

Performance Assessment of Thermoplastic Road Markings on Kenyan Roads: Bridging Infrastructure Challenges through Retroreflectivity, Luminance, and Thickness Analysis

Clarice Jepkemoi Kimwei, Simpson Osano, Francis Gichaga

Department of Civil & Construction Engineering, University of Nairobi, Nairobi, Kenya

Email: clakimwei@gmail.com

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Abstract

Road markings are a vital, low-cost road safety intervention, yet their real-world performance in Kenya's tropical environment remains poorly understood. This study evaluates thermoplastic road markings across nine sites with varying environmental, traffic, and surface conditions over 33 weeks. Using retroreflectivity, luminance, and thickness as key performance indicators, the study combines laboratory testing with field measurements and statistical analysis. Results show severe premature deterioration, with retroreflectivity declining by 79.3%, luminance by 56.1%, and thickness by 32.3%. All sites failed the minimum retroreflectivity standards within 23 weeks. No statistically significant differences were found across environmental or traffic conditions, though trends suggest a strong environmental influence. The findings reveal a mismatch between laboratory compliance and field performance. The study recommends performance-based standards, improved material specifications, and enhanced monitoring systems, while contributing new empirical evidence and an integrated evaluation framework for thermoplastic road marking performance in tropical conditions.

Keywords

Luminance, Performance Assessment, Retroreflectivity, Road Safety, Thickness Loss, Thermoplastic Road Markings, Tropical Environments

1. Introduction

Worldwide, road traffic injuries continue to be a major cause of death and disa-

bility, with recent estimates suggesting 1.19 million people die each year, with marginal improvement over the last decade [1]. The impacts are disproportionately borne by low- and middle-income nations, especially in the African region, which still experiences the highest rate of deaths globally—over 25 per 100,000 population—despite a lower rate of motorization [1]. In Kenya, road safety is acknowledged as a key development priority, and the National Road Safety Action Plan (2024-2028) aims to reduce road traffic deaths and severe injuries by 50% [2]. This goal demands a mix of behavioral, enforcement, and infrastructural measures, including road markings, which is a key but often overlooked component.

Road markings are one of the most economical and deployable traffic control strategies, offering continuous visual feedback that improves lane control, delineation, and hazard awareness during both day and nighttime hours [3]. Their impact is especially significant in low-visibility conditions, such as nighttime driving and rain, where retroreflectivity and luminance affect driver reaction times and lane maintenance [4]. In Kenya, thermoplastic road markings have increasingly become the preferred type of road markings over traditional solvent-based paints due to their superior initial retroreflectivity, skid resistance, and expected longevity [5]. But although laboratory and temperate weather climate research shows good durability, their field performance in tropical African environments is poorly understood.

The Kenyan Road environment is distinctive in providing a combination of factors that affect degradation, including high ultraviolet radiation, high pavement surface temperatures, rainfall variability, and the rapid growth of traffic with a significant heavy vehicle component [6]. These can hasten binder oxidation, glass bead loss, and abrasion, inducing loss in retroreflectivity and luminance [7]. Previous research in temperate zones has shown thermoplastic road marking service life ranging from 24 to 84 months [8] [9]; yet, observations in Kenya indicate much shorter service lives, often requiring premature replacement [2]. This variation points to a key challenge in applying British performance standards for tropical environments without empirical verification.

The study tackles the absence of field data on the performance of thermoplastic road marking materials in the Kenyan environment. This limits the capacity of road authorities to develop performance-based specifications, determine optimal maintenance rates, and effectively allocate resources. In the absence of relevant field data, current practices may be overly conservative (and therefore costly) or inadequate (and potentially unsafe). The current study aims to bridge this knowledge gap by conducting a multi-parameter field assessment of thermoplastic road markings on selected roads in Kenya. The study focuses on three key performance parameters, as defined in KS EAS 928-2:2019, retroreflectivity (nighttime visibility), luminance (daytime visibility), and thickness (a measure of durability and abrasion resistance). The combined consideration of these parameters in an integrated analytical model, alongside an analysis of their variation across traffic, pavement,

and environmental conditions, is expected to reveal degradation trends and the primary factors underpinning performance degradation.

This study provides novel empirical evidence from a tropical Sub-Saharan context, where such data is currently scarce. It advances existing knowledge by introducing an integrated multi-parameter performance assessment framework that simultaneously evaluates retroreflectivity, luminance, and thickness under real-world conditions. Unlike previous studies that rely on single-parameter or temperate-climate analyses, this research demonstrates the decoupled yet interrelated nature of optical and structural degradation mechanisms and quantifies the extent of premature failure relative to international service life expectations. The findings establish a foundation for context-sensitive performance modeling and policy development in similar environments.

2. Literature Review

2.1. Theoretical Review

2.1.1. Thermoplastic Road Marking Technology

The development of thermoplastic road marking materials dates back to the early 1940 s in the United Kingdom as a means for assisting vehicle travel during black-outs [2]. Over the years, technological developments have transformed these materials into sophisticated formulations that provide improved visibility, strength, and installation speed. Modern thermoplastic formulations typically include the use of hydrocarbon or maleic-modified resin binders, in combination with mineral fillers (such as calcium carbonate), high-quality pigments (including titanium dioxide for enhanced color fastness), and both premixed and surface-treated glass beads to impart retroreflective characteristics [10]. These materials are applied hot (180°C - 220°C) and solidify almost immediately upon cooling to create a durable and well-adhered marking. This rapid set-up time allows for minimal traffic delays and quicker road reopening, a key feature in high traffic areas.

Thermoplastics are solvent-free, which not only aids in environmental sustainability but also enhances worker safety [11]. Beyond their material makeup, road markings are recognized as a vital element of road infrastructure [4], which play the role of continuous visual messaging systems and therefore have a profound impact on driver behavior, vehicle lane keeping, and traffic flow. Research has shown that properly maintained road markings have a considerable impact on drivers' response time and can reduce the number of lane departure accidents, especially during nighttime and poor weather conditions [3] [4] [12]. However, their effectiveness is not only reliant on the initial quality of installation; it is also inevitably tied to the ability to maintain optical performance over time, which is determined by a complex interaction between material characteristics, traffic wear, and environmental degradation. Previous research has emphasized the need for matching of material and application methods to roadway conditions, such as pavement type and traffic load, to optimize long-term performance and cost-effectiveness [5]. This underscores the need for a performance-based approach to

road marking management, rather than a solely prescriptive one.

In this regard, the use of East African Community standards KS EAS 928-1:2019 and KS EAS 928-2:2019 in Kenya is a notable advancement in harmonizing material specifications and performance criteria in the region. KS EAS 928-1:2019 covers the requirements for constituent materials, with KS EAS 928-2:2019 setting minimum in-service requirements for functional parameters. The standard specifies a minimum retroreflectivity of 150 mcd/m²/lux for new white markings to provide sufficient visibility at night. For daytime visibility, minimum luminance values are set at 100 mcd/m²/lux for both transverse and longitudinal markings, ensuring they are visible against asphalt surfaces under daylight conditions. A minimum marking thickness of 1.5 mm is specified to achieve desirable durability against abrasion. Although numerous studies in temperate climates report life expectancies for thermoplastic markings of 24 - 84 months, depending on traffic load and exposure [7] [8], there is some evidence to suggest that such performance may not be replicated under tropical conditions in Kenya. This highlights the importance of region-specific, evidence-based assessments to inform more realistic service life expectations and road asset management strategies.

2.1.2. Performance Parameters and Degradation Mechanism

The retroreflectivity of pavement markings that determine their visibility at nighttime is largely dictated by the optical efficiency of glass beads embedded in the thermoplastic binder system. The beads work by reflecting and redirecting light from vehicle headlamps back to the driver, thus improving nighttime lane visibility. But the sustained efficacy of this process is limited by material degradation. Recent research reveals that loss of retroreflectivity is primarily due to traffic abrasion, which results in glass bead loss, and binder degradation due to ultraviolet (UV) exposure, thermal treatment, and environmental effects [7] [8]. Wang [9] recognizes that microstructural deterioration of the binder-bead interface, such as debonding and surface polishing, also accelerates the decline in retroreflectivity under traffic load. As the binder deteriorates, the exposed beads are then removed by traffic, leading to a gradual non-linear loss of retroreflectivity. This loss affects road safety, as lower retroreflectivity affects driver detection and lane keeping under nighttime conditions [4] [12].

However, luminance, responsible for daytime visibility through diffuse reflectance, is primarily dependent on the pigment content and surface reflectance of the marking material. This is often achieved by a high content of titanium dioxide pigment for brightness and contrast on asphalt. In contrast to retroreflectivity, the degradation of luminance is somewhat independent, primarily affected by surface fouling, pigment degradation, and environmental weathering, such as dust accumulation and rainfall variability [6] [9]. Lin [7] suggests that surface fouling and particle deposition can lead to considerable reductions in luminance even where structural degradation is minimal, suggesting a strong dependence on environmental factors that affect daytime visibility. While luminance decline rates tend to be slower than retroreflectivity, it is still an important consideration for overall

marking performance and particularly in areas subject to high dust emissions and seasonal weather variations.

Thermoplastic marking thickness is a critical measure of structural integrity and performance. Thinning typically results from mechanical wear caused by traffic, lack of bonding between the pavement and marking, and thermal stresses due to expansion and contraction. This leads to progressive loss of material, not only affecting the thickness of the marking but also the exposure and abrasion of glass beads. Experimental evidence demonstrates that wear is heavily dependent on traffic load, vehicle axle configurations, and asphalt surface properties, with smooth asphalt surfaces having reduced bonding and accelerated wear rates compared to textured surfaces [7] [9]. Garbarski's research on thermoplastic materials shows that material properties, especially types of fillers, also affect wear and deformation resistance [10]. Therefore, thickness loss is not only directly related to the degradation of the structure, but also indirectly related to the deterioration of the optical performance.

In terms of modeling the performance of thermoplastic road markings, the rate of deterioration differs among performance characteristics. Exponential models are typically used to describe retroreflectivity loss, reflecting an initial accelerated rate of loss and subsequent stabilization in bead loss [8]. By contrast, wear is often linearly related to thickness loss, due to progressive removal of material under traffic loads. Environmental conditions play a critical role in these processes, with temperature being a major factor due to its impacts on binder softening, chemical reactions, and thermal expansion. Higher temperatures increase chemical degradation, while temperature cycles lead to cracking and loss of adhesion. Water content and precipitation variability also play a role in degradation by softening the binder matrix and causing interface degradation [6]. State-of-the-art durability evaluation also reveals that the interaction of environmental and mechanical stresses results in synergistic degradation, which accelerates loss in performance beyond what might be anticipated from the individual stresses [9].

Surface texture also has a significant impact on performance. Rough surfaces, like chip seals, increase mechanical interlocking and adhesion, which increases resistance to shear stresses and results in less material loss. By contrast, dense-graded asphalt concrete surfaces offer minimal macrotexture, leading to lower adhesion and higher wear rates in high traffic [7]. These insights are increasingly significant in the era of transportation infrastructure, where quality road markings are also required for machine vision systems to support automated driving systems and advanced driver assistance systems (ADAS), underlining the need for long-lasting marking performance [12].

2.2. Empirical Review

2.2.1. Existing Studies

There has been a trend towards considering optical, mechanical, environmental, and traffic parameters, as opposed to single-parameter optical performance, in empirical studies of road marking performance in recent years. This trend is in

line with the primary objective of the current study, which is to evaluate the performance of thermoplastic road markings on Kenyan roads using retroreflectivity, luminance, and thickness. The particular objective of this review is thus an assessment of how earlier studies have quantified and described the deterioration mechanisms of the performance of thermoplastic road markings.

Babić [3] investigated the role of road markings and road signs in road safety, highlighting that road markings do not simply provide passive road safety information but also act as dynamic visual indications that shape driver behavior, lane keeping, and road safety. Their research demonstrated that the visibility of road markings is highly related to road users' decision-making, especially in dark and poor visibility conditions. But this study primarily offered a general synthesis with a safety focus, and did not empirically define the effects of the combined loss of retroreflectivity, luminance, and thickness under real road conditions.

Sayer [4] examined the retroreflectivity of pavement marking and driver performance under nighttime conditions. Their results validated the notion of increased retroreflectivity leading to better driver lane recognition and nighttime guidance, thereby reinforcing the role of retroreflectivity as a key performance metric. However, this study was primarily concerned with nighttime visibility and did not consider daytime luminance or temperature loss-induced thickness loss, so it was of limited value for evaluating the performance of thermoplastic markings.

Tajnin [5] proposed a road marking management plan for the state of Wyoming, which covered maintenance management and performance-based asset management. This study highlighted the importance of data collection and lifecycle-centered maintenance planning to enhance road markings' performance. But it was undertaken under temperate climatic conditions, which are quite different from tropical conditions in Kenya, where high temperatures, variable rainfall, and high ultraviolet light exposure could lead to deterioration.

Lin [7] evaluated the durability of thermoplastic road marking under environmental and traffic loads. They concluded that the deterioration of the material is significantly affected by traffic wear and environmental factors, such as temperature and moisture. This research is relevant to the present study because it focuses on the durability of thermoplastic markings. But it doesn't offer evidence that is specific to Kenyan roads or that evaluates deterioration against the KS EAS 928-2:2019 performance criteria.

Zhao [8] modeled the service life of thermoplastic road markings on expressways using performance deterioration modeling. They observed that the degradation of retroreflectivity follows a non-linear trend, showing an initial fast degradation and then slow deterioration. This offers insight for service life modeling. But the study primarily considered expressway environments and retroreflectivity-based prediction, with little emphasis on integration of luminance and thickness as additional measures of performance deterioration.

2.2.2. Knowledge Gap

The existing research summarized in **Table 1** confirms that road marking perfor-

mance is affected by visibility, material durability, traffic, and environmental factors. However, most current studies either consider only retroreflectivity, evaluate performance under temperate climate conditions, or discuss maintenance planning without including optical and physical performance indicators. This poses a significant problem for Kenya, where thermoplastic markings are exposed to extreme heat and high UV exposure, combined with seasonal rain and ever-growing traffic loads. The issue with this is that road agencies do not have empirical data for local conditions to verify whether thermoplastic markings comply with the KS EAS 928-2:2019 criteria for retroreflectivity, luminance, and thickness. So, this study fills the gap by offering an integrated empirical performance evaluation in the Kenyan environment.

Table 1. Summary of the empirical literature.

Author	Study Variables	Findings	Research Gap	Critique
Babić [3]	Road markings, signs, road safety	Markings improve driver guidance, lane discipline, and traffic safety	Limited empirical focus on thermoplastic degradation parameters	Broad safety review; lacks field-based material performance analysis
Sayer [4]	Retroreflectivity, nighttime driving performance	Higher retroreflectivity improves nighttime lane visibility and driver response	Excludes luminance and thickness deterioration	Strong visibility evidence but narrow single-parameter focus
Tajnin [5]	Pavement marking management, maintenance planning	Systematic marking management improves lifecycle maintenance decisions	Based on temperate conditions, not tropical road environments	Useful management framework but limited climatic transferability
Lin [7]	Thermoplastic durability, traffic loading, environment	Traffic and environmental exposure accelerate thermoplastic deterioration	Does not assess Kenyan roads or KS EAS thresholds	Closely related but lacks local regulatory and climatic context
Zhao [8]	Service life, retroreflectivity, expressways	Retroreflectivity follows rapid early decline and gradual later decay	Limited integration of luminance and thickness indicators	Strong modelling approach but mainly retroreflectivity-centered

3. Methodology

3.1. Laboratory Characterization

Three commercially available thermoplastic materials were characterized at a national material testing laboratory. Testing methods assessed binder content, aggregate content, luminance factor, heat stability, and softening point against KS EAS 928-1:2019. Glass beads were evaluated for moisture proofing, flow properties, and particle size distribution in accordance with AS 2009/BS 6088 standards.

3.2. Site Selection

Nine strategic locations were selected to represent Kenya's diverse environmental zones, traffic classes, and surface types. Sites included coastal hot-humid roads (Mtwapa-Kilifi; Port Reitz-Moi International Airport (110) Access Road), high-land Cool-wet roads (Naivasha-Rironi, Kenol-Sagana), arid very hot and dry roads (Isiolo-Merille), hot-dry semi-arid roads (A8 Kibwezi-Makindu; Emali-Oloitoktok), and hot-wet urban routes (Nairobi Southern Bypass; T-Mall Flyover). Each site featured controlled trials of 0.1 m wide stripes spaced at 150mm intervals to form bundles representing a specific thermoplastic brand, as shown in **Figure 1**. At each of the nine sites, all three thermoplastic brands were installed within the same trial section to minimize between-site bias. Each brand was represented by five 100 mm trial stripes/lines labeled L1, L3, L5, L7, and L8, spaced at 150 mm intervals. For each brand and time point, retroreflectivity and luminance were measured at five transverse positions, M1 to M5, from the edge-line offset to the center of the trial lane. The site-level value was obtained by first averaging the five readings per stripe, then averaging the five stripes per brand, and finally averaging the three brands to obtain one site-level mean per parameter and monitoring week.

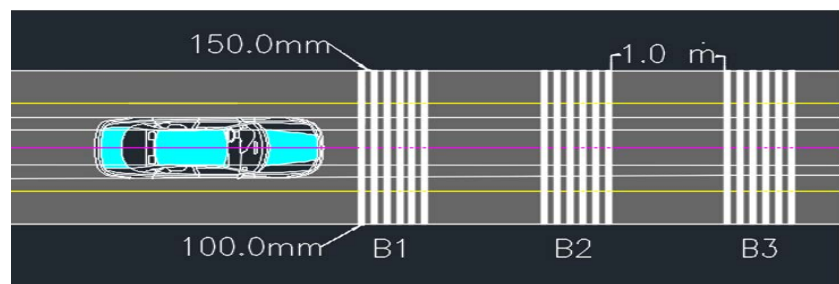


Figure 1. Trial sections: B1—Brand 1, B2—Brand 2, and B3—Brand 3.

Both application and ground temperatures were recorded. Thermoline was applied at 150°C - 180°C, Duratherm at 180°C - 200°C, and Automark at 180°C - 220°C. Ground temperatures at application ranged from 37.5°C (Nairobi) to 64°C (T-Mall Flyover).

3.3. Performance Monitoring

Field measurements were taken during application at baseline (week 0), after approximately 23 weeks (first monitoring), and after 33 weeks (second monitoring). Parameters monitored included retroreflectivity and luminance, which were measured using calibrated mobile retroreflectometers per EN 1436. Thickness was measured with calibrated electronic gauges at five positions per trial stripe. Width was measured using a steel rule.

The same trial stripes and measurement positions were remeasured at baseline, Week 23, and Week 33. Retroreflectivity and luminance readings were taken at M1 to M5 for each stripe/brand combination, while thickness was measured at the

middle and wheel-path positions using calibrated electronic gauges. Missing or visibly invalid readings caused by obstruction, dirt, or instrument non-response were excluded from the arithmetic mean. Where cleaning checks were conducted, the cleaned readings were treated as diagnostic observations and were not used to replace the primary uncleaned monitoring values unless explicitly stated.

3.4. Statistical Analysis

Temporal degradation within each site was assessed by one-way ANOVA with Tukey's HSD post-hoc test applied to the three time-point means (Week 0, Week 23, Week 33). Between-site comparisons within each environmental condition were made using independent-samples t-tests. The effect of environmental condition, traffic classification, and surface type on Week 33 performance was assessed by one-way ANOVA. Pairwise relationships among the three performance loss metrics were quantified by Pearson correlation. Statistical significance was set at $\alpha = 0.05$ throughout. Where groups contained only one site, pairwise comparisons could not be performed, and results are reported as descriptive.

The site was treated as the primary unit of analysis for between-group comparisons. Because each environmental, surface, and traffic group contained a small number of sites, and because repeated observations from the same site are not fully independent, ANOVA, t-tests, and Pearson correlations were interpreted as exploratory screening tools rather than definitive inferential tests. Accordingly, emphasis was placed on effect direction, threshold exceedance, percentage loss, and consistency of temporal patterns. Confirmatory modeling would require a larger number of replicated sites per environmental and traffic class or a mixed-effects repeated-measures design.

4. Results and Findings

4.1. Laboratory Characterization

Table 2 summarises the laboratory test results. All three brands met the KS EAS 928-1:2019 aggregate content specification of $80\% \pm 2\%$. For binder content, the standard specifies $20\% \pm 2\%$, which defines an acceptable range of 18.0% - 22.0%. All three brands fall within this range: Thermoline (21.3%) near the upper bound, Duratherm (18.8%), and Automark (19.0%) near the lower bound. While technically compliant, the proximity of Duratherm and Automark to the lower tolerance limit warrants quality-control attention, as binder content at the lower end of the range may reduce long-term adhesion and flexibility under Kenyan temperature cycling.

Luminance factor ranged from 70.36% (Automark) to 92.05% (Thermoline), all meeting the $\geq 70\%$ minimum. Heat stability exceeded 65% for all brands. Softening point exceeded the 85°C minimum for all brands. Glass bead characterization confirmed compliance with AS E42/BS 6088 across all brands, indicating that retroreflectivity failures observed in the field are attributable primarily to binder matrix degradation rather than inadequacy of the reflective media.

4.2. Field Performance Overview

Table 3 presents the complete performance dataset for all nine sites at all three measurement intervals, together with percentage losses at Week 33. All sites recorded severe degradation across all three parameters. The mean retroreflectivity loss of 79.3% (Standard Deviation at 9.5%) and mean thickness loss of 32.4% (Standard Deviation at 21.8%) represent severe premature deterioration relative to international service life expectations.

Effective service life was calculated from the time at which retroreflectivity first crossed the KS EAS minimum threshold of 150 mcd/m²/lux. Since all sites were above the threshold at baseline and below it by Week 23, crossing time was estimated separately for each site by linear interpolation: Service life (weeks) = $23 \times (R_0 - 150) / (R_0 - R_{23})$, where R_0 is baseline retroreflectivity, and R_{23} is Week 23 retroreflectivity. The site-specific service lives were then converted to months by dividing by 4.345 and summarised as mean $\pm$ standard deviation across the nine sites.

Table 2. Laboratory characterization results for three thermoplastic paint brands against KS EAS 928-1:2019.

Parameter	Thermoline	Duratherm	Automark	KS EAS 928-1:2019
Aggregate Content (%m/m)	78.7	81.2	81.0	80 $\pm$ 2
Binder Content (%m/m)	21.3	18.8	19.0	20 $\pm$ 2
Luminance Factor (%)	92.05	81.51	70.36	White $\geq$ 70
Heat Stability (%)	91.09	81.81	70.77	White $\geq$ 65
Softening Point ($^{\circ}$ C)	86.8	112.7	115.8	$\geq$ 85 $^{\circ}$ C

Table 3. Comprehensive performance data—retroreflectivity (R), luminance (L), and thickness (T) at Baseline, Week 23, and Week 33. DSD = Double Seal Surface Dressing; AC = Asphalt Concrete; SSD = Single Seal Surface Dressing.

Road	Env.	Traf Surf.		R ₀	R ₂₃	R ₃₃	R %loss	L ₀	L ₂₃	L ₃₃	L %loss	T ₀ (mm)	T ₂₃	T ₃₃	T %loss
Nairobi Southern Bypass	Hot & Wet	T1	DSD	194.3	34.4	33.4	82.84%	252.4	138.8	128.14	49.23%	3.05	2.11	1.96	34.92%
T-Mall Flyover	Hot & Wet	T1	AC	212.0	45.9	43.7	79.40%	270.6	95.92	87.95	67.50%	2.79	1.44	1.13	59.57%
Naivasha-Rironi	Cool & Wet	T1	DSD	207.8	37.0	29.5	85.80%	221.3	113.55	83.78	62.13%	2.68	1.97	1.93	27.99%
Kenol-Sagana	Cool & Wet	T1	SSD	169.2	75.8	67.9	59.85%	255.8	113.96	106.89	58.21%	3.78	3.42	3.31	12.58%
Isiolo-Merille	V.Hot & Dry	T2	DSD	176.2	30.5	24.7	85.99%	259.68	94.15	80.23	69.10%	3.86	3.78	3.73	3.60%
A8 Kibwezi-Makindu	Hot & Dry	T2	DSD	184.7	42.9	34.8	81.16%	254.23	175.76	150.65	40.75%	3.77	3.29	3.29	12.74%
Mtwapa-Kilifi	Hot & Humid	T1	AC	191.9	48.7	33.1	82.75%	249.5	144.53	100.98	59.52%	3.78	2.80	2.14	43.34%
Port Reitz-Moi International Airport (110) Access Road	Hot & Humid	T1	SSD	215.1	28.5	25.0	88.30%	239.52	108.99	104.85	56.23%	3.97	1.74	1.26	68.15%
Emali-Oloitoktok	Hot & Dry	T2	DSD	241.9	82.0	79.1	67.30%	224.5	143.9	134.47	40.07%	3.78	3.2	2.71	28.25%
MEAN	—	—	—	199.2	47.3	41.2	79.3%	247.8	125.5	108.7	55.9%	3.49	2.64	2.38	32.3%

Traffic class T1 denotes the higher-traffic trial roads, mainly urban, trunk or access routes with heavier vehicle exposure, whereas T2 denotes lower-to-moderate traffic routes within the selected trial network. Environmental categories were assigned using the nearest Kenya Meteorological Department station or gridded climate series, supported by monthly rainfall, maximum/minimum temperature, relative humidity, and radiation records. Hot and Wet sites combine high temperature with relatively high rainfall/humidity; Cool and Wet sites have lower highland temperatures and higher rainfall; Very Hot and Dry sites have high temperatures and low rainfall; Hot and Dry sites have high temperatures and low-to-moderate rainfall; and Hot and Humid sites represent coastal exposure with high humidity and rainfall influence.

4.3. Retroreflectivity Performance

4.3.1. Temporal Degradation

Figure 2 shows retroreflectivity at all three time points across the nine study sites. All sites recorded a steep initial decline between baseline and Week 23, with losses ranging from 55.2% (Kenol-Sagana) to 86.8% (Port Reitz-Moi International Airport (110) Access Road) at Week 23. Critically, all nine sites had fallen below the 150 mcd/m²/lux minimum standard by Week 23. No meaningful recovery was observed; minor variations between Week 23 and Week 33 are attributable to measurement variability rather than material recovery. The rate of decline decelerated markedly after Week 23 (mean rate: 6.61 mcd/m²/lux per week from W0-W23, falling to 0.61 mcd/m²/lux per week from W23 - W33), consistent with the exponential decay pattern documented in the literature. The overall picture is one of irreversible failure across all sites and conditions.

4.3.2. Environmental Condition Effects

Figure 3 compares retroreflectivity at Week 23 and Week 33 grouped by environmental condition. One-way ANOVA found no statistically significant difference in

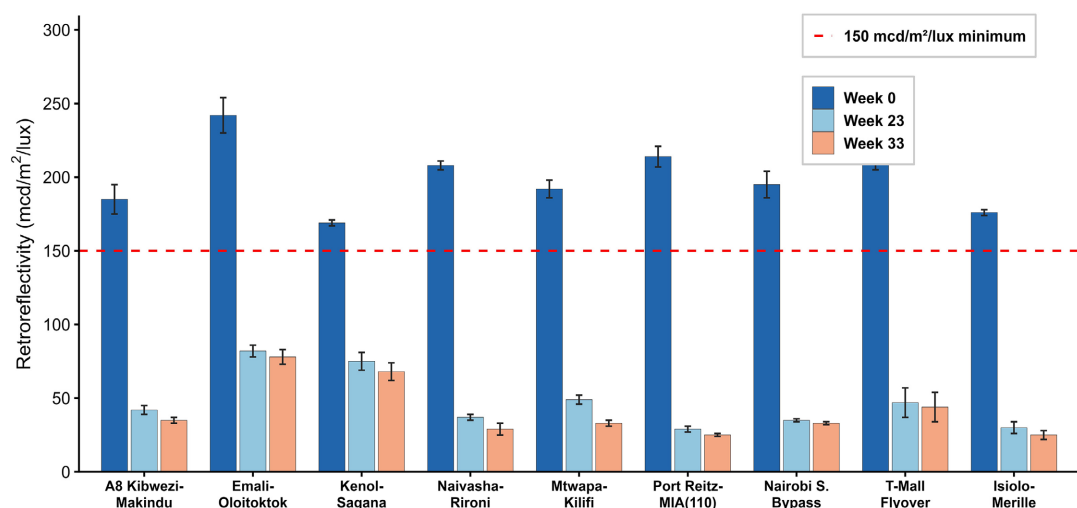


Figure 2. Retroreflectivity (mcd/m²/lux) at Baseline, Week 23, and Week 33 across all study sites. Red dashed line = 150 mcd/m²/lux minimum standard. All nine sites fall below standard by Week 23.

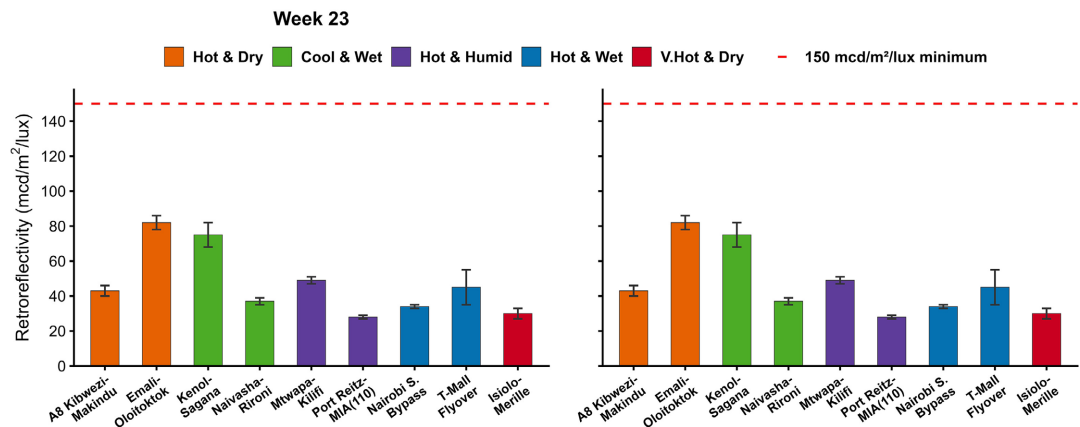


Figure 3. Comparative retroreflectivity by environmental condition at Week 23 (left) and Week 33 (right). Red dashed line = 150 mcd/m²/lux minimum standard.

Week 33 retroreflectivity across environmental conditions ($F(4, 4) = 0.660$, $p = 0.652$). This result must be interpreted with caution: each environmental group contains only one or two sites ($n = 1 - 2$ per group), which severely constrains statistical power. Descriptively, the very hot and dry site (Isiolo-Merille, mean 24.7 mcd/m²/lux) and hot and humid sites (Port Reitz-Moi International Airport (110) Access Road, mean 25.0 mcd/m²/lux) performed worst, while hot and dry roads (Emali-Oloitoktok, mean 79.1 mcd/m²/lux) retained comparatively more retroreflectivity. Pairwise t-tests between environmental groups (Table 4) returned no significant differences after multiple comparisons; wider replication would be needed to confirm the descriptive pattern.

Table 4. Pairwise t-tests for Week 33 retroreflectivity by environmental condition (n.s. = not significant at $\alpha = 0.05$; $n \leq 2$ per group limits statistical power).

Comparison (Retro W33)	Mean Grp A	Mean Grp B	t	p	Result
Hot & Wet vs Cool & Wet	38.5	48.7	-0.511	0.691	n.s.
Hot & Wet vs Hot & Dry	38.5	56.9	-0.809	0.556	n.s.
Hot & Wet vs Hot & Humid	38.5	29.1	1.450	0.291	n.s.
Cool & Wet vs Hot & Dry	48.7	56.9	-0.281	0.805	n.s.
Cool & Wet vs Hot & Humid	48.7	29.1	1.001	0.488	n.s.
Hot & Dry vs Hot & Humid	56.9	29.1	1.239	0.422	n.s.

4.4. Luminance Performance

Temporal Degradation

Figure 4 and Figure 5 show that the mean baseline luminance of 247.8 mcd/m²/lux fell to 125.5 mcd/m²/lux by Week 23 (49.3% decline) and to 108.7 mcd/m²/lux by Week 33 (56.1% overall decline). Two sites fell below the 100 mcd/m²/lux minimum by Week 23 (T-Mall Flyover at 95.92 and Isiolo-Merille at 94.15), increasing to three sites below standard at Week 33 (T-Mall Flyover, Naivasha-Rironi, and Isiolo-Merille). Luminance continued to decline at all sites between Week 23 and Week

33, with no site recording a recovery. The largest W23 - 33 decline was recorded at Mtwapa-Kilifi ($-43.6 \text{ mcd/m}^2/\text{lux}$), consistent with continued binder degradation and pigment bleaching under coastal humid conditions.

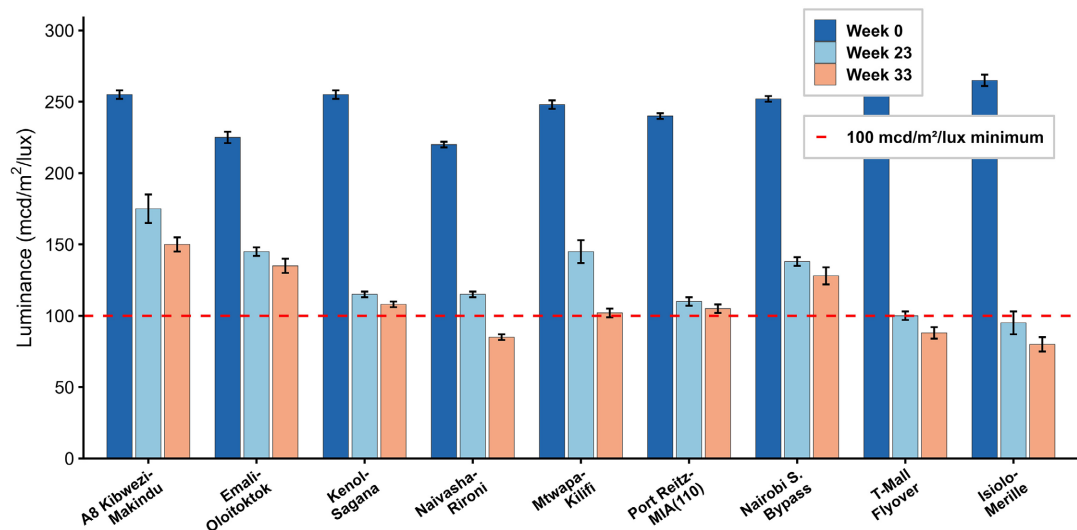


Figure 4. Luminance ($\text{mcd/m}^2/\text{lux}$) at Baseline, Week 23, and Week 33 across all study sites. Red dashed line = $100 \text{ mcd/m}^2/\text{lux}$ minimum standard.

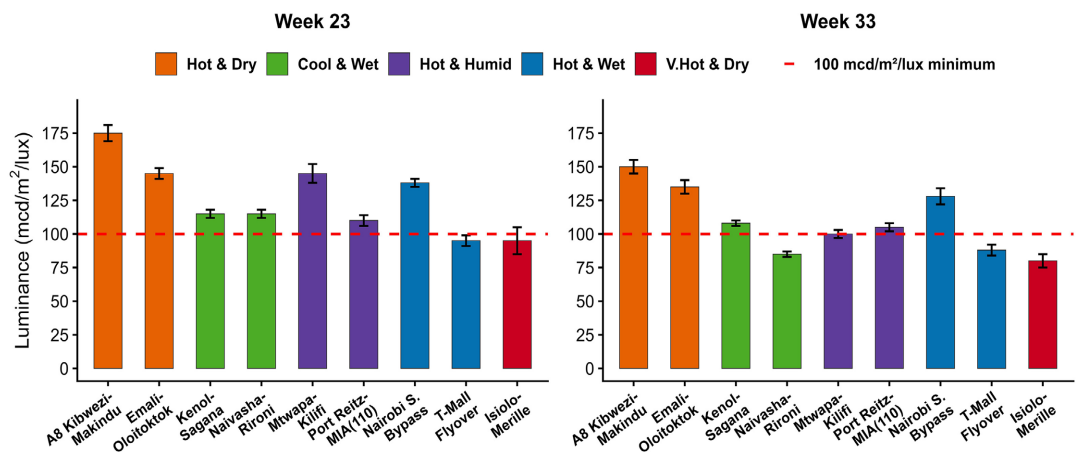


Figure 5. Comparative luminance by environmental condition at Week 23 (left) and Week 33 (right). Red dashed line = $100 \text{ mcd/m}^2/\text{lux}$ minimum standard.

Comparative luminance performance by environmental condition is shown in Figure 5.

4.5. Thickness Performance

Temporal Degradation

Figure 6 shows thickness trajectories for all nine sites. Mean thickness fell from 3.49 mm at baseline to 2.64 mm at Week 23 and 2.38 mm at Week 33, representing 32.3% average loss over 33 weeks. The most severe loss was recorded at Port Reitz-Moi International Airport (110) Access Road (68.15%), where the Week 33 thick-

ness of 1.26 mm represents substantial material loss. Isiolo-Merille recorded the lowest loss (3.6%), consistent with its lower traffic volume (T2 classification), limiting abrasive wear despite extreme thermal exposure.

One-way ANOVA across environmental conditions found no statistically significant difference in Week 33 thickness ($F(4,4) = 2.714$, $p = 0.178$), again constrained by small group sizes. Descriptively, the hot and humid group recorded the highest mean thickness loss (55.8%), while the very hot and dry group showed the least (3.4%), which is consistent with dominant UV-driven surface degradation at Isiolo rather than bulk material abrasion. Thickness variation by traffic classification is illustrated in **Figure 7**.

4.6. Integrated Percentage Loss Comparison

Figure 8 presents the percentage losses for all three parameters side by side at

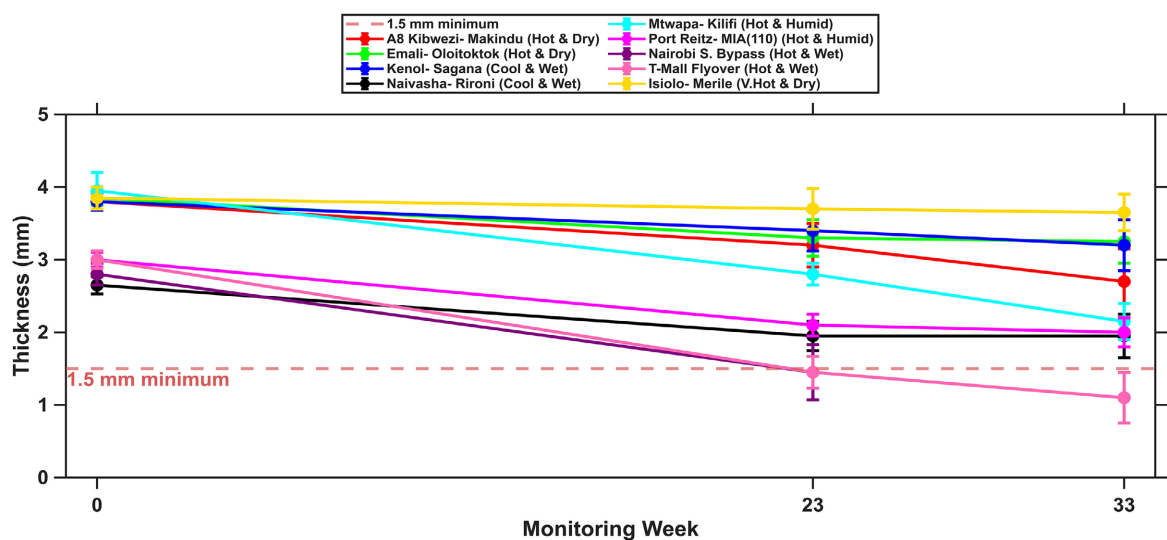


Figure 6. Thickness at Week 23 (left) and Week 33 (right) by traffic classification. T2 (lower traffic) sites are on the left of each panel, T1 (higher traffic) on the right. Red dashed = 1.5 mm minimum.

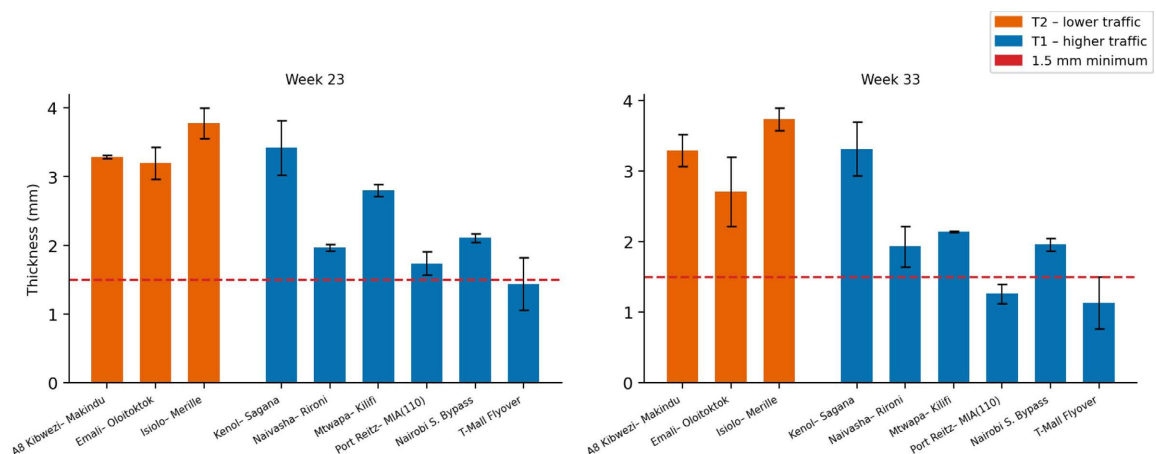


Figure 7. Thickness (mm) trajectories at Baseline, Week 23, and Week 33 for all study sites. Red dashed line = 1.5 mm minimum application thickness. Sites colour-coded by environmental condition.

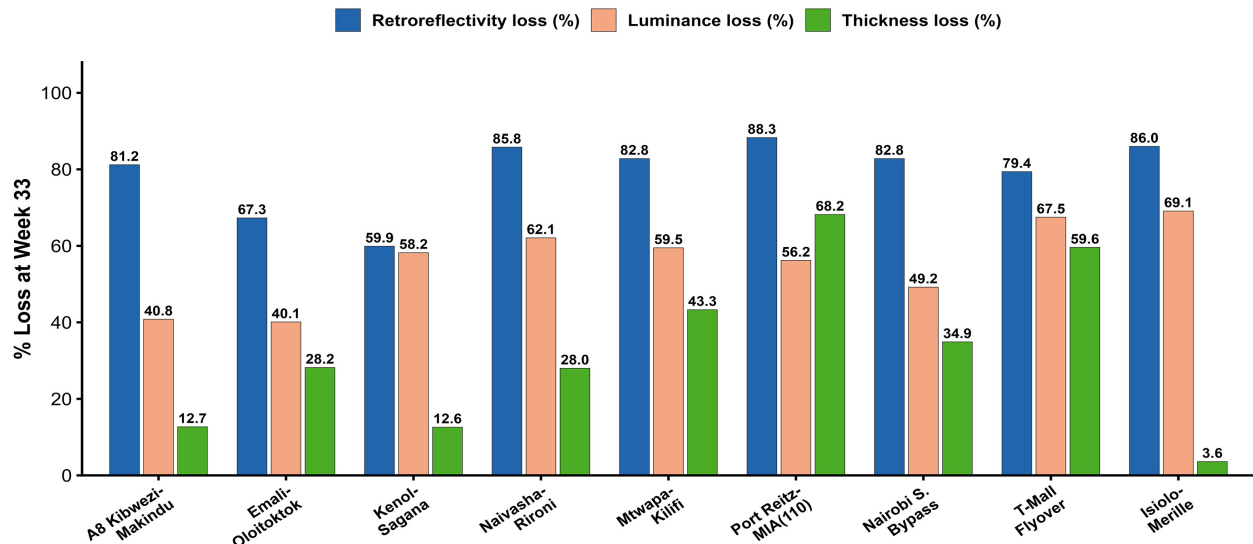


Figure 8. Percentage loss of retroreflectivity (blue), luminance (orange), and thickness (green) at Week 33 for all study sites. Values above bars show the actual percentage loss.

Week 33. The pattern of relative losses varies considerably by site, reinforcing that no single parameter is sufficient to characterize overall marking condition. Port Reitz-Moi International Airport (110) Access Road shows extreme thickness loss (68.15%) while its retroreflectivity loss (88.4%) and luminance loss (56.2%) are severe but less extreme, indicating that binder loss at this site is near-total but that some surface reflectance remains. Conversely, Isiolo-Merille shows moderate thickness loss (3.4%) but severe retroreflectivity loss (86.0%) and luminance loss (69.1%) among the sites with lower thickness change, consistent with UV bleaching and bead extraction without equivalent bulk material loss.

4.7. Surface Type Effects

Figure 9 shows Week 33 performance grouped by road surface type. One-way ANOVA found no significant effect of surface type on retroreflectivity ($F(2, 6) = 0.077$, $p = 0.927$). Descriptively, Asphalt Concrete (AC) and Single Seal Surface Dressing (SSD) sites recorded slightly lower retained retroreflectivity than Double Seal Surface Dressing (DSD) sites, contrary to some international findings that AC provides superior bonding. The small sample ($n = 2$ per non-DSD group) and confounding by environmental conditions prevent firm conclusions. Port Reitz-Moi International Airport (110) Access Road (SSD, hot and humid), with its exceptional thickness loss of 68.15%, most likely reflects the combination of surface type and extreme coastal climate rather than either factor alone.

4.8. ANOVA Summary

Table 5 summarizes the one-way ANOVA results for all grouping variables. None of the between-group tests reached statistical significance at $\alpha = 0.05$. The consistent pattern of non-significance must be interpreted in light of the study's structural limitation: with $n = 1 - 2$ sites per environmental group, the between-group

ANOVA is severely underpowered. The failure to reject the null hypothesis should not be read as evidence that environmental condition, traffic class, or surface type are unimportant; rather, the study design precludes definitive statistical conclusions on this question, and descriptive patterns are reported to guide hypotheses for future larger-scale studies.

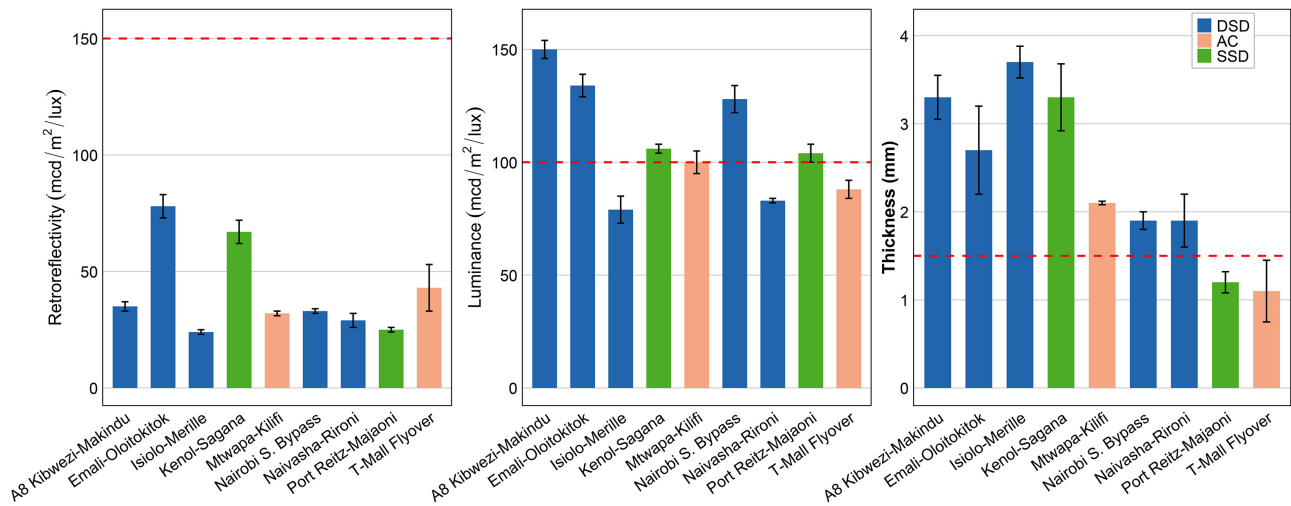


Figure 9. Retroreflectivity, luminance, and thickness at Week 33 by road surface type. Red dashed lines = minimum standards (150, 100 mcd/m²/lux, 1.5 mm respectively).

Table 5. Summary of one-way ANOVA results for Week 33 performance by grouping variables.

Test	Grouping Variable	F-Statistic	p-Value	Interpretation
Retro (W33)	Environmental Condition	0.660	0.652	Not Significant
Retro (W33)	Traffic Classification	0.268	0.620	Not Significant
Retro (W33)	Road Surface Type	0.077	0.927	Not Significant
Luminance (W33)	Environmental Condition	2.909	0.163	Not Significant
Thickness (W33)	Environmental Condition	2.714	0.178	Not Significant

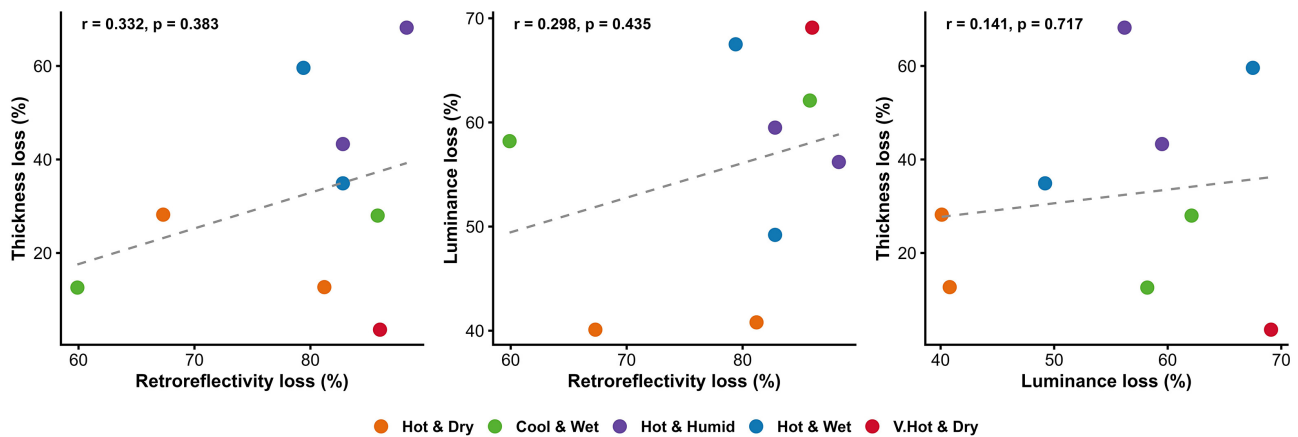
4.9. Correlation Analysis

Table 6 presents Pearson correlations between the three performance loss metrics at Week 33. The retroreflectivity-thickness loss correlation is weak and positive ($r = 0.335$) and does not reach statistical significance ($p = 0.378$, $n = 9$). This indicates only a limited tendency for sites with greater thickness loss to also show greater retroreflectivity loss; the current sample of nine sites is insufficient to establish the relationship as statistically reliable. The retroreflectivity-luminance correlation is similarly weak ($r = 0.298$, $p = 0.436$), reflecting the partial independence of these two degradation pathways. Luminance loss and thickness loss show negligible correlation ($r = 0.135$, $p = 0.729$), confirming that daytime visibility is driven primarily by pigment bleaching and surface soiling rather than material loss per se.

The relationships between performance loss variables are illustrated in **Figure 10**.

Table 6. Pearson correlation coefficients between performance loss metrics at Week 33 (n = 9). n.s. = not statistically significant.

Variable Pair	Pearson r	p-Value	n	Interpretation
Retroreflectivity Loss vs Thickness Loss	0.335	0.378	9	Weak Positive, Not Significant
Retroreflectivity Loss vs Luminance Loss	0.298	0.436	9	Weak Positive, Not Significant
Luminance Loss vs Thickness Loss	0.135	0.729	9	Negligible Positive, Not Significant

**Figure 10.** Pairwise scatter plots for retroreflectivity, luminance, and thickness percentage losses at Week 33. Dashed lines = linear trend. All correlations were non-significant ($p > 0.05$, $n = 9$).

The results in **Figures 2-10** and **Tables 2-6** demonstrated a consistent pattern of rapid and irreversible performance deterioration across all study sites, irrespective of environmental condition, traffic classification, or surface type. Although statistical tests did not yield significant differences between groups, this outcome is primarily attributable to the limited sample size rather than the absence of underlying physical effects. Descriptive trends indicate that environmental exposure, particularly temperature and humidity, plays a dominant role in driving degradation processes. Critically, the observed rate of performance loss far exceeds internationally reported service life expectations, with all sites failing minimum retroreflectivity requirements within 23 weeks. This indicates that current thermoplastic materials, while compliant with existing specifications, are not adequately suited to the combined effects of tropical climate, high ultraviolet radiation, and increasing traffic loading conditions in Kenya. The findings, therefore, point to a systemic mismatch between laboratory-based material specifications and actual field performance.

4.10. Exploratory Statistical Assessment of Performance Variation

To further examine whether thermoplastic road-marking deterioration varied across environmental and traffic conditions, exploratory statistical analyses were conducted using Week 33 site-level retroreflectivity data. Due to the limited num-

ber of monitored sites within each category, the analyses were interpreted descriptively rather than as confirmatory statistical tests. One-way analysis of variance (ANOVA) was used to assess differences among environmental and traffic classes, while Pearson correlation analysis was applied to evaluate relationships among percentage losses in retroreflectivity, luminance, and thickness. In addition, a service-life interpolation analysis based on retroreflectivity threshold crossing was performed to estimate the effective operational lifespan of the markings under Kenyan field conditions. The results are presented in **Tables 7-9**.

Table 7. ANOVA by environmental and traffic category.

Source	Df	Sum Sq	Mean Sq	F Value	Pr (>F)
Environment	4	1619.0	404.7	1.012	0.496
Residuals	4	1600.0	400.0	—	—
Traffic Class	1	118.8	118.8	0.268	0.620
Residuals	7	3100.0	442.9	—	—

Table 8. Correlation of percentage losses.

Variable	Retroreflectivity	Luminance	Thickness
Retroreflectivity	1.000	0.391	0.486
Luminance	0.391	1.000	0.105
Thickness	0.486	0.105	1.000

Table 9. Service-life summary.

mean_months	sd_months	min_months	max_months
1.40	0.427	0.772	2.03

The exploratory ANOVA results indicated no statistically significant differences in retroreflectivity deterioration across environmental categories ($p = 0.496$) or traffic classes ($p = 0.620$), although noticeable variability was observed between sites. This suggests that deterioration trends were influenced by multiple interacting factors rather than a single categorical variable. Correlation analysis showed moderate positive relationships between retroreflectivity loss and thickness loss ($r = 0.486$), and between retroreflectivity and luminance losses ($r = 0.391$), implying that physical wear and optical degradation may occur concurrently during field exposure. The estimated mean service life based on retroreflectivity threshold interpolation was approximately 1.40 months $\pm$ 0.43 months, with site-specific values ranging from 0.77 to 2.03 months. These findings further demonstrate the substantial disparity between laboratory conformity and actual field durability under tropical operational conditions.

4.11. Discussion

The Kenyan sites failed the retroreflectivity threshold within the first monitoring

interval, indicating a substantially shorter effective life than the 24 - 84 months commonly reported in temperate studies. This contrast shows that laboratory compliance alone is not sufficient to guarantee field durability under tropical exposure, high pavement temperature, humidity/rainfall variability, traffic abrasion, and local surface conditions. The mismatch is important because all brands met key laboratory specifications, yet field optical performance deteriorated rapidly. Therefore, the study contributes evidence that Kenyan specifications should move beyond initial material conformity toward performance-based acceptance, periodic retroreflectivity monitoring, and climate-sensitive maintenance planning.

5. Conclusions

5.1. Economic and Safety Implications

The observed failure of all nine sites to meet the minimum retroreflectivity threshold within 23 weeks corresponds to an estimated effective service life of 2.9 months $\pm$ 1.3 months, derived through interpolation between baseline and Week 23 measurements. This is approximately 8 - 24 times shorter than internationally reported service lives (24 - 84 months), indicating a fundamental performance deficit under Kenyan conditions.

The safety implications are significant. With retroreflectivity falling below acceptable levels within the first months of service, nighttime lane delineation becomes inadequate, increasing the risk of lane departure and collision events. Luminance falling below standard at two sites by Week 23 further indicates that daytime visibility is also compromised in more aggressive environments. In addition, the near-complete thickness loss observed at the Port Reitz-Moi International Airport (110) Access Road (68.15%) suggests a loss of surface aggregate and associated skid resistance, thereby increasing the risk of vehicle instability, particularly under wet conditions.

The field dataset did not directly measure binder chemistry, bead retention, skid resistance, or microstructural bead-binder bonding. Therefore, observed reductions in retroreflectivity, luminance, and thickness are interpreted as field-performance outcomes, while binder degradation, bead loss, pigment weathering, and abrasion are discussed as probable mechanisms supported by the literature rather than as directly measured causes.

5.2. Recommendations

5.2.1. Material and Application Standards

Although all tested thermoplastic materials met KS EAS 928-1:2019 requirements, field performance indicates that current specifications are not sufficiently adapted to tropical conditions. It is recommended that:

- i) Current thermoplastic specifications should be revised from composition-based requirements to performance-based standards that evaluate retained field performance over time. This should include measurable criteria such as retroreflectivity retention, bead retention, and durability under simulated tropical expo-

sure conditions (UV, temperature, and moisture). Such a framework will ensure that materials are approved based on demonstrated in-service performance rather than initial compliance alone.

ii) Within the revised performance-based framework, material standards should place specific emphasis on binder durability and glass bead retention. This should include requirements for resistance to ultraviolet and thermal-oxidative degradation, as well as improved bead embedment and retention performance. These enhancements are necessary to address premature loss of retroreflectivity, which is primarily driven by early surface degradation rather than insufficient bulk thickness.

iii) Application quality control should be strengthened through strict monitoring of application temperature, pavement surface condition, bead embedment, and adhesion at the pavement-marking interface.

These reforms are necessary to align laboratory specifications with actual field performance requirements in tropical environments. Together, these measures establish a performance-driven specification framework capable of addressing the premature failure observed in this study.

5.2.2. Transition to Performance-Based Maintenance

The rapid deterioration observed renders fixed-interval maintenance approaches ineffective. It is recommended that road agencies should adopt performance-based maintenance contracts in which contracts are structured around performance guarantees, not just installation. Payment and defect liability should be linked to retained field performance over time, particularly on established thresholds. Contractors should be required to remedy premature failures within defined liability periods.

This enables targeted interventions on high-risk road segments, enhancing safety and operational effectiveness; reduces unnecessary re-marking in slower-degrading environments, lowering lifecycle costs and material waste; and improves the allocation of maintenance budgets through data-driven prioritization of interventions.

5.2.3. Research Priorities

The current study is limited by the small number of sites ($n = 9$) and the 33-week monitoring horizon. Statistical analyses, particularly the ANOVA and correlation results, are inconclusive and must be considered exploratory. Future research should extend monitoring to 24 months across a larger site network (minimum $n = 5$ per environmental group to achieve adequate ANOVA power), incorporate weigh-in-motion traffic data for precise load quantification, and include controlled application temperature logging to isolate workmanship effects from material and environmental factors.

5.3. Research Summary

This study provides the first systematic, multi-parameter assessment of thermo-

plastic road marking performance across Kenya's diverse environmental zones. The findings demonstrate that all nine sites failed the 150 mcd/m²/lux retroreflectivity minimum by Week 23, with losses ranging from 59.9% to 88.4% by Week 33. Mean luminance loss reached 56.1%, with two sites falling below the 100 mcd/m²/lux minimum by Week 23 and three by Week 33, while mean thickness loss reached 32.4%, including near-complete material failure at Port Reitz-Moi International Airport (110) Access Road.

Although all tested materials were technically compliant with KS EAS 928-1:2019 specifications, their in-service performance under Kenyan environmental and traffic conditions was significantly below expected standards. The estimated service life of approximately 2.9 months $\pm$ 1.3 months is substantially lower than international benchmarks of 24 - 84 months, confirming a significant mismatch between current specifications and actual field performance in tropical environments.

While statistical analysis did not identify significant differences across environmental conditions, traffic classifications, or road surface types, this outcome reflects limited sample size rather than the absence of meaningful effects. Descriptive trends, supported by deterioration modeling, consistently indicate that environmental exposure, particularly temperature and humidity, is the dominant driver of degradation, with traffic loading acting as a secondary contributor.

The findings demonstrate that current thermoplastic road marking practices in Kenya are not fit for purpose under prevailing environmental and operational conditions. The integration of empirical field data with deterioration modeling highlights the need for a transition from specification-based approaches to performance-based, climate-adapted standards and predictive maintenance frameworks. Without such reforms, road markings will continue to underperform, undermining their effectiveness as a critical road safety intervention.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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