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Cost-effective Road Reflectors Integrating Glow-in-the-dark and Recycled Glass for Improved Traffic Safety: A Case Study in Thailand's Rural Roads

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Abstract

This study develops an innovative approach to road safety by developing cost-effective road reflectors that integrate glow-in-the-dark (GiD) materials and recycled glass powder. The developed road reflectors were integrated onto passive road studs to reduce nighttime traffic accidents. Through as a case study, the research aims to enhance nighttime road visibility while promoting environmental sustainability using recycled glass powder. The reflectors combine phosphorescent compounds with recycled glass, creating a surface that absorbs light during the day and emits a prolonged glow at night, thus addressing some of the current limitations of conventional road reflectors. Different proportions (0%, 5%, 10%, 15%, 20%, 25% and 30%) of different mixtures with GiD (strontium aluminate) were investigated in the laboratory to examine their glow. A mixture with 25% of GiD material was found optimum to provide adequate glow for several hours. This mixture was also found to have a high compressive strength (91 MPa) and tensile strength (8.7 MPa). Quantitative performance tests in both laboratory and field conditions, involving 30 specimens, show that the studs maintain a luminosity of 150 millicandela per square meter after 8 h of darkness, consistently exceeding the brightness levels of traditional reflectors. By reducing material costs and diverting waste from landfills, this practical application improves road safety and aligns with sustainable development goals. Findings from the field trials conducted at Walailak University underscore the potential for GiD stud technology to achieve large-scale adoption, offering a viable, eco-friendly solution for enhanced road safety infrastructure.

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1. Introduction

Road safety is a critical societal and financial issue worldwide. Every day, there are 3,700 fatalities in traffic accidents worldwide, costing the global economy US$ 1.8 trillion per year.[1] In Southeast Asia, a region with an increasing number of vehicles and road networks, most of the fatal accidents are attributed to poor visibility and inadequate road signage, particularly at night. In Thailand, road traffic accidents remain a significant concern, with the country ranking among the highest in road traffic fatalities. According to the World Health Organization,[1] Thailand's road traffic fatality rate was 32.7 per 100,000 inhabitants in 2018, well above the global average of 18.2. Many of these preventable accidents occur in rural roads with poorly lit sections, where insufficient signage and low visibility contribute to a high number of crashes. Reflective materials have proven vital in enhancing road safety by improving the visibility of road signs, markings, and other road infrastructure.[2] Traditionally, road reflectors and signage have relied on retroreflective materials (glass beads, reflective tape, fabrics, paints) that require an external light source to function effectively.[3] While these materials have significantly improved night-time visibility, they have several limitations, including high production costs and dependency on ambient light, which may not always be sufficient in rural areas.[4-6] Additionally, the manufacturing processes of conventional reflective materials often involve non-renewable raw materials, contributing to environmental issues.[7]

In recent years, there has been a growing interest in developing sustainable construction materials that incorporate waste products, thus reducing environmental impact.[8] For

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instance, the use of recycled glass powder has been explored for various applications, including in concrete and asphalt infrastructure. The use of recycled glass in civil engineering applications promote a better waste management, also being beneficial as glass has desirable properties such as good durability and reflective capabilities. Recycled glass is also known for its optical properties, including high reflectivity, which can enhance the luminosity and visibility of road reflectors. Integrating recycled glass powder into road reflectors presents a novel approach to improving road safety while promoting the adoption of circular economy approaches in construction.[9]

In the last decades, glow-in-the-dark (GiD) materials have offered innovative road solutions to the limitations of traditional reflective materials, which can suffer from reduced effectiveness with aging, dependence on angle of incidence, limited reflective range, and visual discomfort in high intensity light. GiD materials absorb and store light from natural (or artificial) sources and eventually emit it in the dark, thereby enhancing visibility without relying on external light sources.[10,11] Phosphorescent compounds, such as strontium aluminate ($SrAl_2O_4$), calcium sulphide (CaS), yttrium oxide (Y_2O_3), and zinc sulphide (ZnS) have been widely studied due to their excellent luminescent properties and long afterglow duration.[12] Amongst all phosphorescent compounds, strontium aluminate ($SrAl_2O_4$) is commonly used in road studs due to its long afterglow, brighter glow and durability.[13] Strontium aluminate is widely used in road safety signage and paints, further supporting its effectiveness to enhance visibility in low-light conditions, making it one of the most cost-effective GiD materials for road safety applications. As a result, combining GiD materials with recycled glass powder can create a cost-effective and environmentally friendly road reflector.[14]

Traditional passive road studs bounce the vehicle's headlights back to the driver, but such passive studs can be less effective in low-light areas[15,16] or during heavy rain or fog. Active road studs were proposed as a potential alternative. Active studs incorporate LED lights powered by solar panels or batteries. This active illumination enables the studs to be more effective in low-light, high-risk areas and adverse weather, enhancing road safety.[17] However, active road studs are more costly in both production and installation and require routine maintenance. Current road studs available in Thailand (see *Supporting Information file Appendix A-2*) face inherent limitations: traditional reflectors depend on external light sources and are susceptible to degradation, whereas active studs incur high costs and require maintenance that can impact long-term sustainability.[21] As such, there is a research gap in developing solutions that are durable, environmentally friendly, and without reliance on external electric sources. The integration of (GiD materials into road studs represents a promising area of research that could bridge this gap by providing a cost-effective solution that requires no external power. Whilst GiD road studs can offer continuous nighttime visibility after exposure to sunlight,[18] limited research exists on the optimal material composition of GiD studs and their actual behaviour under traffic loads.[19] This is relevant as previous studies showed that road reflectors can degrade when subjected to heavy traffic loads.[20] Most existing studies have focused on the individual properties and benefits of these materials, but without exploring field trials in actual roads so that lessons can be learnt and applied in practice.

This article introduces a novel road stud that integrates GiD materials with recycled glass powder to enhance traffic safety in rural roads. Unlike traditional road studs that rely on passive reflectivity or costly, maintenance-intensive electric sources, the novel studs utilise phosphorescent materials to absorb and re-emit light.[21,22] The use of local recycled glass enhances reflectivity while contributing to waste reduction, diverting glass from landfills. The study evaluates a prototype stud's performance and luminosity both in the laboratory and in rural roads, as well as its cost-effectiveness. The results of this study provide insights into the potential of GiD materials for enhancing infrastructure and road safety in developing regions, which is of particular interest for road constructors, governments and stakeholders involved in road safety and insurance. This research is part of a wider effort implemented by Thailand's Department of Highways to improve safety and reduce accidents in roads and motorways across the country.[23-26]

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2. Experimental programme

The experimental testing was carried out in three main phases. Phase I comprised of preliminary trials with GiD paint and included the optimisation of GiD materials and recycled glass powder mixes through examination of mechanical and durability properties. In phase II, field trails were carried out to check the visibility and bearing capacity of the prototype studs under traffic loads. The last phase involved numerical investigations on road studs, considering different loading conditions. A conceptual flowchart of the methodology framework adopted in the present study is shown in Fig. 1.

2.1 Phase I: Optimisation of GID mix design and road stud geometry

GiD road paint was initially trialled at a rural road within Walailak University Thailand. Fig. 2a shows the appearance of the GiD paint at noon, where the markings are barely glowing under full daylight. This subtlety is crucial as it prevents visual clutter on roads and pathways, ensuring that the GiD paint works as a normal road safety marker. In Fig. 2b at 18:00 h, the paint begun emitting a gentle glow, responding to the fading daylight. This transitional phase provides enhanced visibility during dusk—a time of heavy campus

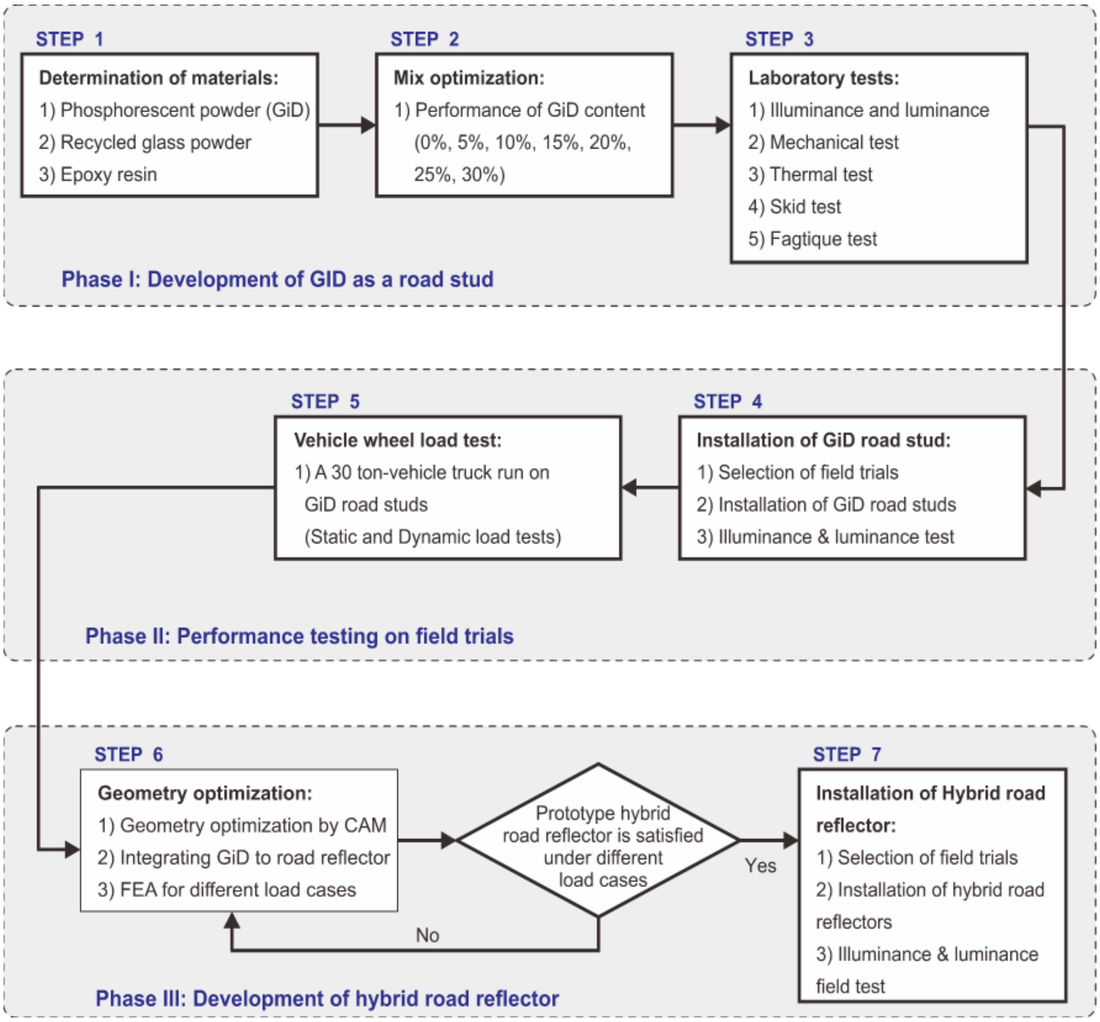

Fig. 1: Conceptual flowchart illustrating the research methodology and experimental framework adopted in this study.

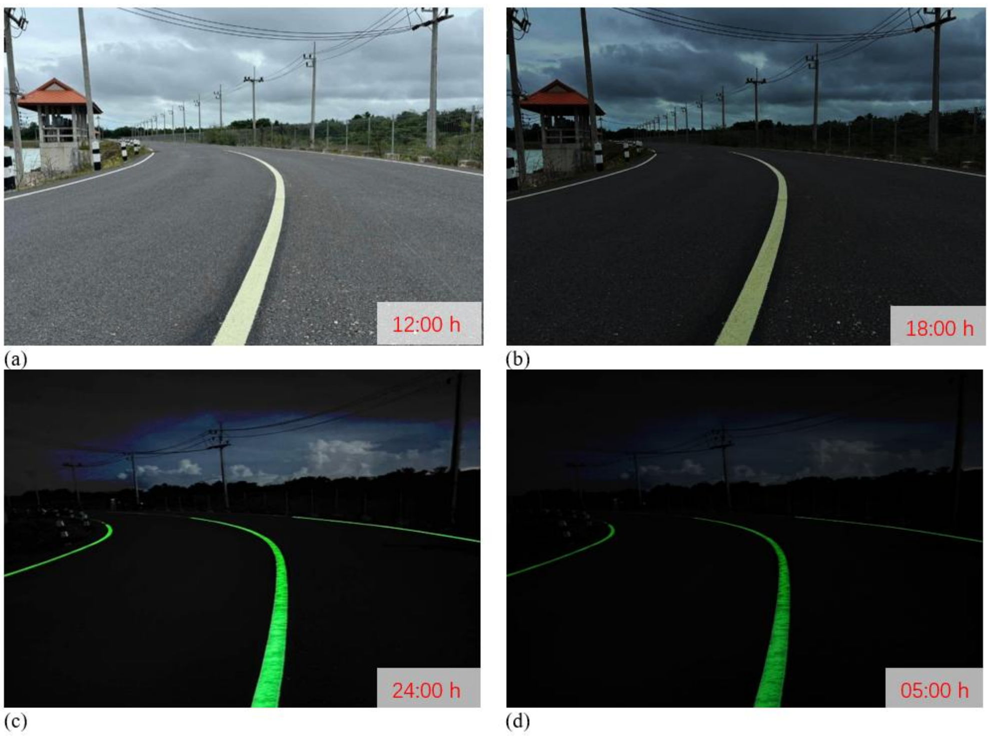

Fig. 2: View of GiD road paint on rural road at Walailak University at (a) 12:00h, (b) 18:00 h, (c) 24:00 h, and (d) 05:00 h.

traffic—alerting drivers and pedestrians alike. This early luminescence also serves as a natural guide along crossings and edges, gently marking paths and reducing the need for additional lighting infrastructure, which saves energy and costs. At midnight (Fig. 2c) the GiD paint is at its peak luminescence. At 5:00 am (Fig. 2d) paint glowing fades away as natural light starts to return. This gradual reduction of luminescence still provided enough visibility for early morning campus activity, making it effective for users before dawn. Whilst the application of GiD road paint proved effective at enhancing nighttime visibility, the high vehicular traffic and aggressive environment at Walailak University led to quick deterioration of the paint. This suggested the need for more resilient and permanent alternatives, such as GiD road studs, which were developed as described in the following sections.

2.1.1 Phosphorescent, glass and thermoplastic binder materials

The primary phosphorescent compound used for the stud reflectors was strontium aluminate ($SrAl_2O_4$: Eu^{2+}, Dy^{3+}). Strontium aluminate is typically used in powder form and is doped with Eu^{2+} (Europium) or Dy^{3+} (Dysprosium) to enhance its luminescent properties and afterglow duration. The material absorbs light during the day and emits it at night, providing prolonged visibility for road safety applications. Strontium aluminate is chosen for its superior luminescent properties, long afterglow duration, stability and local availability. If activated by a light source, strontium aluminate can emit light for several hours, making it ideal for applications requiring sustained visibility in the dark.[27] Fig. 3a shows the typical GiD powder material used in this study, whereas Figs. 3b-c show the dry recycled glass material with two different sizes of 0.85 mm and 1.70 mm, respectively.

In addition, recycled glass powder, which is also in powder form, was selected for its high reflectivity and durability. The inclusion of recycled glass aggregates[28] ensures that the studs provide adequate skid resistance, especially in wet conditions. The glass also contributed to the mechanical strength and durability of the studs, enabling them to withstand the mechanical stresses of vehicular traffic. To ensure the structural integrity and durability of the road studs, an appropriate binder was necessary. The epoxy resin, used as the binder, is in liquid form and serves to bond the phosphorescent compound and recycled glass powder together. The resin also enhances the durability and chemical resistance of the final product, ensuring the road studs maintain their structural integrity under heavy traffic and environmental exposure. Epoxy resin was selected as binder due to its excellent adhesive properties, chemical resistance, and mechanical strength. Epoxy resin helps to firmly bind the phosphorescent compounds and recycled glass powder, thus creating a robust composite material suitable for harsh environmental conditions. In addition to the primary components, additives were incorporated to improve the performance and usability of the road reflectors. For instance, UV stabilisers were added to protect the phosphorescent compounds and epoxy resin from UV radiation, which can cause photodegradation and reduce the service life of the luminescent effect. Likewise, small amounts of anti-yellowing agents were included to maintain the clarity and appearance of the studs over time.

2.1.2 Mixture optimisation and specimen preparation

The manufacturing process began with the measurement and mixing of the phosphorescent compound, recycled glass powder, epoxy resin, and additives. Table 1 summarises the mixture proportions of materials examined in this study. Different GiD proportions (0%, 5%, 10%, 15%, 20%, 25% and 30%) were investigated to initially examine their brightness/glow over a 2 h period. Fig. 4a shows the mixing of recycled glass powder and GID material along with the epoxy resin. First, the thermoplastic resin was added into the heating system to melt down the mixture and to bring it to the normal temperature. The mixture was then poured into circular moulds (Fig. 4b), which simulate a simplified version of actual road studs. Fig. 4c shows the stud specimens in the moulds with the optimised dosage. The moulds were then subjected to a curing process, where they were left to harden and set under controlled temperature and humidity in the laboratory. Specifically, the road stud specimens were cured under controlled ambient conditions (temperature range of 27°C) to ensure the full hardening of the epoxy resin and proper bonding of the materials, ensuring the durability and effectiveness of the final product. Once cured, the studs were demolded to undergo a series of finishing processes, including surface polishing and quality inspections, to ensure they met the required standards for luminosity and durability.

Table 1: Mix proportions of stud specimens.

No.	Glow-in-the-dark material (%) by volume	Recycled glass powder (g)	Epoxy resin (ml)
1	0	30	5
2	5	25	7
3	10	25	8
4	15	20	10
5	20	20	12
6	25	20	12
7	30	20	14

Circular GiD specimens (diameter of 100 mm, thickness of 8 mm) were adopted in this study to evaluate the brightness luminex index (Fig. 5a-b). The optimisation of the GiD mixture was also determined through compressive strength tests, as explained later. Fig. 5c shows the final view of the stud specimens with different GiD contents. Initial tests were subsequently performed to assess the illuminance of the circular specimens. A lux meter was used to collect illuminance emitted from the studs after exposure to full sunlight. The data was collected from one day morning till

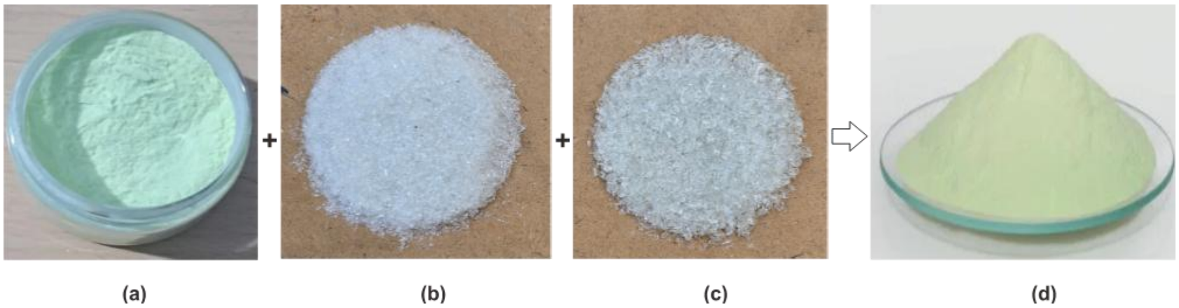

Fig. 3: Mix components: (a) dry thermoplastic binder powder, (b) recycled glass powder (0.85 mm), (c) recycled glass powder (1.70 mm) and (d) mix of GiD thermoplastic powders prior application of heat.

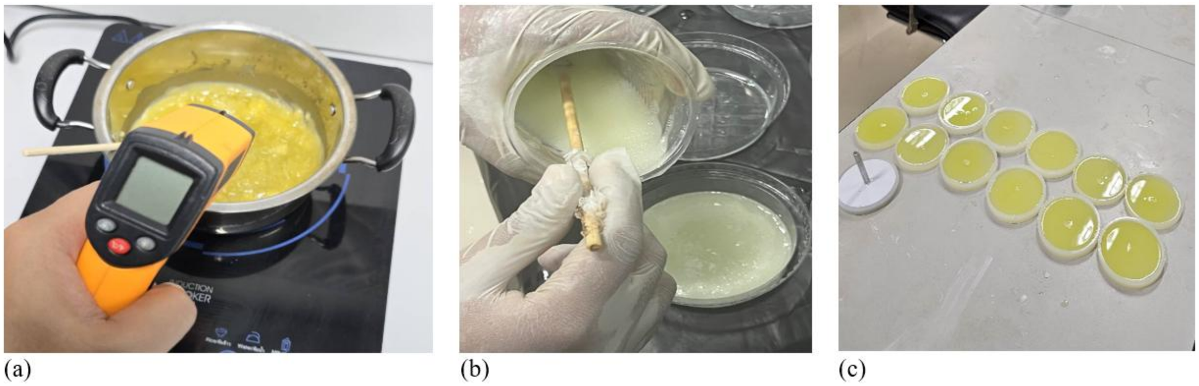

Fig. 4: (a) Mixing of GiD with thermoplastic resin, (b) heating is used to melt down the mixture, and (c) preparation of specimens in molds.

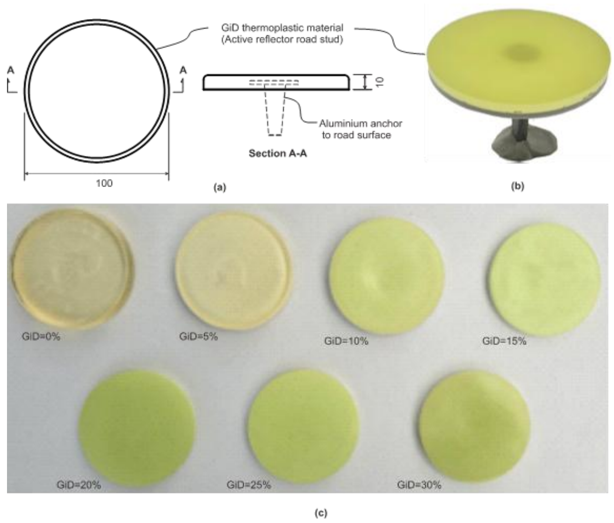

Fig. 5: (a) Geometry of circular GiD stud, (b) view of GiD road stud including base, and (c) road stud specimens with different GiD contents.

next day evening at Walailak University, Nakhon Si Thammarat, Thailand. It was found that the optimum amount of GiD was 25% by volume, and therefore this amount was adopted in this study.

2.1.3 Illuminance and luminance measurements in laboratory conditions

The illuminance from sunlight on the GiD studs was measured using a lux meter. The testing was conducted in both sunny and rainy weather conditions to assess the performance of the GiD studs under varying environmental factors. The GiD stud specimens were placed 24 h in an ad hoc obscure box with a simulated road surface of thickness 50 mm and length 400 mm. Fig. 6a shows a lateral view of the luminance measurement box. A lux meter (model Ut383) was used as it can measure the intensity of visible light over time, independently of colour. The monitoring was also done with via a CCTV system and a PC. Internal and external thermos-hygrometers were used tomeasure the air and humidity levels inside the box. Fig. 6b shows a typical geometry of a GiD stud inside the ad hoc obscure box. The measured luminance from the GiD stud monitored at 12:00 h and 24:00 h is shown in Fig. 6c and 6d, respectively. It can be observed from the figures that the illumination intensity increased in the nighttime. The data was collected at Walailak University in May 2024 from everyday evening (7:00 pm to 9:00 pm).

2.1.4 Mechanical performance testing

Six samples were cast for each mixture proportion (0%, 5%, 10%, 15%, 20% 25% and 30% GiD contents) to investigate the mechanical properties of the stud material. Accordingly, 50 mm cubes (Fig. 7a) were cast and tested in compression with a standard loading rate of 0.6 mm/min as per the ASTM D695-15.[29] Likewise, briquets (Fig. 7b) as per ASTM C307-03[30] were cast and tested in tension with a standard loading rate of 0.04 mm/min. The average compressive and tensile strength of each mix proportion was taken from six specimens. A total of 42 samples were tested.

2.2 Phases II and III: Field investigations

A field test was carried out on the stud prototype to determine its suitability for utilisation in real rural roads. The field trails took place at a stretch of a rural road within Walailak University's campus. The studs were installed along the centreline of the road. Fig. 8a shows a view of the stud prototypes at 12:00 h, whereas Fig. 8b shows the same studs but at 00:00 h after a full days' exposure to sunlight. It is evident that the road studs improve the visibility of the dividing line between traffic lanes. The performance of the GiD road reflector was subsequently investigated in real traffic conditions. This was done by applying a tyre load from a truck, as displayed in Fig. 9.

As such, the stud's type and traffic conditions should be taken into consideration while determining the precise load capacity requirements. In this field trail test, a load from the truck tyre was considered in both static and moving conditions. In the case of static conditions, the truck was allowed to stand on the stud prototype applying constant pressure for 10 minutes. In moving conditions, the truck was allowed to run over the stud at a speed of 20 km/h to 40 km/h.

A standard Thai truck (HGV lorry) with two double wheel rear axles and a single wheel front axle was considered in this experimental programme. The total weight transmitted from the body of the truck to the road by a single wheel is calculated to be 20 t to 30 t, together with the weight of the wheel and the truck. The test has been carried by the moving truck with a single wheel pressure of 0.7 MPa. The tests were performed at 30 and 60 days after the installation of GiD stud onto the road. The tyre loads were applied in the direction of traffic along the whole road. A line painted along the asphalt surface, 50 cm from the edge of the lane, served as the test truck designated right side wheel path during testing. It should be noted that the same truck loads have been considered in the numerical analysis shown later in this study.

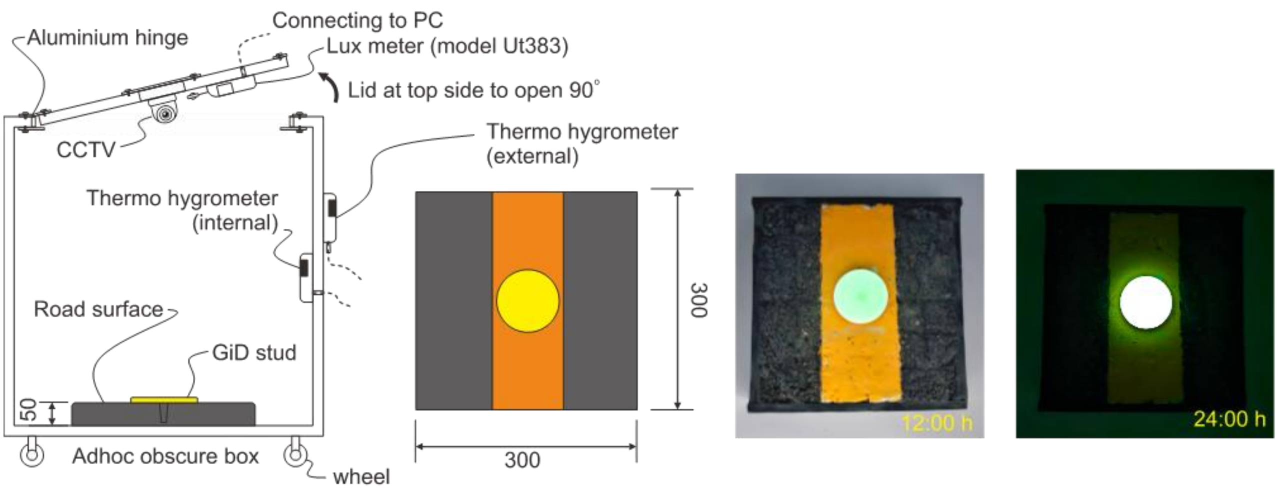

Fig. 6: Schematic view of luminance measurement test: (a) ad hoc obscure box with instrumentation used to measure luminance of the GiD stud on a road surface, (b) view of the GiD studs at 12:00 h (c) and (d) 24:00 h (unit in millimetres).

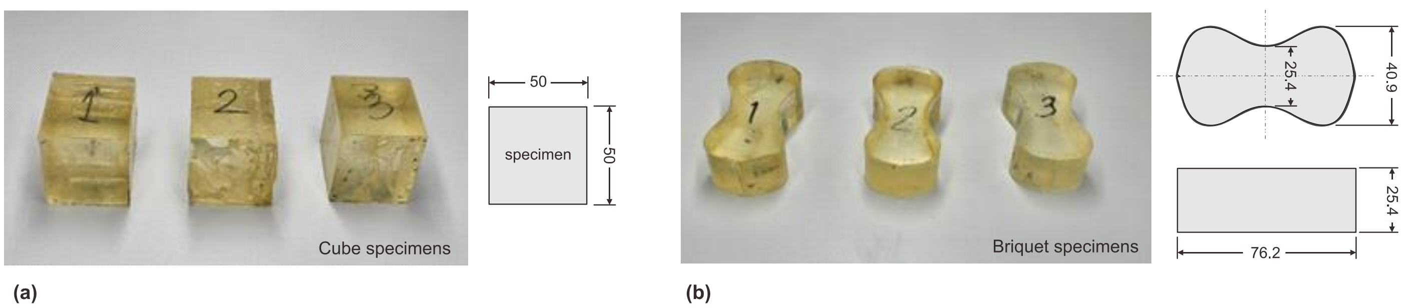

Fig. 7: Specimens for: (a) compressive strength, and (b) tensile strength testing for GiD specimens (unit in millimetres).

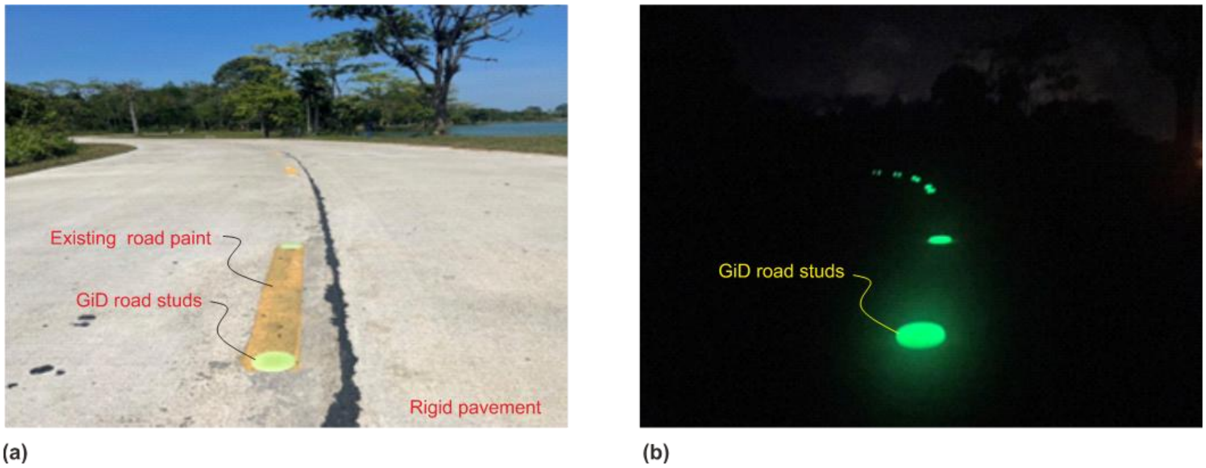

Fig. 8: GiD road studs at Walailak University rural road: (a) at 12:00 h and (b) at 00:00 h.

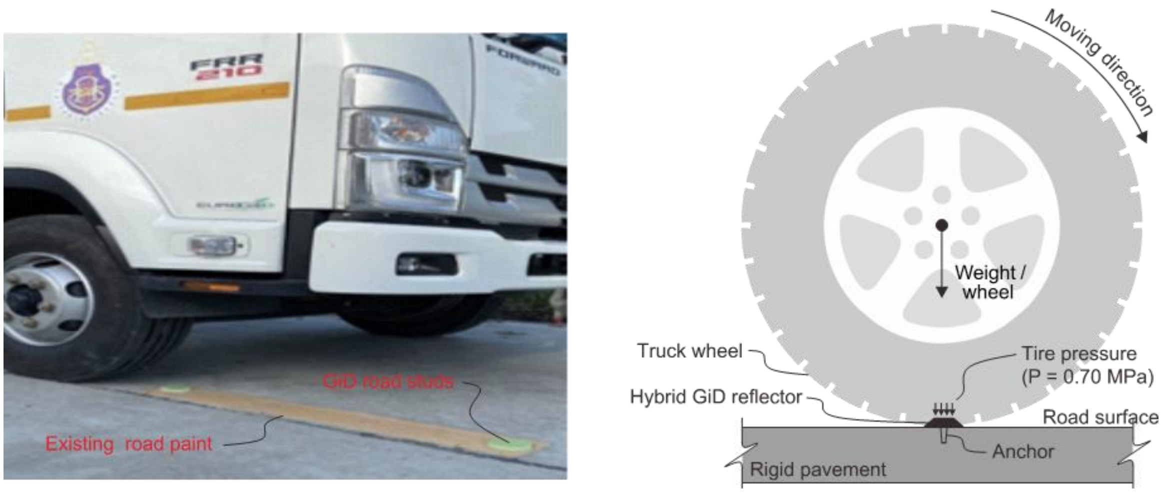

Fig. 9: Field trial with a vehicle cyclic tire loading test. (Real world field test setup, and schematic diagram of test mechanism).

3. Results and discussion

3.1 Phase I

3.1.1 Factors influencing illuminance and luminance

The illuminance from sunlight on the GiD studs was measured using a lux meter (section 2.1.4). The impact of duration of stimulation on light intensity for different percentages of GiD material is shown in Fig. 10. As expected, the intensity of glow increases with the amount of GiD used in the mixture, with

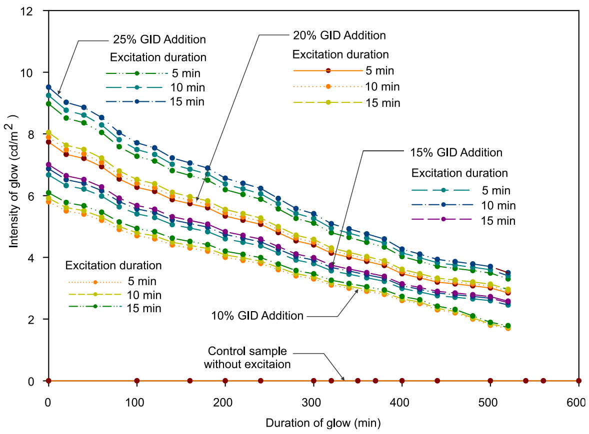

Fig. 10: Impact of duration of stimulation on light intensity for different percentages of GiD material.

maximum glow for a 25% of GiD. The results also show that the afterglow lasts for over 500 min (*i.e.* over 6 h). Fig. 11 shows the luminance data of sunny and cloudy days. The results show that the amount of absorption depends on the illuminance throughout the day (see Fig. 11a and Fig. 11c). The results also vary due to variations in light intensity throughout the day (Fig. 11b). In cloudy days, the afterglow intensity lasts for only about 15 min after 9:00 pm, but on bright sunny days, it fades away after 30 min of darkness (Fig. 11d). As expected, cloudy days are shown to accelerate the fading away of GiD materials. Moreover, when exposed to greater lux intensities, the GiD reaches its maximum luminosity. Nevertheless, even with the variation in light intensity, the brightness at the end of the night is about the same (1 cd/m^2) regardless of the amount og GiD material used in the mixture.

3.1.2 Compressive and tensile strengths

The compressive strength and tensile strength test results are shown in Table 2. Previous research found that many studs' failures were attributed to ruptures, which is caused by the brittle nature of the manufacturing materials followed by the dislodging of epoxy resin. Steel reflector casing is also used in the production of commercial studs, and they are evaluated according to ASTM D4280[31] guidelines. This specification requires that the average stud should have a minimum resistance of 82 MPa. Although no obvious specimen fracture was observed during the field trial, it was concluded from the tests that the samples had some edge cracking and discoloration because of applied loading, which led to stress concentrations. The tests results summarised in Table 2 indicate that the GiD mixture resisted high stresses above 82 MPa if more than 15% GiD material was used in the mixture. The maximum compressive strength (91 MPa) was for a sample cube with 25% GiD material. Note that above such value, the compressive and tensile strengths of the mixture started to reduce. As a result, it is recommended to use a maximum of 25% GiD material in mixtures for stud reflectors. The prototype produced in this study was also able to withstand the compressive forces applied by the truck loading.

Table 2: Compressive strength and tensile strength test results of GiD samples in laboratory.

Glow-in-the-dark material (% by volume)	Compressive strength (MPa)	Tensile strength (MPa)
0	64.0	6.9
5	72.0	7.4
10	76.0	7.8
15	82.0	8.1
20	86.0	8.3
25	91.0	8.7
30	89.0	8.4
Mean	80.0	7.9
Std Dev	9.1	0.6

3.2 Development of a GiD road stud reflector (Phases II & III)

3.2.1 Conceptual design and finite element study

The design concept of integrating GiD materials into passive conventional road studs is shown in Fig. 12a. A commercial square passive road stud of 100 mm with two reflective sides is assumed. The developed active GiD prototype was integrated onto the passive road stud, as shown in Fig. 12b. This design is proposed here to implement GiD reflectors at certain intervals and warn about potential hazards. This combination of active GiD reflectors onto the passive road studs can also be used to enhance existing studs, thus providing additional information and reducing vulnerability of road users. A graphical abstract of the concept is presented in *Supporting Information file Appendix A-1*.

To gain a deeper understanding of the performance of the conceptual GiD studs, a nonlinear finite element analysis (FEA) was performed using Abaqus® considering the nonlinearity of the material and geometry in the analysis. For all the GiD studs, 8-node brick elements (type C3D10M) were used to model the road studs, as shown in Fig. 13a. The road stud base was modelled as an aluminium body considering an element type C3D10M with a modified second-order integration scheme. Mesh sizes of 3 mm and 2 mm for the composite resin were selected based on the mesh sensitivity analysis for optimization in Abaqus®. The model consisted of 49,991 elements and 399,928 nodes. The compression force was applied as an applied load, which was directly applied on the road studs to simulate a real-world field tire compression test with an air pressure in the tire of (0.7 MPa) pressure as shown in Fig. 13c. Three load cases were considered: 1) Load case 1 = compressive stress of 0.7 MPa applied on the

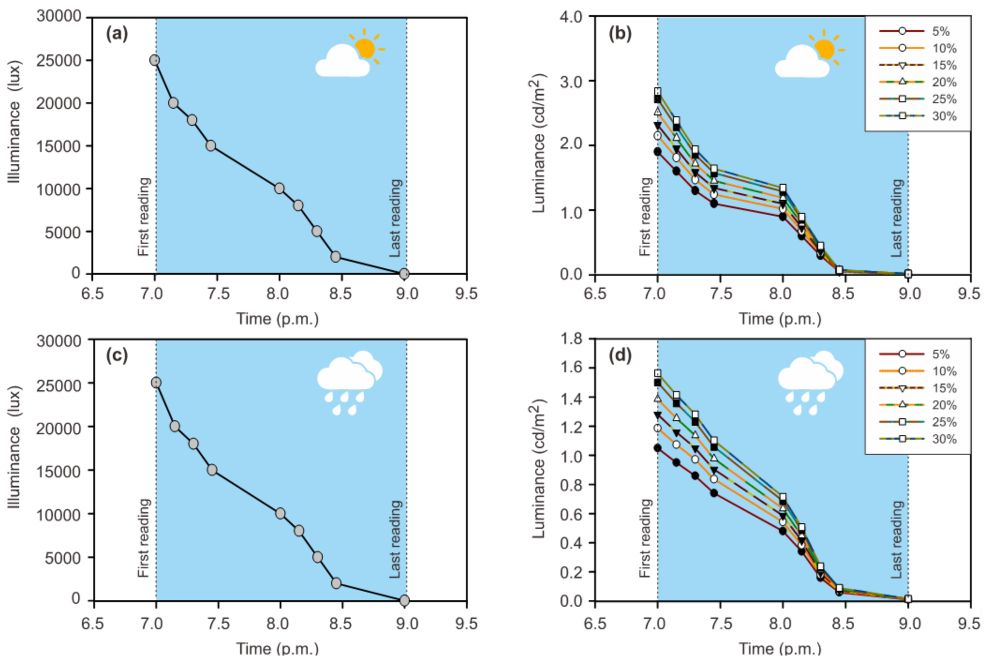

Fig. 11: Illuminance and luminance data on sunny day and rainy day: (a) Illuminance vs time measured at different hours on sunny day, (b) Luminance vs time with different GID variations on sunny day, (c) Illuminance vs time measured at different hours on rainy day, and (d) Luminance vs time with different GID variations on rainy day.

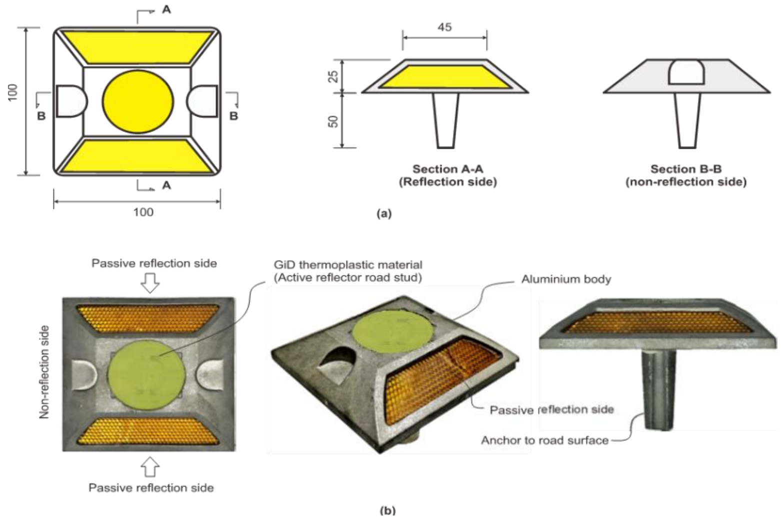

Fig. 12: Design concept to integrate GiD into conventional passive studs: (a) geometry of road stud, and (b) integrating GiD to passive road studs.

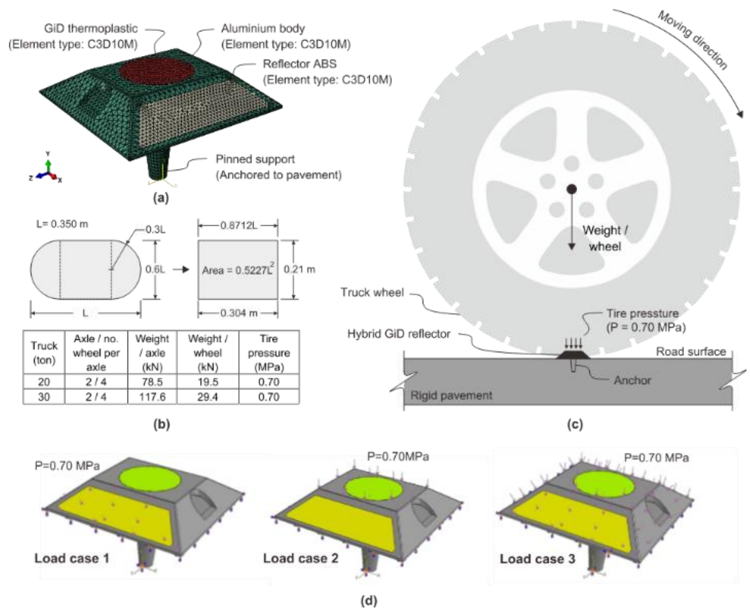

Fig. 13: Modelling of active GID with passive road stud; (a) road stud model, (b) application of load on top surface, (c) application of load on side surface and (d) application of load on both top and side surfaces, the tire pressure is set to 0.70 MPa.

passive reflection side (Fig. 13d), 2) Load case 2 = compressive stress of 0.7 MPa applied on top of the stud only, and 3) Load case 3 = compressive stress of 0.7 MPa applied to all the stud surfaces.

The Abaqus® analysis stopped at a pre-defined number of steps, determined by the maximum recorded compression force, which corresponds to the maximum compression force applied during the tests. The maximum stresses and strains resulting from the application of compressive force on the passive reflection side of the road stud for Load case 1 are displayed in Fig. 14a and Fig. 14b. The maximum stress under the compressive load on top surface of the passive reflection side is about 59.1 MPa. Similarly, the maximum stress and strain for Load case 2 are shown in Fig. 14c and Fig. 14d. In this case, the maximum stress under the compressive load on the top surface is about 1.12 MPa, whereas the maximum strain is about 0.0009. From the FEA results, it was observed that the stress was higher in Load case 2 when compared to the side face of the road stud. The FEA maximum stress and strain results for Load case 3 are presented in Fig. 14e and Fig. 14f. The maximum stress under Load case 3 is about 1.14 MPa and the maximum obtained strain is 0.00091. Amongst the different loading cases, the maximum stress was attained for the compressive force on both top and side surfaces of the road stud (Load case 3), which falls under the Von Mises yield stress criteria.

3.3 Material cost analysis

A cost comparison of the prototype stud is carried out to estimate the cost increase resulting from the use of GiD material. Whilst utilising GiD and recycled glass is expected to increase the initial cost of the studs, it is important to consider the improvements of road safety. The study compares the costs of adding 25% GiD mixture to conventional Bott's dots, which are sold commercially in Thailand. The comparison assumes that the costs associated with labour, handling, placement, shipping, and installation are the same. It is also assumed that the installation process for both devices is similar. The cost analysis reveals that the material cost of GID-integrated road studs is approximately 15% lower “than that of conventional passive road studs. This reduction is achieved primarily through the substitution of expensive retroreflective materials with more cost-effective recycled glass powder and GID phosphorescent compounds. Conventional road studs typically rely on high-quality glass beads or micro prismatic elements, which contribute significantly to the overall cost. By incorporating recycled glass powder, the material costs are significantly reduced without compromising the essential reflective properties. Furthermore, the GID material, which charges during daylight hours and emits light at night, replaces the need for additional retroreflective components, thus further lowering the cost.

3.4 Field performance and visibility at night

Studs were installed along a 1 km stretch of road within Walailak University campus, in a rural road with poor light. Fig. 15 shows part of the road at 12:00 h, 17:00 h and 19:00 h. This site provided an ideal testing ground to assess the performance of the GiD-enhanced studs under real conditions. The studs were fixed to the road surface using a high-strength adhesive designed to withstand the local climate, ensuring their stability under the stresses of vehicular traffic and environmental exposure. The testing of the study was conducted over six months, with a focus on assessing the luminance, and overall effectiveness of the GiD road studs in enhancing night-time road safety. Luminance measurements were taken at regular intervals throughout the night using a luminance meter, capturing data under various weather conditions. The results consistently showed that the GiD road studs emitted light levels that met or exceeded the required

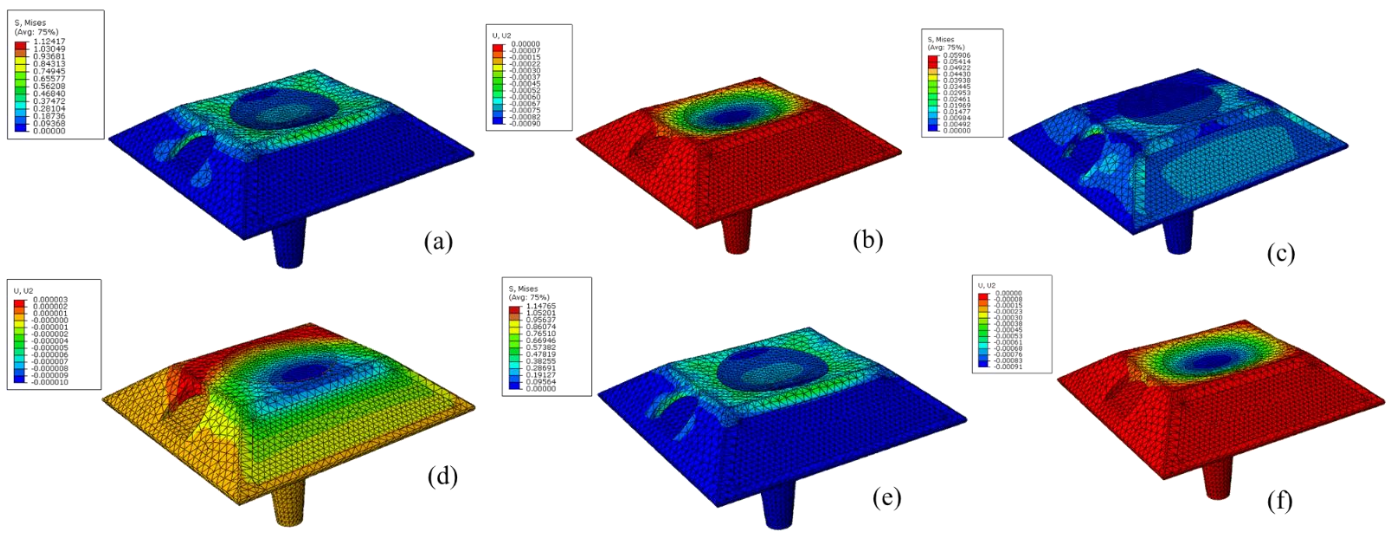

Fig. 14: Simulation of integrated road stud (a) stress for Load case 1, (b) deformation for Load case 1, (c) stress for Load case 2, (d) deformation for Load case 2, (e) stress for Load case 3 and, (f) deformation for Load case 3.

Fig. 15: Photos of GiD studs on rural road of walailak university at 12:00 h, 17:00 h and 19:00 h.

standards for road safety[32] even after prolonged periods of darkness. This demonstrated the effectiveness of the GID technology in maintaining road visibility in low-light conditions, a significant improvement over traditional road studs that depend solely on vehicle headlights. The road studs exhibited remarkable resilience, showing no significant wear or loss of functionality after months of continuous use. These findings highlight the robustness of the GID-integrated road studs, confirming their potential for long-term use in various traffic environments.

The novelty of this approach is further underscored by the dual functionality of the road studs, which combine the benefits of conventional retroreflective materials with the added advantage of GiD luminescence. The GiD technology used in these road studs leverages natural and artificial light sources to charge during the day, providing sustained luminescence throughout the night without the need for additional power sources. This makes it particularly suitable for rural or remote areas where conventional street lighting may be limited.

The findings from this study suggest that GID technology could be widely adopted in various road safety applications, particularly in areas where conventional lighting infrastructure is insufficient or impractical. However, future research could explore further optimisation of GiD mixtures and their potential applications in other aspects of transportation infrastructure. It is also recommended to conduct more studies on the durability and capacity of GiD road studs in tropical climates typical of Southeast Asia. Specifically, the effects of prolonged exposure to high temperatures and humidity on the structural integrity, luminescent performance, and adhesive properties should be thoroughly investigated. Additionally, testing under cyclic thermal loading and real-world traffic conditions can provide insights into the long-term resilience of these road studs. These studies can help optimise the design and material composition for enhanced performance and durability in regions with extreme climates.

4. Practical recommendations

Based on the field installation and performance testing of the GiD road studs, several design recommendations can be made to Thailand's Department of Highways to improve safety and reduce accidents in roads and motorways across the country. The primary focus of these recommendations is to enhance the luminance, durability, and cost-effectiveness of the GID road studs while ensuring their adaptability to various road environments and conditions. Firstly, the selection of materials plays a crucial role in the overall performance of the road studs. It is recommended to use local strontium aluminate as the phosphorescent material due to its superior luminescent properties and long afterglow duration. Additionally, the use of local recycled glass powder as a reflective component not only improves the environmental credentials of the road studs but also enhances their reflective properties. The studs should also be positioned at optimal intervals along the road to provide continuous visibility without causing visual clutter or distraction to drivers. The design could incorporate features that enhance the durability of the road studs, such as an epoxy resin binder that can withstand mechanical stress and environmental exposure, although other binders should be also explored. These design enhancements, coupled with strategic maintenance planning, can improve the effectiveness of the road studs in enhancing night-time road safety and extend their service life.

5. Conclusion and future work

This study presents the development of cost-effective glow-in-the-dark (GiD) studs with recycled glass, aimed at enhancing night-time road safety and promoting sustainability. Field trials were conducted at Walailak University Thailand to assess the visibility and durability of the studs. The main conclusions can be drawn as follows:

- The optimisation of the mixture indicated that 25% of GiD material (strontium aluminate) was adequate to provide adequate glow for several hours. This mixture was also found to have a high compressive strength (91 MPa) and tensile strength (8.7 MPa). A higher level of GiD material (30%) led to reductions in compressive and tensile strengths.
- GiD road reflectors maintain 300 mcd/m^2 luminosity for eight hours, doubling the visibility duration of traditional reflectors (150 mcd/m^2).
- Integrating GiD materials with recycled glass, offering a 15% cost reduction.
- The FEA results confirm the GiD road stud's structural integrity, withstanding compressive stress up to 1.14 MPa under tire pressure.
- The successful installation of studs at Walailak University demonstrates the potential for large-scale application in rural roads, which can help inform Thailand's Department of Highways policies for improving safety and reduce accidents in roads and motorways across the country. In turn, this shows that GiD technology has potential in rural areas of other developing countries were installing and maintaining traditional studs are often too costly or impractical. The use of recycled materials in the GiD studs also aligns with efforts of adopting circular economy approaches in construction.

Overall, GiD studs can offer a solution to increase road visibility without the need for external power, using recycled glass and non-electric components. This makes them ideal for regions with insufficient street lighting and limited electricity access. However, future research should explore further optimisation of GID materials and their potential applications in other aspects of transportation infrastructure. It is also recommended to conduct more studies on the durability and capacity of Gi road studs in tropical climates typical of Southeast Asia. Specifically, the effects of prolonged exposure to high temperatures and humidity on the structural integrity, luminescent performance, and adhesive properties should be thoroughly investigated. Additionally, testing under cyclic thermal loading and real-world traffic conditions will provide insights into the long-term performance of these road studs.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Applicable.

CRediT Statement

Thanongsak Imjai & Nukul Suksuwan: Investigation, Formal analysis, Writing – original draft. **Radhika Sridhar & Pakjira Aosai:** Conceptualization, Funding acquisition, Supervision, Investigation, Formal analysis, Writing – original draft. **Achmad Wicaksono & Reyes Garcia:** Investigation. **Mohd Mustafa Al Bakri Abdullah:** Supervision, Review & editing.

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