ENHANCING VISIBILITY AND SAFETY OF THERMOPLASTIC ROAD MARKINGS WITH PHOSPHORUS ADDITIVES AND ROSIN ESTER BINDER

M. Isya, Cut Mutiawati*, Fadhlullah Apriandy, Hadhrat Alfajri

Department of Civil Engineering, Syiah Kuala University, Banda Aceh, Indonesia

*E-mail of corresponding author: cutmutiawati@usk.ac.id

M. Isya 0000-0001-5648-9456, Cut Mutiawati 0000-0001-9391-8037,
Fadhlullah Apriandy 0000-0002-0354-1924

Resume

Road markings are essential traffic control devices that guide drivers, particularly at night and under adverse weather conditions common in tropical regions. In this study is investigated the performance of thermoplastic road markings enhanced with phosphorescent phosphorus using rosin ester as a binder. Laboratory experiments with varying phosphorus concentrations were conducted to evaluate luminance, retroreflectivity, and skid resistance under dry and wet conditions. The results show that a 30% phosphorus content provides the best overall performance by improving the nighttime visibility and retroreflective properties without compromising the skid resistance. All measured parameters comply with the Indonesian SKh-1.M-03 road marking standard. The proposed material demonstrates strong potential to enhance the road marking visibility and driving safety in tropical environments.

Article info

Received 8 July 2025
Accepted 2 December 2025
Online 13 January 2026

Keywords:

thermoplastic road marking
phosphorus additive
rosin ester
retroreflectivity
driving visibility
skid resistance

Available online: https://doi.org/10.26552/com.C.2026.007

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

Road markings are among the most crucial elements in modern transportation systems, serving as indicators for lane boundaries, stop zones, and vehicle movement directions. Their presence is critical in supporting the road safety, especially at night or during adverse weather conditions. According to the World Health Organization (WHO), more than 1.3 million people die annually due to traffic accidents, with a significant portion occurring during nighttime or in poor visibility conditions. In Indonesia, data from the National Police Traffic Corps (Korlantas Polri) show that over 50% of accidents are caused by low visibility, particularly in poorly lit areas.

The visibility of road markings is thus a vital component of transportation infrastructure aimed at improving the road user safety. Under conditions such as heavy rainfall or nighttime darkness, adequate visibility of road markings can be a determining factor in preventing collisions. One common strategy to enhance visibility is the use of thermoplastic road marking paint, which is widely applied and regulated due to its durability, abrasion resistance, and long-lasting performance under various lighting conditions [1].

In recent years, phosphorescent pigments, especially those based on strontium aluminate, have emerged as promising additives for increasing the road marking visibility. These materials can absorb energy from sunlight or vehicle headlights and re-emit it gradually in darkness, providing a glow-in-the-dark effect without requiring external power sources [2-3]. Various activation methods have been explored to optimize glow performance in phosphorus-based luminescent systems, including UV irradiation for persistent phosphors and chemical oxidation routes in which phosphorus-containing materials exhibit chemiluminescence when exposed to oxidizers, such as hydrogen peroxide [4-5], as well as thermal processing inherent to thermoplastic road marking production and application [6].

Additionally, studies have shown that phosphate-based or phosphorus-containing luminescent materials with specific crystal structures can enhance glow intensity and emission stability [7-8]. Furthermore, in a previous study [9] the chemiluminescent activation of phosphorus-based compounds using oxidants such as hydrogen peroxide, was investigated, demonstrating potential applications in sensing, forensic detection, and diagnostics.

Among various phosphorescent materials, strontium aluminate-based pigments are widely recognized for their high brightness and long afterglow duration, outperforming older phosphorescent compounds such as zinc sulfide [4-5]. To effectively incorporate these active materials into the road markings, suitable binders are required to ensure optimal adhesion and durability. Rosin ester, a natural resin derivative, has been identified as an effective binder due to its superior adhesion, chemical resistance, and water resilience, compared to conventional hydrocarbon resins [6]. Previous research [7] demonstrated that modified rosin sources, such as pine and tall oil rosin, can improve softening point, UV resistance, and esterification efficiency, thereby enhancing paint performance.

Several studies have investigated the use of phosphorescent pigments in road markings. Earlier studies [4-5] reported that incorporating phosphorescent additives significantly increases reflectivity and improves durability under extreme weather conditions. Various concentrations of glow-in-the-dark phosphorus powder were evaluated in [10], which reported that a 30% content produced maximum luminance with acceptable skid resistance, while [11] and [12] confirmed improvements in reflective performance under nighttime visibility conditions.

In addition to physical performance, some studies have utilized spectroscopic techniques, such as Fourier Transform Infrared (FTIR) and FT-Raman spectroscopy, to characterize the chemical structure and microscopic stability of thermoplastic materials. The methods described in [13] were successfully applied to irradiated starch, and similar analytical approaches can be adopted in future studies to investigate the molecular interactions between the phosphorus pigments and binder matrices in road marking paints.

However, research specifically evaluating the integration of strontium aluminate-based phosphorescent pigments, with rosin ester binders in thermoplastic road marking formulations, remains limited, particularly under tropical environmental conditions characterized by high rainfall and limited street lighting. Previous studies have predominantly focused on epoxy or polyurethane-based systems [14-15], while the practical application and performance evaluation of phosphorescent thermoplastic paints incorporating natural resin binders for improving road safety in developing regions has not been extensively explored [16-17]. Therefore, in this study is addressed this gap by evaluating the novel combination of strontium aluminate-based phosphorescent pigment with rosin ester binder in thermoplastic road marking paint. The effects on luminance intensity, retroreflectivity, and skid resistance under both dry and wet tropical conditions were quantitatively examined, aiming to develop safer, more durable, and environmentally conscious road marking materials to improve nighttime driving safety in regions with limited lighting.

2 Research methodology

In this section are outlined the procedures for data collection, material formulation, sample preparation, testing, and data analysis conducted to evaluate the safety performance improvements of thermoplastic road markings enhanced with phosphorescent phosphorus additives.

2.1 Research location

The research was conducted in the Highway Engineering Laboratory at the Faculty of Engineering, Syiah Kuala University, Banda Aceh, Indonesia. This laboratory is equipped with facilities to perform experimental studies in transportation materials, including equipment for visibility and skid resistance testing under controlled conditions.

2.2 Research approach

A quantitative experimental approach was employed to assess the effects of phosphorus addition on the visibility and surface safety performance of thermoplastic road markings. The independent variable was phosphorus concentration (0%, 10%, 20%, 30%), while the dependent variables included luminance intensity, retroreflectivity, and skid resistance. This approach is categorized as experimental research, involving the collection of empirical data through direct observation and manipulation of variables within controlled environments [18]. In addition, a quantitative approach was utilized to gather data in numerical or measurable form, which was subsequently analyzed statistically to identify specific patterns, relationships, or trends [19]. Such an analysis provides a deeper understanding of the direct impact of phosphorus additives on driving visibility, ultimately contributing to improved traffic safety. Experiments were carried out under controlled laboratory conditions simulating field environments to ensure systematic, reproducible, and measurable outcomes. This approach enables rigorous evaluation of how phosphorus additives influence the road marking performance and potential contributions to traffic safety improvement [9].

The phosphorus concentration range of 0-30%, adopted in this study, was determined based on previous findings [10], which indicated that a 30% phosphorus content yielded the highest luminance while maintaining adequate skid resistance. Concentrations below 10% showed minimal improvement in glow intensity, whereas higher proportions reduced mixture uniformity and surface smoothness. Therefore, this range was selected to verify and extend earlier results under tropical conditions using rosin ester as a natural binder, representing the main research gap addressed in this study.

2.3 Materials and testing equipment

All materials were sourced from local suppliers in Banda Aceh, Indonesia. The material descriptions were based on established standards and manufacturer specifications, including:

- Glow-in-the-dark phosphorus powder, a phosphorescent additive based on strontium aluminate, containing $SrAl_2O_4:Eu^{2+},Dy^{3+}$,
- Thermoplastic road marking paint, containing a rosin ester binder with a main composition of approximately 20.05% binder, 39.68% glass beads, 10.11% TiO_2 (titanium dioxide), and 30.16% $CaCO_2$ with inert fillers,
- Glass beads, used as a standard reflective additive for road markings.

The equipment utilized for testing comprised:

- Lux meter, for measuring luminance intensity,
- British Pendulum Tester, for evaluating skid resistance,
- Thermometer and oven, for temperature control during sample preparation,
- Digital balance, with a precision of 0.01 g, for accurate material weighing,
- Beakers and impact testing apparatus, for sample preparation and testing.

All testing procedures were conducted in accordance with standard laboratory safety protocols to ensure researcher protection and environmental compliance. Illustrations of the materials and preparation procedures are presented in Figures 1 and 2.

2.4 Physical properties testing

The physical properties of thermoplastic road marking paint were evaluated to assess their compliance with the Indonesian National Standard SNI 06-4826-1998 [20] and the Ministry of Public Works guideline SKh-1.M.03 [21]. The paint formulations tested included a control sample without phosphorus additive and experimental samples with phosphorescent phosphorus powder added at concentrations of 10%, 20%, and 30% by total weight. All samples were formulated using a rosin ester binder as the main adhesive component. The phosphorus powder was thoroughly mixed into the thermoplastic paint before heating to ensure homogeneity. Each formulation was then heated, molded into standardized test specimens, and cooled to room temperature before testing. This preparation ensured consistency and allowed direct comparison between the baseline (control) and phosphorus-enhanced samples to evaluate the effect of the additive on physical and optical performance. The physical tests conducted included:

Figure 1 *Thermoplastic road marking paint and phosphorus powder*

Figure 2 *Phosphorus addition to road marking paint and heating of thermoplastic paint*

Table 1 *Composition and distribution of test specimens*

Thermoplastic paint (g)	Phosphorus powder (g)	Luminance test	Skid resistance	Reflectivity test
400	-	2	2	2
400	40	2	2	2
400	80	2	2	2
400	120	2	2	2

Total specimens: 8 (per test type) → Total: 24 specimens

1. Specific gravity
   Samples (400 g) were heated at 218 ± 2°C for 4 hours, stirred for 10 seconds, then poured into a container for vacuum treatment to remove trapped air. After the cooling, specific gravity was calculated by weighing samples in air and water, following standard immersion methods.
2. Drying time
   Paint was heated to 211 ± 7°C, poured to a thickness of 3.2-4.8 mm at 32 ± 2°C, and drying time was recorded using tack-free tests conducted at 60-second intervals until the paint surface no longer deformed or adhered to the testing tool.
3. Low-Temperature crack resistance
   Samples were heated (400 g, 218 ± 2°C for 4 hours), stirred, and molded to a thickness of 3-5 mm. After reaching the room temperature, they were stored in a freezer at −9.4 ± 2°C for 24 hours and subsequently inspected for cracks under uniform indirect lighting from a distance of 305 mm.
4. Softening point
   Test specimens were mounted with steel balls in a glass vessel containing distilled water at 5 ± 1°C. After the temperature stabilization for 15 minutes, the vessel was heated at 5°C per minute, and the softening point was recorded when the specimen deformed under the ball load, in line with standard ring-and-ball test procedures.
5. Flow resistance
   Heated samples (400 ± 0.1 g at 218 ± 2°C for 4 hours) were stirred and immediately placed on a 45° inclined surface. Residual material was weighed to calculate flow resistance as a percentage of the original sample mass.
6. Flow resistance with overheating
   Similar to the standard flow resistance test, but samples were heated for 8 hours, stirred after 6 hours, and then tested to assess material stability under prolonged heating.

This integrated testing approach allowed for systematic evaluation of specific gravity, drying time, low-temperature crack resistance, softening point, and flow resistance of thermoplastic road marking paint formulations with varying phosphorus concentrations. Results from these tests provided a comprehensive assessment of how the addition of phosphorescent phosphorus influenced the durability and surface characteristics of the road marking materials under standardized testing conditions.

2.5 Sample preparation and formulation

Four different formulations were prepared with phosphorus powder concentrations of 0%, 10%, 20%, and 30% by weight, maintaining a constant thermoplastic paint weight of 400g for each sample. These formulations allowed for direct comparison between the control (0%) and phosphorus-enhanced samples. Samples were prepared by thoroughly mixing the thermoplastic paint and phosphorus powder in a container, followed by heating for 4 hours at 218 ± 25°C. After the heating, the mixture was stirred rapidly with a spatula for 10 seconds and poured onto tin plates (75 mm diameter) to form test specimens. The specimens were then cooled to room temperature before testing. Specimen distribution is shown in Table 1.

Specimen preparation began by mixing the thermoplastic paint with phosphorus powder according to the specified percentages. The mixture was placed in a container and heated for 4 hours at 218 ± 25 °C. After the heating, the mixture was quickly stirred with a spatula for 10 seconds and poured onto a tin plate (75 mm diameter), then cooled to room temperature.

2.6 Visibility and safety performance testing

Three primary performance tests were conducted to evaluate the practical safety benefits of phosphorus addition:

1. Luminance intensity measurement
   Luminance measurements assessed phosphorescent performance under both clear and rainy conditions. Measurements were conducted between 18:30 and 19:30 at 15-minute intervals using a calibrated lux meter positioned perpendicularly above the sample surface at a fixed distance in a completely dark room. All the samples were pre-exposed to natural sunlight to activate phosphorescence before testing. Control samples were included for comparative analysis.
2. Skid resistance test
   Skid resistance was evaluated under both dry and wet conditions using a British Pendulum Tester. Wet conditions were simulated by uniformly spraying water onto the sample surfaces. The British Pendulum Number (BPN) was recorded for each condition to assess slip resistance and surface safety characteristics, following standard procedures [22].

***Table 2** Physical properties of thermoplastic paint*

No.	Tested parameter	Unit	Test Result	SKh-1.M-03 Standard
1.	Specific gravity	-	2.02	Max. 2.15
2.	Drying time	Min	5	Max. 10
3.	Softening point	°C	101	102.5 ± 9.5
4.	Low-Temp crack resistance	-	No cracks	No cracks
5.	Flow resistance	%res	7.36	Max. 18
6.	Flow resistance with overheating	%res	11.54	Max. 28

***Table 3** Physical properties with phosphorus addition (10%, 20%, 30%)*

No.	Tested parameter	Unit	Test Results			SKh-1.M-03 Standard
			10%	20%	30%	
1.	Spesific gravity	-	2.08	2.10	2.13	Max. 2.15
2.	Drying time	min	5	5	5	Max. 10
3.	Softening point	°C	101	105	107	102.5 ± 9.5
4.	Low-Temp crack resistance	-	No cracks	No cracks	No cracks	No cracks
5.	Flow resistance	% res	9.11	11.63	14.42	Max. 18
6.	Flow resistance after overheating	% res	14.42	15.96	19.21	Max. 28

3. Retroreflectivity test
   Retroreflectivity measurements assessed the effectiveness of markings under the nighttime driving conditions. Tests were performed using a lux meter with vehicle headlights as the illumination source, directed at a 30°-45° incidence angle to simulate real driving scenarios. Wet conditions were simulated by spraying water over the sample surfaces for 30 seconds before measurement. According to SNI 06-486-1998 and SKh-1.M.03, the minimum retroreflectivity requirements are ≥ 200 mcd/m² for dry surfaces and 100-150 mcd/m² for wet surfaces.

2.7 Data analysis technique

In this study, the effect of phosphorus concentration on the performance of thermoplastic road markings utilizing a rosin ester binder derived from natural pine resin was investigated. The experimental design includes two primary variables: the independent variable is the phosphorus concentration, varied at 0%, 10%, 20%, and 30%; and the dependent variable is the overall performance of the thermoplastic road marking material. Performance evaluation focuses on three key parameters: luminance, reflectivity, and skid resistance. Those indicators were quantitatively measured to determine how the addition of phosphorus influences the visibility and safety characteristics of the road marking under both dry and wet conditions. The findings aim to support the development of improved road marking materials, particularly suited for tropical climates that experience high rainfall and limited night-time illumination. Moreover, this research contributed to the sustainable use of natural resources by promoting rosin ester, a renewable binder derived from pine resin, as a key component in the thermoplastic formulation.

3 Results and discussion

In this section are presented and discussed the results obtained from the experimental evaluation of thermoplastic road marking paints formulated with varying phosphorus additive concentrations. The analysis covers their physical properties, visibility performance under different weather conditions, and safety-related characteristics, aiming to determine compliance with national standards and to assess their potential benefits for road safety applications.

3.1 Physical properties of thermoplastic paint

Tests included specific gravity, drying time, low-temperature crack resistance, softening point, flow resistance, and flow resistance after overheating. Table 2 shows that all the tested parameters met the SKh-1.M-03 standard.

3.2 Physical properties with phosphorus addition

Tests with 10%, 20%, and 30% phosphorus showed compliance with SKh-1.M-03 standards. Results are detailed in Table 3.

The test results showed an increase in specific gravity from 2.02 (without phosphorus) to 2.11 (with

Table 4 Regression summary (clear and rainy conditions)

Condition	Time	Intercept	Slope (per %)	R^2	p-value (slope)	F-statistic
Rainy	18:30	2.5	12.35	0.9929	0.00354	280.6302
	18:45	-1.9	11.41	0.9944	0.00279	356.9731
	19:00	-9.4	10.66	0.9946	0.00273	365.1530
	19:15	-13.9	9.26	0.9820	0.00902	109.3440
	19:30	-14	7.4	0.9722	0.01402	69.8469
Sunny	18:30	2.6	17.91	0.9999	0.00007	14130.7533
	18:45	0.9	16.79	0.9985	0.00077	1288.9991
	19:00	-2.1	15.59	0.9981	0.00095	1053.5245
	19:15	-15.9	14.66	0.9921	0.00396	251.0110
	19:30	-11.2	11.88	0.9868	0.00660	150.01531

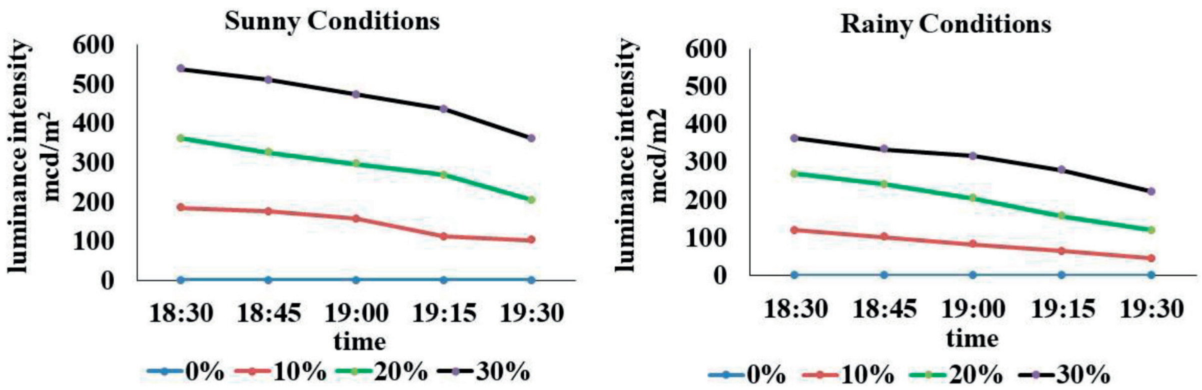

Figure 3 *Phosphorus content versus luminance intensity*

30% phosphorus), remaining below the maximum limit. Drying time remained consistent at 5 minutes. Softening point increased, from 101°C to 107°C, but stayed within the acceptable range. All the variations showed good low-temperature crack resistance. The flow resistance residue rose from 7.36% to 14.42%, and after overheating, from 11.54% to 19.21%, both remaining within limits. These results confirm that phosphorus can be added up to 30% without compromising paint quality.

3.3 Road marking performance

In this section, the performance evaluation of road markings enhanced with phosphorus additives is presented. The tests focused on two key parameters affecting the visibility of road markings, namely luminance and retroreflectivity, under various weather conditions. The detailed results for each parameter are described below.

3.3.1 Luminance of road markings

This experiment was aimed at assessing the influence of phosphorus additive concentration on the luminous intensity of thermoplastic road markings under two distinct weather conditions: clear (sunny) and rainy. Measurements were conducted periodically using a lux meter to compare the luminance of samples with varying phosphorus concentrations. The measurement results are presented in Figure 3.

Based on measurements using a lux meter, it was observed that the addition of phosphorus significantly increased the luminance intensity. On clear days, the luminance increased with higher phosphorus content, from 185 mcd/m² (10%) to 538 mcd/m² (30%). On rainy days, although the overall luminance intensity was lower, a similar upward trend was observed, with luminance rising from 120 mcd/m² (10%) to 362 mcd/m² (30%). This indicates that phosphorus possesses strong light-emitting properties, particularly under clear conditions, and can retain a substantial portion of its luminance even under less favorable conditions (rain).

On clear days, the peak luminance was recorded between 18:30 and 19:00, after which it tended to decline. Higher phosphorus content (30%) consistently produced greater luminance intensity compared to lower concentrations (0% and 10%) until 19:30. A similar trend was observed on rainy days, despite the lower overall light levels compared to clear weather, the decline in luminance was more pronounced in samples with lower phosphorus concentrations.

To validate these observations, statistical regression analyses were conducted separately for clear and

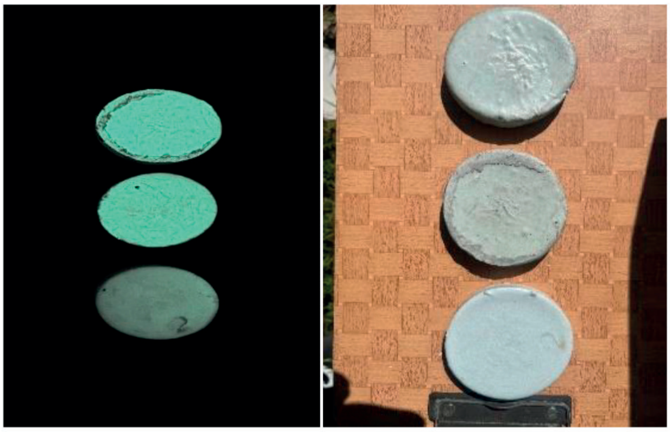

Figure 4 *Phosphorescence intensity of phosphorus*

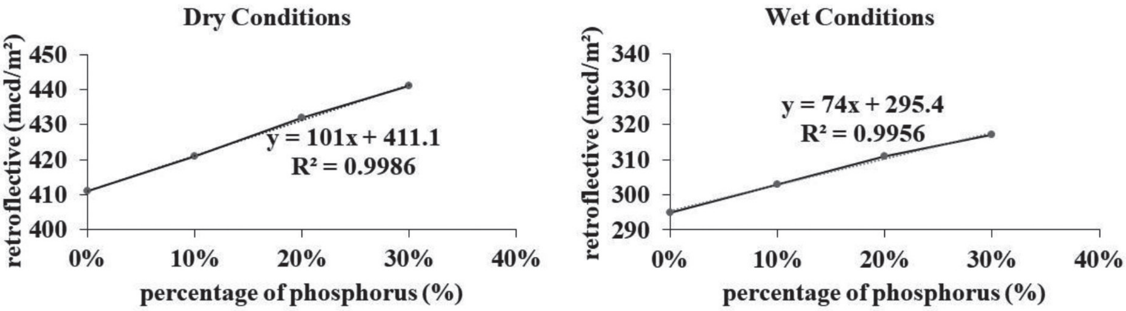

Figure 5 *Effect of phosphorus content on reflectivity*

rainy conditions, as well as using a pooled model with interaction terms. The results confirmed a strong linear relationship between the phosphorus concentration and a luminance intensity. The statistical outcomes of these regression analyses are summarized in Table 4.

The regression analysis confirmed a strong and statistically significant linear relationship between the phosphorus concentration and a luminance intensity under clear and rainy conditions. Under rainy conditions, the slopes ranged from 12.35 mcd/m^2 per % at 18:30 to 7.4 mcd/m^2 per % at 19:30, with R^2 values between 0.9722 and 0.9946, indicating that phosphorus concentration explains more than 97% of the luminance variability at all observation times. All slopes were statistically significant ($p < 0.05$), and F-statistics ranged from approximately 69.8 to 365.2, confirming the robustness of the linear relationships. The progressive decrease in slope across time reflects the gradual decline of luminance intensity as the evening progressed, though the phosphorus-induced enhancement remained evident throughout the wet surface condition.

Under sunny conditions, the relationship was even stronger. The slopes started at 17.91 mcd/m^2 per % at 18:30 and gradually decreased to 11.88 mcd/m^2 per % at 19:30. All the regressions exhibited very high R^2 values (0.9868 - 0.9999), with F-statistics ranging from 150.0 to 14,130.8 and p-values well below 0.01, indicating highly significant effects. The higher slopes under sunny conditions compared to rainy conditions highlight the superior luminance performance of phosphorus-enhanced markings in dry environments, particularly during the earlier evening hours when ambient light is still present.

Overall, these results demonstrate that phosphorus concentration is a dominant predictor of luminance in both weather scenarios, with consistently strong linear fits. However, the magnitude of the effect (slope) is notably greater under sunny conditions, suggesting that the reflective and luminance-enhancing properties of phosphorus are maximized on dry surfaces. This finding supports the potential application of phosphorus-enhanced thermoplastic markings to improve the night-time visibility, especially in dry weather.

The addition of phosphorus to road markings, particularly at a concentration of 30%, significantly improves lighting and illumination performance under both clear and rainy conditions. This confirms that phosphorus is a highly promising material for enhancing the visibility and effectiveness of road markings in accordance with established standards. The luminance intensity of the samples is presented in Figure 4.

3.3.2 Retroreflectivity of the road markings

The results of the road marking reflectivity test, or light reflectance of the markings, with phosphorus additions of 10%, 20%, and 30% are shown in Figure 5.

Table 5 Regression summary (dry vs wet conditions with interaction)

Condition	Intercept	Slope (per %)	R^2	F-statistic	p-value (slope)
Dry	411.10	101.00	0.999	1457.0	0.001
Wet	295.40	74.00	0.996	456.3	0.002

Table 6 Regression summary - skid resistance (dry vs wet)

Condition	Intercept	Slope (per %)	R^2	F-statistic	p-value (slope)
Dry	50.90	0.290	0.984	120.1	0.008
Wet	47.10	0.210	0.969	63.0	0.016

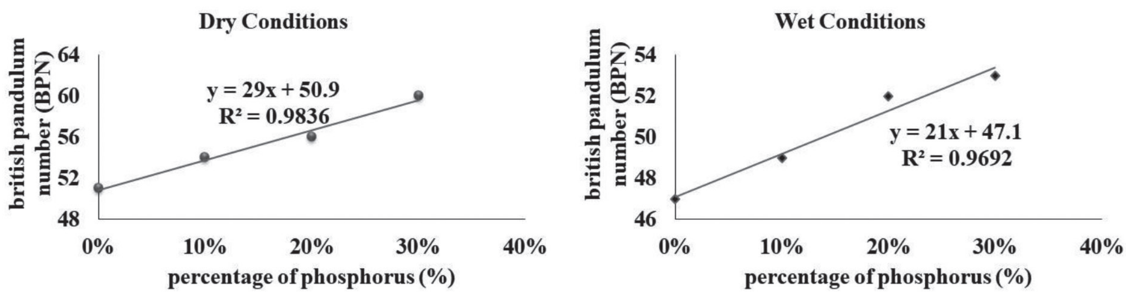

***Figure 6** Effect of phosphorus content on skid resistance*

The test results graph shows the effect of phosphorus addition on the reflectivity of road markings. Under the dry conditions, reflectivity tests revealed that increasing phosphorus content led to higher retroreflective values. Without phosphorus (0%), the retroreflectivity was 411 mcd/m², while the addition of 30% phosphorus raised it to 441 mcd/m². All the values exceeded the minimum standard for road marking retroreflectivity (200 mcd/m²), indicating that phosphorus-enhanced markings have excellent reflectivity under dry conditions.

Under the wet conditions, phosphorus addition continued to improve retroreflectivity, though values were lower than those under dry conditions. At 0% phosphorus, retroreflectivity measured 295 mcd/m², increasing to 317 mcd/m² with 30% phosphorus. All the measurements remained above the minimum requirement (200 mcd/m²), proving that phosphorus-enhanced markings remain effective even in rainy conditions.

The incorporation of phosphorus in road marking materials significantly enhances the light reflectance under both dry and wet conditions. This demonstrates that phosphorus improves visibility, which is essential for driving safety, particularly at night or during the rain. Although the retroreflectivity values are lower under the wet conditions, all samples met the minimum standard, which is reasonable since water typically reduces light reflection. Thus, all phosphorus variations tested fulfill the required retroreflectivity standards, making them suitable for road marking applications.

The statistical regression analysis further confirmed the consistency of these trends, as summarized in Table 5.

The regression analysis confirmed a strong linear relationship between the phosphorus concentration and retroreflectivity under both dry and wet conditions. In dry conditions, retroreflectivity increased sharply with phosphorus addition (slope ≈ 101 mcd/m² per 1%, $R^2 = 0.999$), whereas under wet conditions the slope was lower (≈ 74 mcd/m² per 1%, $R^2 = 0.996$) but remained highly significant. The interaction term further demonstrated a statistically significant difference between the two conditions, indicating that the positive effect of phosphorus on retroreflectivity was attenuated under wet surfaces. All measured values were well above the international minimum standard of 200 mcd/m², demonstrating that phosphorus-enhanced thermoplastic road markings are highly effective for ensuring visibility and road safety, even under adverse weather conditions.

3.4 Skid resistance performance of road markings

The results of the skid resistance test, conducted using a Skid Resistance Tester with phosphorus additions of 10%, 20%, and 30%, are shown in Figure 6.

The skid resistance testing was carried out under two surface conditions: dry and wet, with phosphorus addition variations of 0%, 10%, 20%, and 30%. The test result table shows the effect of phosphorus addition on the skid resistance values of the road markings, all of which exceed the minimum standard for road marking skid resistance (Min. 45). The increase in values indicates that the addition of phosphorus significantly contributes to the improvement of the road marking's grip performance. Under the dry conditions, the increase in skid resistance is more significant compared to wet conditions. This may be due to differences in interaction between the marking material and water, which tends to reduce friction. Nevertheless, the skid resistance values under the wet conditions remained above the required minimum threshold.

Table 6 presents the regression summary of skid resistance responses to phosphorus concentration under both dry and wet surface conditions. The regression analysis indicates that the skid resistance increases with phosphorus concentration under both dry and wet conditions. In dry surfaces, the slope was approximately 0.290 SRT per 1% phosphorus (R^2 = 0.984), while in wet surfaces the slope was about 0.210 SRT per 1% phosphorus (R^2 = 0.969). The interaction term (Concentration×Wet) was -0.080 with p = 0.099, suggesting that the difference in slopes between dry and wet conditions is not statistically significant at the 5% level (marginal at the 10% level).

4 Discussion

The findings of this study demonstrate that incorporating up to 30% phosphorus into thermoplastic road marking paint with rosin ester binder significantly enhanced marking visibility, particularly under low-light conditions. Visibility parameters tested luminance intensity, retroreflectivity, and skid resistance, all improved consistently with increasing phosphorus content. Regression and interaction analyses further confirmed that these improvements were statistically significant under both dry and wet conditions, with slightly lower effects observed in wet conditions.

This study results supported the findings of Ismail and Nazri [10], who reported that glow-in-the-dark phosphorus could produce luminance up to 6 cd/m² in dry conditions, with skid resistance and reflectivity meeting international standards. The maximum reflectivity in this study reached 441 mcd/m² (dry) and 317 mcd/m² (wet), surpassing the global minimum threshold of 200 mcd/m². These results are consistent with earlier research [4], which confirmed that phosphorus is a more effective additive than conventional glass beads.

Previous studies [12] reported that the phosphorus-based resins exhibit high reflectivity performance across various light wavelengths relevant to nighttime visibility. Similarly, research [15] developed polyurethane-based road marking paint with phosphorus that showed the improved weather resistance and stable luminance throughout the observation period. Another study [5] reported that phosphorus enhances the mechanical durability of road markings under extreme weather conditions such as rain and cold.

Moreover, integration of the current findings with recent studies [14] highlights that aluminate-based luminescent materials such as strontium aluminate ($SrAl_2O_4:Eu^{2+},Dy^{3+}$) have significant potential for road marking due to their long-lasting glow capability. Moisture-related degradation challenges were successfully addressed using dual organic-inorganic coating techniques that enhance hydrothermal durability.

The study [23] authorsexamined active luminescent phosphorus-based road marking paint and found that a layer thickness of 500 μm resulted in an initial luminance of 4.38 cd/m² with optimal abrasion resistance, even under high temperatures. This strengthens the experimental rationale that controlling the composition and thickness of the coating directly impacts its optical and functional performance.

The improvement in luminance and surface performance can be attributed to the physicochemical interactions between the phosphorescent phosphorus compound and the rosin ester binder. The rosin ester, primarily composed of abietic acid derivatives, forms a hydrophobic polymeric network that encapsulates $SrAl_2O_4:Eu^{2+},Dy^{3+}$ particles. This structure prevents excessive moisture penetration and protects the phosphor particles from hydrolysis, which is a major factor reducing luminescence stability. During the thermoplastic melting and mixing process, partial interfacial bonding occurs between ester functional groups and the phosphor particle surfaces, enhancing particle dispersion within the binder matrix. This uniform dispersion improves the photon absorption and energy release, leading to a more stable and prolonged afterglow performance under the dark conditions. Furthermore, the viscoelastic property of rosin ester supports mechanical flexibility and microtexture retention on the pavement surface, which maintains sufficient skid resistance while improving optical brightness. These combined mechanisms explain how the phosphorus rosin ester system effectively enhances both luminance and surface performance, confirming the synergistic interaction between optical and structural properties of the composite material.

Thus, these research results are not only consistent with previous studies but also align with the latest global findings. The main contribution of this study lies in its innovative combination of phosphorus and natural rosin ester binder, an area rarely explored systematically. This formulation significantly enhances visibility and addresses sustainability by utilizing environmentally friendly materials. Therefore, the approach offers strong potential as a technical solution for improving traffic safety, especially in poorly lit or tropical rainy environments. The role of road markings in reducing the crash frequency has been further supported by recent field safety audits and predictive safety studies. Inadequate road markings and the absence of reflective devices have been identified as dominant contributors to blackspot formation on highways, while improved visibility and surface markings have been shown to effectively reduce accident rates. Hence, enhancing the luminance and durability of thermoplastic road markings, as confirmed in this study, aligns with global efforts to reduce visibility-related traffic crashes and supports evidence from recent safety audits and predictive analyses worldwide [24-25].

In practical terms, the adoption of higher phosphorus concentrations has not yet been standardized in current road marking specifications. Most commercial products still rely on conventional glass beads for cost efficiency and regulatory acceptance [26]. From an economic perspective, the introduction of phosphorus-based thermoplastic paint may increase initial production costs compared with conventional markings, primarily due to the higher price of phosphorescent pigments. However, these additional expenses could be offset by performance benefits, such as improved nighttime visibility, extended service life, and reduced repainting frequency, which ultimately contribute to more favorable long-term life-cycle costs [27]. These findings align with broader evidence on sustainability from previous studies. As reported in [28], advanced road marking systems reduced glass bead consumption by approximately 54%, paint usage by 63%, and organic solvent emissions by 97% over a 10-year life cycle. This supports the economic and environmental arguments presented in this study, confirming that the high-performance materials, such as phosphorus-based thermoplastic markings, can simultaneously enhance safety and resource efficiency. The economic and environmental discussions in this paper are based on theoretical assessments and literature evidence; further experimental validation is recommended.

In terms of environmental aspects, the phosphorescent additive $SrAl_2O_4:Eu^{2+},Dy^{3+}$ is generally considered chemically stable and largely insoluble in water, which minimizes the risk of leaching and offers a safer profile compared to the conventional heavy-metal-based phosphors. However, previous studies have shown that prolonged exposure to moisture may induce partial hydrolysis, thereby reducing luminescent performance [29]. To address this issue, surface coating and modification techniques, such as silica or fluoride layers, have been reported to significantly improve water resistance and long-term stability [30-31]. These findings suggest that while the environmental risks of leaching are relatively low under normal conditions, further long-term durability and environmental impact studies are necessary to ensure sustainable use of road-marking materials.

Overall, those results confirm that the phosphorus additives enhance luminance, retroreflectivity, and skid resistance of thermoplastic road markings under both dry and wet conditions. Nevertheless, one limitation of this study is the absence of the long-term durability data and field validation. Future research should therefore include expanded testing, such as extended durability evaluation under real traffic and weather conditions, to validate and strengthen the laboratory findings.

5 Conclusion

Based on the findings, adding phosphorescent phosphorus to thermoplastic road marking paint with rosin ester binder significantly improves both visibility and surface safety performance. A concentration of 30% yielded the highest light emission intensity (538 mcd/m² under clear conditions), enhancing nighttime and rainy-weather visibility for drivers. All the modified samples met the SKh-1.M.03 technical specifications and maintained safe skid resistance values on both dry and wet surfaces, with maximum readings of 60 and 53, respectively. Therefore, incorporating up to 30% phosphorus is recommended as an effective safety improvement strategy to reduce accident risks by ensuring clearer and safer road markings under low-light or adverse weather conditions, without compromising paint quality.

Acknowledgment

The authors received no financial support for the research, authorship and/or publication of this article.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Ministry of Public Works and Housing (PUPR). Special Specification SKh-1.9.21: Road markings. Jakarta: Directorate General of Highways, 2024.

[2] LYU, L., CHEN, Y., YU, L., LI, R., ZHANG, L., PEI, J. The improvement of moisture resistance and organic compatibility of $SrAl_2O_4:Eu^{2+},Dy^{3+}$ persistent phosphors coated with silica-polymer hybrid shell. *Materials* [online]. 2020, **13**(426), 426. eISSN 1996-1944. Available from: https://doi.org/10.3390/ma13020426

[3] MUNIKANAN, V., PENG, N. C., YAHYAA, M. A., YUSOF, M. A. Strontium aluminate compound as road line materials application. *Jurnal Kejuruteraan/Engineering Journal* [online]. 2021, **4**(2), p. 17-21. eISSN 2289-7526. Available from: https://doi.org/10.17576/jkukm-2021-si4(2)-03

[4] POULOSE, A. M., ANIS, A., SHAIKH, H., ALHAMIDI, A., SIVA KUMAR, N., ELNOUR, A. Y., AL-ZAHRANI,

S. M. Strontium aluminate-based long afterglow PP composites: phosphorescence, thermal, and mechanical characteristics. *Polymers* [online]. 2021, **13**(1373), 1373. eISSN 2073-4360. Available from: https://doi.org/10.3390/polym13091373

[5] LIU, H., SUN, M., SU, Y., DENG, D., HUA, J., LV, Y. Chemiluminescence of black phosphorus quantum dots induced by hypochlorite and peroxide. *Chemical Communications* [online]. 2018, **54**, p. 7987-7990. ISSN 1359-7345. Available from: https://doi.org/10.1039/C8CC04513E

[6] MUVAZIZ, O. Understanding thermoplastic road markings and their functions. Solidline (in Indonesian) [online]. 2024. Available from: https://solidline.id/marka-jalan-thermoplsatic

[7] YILMAZ, B., DENIZ, I., FAZLI, H., BEKIRCAN, O., PRANOVICH, A., KARAOGUL, E. Sustainable thermoplastic road marking paint production from natural modified rosins. *Bioresources* [online]. 2024, **19**(2), p. 2160-2178. ISSN 1930-2126. Available from: https://doi.org/10.15376/biores.19.2.2160-2178

[8] DHAPODKAR, T. S., KADAM, A. R., DURAGKAR, A., DHOBLE, N. S., DHOBLE, S. J. Recent progress in phosphate based luminescent materials: a case study. *Journal of Physics: Conference Series* [online]. 2021, **1913**(1), 012024. eISSN 1742-6596. Available from: https://doi.org/10.1088/1742-6596/1913/1/012024

[9] XU, L., CHEN, Z., LI, X., XIAO, F. Performance, environmental impact and cost analysis of marking materials in pavement engineering: the state-of-the-art. *Journal of Cleaner Production* [online]. 2021, **294**(126302), 126302. ISSN 0959-6526, eISSN 1879-1786. Available from: https://doi.org/10.1016/j.jclepro.2021.126302

[10] ISMAIL, N., NAZRI, S. N. Performance of the glow in the dark thermoplastic road marking in Uniten. *International Journal of Civil Engineering and Technology (IJCIET)* [online]. 2019, **10**(11), p. 235-242. ISSN 0976-6308, eISSN 0976-6316. Available from: https://iaeme.com/Home/article_id/IJCIET_10_11_024

[11] NANCE, J., SPARKS, T. D. Comparison of coatings for $SrAl_2O_4:Eu^{2+},Dy^{3+}$ powder in waterborne road striping paint under wet conditions. *Progress in Organic Coatings* [online]. 2020, **144**, 105637. ISSN 0300-9440, eISSN 1873-331X. Available from: https://doi.org/10.1016/j.porgcoat.2020.105637

[12] LI, G., LI, N., ZHANG, Y., HAN, J., YAO, T., FENG, X. Preparation of long afterglow luminescent road marking coatings and its applicability simulation. *PLOS One* [online]. 2025, **20**(9), e0330387. eISSN 1932-6203. Available from: https://doi.org/10.1371/journal.pone.0330387

[13] KIZIL, R., IRUDAYARAJ, J., SEETHARAMAN, K. Characterization of irradiated starches by using FT-raman and FTIR spectroscopy. *Journal of Agricultural and Food Chemistry* [online]. 2002, **50**(14), p. 3912-3918. ISSN 0021-8561, eISSN 1520-5118. Available from: https://doi.org/10.1021/JF011652P

[14] ZHANG, F., XIE, Y., ZHAO, X., HE, Y., PEI, J., XING, Y., WANG, S., ZHANKG, J. Aluminate long afterglow luminescent materials in road marking field: research progress and development a review. *Buildings* [online]. 2024, **14**(7), 2152. 2152. eISSN 2075-5309. Available from: https://doi.org/10.3390/buildings14072152

[15] YANG, X., FAN, Z., YULIN, H., CUI, K., WEI, L., ZHANG, H., LI, J. Mechanical properties, luminescent properties, and durability of solvent-free polyurethane-based phosphorescent road markings on asphalt pavements. *Construction and Building Materials* [online]. 2024, **414**, 135053. ISSN 0950-0618, eISSN 1879-0526. Available from: https://doi.org/10.1016/j.conbuildmat.2024.135053

[16] VILLA, C., EYMOND, F., MARQUET, P. L., BREMOND, R., SAINT-JACQUES, E. Method to predict the performance of luminescent road markings over a year. *Results in Engineering* [online]. 2024, **24**, 103388. eISSN 2590-1230. Available from: https://doi.org/10.1016/j.rineng.2024.103388

[17] AQSHA, A., WINOTO, H. P., ADHI, T. P., ET AL. Sequential esterification-Diels-Alder reactions for improving pine rosin durability within road marking paint. *Molecules*. 2023, **28**(13), 5236. ISSN 1420-3049. Available from: https://doi.org/10.3390/molecules28135236

[18] NOTOATMODJO, S. *Health research methodology*. Jakarta: Rineka Cipta, 2018. ISBN 978-979-518-984-8.

[19] ALFATIH, A. *Social research methodology*. Jakarta: Unsri Press, 2023. ISBN 978-979-587-758-5.

[20] National Standardization Agency of Indonesia. SNI 06-4826-1998: Specification for reflective thermoplastic road marking paint. Jakarta, Indonesia, 1998.

[21] Ministry of Public Works and Housing (PUPR). Interim special specification SKh-1.M-03: Thermoplastic road marking paint with Rosin Ester binder. Jakarta: Directorate General of Highways, 2024.

[22] AJI, S. Evaluation of surface skid resistance of asphalt concrete wearing course (AC-WC) pen 60/70 and buton natural asphalt (BNA) blend 75/25 under wet conditions with temperature variations. Undergraduate thesis. Indonesia: University of Indonesia, 2011. Available from: https://lib.ui.ac.id/detail?id=20290564&lokasi=lokal&utm

[23] WANG, K., LU, Z., ZOU, Y., ZHU, Y., YU, J. Preparation and performance characterization of an active luminous coating for asphalt pavement marking. *Coatings* [online]. 2023, **13**(6), 1108. eISSN 2079-6412. Available from: https://doi.org/10.3390/coatings13061108

[24] KHAN, M. N., SABIR, DASS, S., SINGH, G., JAGLAN, S. Road accident analysis and safety audit: a case study of MDR 132. *Communications - Scientific Letters of the University of Zilina* [online]. 2023, **25**(2), p. F26-F38. ISSN 1335-4205, eISSN 2585-7878. Available from: https://doi.org/10.26552/com.C.2023.026

[25] GORZELANCZYK, P., GROBELNY, M. An estimate of the number of accidents on polish highways based on the kind of road. *Communications - Scientific Letters of the University of Zilina* [online]. 2024, **26**(1), p. F13-F22. ISSN 1335-4205, eISSN 2585-7878. Available from: https://doi.org/10.26552/com.C.2024.012

[26] XU, L., SHI, Y., YANG, W. Performance, environmental impact and cost analysis of marking materials in pavement engineering: the state of the art. *Journal of Cleaner Production* [online]. 2021, **294**, 126302. ISSN 0959-6526, eISSN 1879-1786. Available from: https://doi.org/10.1016/j.jclepro.2021.126302

[27] PICARDO, A., GALVAN, M. J., SOLTERO, V. M., PERALTA, E. A comparative life cycle assessment and costing of lighting systems for environmental design and construction of sustainable roads. *Buildings* [online]. 2023, **13**(4), 983. eISSN 2075-5309. Available from: https://doi.org/10.3390/buildings13040983

[28] BURGHARDT, T. E., PASHKEVICH, A. Materials selection for structured horizontal road markings: financial and environmental case studies. *European Transport Research Review* [online]. 2020, **12**, 11. eISSN 1866-8887. Available from: https://doi.org/10.1186/s12544-020-0397-x

[29] GUO, C., LUAN, L., HUANG, D., SU, Q., LV, Y. Study on the stability of phosphor $SrAl_2O_4$:Eu^{2+},Dy^{3+} in water and method to improve its moisture resistance. *Materials Chemistry and Physics* [online]. 2007, **106**(2-3), p. 268-272. ISSN 0254-0584, eISSN 1879-3312. Available from: https://doi.org/10.1016/j.matchemphys.2007.05.052

[30] QI, T., XIA, H., ZHANG, Z., KONG, S., PENG, W., ZHAO, Q., HUANG, Z. Improved water resistance of $SrAl_2O_4$: Eu^{2+}, Dy^{3+} phosphor directly achieved in a water-containing medium. *Solid State Sciences* [online]. 2017, **65**, p. 88-94. ISSN 1293-2558, eISSN 1873-3085. Available from: https://doi.org/10.1016/j.solidstatesciences.2017.01.006

[31] ACHARI, A. M., PERUMALSAMY, V., SWATI, G., KHARE, A. $SrAl_2O_4$:Eu^{2+},Dy^{3+} long afterglow phosphor and its flexible film for optomechanical sensing application. *ACS Omega* [online]. 2023, **8**(48), p. 45483-45494. eISSN 2470-1343. Available from: https://doi.org/10.1021/acsomega.3c05222