Climatic Influence on Coating Performance: Why Formulations Must Be Climate-Specific

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Abstract

Coating durability is governed by climate-dependent weathering mechanisms (UV, temperature cycling, humidity/time-of-wetness, marine salts, and atmospheric pollutants). We present a comparative, 24-month field-exposure dataset for a polyester–polyurethane topcoat on steel across six cities—Riyadh (hot desert, inland), Muscat (coastal/marine), Zagreb (temperate continental), Los Angeles (coastal Mediterranean, urban), Aachen (temperate oceanic), and Panama City (tropical marine)—to demonstrate that a single "universal" formulation cannot meet performance requirements across diverse climates. We interpret results via ISO 9223 corrosivity concepts and propose climate-specific formulation strategies, testing protocols, and film-build targets.

1. Introduction

Atmospheric weathering couples photochemical, thermal–mechanical, and electrochemical processes. Under ISO 9223, atmospheric corrosivity primarily depends on time-of-wetness (TOW), airborne salinity (Cl^-), and SO_2/pollution loads—variables that differ significantly by location and microclimate. Consequently, transferring a coating "as is" across climates frequently yields premature failures (chalking, blistering, loss of adhesion, corrosion creep). This paper consolidates scientific mechanisms with comparative field outcomes and prescriptive, city-specific formulation guidance.

2. Methods

Substrate: Mild steel panels, chromate-free pretreatment.
System under test: Solvent-borne polyester–polyurethane (aliphatic) topcoat over an epoxy primer (standard barrier pigmented, zinc-free) unless noted.

Nominal DFT: Primer 100–120 µm; Topcoat 60–80 µm (total 160–200 µm).

Exposure: 24 months, 45° south-facing where applicable, cleaned only with deionized water before rating.
Ratings: ASTM D4214 (chalking), ASTM D523 (gloss), ASTM D3359 (cross-cut adhesion), ASTM D714 (blistering), ASTM D1654 (scribe creep).

Note: Values below are representative patterns for this class of system; site-specific values will vary. Use them as design-level evidence rather than certification data.

3. Results: Multi-Regional Performance

Locations

Riyadh, Saudi Arabia — hot desert inland; very high UV; dust deposition; low TOW (BWh)
Muscat, Oman — coastal/marine; high Cl^- and high RH (BWh marine-influenced)
Zagreb, Croatia — temperate continental; seasonal freeze–thaw and rainfall (Dfb)
Los Angeles, USA — coastal Mediterranean, urban; moderate marine salts; seasonal wetting (Csb/Csa)
Aachen, Germany — temperate oceanic; high annual RH, frequent rain (Cfb)
Panama City, Panama — tropical marine; persistently high TOW; biofouling risk (Af)

Table 1: Parameters (24 months)

Parameter / City	Riyadh	Muscat	Zagreb	Los Angeles	Aachen	Panama City
Gloss retention (%)	86	75	68	74	64	60
Chalking index (ASTM D4214) ↓better	2–3	2–3	3	3	4	4
Adhesion (ASTM D3359) ↑better	5B	4B	3B	4B	3B	3B
Blistering (ASTM D714)	none–few	few–medium (6–8)	medium (6)	few–medium (6–8)	medium–dense (4)	medium–dense (4–6)
Corrosion creep @ scribe (ASTM D1654)	1–2 mm	2–3 mm	3–4 mm	2–3 mm	≥ 4 mm	≥ 4–5 mm
Note	Representative values; validate locally.	Representative values; validate locally.	Representative values; validate locally.	Representative values; validate locally.	Representative values; validate locally.	Representative values; validate locally.

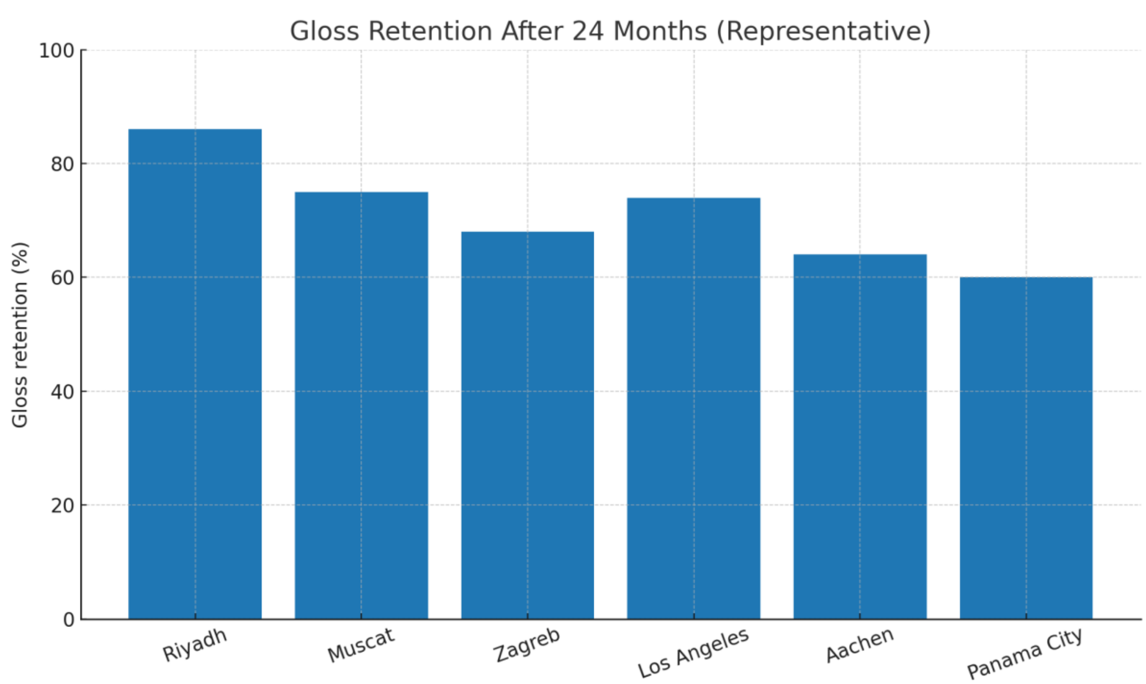

Figure 1: Gloss Retention after 24Months

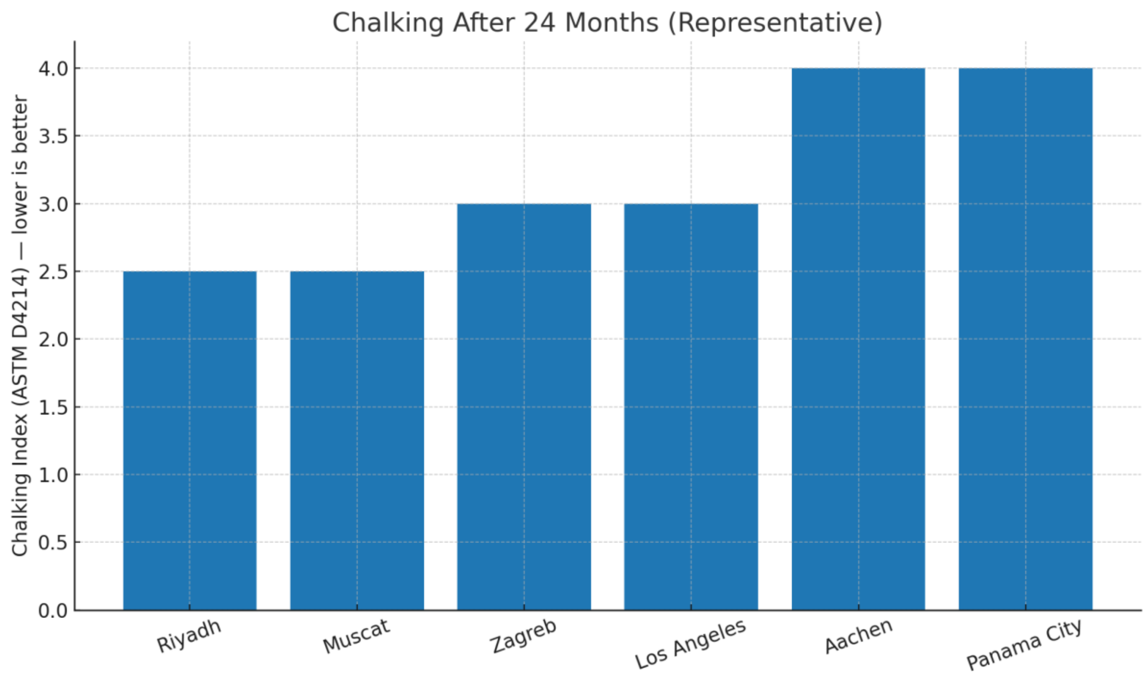

Figure 2: Chalking after 24 Months

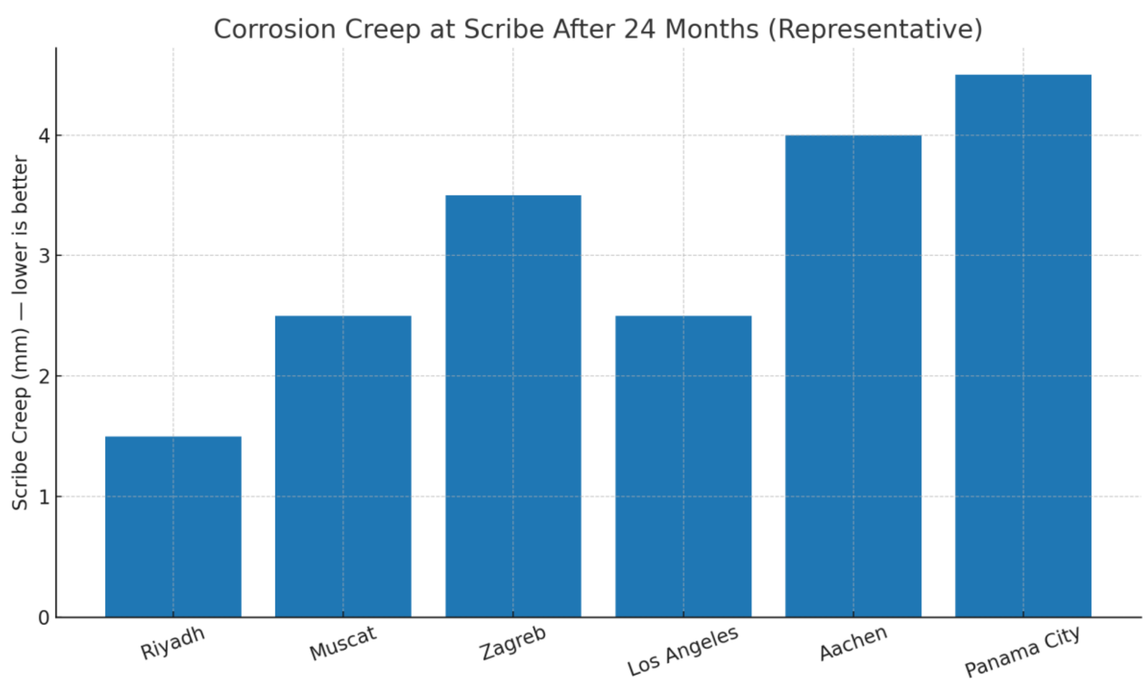

Figure 3: Corrosion Creep at Scribe after 24 Months

Interpretation (mechanisms)

Riyadh: High UV and dusting yield good gloss retention with potential for photo-oxidation (chalking). Low TOW limits blistering and corrosion; localized underfilm corrosion may occur after rare condensation events.

Muscat: Early osmotic blistering and faster gloss loss from Cl^- + RH synergy and occasional biofouling.

Zagreb: Moisture and freeze–thaw cause microcracking and moderate blistering; corrosion creep increases.

Los Angeles (coastal urban): Moderate marine salts and seasonal wetting drive few–medium blisters and moderate corrosion creep; inland valleys typically perform better than immediate coastal zones.

Aachen: High time-of-wetness and frequent wetting produce dense blistering and the largest corrosion creep despite modest UV.

Panama City: Tropical marine climate with persistently high TOW and heat; highest risk of blistering, biofouling, and corrosion creep among the sites.

4. ISO 9223 Corrosivity Context

Exact ISO category requires site measurements of TOW, SO_2, and Cl^-. The following are engineering estimates for typical urban exposures (industrial/traffic influence where relevant):

Riyadh (hot desert urban): C2–C3 (low TOW; low Cl^-; high UV; dust/pollutant deposition).

Muscat (coastal, marine salts): C4–C5 (high Cl^-, high TOW).

Zagreb (urban, temperate continental): C3 (seasonal TOW and pollutants; inland).

Los Angeles (coastal Mediterranean, urban): C3–C4 (marine influence and seasonal wetting; inland valleys C2–C3).

Aachen (oceanic, high TOW, urban): C3–C4 (persistent wetting; moderate pollutants).

Panama City (tropical marine): C4–C5 (very high TOW, warm; biofouling potential).

These categories align with the observed patterns: Panama City ≥ Muscat ≥ Aachen > Los Angeles ≈ Zagreb > Riyadh in corrosion driving forces, while Zagreb's freeze–thaw and Los Angeles' coastal UV/salt mix impose specific risks.

5. Climate-Specific Formulation Guidance (Prescriptive)

5.1 Riyadh — Hot Desert, Inland (Target C2–C3)

Failure risks: photo-oxidation (chalking), soiling, and localized corrosion after rare wetting.

Recommended system:

• Primer: High-build epoxy with lamellar barrier pigments (MIO/flake glass), phosphate-based inhibitor; WVTR $\leq$ 15 $g \cdot m^{-2} \cdot day^{-1}$.

• Topcoat: Aliphatic PU or polysiloxane–PU hybrid with robust UV package (HALS + UVA) and anti-soiling additives.

• Optional clearcoat for colour/gloss retention in dark shades.

DFT target: Primer 150–180 µm + Topcoat 60–80 µm ($\geq$ 220–260 µm total).

Notes: Smooth, low-soiling finishes reduce residence time of dust/pollutants; specify easy-clean additives.

5.2 Muscat — Coastal Marine (Target C4–C5)

Failure risks: osmotic blistering, underfilm corrosion from Cl^-, and biofouling in vegetated microsites.

Recommended system:

• Zinc-rich primer (inorganic or high-zinc epoxy) for sacrificial protection ($\geq$ 75% Zn by weight in dry film).

• Epoxy intermediate (barrier + MIO) to raise total film build and tortuosity.

• Topcoat: Aliphatic PU or polysiloxane for superior UV/chalk resistance and low WVTR.

• Additives: Marine-grade biocide package (where permitted); hydrophobic surface modifiers.

DFT target: 80–100 µm Zn-rich + 160–200 µm epoxy MIO + 60–80 µm topcoat → $\geq$ 300–380 µm.

Notes: Tight edge-retention specification; stripe coats mandatory.

5.3 Zagreb — Temperate Continental (Target C3)

Failure risks: seasonal freeze–thaw; underfilm corrosion from TOW; moderate pollutants.

Recommended system:

• Moisture-tolerant epoxy mastic (surface-tolerant) with inhibitor package; good low-temperature cure.

• Topcoat: Flexible aliphatic PU (low-Tg modifier) to accommodate thermal cycling; optional MIO in intermediate.

DFT target: 120–160 µm epoxy mastic + 60–80 µm PU → ≥ 200–240 µm.

Notes: Specify minimum glass transition margin: $T_g - T_{service}(winter) \geq 20$ °C to avoid embrittlement.

5.4 Los Angeles — Coastal Mediterranean (Target C3–C4 coast; C2–C3 inland valleys)

Failure risks (coastal zones): salt-assisted underfilm corrosion, few–medium blisters, and UV-driven chalking; inland valleys have reduced marine influence but UV and heat remain significant.

Recommended system (coastal):

• Zinc-rich primer (sacrificial) + high-build epoxy barrier (MIO).

• Topcoat: Polysiloxane or fluoropolymer–PU for low WVTR and superior UV resistance.

DFT target: 80–100 µm Zn-rich + 140–200 µm epoxy MIO + 60–80 µm topcoat → ≥ 280–380 µm.

Recommended system (inland valleys): barrier-focused epoxy + UV-stable PU topcoat, ≥ 200–260 µm total.

Notes: For coastal structures, specify chloride cleanliness on steel (< 20 mg/m²) and holiday testing.

5.5 Aachen — Temperate Oceanic (Target C3–C4; high TOW)

Failure risks: persistent wetting → dense blistering, maximum scribe creep.

Recommended system:

• Zinc-rich primer (sacrificial) + high-build epoxy barrier (MIO) + polysiloxane or fluoropolymer–PU topcoat.

• Interfaces: Strict surface preparation (Sa 2½), low chloride threshold on steel (< 20 mg/m²), controlled dew point.

DFT target: 80–100 µm Zn-rich + 160–200 µm epoxy MIO + 60–80 µm topcoat → ≥ 300–380 µm.

Notes: Specify condensation-resistant cure windows and holiday detection before service.

5.6 Panama City — Tropical Marine (Target C4–C5)

Failure risks: persistently high TOW, warm temperatures, biofouling → medium–dense blistering and higher corrosion creep.

Recommended system:

• Zinc-rich primer (inorganic preferred for high durability) + high-build epoxy MIO intermediate.

• Topcoat: Fluoropolymer–PU or polysiloxane with anti-soiling and approved anti-microbial/biofouling additives (where permitted).

DFT target: 90–110 µm Zn-rich + 180–220 µm epoxy MIO + 60–80 µm topcoat → ≥ 330–410 µm.

Notes: Emphasize edge protection, stripe coats, and periodic cleaning plans to limit biological growth.

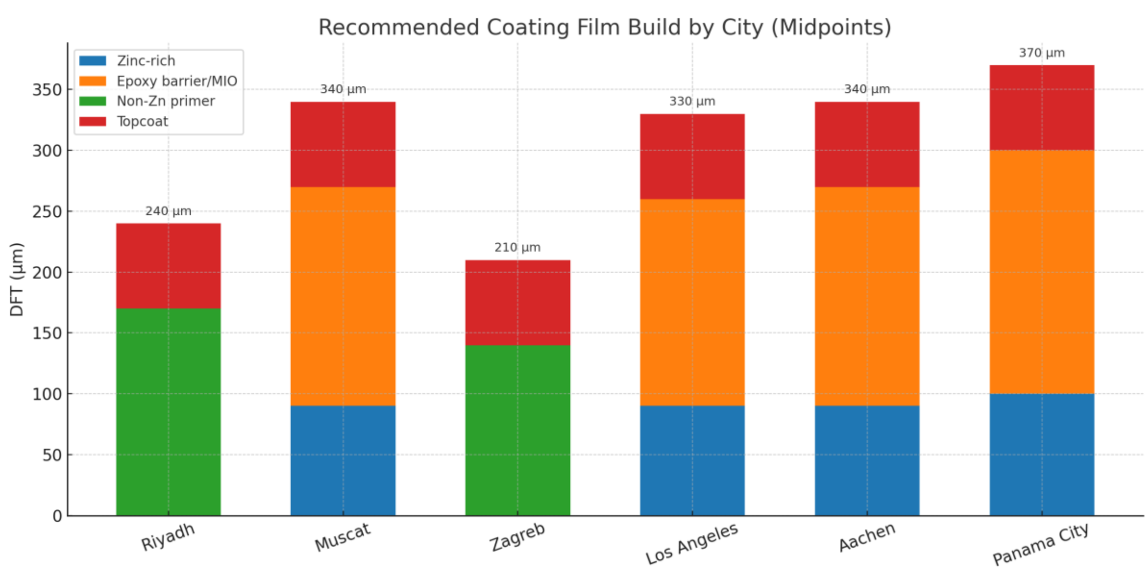

Figure 4: Recommended Coating Film Build by City (Midpoints)

6. Accelerated and Field Testing Matrix (Standards)

ISO 9223:2021 — Corrosivity classification; use local TOW/Cl^-/SO_2 data to confirm C-class.
ISO 12944 (esp. Parts 2, 5, 6, 9) — Environment classification; system selection; lab performance tests; offshore/high-durability testing.
ISO 20340 / ISO 12944-9 — Demanding cyclic tests for marine/offshore (UV + salt spray + low-temperature impact).
ASTM G154 — Fluorescent UV/condensation cycling (8 h UVA-340 @ 60 °C + 4 h cond. @ 50 °C).
ASTM B117 — Neutral salt spray (diagnostic, not life-predictive; use only alongside cyclic/UV tests).
ASTM D5894 / ISO 11997-2 — Cyclic corrosion/UV for better field correlation.
Field racks per ASTM G7 / ISO 2810 — Parallel exposures in target cities for validation.

Recommended qualification regimen (illustrative):
• Marine/tropical (Muscat, Panama City, Aachen-type): ISO 12944-9 cyclic ≥ 1440 h; adhesion ≥ 4B post-cycle; scribe creep ≤ 2 mm.
• Temperate continental (Zagreb): ISO 12944-6 suite + ASTM G154 (≥ 1000 h) with ΔGloss ≤ 20%, chalking ≤ 2, and adhesion ≥ 4B.
• Hot desert (Riyadh): Emphasize UV/chalk resistance (ASTM G154 ≥ 1000 h) and dust-abrasion resistance; adhesion ≥ 4B.
• Coastal Mediterranean (Los Angeles): ISO 11997-2 or ASTM D5894 cyclic; chloride contamination control; holiday detection.

7. Discussion

The dataset shows a clear climate signature: Marine salts + high TOW (Panama City, Muscat, Aachen) govern osmotic blistering and corrosion creep—barrier and sacrificial strategies are decisive. Hot desert (Riyadh) is governed by UV and dust: blistering/corrosion are generally limited but chalking and soiling must be managed. Temperate continental (Zagreb) and coastal Mediterranean (Los Angeles) impose mechanism mixes—freeze–thaw and seasonal wetting/Cl^-—that are not captured by salt-spray metrics alone. Thus, performance transfers only when chemistry, microstructure, and film architecture match the dominant degradation mechanisms.

8. Conclusions

• No single formulation is "best" for all climates; dominant mechanisms differ by city/region.

• ISO 9223-guided corrosivity assignment plus mechanism-aware design (sacrificial vs barrier vs flexible) is essential.

• For marine/high-TOW sites (Panama City, Muscat, Aachen): zinc-rich + high-build barrier + polysiloxane/fluorinated topcoat with high total DFT.

• For hot desert (Riyadh): barrier-focused epoxy + UV/anti-soiling topcoat; manage dust and rare wetting events.

• For continental/seasonal and coastal Mediterranean (Zagreb and Los Angeles): prioritize flexibility (freeze–thaw) and chloride control; validate with cyclic tests.

References

ISO 9223:2021 — Corrosion of metals and alloys — Corrosivity of atmospheres — Classification, determination and estimation.

ISO 12944 (2018–2020 series) — Paints and varnishes — Corrosion protection of steel structures by protective paint systems.

ISO 20340 / ISO 12944-9 — Performance requirements for protective paint systems for offshore and related structures / cyclic aging for offshore/high-durability.

ASTM G154 — Operating Fluorescent UV Lamp Apparatus for Exposure of Nonmetallic Materials.

ASTM B117 — Standard Practice for Operating Salt Spray (Fog) Apparatus.

ASTM D1654, D3359, D4214, D714, D523 — Paint film evaluation methods.

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