfide - incorporated into a two-component DGEBA epoxy resin at five mass fractions, and characterised by qualitative afterglow observation and by instrumental diffuse-reflectance colorimetry.

The comparison showed clear and consistent differences between the three pigments. The phosphorescent Gama S pigment produced the brightest and longest-lasting emission, sustaining a visible afterglow of about six hours, and proved the most suitable for road markings and other applications demanding

high nighttime visibility. The solvent-based pigment gave a comparable, slightly longer visible emission of six to seven hours together with good film formation and the best resistance to environmental factors, making it appropriate for industrial and high-traffic environments. The water-based pigment, while emitting more modestly (three to five hours) and at lower intensity, offered excellent compatibility with waterborne systems, strong adhesion, high chemical stability, and a non-toxic, environmentally friendly profile, recommending it for pedestrian zones, street furniture, and low-traffic urban areas.

The instrumental colorimetric characterisation placed these observations on an objective footing. In every series the luminance factor Ry increased steadily with pigment content, but the gain between 10 and 30% was markedly greater than that between 30 and 50%, where the brightness curve flattened. This diminishing optical return, together with the loss of mechanical integrity observed at the highest loadings, identifies a pigment fraction of approximately 30% as the practical optimum, balancing luminous performance against the durability of the cured film; for the water-based pigment in low-traffic urban use, a slightly higher range of 30-40% remains acceptable. The consistently negative a^* coordinate across all samples confirmed that the green emission characteristic of the phosphors is preserved within the transparent epoxy matrix, while the low fluorescence values showed that the measured brightness reflects genuine body colour rather than a fluorescence artefact.

From an economic and ecological perspective, although formulations with higher pigment content entail greater initial costs, they offer long-term savings through reduced electricity consumption, lower dependence on street lighting, and decreased maintenance, while also contributing to lower greenhouse-gas emissions and helping mitigate light pollution. Applied in critical locations such as curbs, crosswalks, and poorly lit intersections, epoxy coatings loaded with strontium-aluminate pigments can support pedestrian orientation and reduce accident risk, offering a durable and environmentally responsible complement to conventional road lighting.

The limitations of the present work must, however, be acknowledged. The evaluation of brightness and emission duration was qualitative, based on trained-observer ranking under dark-adapted conditions rather than on calibrated photometric measurement; the reported durations therefore denote the persistence of a visible glow, not luminance values expressed in mcd/m^2. The colorimetric data, although quantitative, describe the daytime appearance of the coatings rather than their night-time emission, and the durability of the materials under combined traffic loading and weathering was not yet assessed. The study is thus best understood as a comparative screening that identifies the most promising formulation and defines the conditions for its preparation, rather than as a complete quantitative qualification of the material for road use.

Future work. The standardised tests required for full performance qualification will be addressed in a planned subsequent research stage. The most

promising formulation identified here - 30 wt% Gama S strontium-aluminate phosphor dispersed in DGEBA epoxy resin - will be subjected to: (i) calibrated photometric measurement of the luminance-decay curve in mcd/m² according to DIN 67510-1; (ii) accelerated ultraviolet ageing following ISO 4892-3; (iii) abrasion resistance assessment by ASTM D4060 and adhesion testing by ASTM D4541 or EN 1542; (iv) microstructural and chemical characterisation by FTIR, SEM–EDS, and XRD, to monitor the degree of cure, pigment dispersion, and the hydrolytic transformation of the strontium-aluminate phase under controlled humidity; and (v) triplicate preparation of each formulation followed by analysis of variance (ANOVA), in order to validate statistically the effect of pigment loading. The results of this extended programme will provide the quantitative dataset required to align the present screening with EN 1436 regulatory requirements for road markings and to support the practical deployment of photoluminescent epoxy coatings on real urban infrastructure.

Overall, the study confirms that photoluminescent materials embedded in a two-component epoxy resin offer a durable, energy-efficient, and environmentally responsible alternative for improving nighttime visibility, with the phosphorescent Gama S pigment at a loading of about 30% emerging as the most promising candidate for road-infrastructure applications, subject to the quantitative confirmation outlined above.

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OPTIMIZAREA VIZIBILITĂȚII NOCTURNE ȘI SIGURANȚEI RUTIERE PRIN UTILIZAREA MATERIALELOR FOTOLUMINESCENTE ÎN INFRASTRUCTURA URBANĂ

(Rezumat)

Articolul explorează utilizarea rășinii epoxidice bicomponente și a pigmenților fosforescenți ca soluție inovatoare pentru creșterea vizibilității pe timp de noapte și îmbunătățirea siguranței rutiere și pietonale. Studiul se concentrează pe materialele fotoluminescente, care absorb și stochează energia luminoasă în timpul zilei și o eliberează treptat în întuneric, sporind astfel vizibilitatea trotuarelor, bordurilor și marcajelor rutiere. Implementarea acestor materiale este deosebit de avantajoasă în zonele slab iluminate sau în locațiile predispuse la întreruperi frecvente de energie electrică. Rezultatele experimentale arată că amestecurile de rășină epoxidică și pigmenți fosforescenți mențin un nivel ridicat de luminozitate timp de până la șase ore, oferind o alternativă durabilă și sustenabilă la iluminatul convențional. În plus, aceste materiale contribuie la reducerea consumului de energie și la diminuarea poluării luminoase. Concluziile studiului validează aplicabilitatea tehnologiei fotoluminescente în domeniul siguranței rutiere, subliniind totodată necesitatea unor testări suplimentare pentru optimizarea performanței în condiții variate de trafic și climă.