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Experimental investigation of solar-reflective coatings as thermal insulators for rails in heavy-haul corridors

Investigação experimental de revestimentos refletores solares como isolantes térmicos para trilhos em corredores de transporte de cargas pesadas

Investigación experimental de recubrimientos reflectantes solares como aislantes térmicos para rieles en corredores de transporte pesado

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ABSTRACT

Rails are critical components of railway infrastructure, responsible for distributing loads, guiding vehicles, and ensuring operational safety. However, temperature variations and solar irradiance induce thermal stress, leading to rail expansion and contraction, as well as potential buckling. While previous studies have explored rail profile optimization and lubrication strategies, limited research exists on thermal mitigation through coatings. This study evaluates the effectiveness of three commercial coatings in reducing rail temperature variations on AREMA 136RE rails under real environmental conditions. Thermocouples monitored temperature changes on coated and uncoated rail samples over multiple seasons, while a pyranometer recorded solar irradiance. Results indicate that coated rails exhibited significantly lower peak temperatures compared to uncoated rails, with maximum reductions exceeding 10°C in summer. Coatings with nanometric hollow ceramic spheres demonstrated superior thermal performance. They maintained temperatures 8–10% lower than Alkyd resin-based coatings on semi-drying vegetable oil when temperatures exceeded 20°C. Seasonal analysis confirmed consistent behavior, with temperature differentials decreasing in cooler months. The findings suggest that reflective coatings can mitigate thermal buckling risks, particularly in tight curves (radius < 50 m), where critical temperature differentials are below 12°C.

RESUMO

Os trilhos são componentes críticos da infraestrutura ferroviária responsáveis por distribuir cargas, guiar veículos e garantir segurança operacional. No entanto, variações de temperatura e irradiação solar induzem estresse térmico, levando à expansão e contração dos trilhos, bem como ao potencial de flambagem. Embora estudos anteriores tenham explorado a otimização do perfil e lubrificação, há pouca pesquisa sobre mitigação térmica via revestimentos. Este estudo avalia a eficácia de três revestimentos comerciais na redução da variação de temperatura em trilhos AREMA 136RE. Termopares monitoraram as temperaturas em amostras revestidas e não revestida ao longo de várias estações, enquanto um piranômetro registrava a irradiação solar. Os resultados mostram que os trilhos revestidos tiveram picos de temperatura significativamente menores, com reduções superiores a 10°C no verão. Revestimentos com nanoesferas cerâmicas ocas tiveram desempenho superior. Eles mantiveram temperaturas 8–10% menores que a resina alquídica acima de 20 °C. A análise sazonal confirmou comportamento consistente, com diferenciais diminuindo nos meses frios. Os resultados sugerem que revestimentos refletivos podem mitigar riscos de flambagem térmica, principalmente em curvas acentuadas (raio < 50 m), onde os diferenciais de temperatura críticos são inferiores a 12 °C.

RESUMEN

Los rieles son componentes críticos de la infraestructura ferroviaria, responsables de distribuir cargas, guiar vehículos y garantizar la seguridad. Sin embargo, las variaciones de temperatura y la irradiación solar inducen estrés térmico, provocando expansión y contracción de los rieles, así como potencial pandeo. Aunque estudios previos han explorado la optimización del perfil y la lubricación, existe poca investigación sobre mitigación térmica mediante revestimientos. Este estudio evalúa la efectividad de tres revestimientos comerciales para reducir la variación de temperatura en rieles AREMA 136RE. Termopares monitorearon las temperaturas en muestras revestidas y no revestida a lo largo de varias estaciones, mientras un piranómetro registraba la irradiación solar. Los resultados muestran que los rieles revestidos tuvieron picos significativamente menores, con reducciones superiores a 10°C en verano. Los revestimientos con nanoesferas cerámicas huecas demostraron desempeño térmico superior. Mantuvieron temperaturas entre un 8% y un 10% inferiores a las de los recubrimientos a base de resina alquídica sobre aceite vegetal semisecante a temperaturas superiores a 20 °C. El análisis estacional confirmó comportamiento consistente, con diferenciales que disminuyen en meses fríos. Los resultados sugieren que los revestimientos reflectantes pueden mitigar riesgos de pandeo térmico, principalmente en curvas cerradas (radio < 50 m), donde los diferenciales de temperatura críticos son inferiores a 12°C.

INTRODUCTION

The railway superstructure is a critical engineering system designed to support, guide, and distribute dynamic loads from rolling stock to the underlying infrastructure (substructure) (Steffler, 2013; Qi & Indraratna, 2021). Within this system, the rail is a primary asset, responsible for guiding vehicles, transmitting vertical and lateral forces to the sleepers, and providing a rolling surface for wheels (Kukulski, 2015; Kaewunruen & Remennikov, 2010). The integrity and performance of the rail are, therefore, paramount to the safety, efficiency, and reliability of railway operations.

Extensive research has been dedicated to enhancing rail performance and durability, focusing on optimizing profiles, mitigating wear, and managing rolling contact fatigue through various advanced techniques (Reddy et al., 2007; Cui et al., 2023; Qi, Gan, & Sang, 2023). A significant challenge to rail integrity is the management of thermal stresses in Continuous Welded Rail (CWR). Temperature variations cause the rail to expand and contract, generating significant internal thermal stress. In extreme heat, excessive compressive stress can lead to track buckling, a sudden lateral misalignment that poses a severe derailment risk (Takahashi et al., 2019). The threat is substantial; for instance, over 4,000 buckling incidents were recorded on a single Brazilian railway in three years, resulting in significant accident costs (Junior, Lopes, & Castro, 2017). Climate change, leading to more frequent and intense heatwaves, is exacerbating this challenge globally, driving the need for resilient infrastructure solutions (Kang et al., 2022).

Current strategies to mitigate buckling risk include speed restrictions during hot weather and ensuring rails are laid at an appropriate stress-free, or "neutral," temperature. However, these measures can be reactive, operationally disruptive, and their effectiveness can diminish over time due to track settlement and maintenance activities that reduce the longitudinal restraint (Hoather & Mandal, 2016). Consequently, proactive methods to directly control rail temperature are increasingly attractive.

One promising approach is the application of solar-reflective coatings to the rail surface. These coatings are designed to have high solar reflectance and thermal emissivity, reducing the amount of solar energy absorbed and thus lowering the peak rail temperature. Early research by Wang et al. (2015) and a subsequent report from the U.S. Department of Transportation (2018) demonstrated that a specially formulated low solar absorption coating could reduce peak rail temperatures by up to 10.5°C, significantly decreasing compressive thermal stress. More recently, studies have expanded to explore advanced coatings. Huang et al. (2025) developed a passive radiative cooling coating for ballast less track slabs, achieving a maximum surface temperature reduction of 28.27°C through a combination of high reflectivity and mid-infrared emissivity. Similarly, Brumercikova et al. (2024) investigated reflective thermal insulation coatings on rails and wagons in the Slovak Republic, reporting temperature reductions of up to 15.8°C on rails and 7.9°C inside coated wagons.

While Ritter and Al-Nazer (2014) studied the growing body of international research (Wang et al., 2015; U.S. Department of Transportation, 2018; Brumercikova et al., 2024; Huang, You, & Huang, 2025) confirm the principle's validity, the application of commercial coatings on heavy-haul railways, particularly in regions with intense solar radiation like Brazil, requires further field validation. Many existing studies focus on slab tracks or passenger railways, leaving a gap regarding the performance on traditional ballasted tracks under heavy axle loads.

Therefore, this study aims to experimentally evaluate the effectiveness of three commercially available coatings in mitigating the thermal movement of rails in a Brazilian heavy-haul railway setting. The investigation involves field monitoring of instrumented rail segments to quantify the coatings' impact on temperature variation. By providing empirical data on thermal performance, this research seeks to contribute to the development of practical and cost-effective strategies for enhancing track stability and preventing buckling in freight corridors.

The paper is structured as follows: Section 2 details the research methodology, including sample preparation, instrumentation, and field-testing procedures. Section 3 presents and discusses the results, and Section 4 provides the concluding remarks.

METHODOLOGY

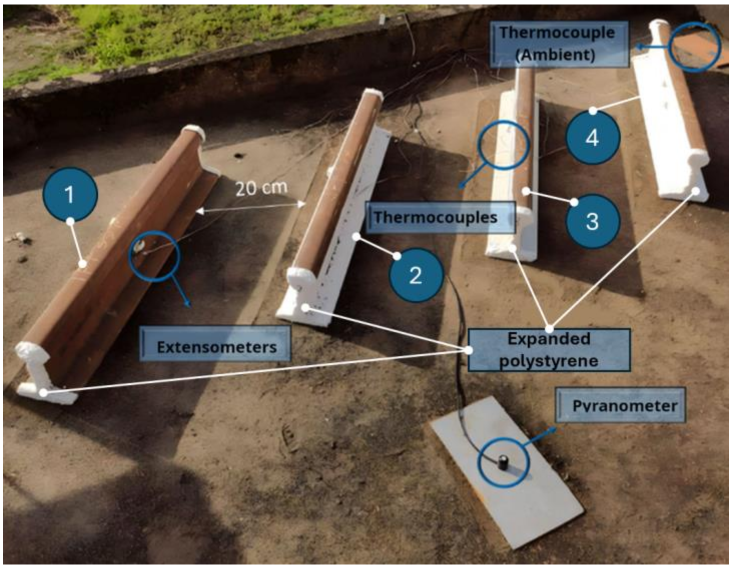
For the present work, AREMA 136RE (TR-68) standard rail was selected. This rail is widely used in the Brazilian heavy-haul railway, with a nominal mass per meter of rail of 67.56 kg/m (ABNT, 2012). The rails, initially in their as-received condition (Figure 1a), were cut into standardized 1-meter sections using a Monrod MR-122 bandsaw (Figure 1b). This sample preparation was essential to enable the experimental setup. It was necessary to apply cutting fluid to reduce the heat-affected zone (HAZ). The rails were then subjected to a cleaning process to remove the oxidation and the superficial impurities.

Figure 1. Preparation of rail samples for the experimental analysis, showing (a) the rails in their initial as-received condition and (b) the subsequent cutting process to create test sections

Source: Authors (2025).

For measurements, 2 thermocouples were used, positioned on the lateral of the head and web of each rail (Figure 2). The positioning of the thermocouples was defined following the guidelines in (Ritter & Al-Nazer, 2014). Type J thermocouples were selected. The sensors were positioned longitudinally to the rail in the middle of the sample. After removing the oxides with an abrasive sander, the thermocouples were fixed using adhesive tape, Silvertec 747, recommended by the sensor supplier. The thermocouples were previously calibrated by the supplier; however, additional calibration was conducted for verification purposes. The calibration of the thermocouples was carried out indirectly. In the measurements, a thermal variation of 5°C to 65°C was applied, with an increase of 10°C. Each temperature was measured five times, aiming to obtain more accurate results in the process. The measured values matched the supplier's specifications, validating the calibration.

Figure 2. Schematic of the experimental setup used for data collection, illustrating the configuration of two thermocouples per rail for temperature measurement, an extensometer to monitor strain, and a pyranometer to record incident solar irradiance



Source: Authors (2025).

A pyranometer SP-420 was used to quantify the global solar irradiance incident on the samples. It was positioned adjacent to the rails, aiming to measure the total amount of solar radiation on the area in which the rails are exposed. The unit of measurement adopted to quantify solar irradiance was expressed in watts per square meter (W/m²). The purpose of collecting data from the pyranometer is to make a comparison between the rail temperature and solar irradiance.

Three different commercial types of coating were examined along the regular rail. The coatings chosen are alkyd resins, due to their characteristics for field application. Alkyd resins have quick drying, high adhesion, and good water resistance, and are easily applicable to surfaces without prior treatment (Senra et al., 2022) (Table 1).

Table 1. Description and composition of the coatings applied to the rail samples

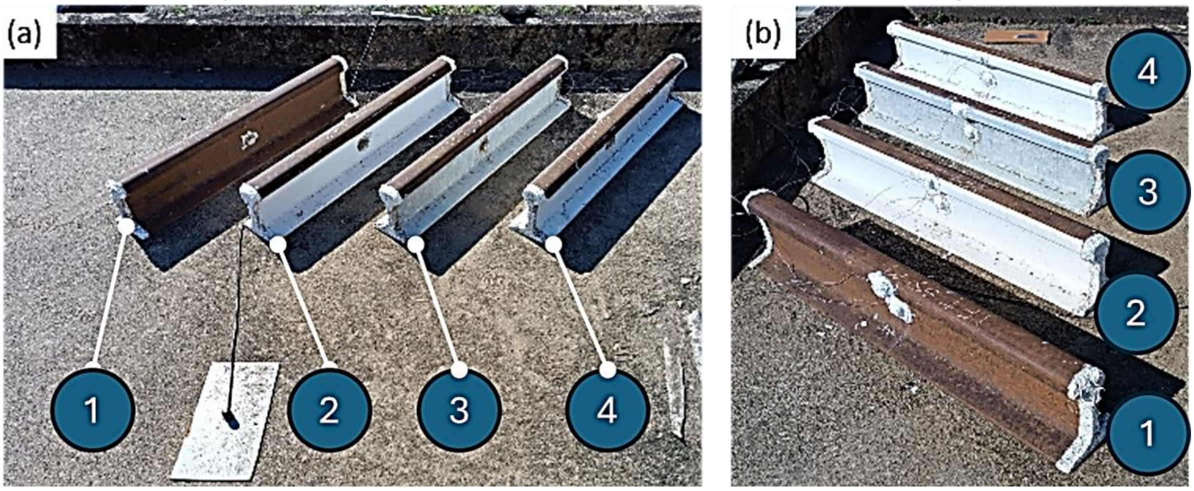
Rails	Coating Composition
1	Not applied
2	Water-based thermal coating composed of nanometric hollow ceramic spheres, resins, and high-performance additives.
3	Alkyd resin based on semi-drying vegetable oil, inert mineral fillers, organic and inorganic pigments, anticorrosive pigments free of heavy metals, aliphatic hydrocarbons, organometallic driers, butanone oxime, zinc bis (2-ethylhexanoate), zinc oxide, zinc phosphate zinc, turpentine, kerosene (petroleum), hydrogen treated light distillates (petroleum), naphtha solvent (petroleum), light aromatic, low boiling point naphtha, cobalt bis(2-ethylhexanoate).
4	Modified alkyd resins, solvents, additives, and pigments. Substances contributing to the hazard: Petroleum naphtha, (petroleum), aliphatic middle distillates (petroleum), hydrogen-treated light, trizinc bis(orthophosphate), calcium bis(2-ethylhexanoate), xylene, methyl ethyl ketoxime, neodecanoic acid, and cobalt salt.

Source: Authors (2025).

The preparation of the coatings was carried out following the recommendations of their respective manufacturers. Coating 2 was diluted with 10% water, while Coatings 3 and 4 were diluted with 10% thinner. The rails received two layers of coating, which were applied at intervals of 2 hours to ensure greater quality coverage of the area. Coatings were applied to the lateral of the head, web, and foot. It was not applied to the top of the head because it could affect the wheel-rail contact, and even if it did not harm the contact, the coating would be easily removed by friction.

Polystyrene plates were fixed to the rail ends to reduce thermal interference at the cross-sections (Figure 3).

Figure 3. The final prepared rail samples, showing (a) a right-side view and (b) a left-side view of the test specimens ready for environmental exposure and thermal monitoring



Source: Authors (2025).

The rails were positioned in the longitudinal direction to the north to guarantee the longest period of solar irradiance. In addition to the installation of thermocouple sensors to capture temperature variations in the rail, monitoring this parameter required the implementation of a data acquisition system. As stated by Camargo et al. (2022), this type of system, classified as SCADA (Supervisory Control and Data Acquisition), is responsible for converting analog inputs into digital signals and must align with the research or project strategy.

Selecting an appropriate system can enhance data processing efficiency and facilitate more effective interpretation by providing real-time graphical visualization. This enables trend analysis, applicability assessment, and serves as a decision-making indicator.

For this project, the ADS2500-VB system was adopted, which features analog channels configured via software. Thus, the system's operation involves installing thermocouple sensors on the rear section of the equipment and requires an internet connection, either via Wi-Fi or Ethernet cable, to initiate recording in the monitoring software. Throughout the project, a connection was only necessary at the start of recording and during the extraction of stored data.

To enhance reliability and organization in data processing, each thermocouple was assigned a unique identifier in the software, correlating it to the web or foot of each rail. This facilitated real-time monitoring of each asset.

For data analysis, 168-hour intervals were adopted between recording sessions to simplify the evaluation of recorded values. The data were collected at a sampling frequency of 1 Hz. Subsequently, the data were refined. The dataset was then examined for outliers to identify inconsistent deviations. This involved analyzing variation curves and applying filters to eliminate unrealistic values that did not align with the study's conditions.

After correcting the temperature behavior dataset, an additional filter was applied to display temperature variations at 2-minute intervals. This optimization allowed for an improved graphical representation of rail temperature fluctuations, aiding in the assessment of different coating types of effects on the rails.

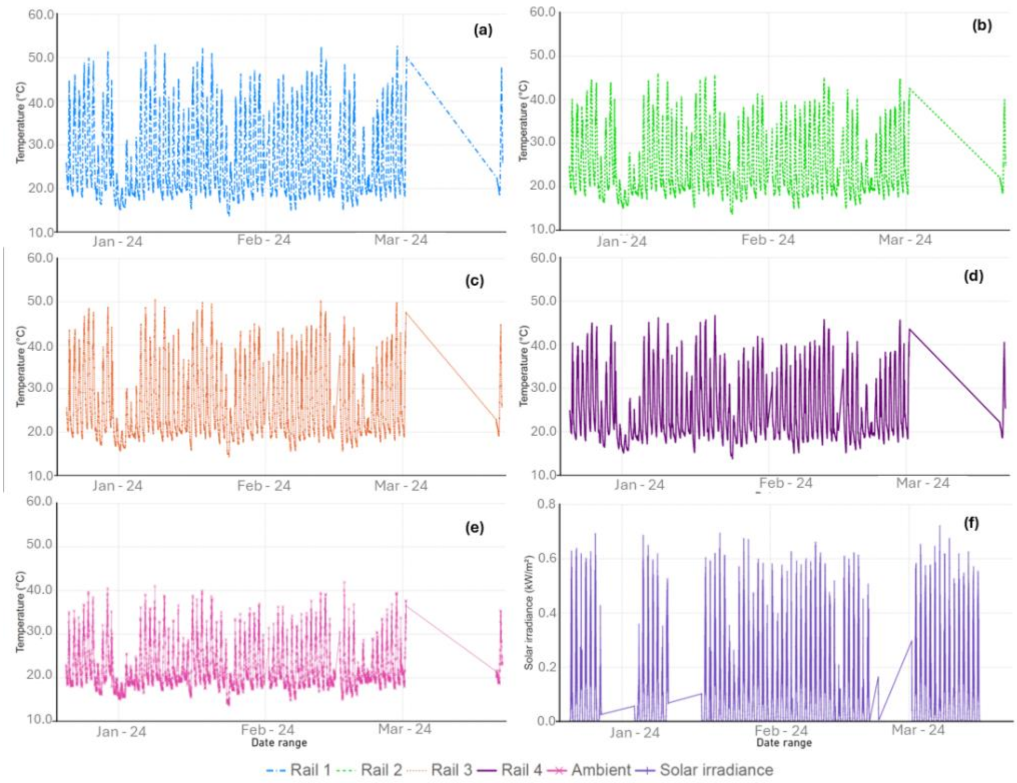
To validate the processed data, a cross-referencing analysis was performed by comparing the acquisition system's readings with measurements from a pyranometer. The SP-420 pyranometer from Apogee, selected for this comparison, features a 180° field of view, measurement repeatability of less than 1%, and a resolution of 0.1 W/m².

This study has certain limitations that should be acknowledged. The experiments were conducted on 1-meter rail segments under static conditions, without the influence of dynamic train loads or real track-bed restraint. Testing was conducted under extreme and unobstructed solar exposure, a scenario highly representative of Brazilian heavy-haul railway environments. Consequently, while the results robustly demonstrate the coatings' inherent thermal properties, their in-service performance under operational heavy-haul conditions may vary and warrants further field validation on a full-scale track section under traffic.

RESULTS AND DISCUSSION

The time history of the rail temperature and solar irradiance during summer (Figure 4). The results indicate that all tested rails exhibit a similar thermal response, with temperatures ranging from 15°C to 53°C, concurrent with solar irradiance levels peaking at approximately 0.72 kW/m². Due to the closely clustered temperature data, a more detailed analysis over a 24-hour interval was conducted to enhance interpretability.

Figure 4. Recorded data from the summer monitoring period, showing the concurrent measurements of rail temperature for both coated and uncoated samples and the corresponding solar irradiance ((a) rail 1; (b) rail 2;(c) rail 3; (d) rail 4; (e) ambient and (f) solar irradiance)

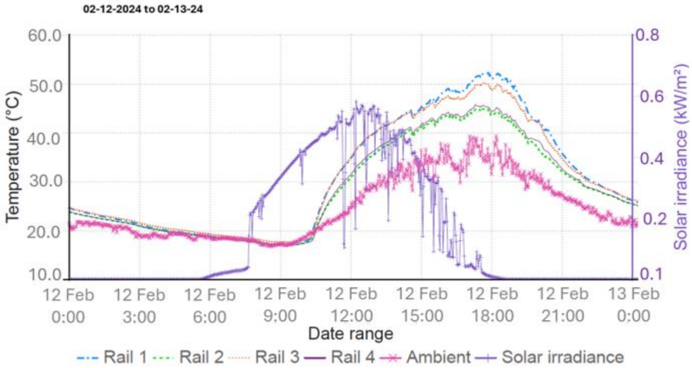


Source: Authors (2025).

The data reveal that between 00:00 and 09:00, rail temperatures remain closely aligned, regardless of coating type. Beginning at 06:00, solar radiation increases, peaking at approximately 0.58kW/m² around 12:00 before declining to zero by 18:00. A critical observation is the consistent time lag of about 3 hours in rail temperature response relative to solar radiation, evident during both heating and cooling phases. This phenomenon is attributed to the rail's high thermal inertia, governed by its specific heat capacity and thermal conductivity. Also demonstrates that all rails maintain temperatures above ambient levels.

The uncoated rail consistently recorded the highest temperatures, while Coatings 2 and 4 exhibited the lowest, with a maximum observed temperature difference exceeding 10°C (Figure 5).

Figure 5. Diurnal temperature profiles of the rail samples and concurrent solar irradiance during a 24-hour summer period, illustrating the thermal response of the coatings to peak solar loading

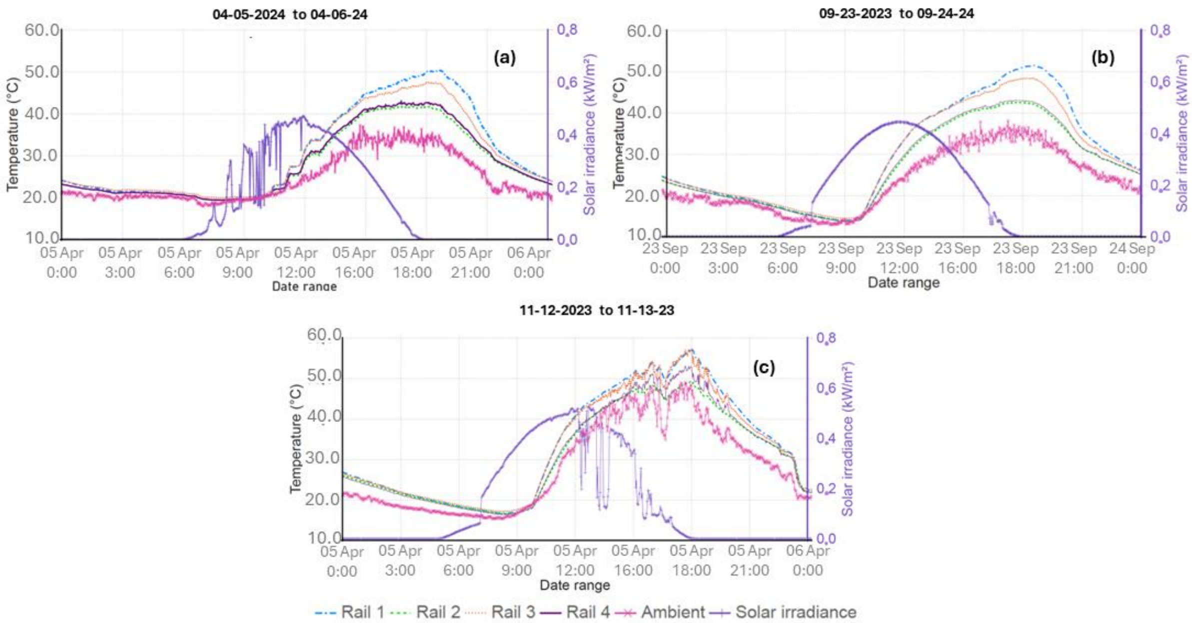


Source: Authors (2025).

The superior performance of Coating 2 is attributed to its high concentration of ceramic-based reflective pigments, which enhance solar irradiance reflectance. In contrast, Coating 4, an organic high-gloss formulation, relies on the synergistic effects of trizinc phosphate (an anti-corrosive and thermal stabilizer) and cobalt salts (which promote cross-linking and film integrity) to improve its thermal resistance.

The measurements for the remaining seasons, (Figure 6) show a behavior like summer, including the characteristic time lag between solar irradiance and rail temperature. However, the peak irradiance intensity is lower, reaching 0.5 kW/m² in autumn and winter and approximately 0.53 kW/m² in spring. Consistent with summer trends, the uncoated rail exhibited the highest temperatures across all seasons, with Coatings 2 and 4 remaining the most effective. The maximum observed temperature differences were: 9.98°C in autumn (Figure 6a), approximately 10.41°C in winter (Figure 6b), and near 9.98°C in spring (Figure 6c). These results confirm the persistent, albeit seasonally modulated, influence of solar-reflective coatings on rail thermal performance.

Figure 6. Seasonal comparison of the thermal performance, showing diurnal rail temperature and solar irradiance profiles over 24 hours during (a) fall, (b) winter, and (c) spring



Source: Authors (2025).

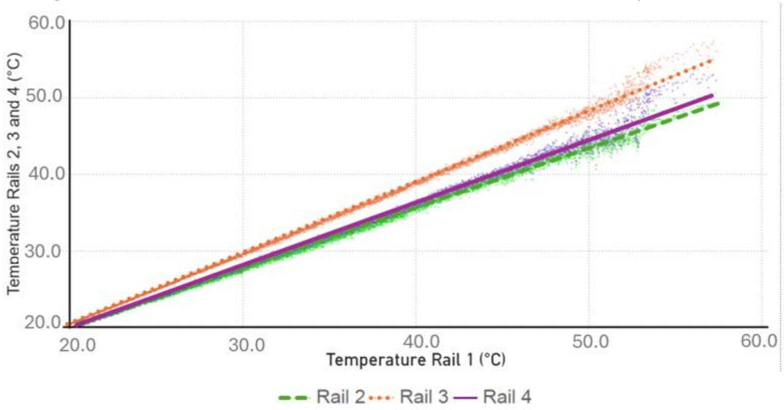
The findings of this study align with and contribute to a growing body of international research on mitigating rail temperatures. The maximum temperature reduction of over 10°C observed with the best-performing coatings in this study is consistent with the performance reported by other researchers. Researchers have also achieved significant temperature reductions, of up to 10.5°C, 28.27°C, and 15.8°C, using low solar absorption and radiative cooling coatings on rails (Wang et al., 2015; U.S. Department of Transportation, 2018; Huang, You, & Huang, 2025; Brumercikova et al., 2024).

The performance of Coatings 2 and 4 in our study, which achieved comparable reductions, validates the effectiveness of commercial coatings in a heavy-haul railway environment and underscores the transferability of this technology across different geographic and operational contexts.

The observed 3-hour thermal lag is a fundamental characteristic of the rail's thermal mass and has been noted in other infrastructure studies. This inertia is a critical factor for accurately modeling rail temperature and predicting the peak thermal stress, which typically occurs in the late afternoon rather than at the peak of solar noon.

The temperature correlation between coated rails and the bare rail, revealing a linear relationship ($R^2 > 0.99$) with a uniform thermal response below 20°C (Figure 7). Beyond this threshold, thermal divergence becomes evident. Coating 3 exhibited an 8-10% higher temperature retention compared to Coatings 2 and 4, highlighting significant variations in the thermal properties of different coating formulations under significant solar loading. This divergence underscores the importance of coating composition. The superior performance of coatings with high solar reflectivity (like Coating 2) aligns with the fundamental principle of passive radiative cooling, which relies on high reflectance in the solar spectrum (0.3–2.5 µm) and high emissivity in the atmospheric window (8–13 µm) to achieve cooling (Huang, You, & Huang, 2025).

Figure 7. Correlation analysis of temperature data, comparing the thermal performance of the coated rail samples against the uncoated reference rail across the entire experimental dataset.



Source: Authors (2025).

This observed thermal divergence, particularly the 8-10% higher temperature retention of Coating 3, has direct implications for rail operational specifications and maintenance. For instance, rail installation at stress-free temperature (SFT) are typically set according to the region's average ambient temperature to prevent thermal stress. Excessive rail temperatures, especially those exceeding common operational thresholds, significantly increase the risk of track buckling and accelerate rail fatigue. The ability of coatings, such as Coating 2, to maintain rail temperatures significantly below a bare rail's temperature can effectively expand the operational safety margin. By reducing peak rail temperatures, these coatings can help keep the rail within its designed stress-free range for longer periods, directly contributing to enhanced long-term rail integrity, reduced buckling risk, and potentially extending intervals for thermomechanical stress-related inspections. This aligns with engineering guidelines that emphasize preemptive thermal management as a key strategy for infrastructure longevity (Esveld, 2001).

As established by Hasan (2021), the critical temperature differential (ΔT_{crit}) in curved rail tracks, representing the threshold for thermal buckling, can be determined through Equation (1), which incorporates track curvature radius and material properties.

$$\Delta T_{crit} = 50\frac{R.F_{QVW}}{A.E.\alpha} \tag{1}$$

where R is the curve radius (m), F_{QVW} is the sleeper resistance (N/cm), A is the rail transversal area (cm²), E is the young modulus (N/cm²), and α is the coefficient of thermal expansion (1/°C). And the $\Delta T_{crit.}$ for different curve radii using Equation (1) are presented in Table 2.

Table 2. Calculated critical temperature differentials (ΔT_{crit}) required to induce thermal buckling for various track curve radii, highlighting the increased risk in tighter curves (FQVW =100 (N/cm), A = 86.52 (cm2), E = 20x106(N/cm2), and α = 0.000012(1/°C))

Radius [m]	$\Delta T_{crit.}$ [°C]
50	12.03
75	18.05
100	24.07
125	30.09
150	36.11
200	48.15
250	60.19
300	72.23
500	120.39
700	168.55

Source: Authors (2025).

Table 2 reveals that curves with radii < 50 m exhibit critical temperature differentials <12°C, equivalent to the performance gap between optimal coated and uncoated rails. This correlation highlights how thermal coatings can enhance buckling resistance by reducing peak rail temperatures.

The primary motivation for reducing rail temperature is to mitigate the risk of track buckling. The temperature differentials achieved by the most effective coatings in this study (exceeding 10°C) are highly significant from an engineering perspective. While the theoretical calculation of a critical temperature differential (ΔT_{crit}) highlights the sensitivity of sharp curves to temperature changes, the practical value of these coatings is best demonstrated by direct comparison with field-based research.

The reduction in compressive thermal stress demonstrated by Wang et al. (2015) directly translates to a lower risk of lateral track instability. By proactively lowering the maximum rail temperature, these coatings effectively increase the safety margin against buckling, particularly on curves with limited radial resistance or in areas where the effective Rail Neutral Temperature (RNT) has degraded over time. This approach offers a passive, persistent safety benefit that complements operational measures like speed restrictions, which are only temporary and disruptive. The consistent performance across all seasons, as confirmed in this study, ensures year-round protection, with the most substantial benefits realized during the summer months when the buckling risk is highest.

FINAL CONSIDERATIONS

This study provides a comprehensive experimental evaluation of the effectiveness of three commercial solar-reflective coatings in mitigating rail temperature rise on AREMA 136RE rails used in Brazilian heavy-haul railway. Based on the long-term field monitoring and subsequent analysis, the following conclusions can be drawn:

- The application of solar-reflective coatings proved to be a highly effective strategy for reducing rail temperatures. The most effective coatings (Coatings 2 and 4) achieved a maximum temperature reduction exceeding 10°C compared to the uncoated rail during summer, with substantial reductions maintained across all seasons.
- A clear performance hierarchy was established among the tested coatings. The superior efficacy of Coating 2 is attributed to its formulation with nanometric hollow ceramic spheres, which provide high solar reflectance. The performance variation underscores that the specific chemical composition and reflective filler content are critical determinants of a coating's thermal performance.
- The magnitude of temperature reduction observed in this study is consistent with findings from international research, using similar technologies. This corroborates the global validity of using reflective coatings for rail thermal management and confirms their effectiveness in the specific context of a ballasted, heavy-haul freight corridor.
- The achieved temperature reductions have direct and critical implications for track safety. By lowering the peak rail temperature, these coatings significantly reduce the compressive thermal stresses that lead to track buckling. This provides a passive, persistent, and proactive safety margin, particularly on sharp curves where the critical temperature differential is low. This strategy is especially valuable as a complement to, or a replacement for, operationally disruptive measures like speed restrictions.

In summary, this research successfully demonstrates that commercially available solar-reflective coatings are a viable and effective engineering solution for enhancing the thermal stability of heavy-haul railway tracks. The findings provide railway operators with practical, evidence-based options for proactively managing buckling risk, improving safety, and ensuring operational reliability in the face of increasing temperatures and climate challenges. Future work should focus on long-term durability studies of these coatings under traffic and environmental conditions and a detailed cost-benefit analysis of their large-scale implementation.

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