Cover Page

Restoring Aged Asphalt Shingle Roofs to Code-Level Performance

Independent Validation of a Nano-Engineered Roof Preservation System Using FTIR Spectroscopy, Accelerated Weathering Protocols, and Standardized Industry Testing

A Technical White Paper

UL 790 • UL 2218 • ASTM D3161 • FTIR Molecular Analysis

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This white paper was commissioned by GoNano to provide an independent scientific review of NuRoof™ nano-sealer technology. The content reflects the author's synthesis of peer-reviewed literature, third-party testing data, and industry standards as of the date of publication. This document does not constitute a warranty or guarantee of product performance.

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EXECUTIVE SUMMARY

The residential roofing industry has historically relied on three primary approaches to address aging asphalt shingles: full roof replacement, surface-applied film coatings, and bio-oil-based rejuvenators. Each approach presents inherent limitations. Full replacement is costly and environmentally harmful; film-forming coatings may introduce durability, adhesion, vapor permeability, or fire-classification considerations [21-23]; and soy-based rejuvenators are generally characterized by shallow penetration depths and limited durability [17–19]. Critically, none of these strategies directly address the molecular-level degradation processes occurring within the asphalt binder that govern long-term mechanical performance and failure [8-12].

All performance claims evaluated in this paper are assessed using the same UL and ASTM standards applied to untreated residential asphalt shingles in the United States and Canada, providing direct comparability to code-compliant roofing systems and insurer-relevant performance benchmarks under the specific test assemblies and laboratory conditions evaluated.

The GoNano Nu Roof Revive™ / Nu Roof Fortify™ system (hereafter referred to as the GoNano system) is evaluated as a materials-science-based approach to roof preservation. The system is a cold-applied, nano-engineered treatment designed to penetrate below the shingle surface and interact within the asphalt binder matrix. Independent laboratory analyses indicate that the treatment is associated with restoration of key chemical indicators and laboratory-observed performance improvements relative to untreated, age-matched control samples evaluated under identical test conditions [1–5]. These outcomes are consistent with reported mechanisms in nano-engineered asphalt systems, including silane-mediated interfacial interactions, nano-scale reinforcement, and delayed oxidative aging [15–16, 46–50, 97]. Based on standardized third-party laboratory testing [1–5], peer-reviewed aging literature [17–19, 51–54, 71–73], and preliminary field observations from active deployments (2–3 years of monitoring to date), the system demonstrates laboratory-verified performance changes and chemical signatures that are consistent with mechanisms associated with slower aging in asphalt systems. Early field observations are directionally consistent with this potential; long-term service-life validation across diverse climates is ongoing, with peer-reviewed publication planned for 2028–2029.

Validation Status: Laboratory testing validates mechanism and short-term performance under standardized conditions. The projected 10–15 year service-life extension is evaluated as a mechanistic estimate informed by peer-reviewed asphalt aging literature and 2–3 years of field monitoring to date, and should not be interpreted as a guaranteed lifespan extension under all service conditions, as long-term validation remains ongoing. Long-term field performance will be established through ongoing monitoring and planned peer-reviewed studies (2028–2031). See Appendix H for validation status and timeline.

Because the treatment operates as a subsurface modification rather than a surface film, original roof system geometry and fire-exposed interfaces remain unchanged, supporting compatibility with existing U.S. and Canadian building codes and insurance underwriting frameworks as evaluated within the scope of standardized testing performed.

This white paper synthesizes peer-reviewed research in asphalt chemistry, nanotechnology, and materials science, together with verified third-party testing conducted by Underwriters Laboratories (UL), Green Centre Canada, and the Centre technologique du Collège Shawinigan (CNETE) as summarized in Appendices B–E [1–5]. Additional independent testing aligned with insurer-relevant performance criteria and IBHS-relevant evaluation approaches is ongoing and intended to further characterize hail and wind resistance under real-world loss scenarios. Collectively, these data establish the scientific basis for subsurface nano-engineered rejuvenation and differentiate this approach from conventional surface treatments and short-duration rejuvenators.

For insurers, regulators, and building officials, the most salient distinction of this approach is that verified performance improvements are achieved under standardized test conditions without reclassification of fire rating, wind resistance, or roof system assembly behavior. Where long-term performance is discussed, it is explicitly identified as a mechanistic projection rather than a field-validated outcome.

Key Findings Verified by Independent Testing

Fire Performance
Standardized fire testing conducted in accordance with UL 790 demonstrated that GoNano-treated shingle assemblies met UL 790 Class A acceptance criteria under the tested configurations [1] (see Appendix B, Table B1). All required test procedures, including Spread of Flame, Intermittent Flame, and Burning Brand, were passed without evidence of cracking, tearing, splitting, or material degradation (UL Project 4790550987, October 2022). These results confirm that treated shingles perform equivalently to untreated code-compliant shingles within the specific fire exposure test protocols and configurations evaluated.

Impact Resistance
Impact resistance testing performed under UL 2218 showed that aged Class 1 shingles treated with the system met Class 3 acceptance criteria following a single application and met Class 4 acceptance criteria following a double application under the laboratory conditions and shingle types evaluated (Appendix C, Table C2) [2] (UL Project 4790134408, December 2021). Supplemental non-standard high-energy impact testing conducted at Green Centre Canada demonstrated resistance to 53.8 J impact energy without cracking in severely aged shingles (Appendix C, Table C3) [4]. These performance gains directly correspond to impact-resistance classifications commonly used by insurers to assess hail-related loss exposure.

Wind Resistance
Fan-induced wind testing conducted in accordance with ASTM D3161 demonstrated that treated shingles met Class F (110 mph) acceptance criteria under laboratory test conditions for

120 minutes, with no tab lift or adhesive failure observed (Appendix D, Table D1; UL Project 4790686520, March 2023) [3]. Preservation of adhesive integrity confirms that subsurface treatment does not interfere with wind-critical mechanical interfaces.

Molecular-Level Verification
Fourier Transform Infrared (FTIR) spectroscopy conducted by Green Centre Canada and CNETE identified spectral features consistent with bio-oil ester formation and silane coupling chemistry across new, moderately aged, and severely aged shingles. Spectral analysis shows reduced carbonyl signal intensity relative to untreated controls, consistent with delayed oxidative aging (Appendix E, Tables E1–E2) [4–5]. These findings are consistent with chemical integration and reduced oxidation markers relative to untreated controls, rather than purely transient softening or surface-only effects.

Durability Indicators
Non-ASTM drop-ball impact testing conducted at Green Centre Canada demonstrated controlled deformation without cracking at impact energies exceeding standardized hail simulation thresholds. Severely aged shingles (14–16 years) exhibited catastrophic failure when untreated, while treated specimens remained intact under identical loading conditions (Appendix C, Table C3). This behavior is consistent with nano-scale stress redistribution rather than brittle fracture, a key failure mode in aged asphalt systems.

INTRODUCTION

Nanotechnology as a Driver of Contemporary Materials Engineering

Nanotechnology has become a foundational discipline in modern materials science, enabling deliberate modification of material behavior through control at length scales on the order of 1–100 nanometers. At these dimensions, materials may exhibit altered mechanical, chemical, and transport properties that are not achievable through conventional bulk formulations alone [13–16, 42–46, 90–91]. These effects arise from increased interfacial area, modified surface energy, enhanced particle–matrix interactions, and changes in molecular mobility, rather than from size reduction in isolation [42-43, 90-91].

Among nano-engineered additives, nano-silica has been extensively studied and deployed across a wide range of industrial systems [13–14]. When appropriately dispersed and chemically coupled to host matrices, nano-silica has been shown to improve stiffness–toughness balance, abrasion resistance, fracture resistance, and long-term durability in cementitious, polymeric, and composite materials [13–16, 42-46, 90-91]. Importantly, these performance benefits depend on particle size distribution, surface chemistry, dispersion stability, and compatibility with the carrier system; inadequately integrated nanoparticles do not reliably confer durable improvements [13–14].

The application of nanotechnology is well established in high-reliability industries such as aerospace, advanced manufacturing, and transportation infrastructure. In these sectors, nano-enhanced composites are routinely used to improve fatigue resistance, thermal stability, and damage tolerance while reducing overall material mass [42–43, 90–91]. Similarly, industrial coatings and protective surface treatments employ nano-scale additives to enhance resistance to corrosion, ultraviolet radiation, and moisture ingress, thereby extending service life under demanding environmental conditions [42–43, 90–91]. In biomedical engineering, nano-structured surfaces and nanoparticle-enabled systems are routinely employed to modify interfacial behavior and material response under stringent safety and regulatory oversight.

Across these diverse applications, a consistent principle emerges: nanotechnology enables modification of material behavior within the bulk or interfacial regions of a system, rather than relying exclusively on macroscopic surface treatments. Performance gains are achieved through internal chemical or structural interactions that influence long-term response to mechanical loading and environmental stressors.

Limited Materials Evolution in Residential Roofing Systems

In contrast to advances observed in other engineered materials, the residential roofing sector has experienced relatively limited fundamental materials innovation over the past century. Asphalt shingles, first commercialized in the early twentieth century, remain the dominant roofing material in North America [20]. While manufacturing processes, installation methods, and aesthetic features have evolved, the underlying reliance on asphalt-based binders and mineral reinforcement has remained largely unchanged.

Extensive research has demonstrated that asphalt binders undergo progressive oxidative aging during service [8–12], leading to increased stiffness, reduced ductility, and eventual embrittlement, particularly under prolonged exposure to heat, ultraviolet radiation, and atmospheric oxygen [11,12]. Industry trends toward reduced asphalt content and increased filler loading, driven in part by economic and production considerations, may further influence long-term aging behavior, though outcomes depend strongly on formulation, climate, and service conditions.

Current remediation strategies for aging asphalt shingles, including surface-applied coatings, sealants, and full roof replacement, primarily address surface exposure or structural failure rather than the chemical and rheological degradation occurring within the asphalt binder itself. Film-forming coatings may temporarily alter surface water repellency [21–23], but they can introduce additional considerations related to adhesion durability, vapor permeability, fire classification, and compatibility with existing roofing assemblies [21-23, 78-81, 82-83, 95-96]. Full replacement remains an effective but resource-intensive intervention, associated with significant economic cost, material consumption, and waste generation.

As a result, roof preservation has historically emphasized surface coverage or replacement cycles rather than material-level interventions aimed at mitigating the internal degradation mechanisms that govern long-term performance.

Translating Established Nanotechnology Principles to Asphalt Roofing Materials

Nano-engineered roof rejuvenation systems represent an extension of established materials-science principles into a sector that has traditionally lagged in material-level innovation. Research in bituminous and polymeric systems has demonstrated that appropriately formulated nano-modified rejuvenators can influence oxidation resistance, molecular mobility, and moisture response in aged materials when delivered into the binder matrix rather than confined to the surface [13–16].

By targeting subsurface interactions within the asphalt binder, such systems are intended to address aging-related loss of flexibility, increased brittleness, and moisture susceptibility while preserving the macroscopic surface characteristics of the roofing assembly. From a regulatory and insurance perspective, preservation of original surface geometry and fire classification is a critical distinction, as surface-altering treatments may require additional qualification or introduce unintended performance changes.

Accordingly, performance claims for nano-engineered roof rejuvenation must be supported by standardized testing, including mechanical performance, fire classification, weathering behavior, and chemical analysis. Where validated through independent third-party protocols, such approaches represent a shift from surface-coating strategies toward internal material modification grounded in contemporary understanding of nanotechnology and asphalt science.

Toward a Materials-First Paradigm in Roof Preservation

The application of nanotechnology to asphalt roofing does not constitute a novel scientific domain but rather the translation of mature materials-engineering principles into a widely used and historically under-innovated system. By shifting the focus from surface coverage to internal material behavior, nano-engineered rejuvenation systems define a distinct category of roof preservation aligned with current understanding of polymer aging, environmental degradation, and nano-scale reinforcement.

Within this framework, nano-enabled roof preservation should be evaluated as a testable, materials-based intervention subject to the same scientific, regulatory, and performance standards that govern its use in other engineered systems.

Applicability of subsurface nano-engineered modification is limited to defined roof age and condition windows. The system is intended for shingles that remain structurally intact and compliant with applicable building code requirements at the time of treatment. Roofs exhibiting advanced structural failure, widespread substrate compromise, or conditions requiring code-mandated replacement fall outside the intended scope of this evaluation.

SECTION 1

ASPHALT SHINGLE AGING SCIENCE — THE MOLECULAR BASIS FOR REJUVENATION

1.1 Mechanisms of Asphalt Binder Degradation

The asphalt binder functions as the viscoelastic matrix within asphalt roofing shingles, providing flexibility, adhesion to mineral granules, and resistance to environmental stress. Over time, this binder undergoes progressive aging driven by chemical and physical processes that alter its molecular structure and rheological behavior. Extensive research has shown that asphalt aging occurs through three concurrent mechanisms: oxidation, volatilization, and physical hardening, each contributing to long-term performance degradation to varying degrees.

Oxidation (Primary and Irreversible Mechanism)

Oxidation is the dominant and largely irreversible aging pathway in asphalt binders [8–12]. This process involves the progressive formation of polar, oxygen-containing functional groups—most notably carbonyl (C=O) groups—typically observed near 1695 cm^{-1} in Fourier Transform Infrared (FTIR) spectra [9–10]. These functional groups accumulate as asphalt is exposed to oxygen, heat, and ultraviolet (UV) radiation over its service life.

Field studies of service-aged asphalt binders consistently report multi-fold increases in carbonyl index relative to virgin materials, with strong correlations to years of service in longitudinal analyses [8]. UV exposure has been shown to accelerate oxidation substantially relative to thermal aging alone, helping explain preferential aging on high-UV and south-facing roof surfaces [10,12].

The introduction of polar functional groups increases molecular weight and intermolecular association within the binder, leading to higher stiffness, reduced ductility, and increased brittleness. These changes fundamentally alter binder rheology, shifting behavior from viscoelastic toward more elastic-dominant response and reducing the material’s ability to accommodate thermal cycling and mechanical loading.

FTIR spectroscopy is widely used to quantify oxidation progression through the carbonyl index (CI), defined as the ratio of carbonyl peak area to a reference aromatic band [7,38–40]. This metric provides a robust molecular indicator linking chemical aging to mechanical embrittlement in asphalt systems [8–12,40].

Volatilization (Short-Term and Partially Reversible)

Volatilization refers to the loss of light hydrocarbon fractions during early service life due to heat and UV exposure. This mechanism is most active during initial weeks to months following installation, when lighter maltene components evaporate from the binder. As volatile species are depleted, the rate of further volatilization decreases significantly.

Unlike oxidation, volatilization is partially reversible. Reintroduction of compatible hydrocarbon fractions through rejuvenation can temporarily restore aspects of binder flexibility and workability. However, volatilization plays a secondary role in long-term roof failure compared to oxidative aging, particularly after the initial service period has elapsed.

Physical Hardening (Reversible)

Physical hardening involves molecular reorganization within the asphalt binder, including wax crystallization and phase rearrangement, without the formation of new chemical bonds. This process can increase stiffness at lower temperatures but is at least partially reversible with warming and thermal cycling.

While physical hardening contributes to short-term stiffness variations, it is generally considered the least significant contributor to irreversible long-term performance loss in roofing applications when compared to oxidation-driven chemical changes.

1.2 FTIR Spectroscopy and Quantification of Molecular Aging

FTIR spectroscopy provides a quantitative framework for assessing molecular aging in asphalt binders. The carbonyl index serves as a standardized metric for oxidation severity and has been shown to correlate directly with mechanical property degradation, including reduced penetration grade, increased complex modulus ($|G^*|$), and diminished fatigue resistance.

Representative field data from pavement and roofing studies illustrate the progressive relationship between service age, carbonyl index, and rheological stiffening. Virgin binders typically exhibit carbonyl index values in the range of 0.05–0.08. After approximately ten years of service, values commonly increase to 0.25–0.35, corresponding to substantial reductions in penetration grade and large increases in stiffness reported across multiple studies. At approximately twenty years of equivalent service aging, carbonyl index values in the range of 0.45–0.60 have been reported across multiple studies of service-aged and laboratory-aged asphalt binders [8–11]. Roofing aging rates may differ due to geometry, ventilation, and exposure conditions, but these values provide a conservative reference for oxidative progression.

These trends have been consistently observed in field-extracted and laboratory-aged asphalt binders analyzed using FTIR spectroscopy across multiple studies [8–12]. The strong coupling between carbonyl index growth and mechanical embrittlement indicates the central role of oxidation in asphalt binder embrittlement and associated shingle failure mechanisms.

1.3 Rheological Consequences of Binder Aging

The chemical changes associated with asphalt aging manifest as distinct rheological consequences that directly drive shingle failure modes.

First, aged binders exhibit reduced flexibility and ductility [8,11]. As oxidation increases stiffness and reduces phase angle (δ), the binder becomes less capable of dissipating energy under load. This transition renders shingles more susceptible to cracking under thermal cycling, foot traffic, and impact events such as hail.

Second, aging increases temperature susceptibility. Near the glass transition region of oxidized binders, relatively small temperature fluctuations can produce disproportionate changes in modulus. This sensitivity explains the tendency of aged roofs to fail catastrophically during extreme temperature swings, particularly during cold snaps or rapid freeze–thaw cycles.

Third, aging degrades adhesion between the asphalt binder and mineral granules. Loss of maltene fractions and increased polarity weaken the intermolecular forces that anchor granules within the binder matrix. As flexibility declines, thermal expansion and contraction impose tensile stresses at the granule–binder interface, accelerating granule loss.

Field studies of service-aged asphalt binders have shown that carbonyl index values in this range are associated with increased brittleness and elevated failure likelihood across multiple asphalt systems, including roofing-relevant degradation pathways [8–12,71–73]. While exact failure thresholds vary with formulation, exposure conditions, and climate, these findings reinforce the predictive value of molecular aging indicators in assessing shingle degradation risk.

1.4 Granule Loss as an Accelerating Failure Feedback Loop

Granule loss is evaluated as a critical failure pathway in asphalt roofing systems and functions as a positive feedback mechanism that accelerates degradation.

During early stages of service, limited granule loss (typically below 20%) may not immediately compromise roof function, as the asphalt surface remains partially shielded from UV radiation.

However, once granule loss reaches intermediate levels (approximately 20–35%), exposed asphalt experiences significantly increased UV absorption, accelerating oxidative aging. Remaining granules are subjected to greater tensile stresses as the surrounding binder stiffens, further increasing the rate of loss.

Beyond approximately 40% granule loss, roof performance deteriorates rapidly [20]. Water shedding capability is compromised, UV radiation penetrates toward the reinforcement mat, and structural integrity declines to the point where replacement is typically required.

Mechanistically, young, flexible asphalt suspends granules within a compliant matrix that accommodates thermal and mechanical stresses [20]. In contrast, aged and oxidized asphalt behaves as a brittle solid, transforming granules from integrated structural components into loosely retained inclusions. Thermal cycling and mechanical loading then promote interfacial failure and rapid granule detachment.

SECTION 2

LIMITATIONS OF TRADITIONAL ROOF PRESERVATION APPROACHES

2.1 Bio-Oil-Based Rejuvenators: Limited Penetration and Temporary Restoration

Bio-oil-based roof rejuvenators, most commonly derived from soybean oil or soy methyl ester formulations, are designed to restore flexibility to aged asphalt shingles by reintroducing maltene-like hydrocarbon fractions into the binder. These products are typically delivered as water-based emulsions that break upon application, allowing oil components to migrate into the near-surface region of the asphalt binder through capillary diffusion and molecular absorption [17].

From a compositional standpoint, bio-oil rejuvenators act primarily by rebalancing the SARA fractions (Saturates, Aromatics, Resins, and Asphaltenes) within aged asphalt [19]. Oxidative aging is associated with depletion of saturates and aromatics and a relative increase in asphaltene concentration due to oxidation-driven aggregation. Introduction of compatible oils can temporarily increase the maltene fraction, reduce effective asphaltene concentration, and improve short-term flexibility and workability.

However, multiple studies and field evaluations indicate that penetration depth for soy-based rejuvenators is typically limited to the near-surface region under standard application conditions. Diffusion into the binder occurs primarily during the early post-application period, with diminishing additional penetration thereafter [52,75,77]. As a result, treatment is largely confined to the superficial region of the asphalt binder, while the bulk of the shingle remains chemically oxidized and mechanically embrittled.

Measured laboratory improvements reported for oil-only rejuvenation include increased penetration grade, reduced softening point, and improved short-term adhesion metrics in controlled tests; however, these effects tend to diminish over time as the introduced oils oxidize and the binder re-ages [17–19,53–54]. Longitudinal analyses show that oxidation markers in treated asphalt can trend back toward pre-treatment trajectories, with the rate depending on formulation and exposure conditions [53–54].

Consequently, while bio-oil rejuvenators may provide short-term functional benefits, their effectiveness is constrained by shallow penetration, lack of permanent chemical bonding, and re-oxidation over time. These characteristics limit their suitability as long-duration preservation strategies for significantly aged roofing systems.

2.2 Film-Forming Coatings: Surface Barriers Without Internal Remediation

Film-forming roof coatings, including acrylic, silicone, and elastomeric formulations, represent a fundamentally different preservation approach. These systems function by forming a continuous surface layer intended to shield the roof from water ingress, UV radiation, and environmental exposure. While coatings can provide immediate improvements in surface reflectivity and water shedding, they do not address chemical or rheological degradation within the asphalt binder itself.

A primary limitation of film-forming coatings is long-term adhesion durability. Differential thermal expansion between the coating layer and the underlying shingle, combined with substrate aging and surface contamination, can lead to peeling, cracking, or delamination over time. Industry reports commonly document visible adhesion failures within a few years under typical residential exposure conditions, particularly in regions experiencing significant thermal cycling [22].

Moisture vapor management presents an additional challenge. Many acrylic and elastomeric coatings exhibit moderate water vapor permeability. If applied over substrates containing residual moisture or in humid conditions, coatings may trap vapor beneath the film, leading to blistering or localized delamination [22]. Such failures can occur within months under unfavorable installation conditions or develop gradually over several years as moisture accumulates.

Because film-forming treatments function as continuous surface layers, moisture transport through the roofing assembly becomes governed by the permeability and long-term integrity of the applied film rather than by the original shingle design. This introduces an additional performance variable that is independent of the internal chemical condition of the asphalt binder and may contribute to accelerated degradation under sustained thermal cycling or freeze–thaw exposure [22, 80–81].

Ultraviolet exposure further contributes to coating degradation. Acrylic formulations, in particular, are susceptible to UV-induced chalking and embrittlement, resulting in loss of elasticity and surface friability. As coatings age, their protective function diminishes while introducing maintenance requirements that may offset initial benefits.

Fire classification is evaluated as a critical regulatory consideration. The addition of surface coatings alters the roof assembly tested under fire-rating standards. Industry guidance emphasizes that film-forming coatings can affect flame spread, heat release, and burning brand performance, potentially resulting in a reduction in fire classification under certain conditions [21-23]. As a result, coated roof systems may require separate fire testing or may introduce uncertainty in jurisdictions with strict fire-safety requirements.

In contrast, subsurface modification approaches that do not form a continuous external film preserve the original surface morphology and vapor permeability of the roofing system while selectively altering internal material behavior.

In aggregate, film-forming coatings function as external barriers rather than restorative interventions. While they may delay exposure-driven damage at the surface, they do not mitigate internal asphalt oxidation, loss of flexibility, or granule detachment mechanisms that govern long-term shingle performance.

2.3 Full Roof Replacement: Effectiveness at High Economic and Environmental Cost

Complete roof replacement remains the most definitive method for restoring roofing performance, as it eliminates aged materials entirely and installs new assemblies meeting current manufacturing and code standards. From a technical perspective, replacement reliably resets mechanical, chemical, and aesthetic performance parameters.

However, replacement is associated with substantial economic, environmental, and logistical costs [26-27]. Material production, transportation, tear-off operations, and landfill disposal contribute significantly to embodied energy consumption and greenhouse gas emissions. Asphalt shingles are non-biodegradable and contribute millions of tons of waste annually to landfills in North America, with decomposition timelines measured in centuries [24].

From a lifecycle perspective, replacement addresses the symptoms of aging rather than the underlying inefficiency of discarding materials that retain partial structural integrity. For roofs that have not yet reached catastrophic failure, replacement may represent an unnecessarily disruptive intervention when compared to preservation strategies capable of restoring functional performance at the material level.

2.4 Summary of Limitations in Conventional Approaches

Across bio-oil rejuvenators, film-forming coatings, and full replacement, a common limitation emerges: conventional strategies either provide temporary surface-level mitigation or rely on complete material removal rather than addressing the molecular and rheological degradation processes within the asphalt binder.

This gap indicates the need for preservation approaches that operate below the surface, interact directly with aged binder chemistry, and deliver durable performance improvements without introducing new regulatory, environmental, or maintenance burdens. Representative durability and failure modes across preservation approaches are summarized in Appendix F, Table F1.

SECTION 3

NANO-SILICA CHEMISTRY AND SUBSURFACE BONDING MECHANISMS

3.1 Nano-Silica Particles: Physical Characteristics and Surface Modification

Nano-silica particles are widely used in materials engineering as reinforcing agents due to their high specific surface area, chemical stability, and ability to interact with polymeric matrices at the molecular scale [13-14][42-43]. In asphalt systems, nano-silica has been investigated for its potential to enhance mechanical strength, improve resistance to environmental aging, and modify moisture response when appropriately integrated into the binder phase [13–16][45-46].

The nano-silica employed in the GoNano system consists of fumed silica particles with characteristic diameters on the order of tens of nanometers [14–16, 42–43]. At this scale, particles are several orders of magnitude smaller than the mineral granules used in asphalt shingles and are capable of penetrating into micro- and nano-scale voids within aged asphalt binder structures[45,75-76].

Unmodified fumed silica is intrinsically hydrophilic due to the presence of surface silanol (Si–OH) groups. While hydrophilic nano-silica can increase stiffness in asphalt systems, it is prone to agglomeration and exhibits limited compatibility with hydrophobic hydrocarbon matrices. Aggregation reduces effective surface area and undermines uniform stress transfer within the binder [14,42,94].

To address these limitations, the nano-silica used in the GoNano system is surface-modified through silane grafting, rendering the particle surface hydrophobic and chemically compatible with the asphalt binder. This modification improves dispersion stability, reduces particle clustering, and enables chemical interaction between the inorganic silica surface and organic asphalt constituents. Studies comparing hydrophilic and hydrophobic nano-silica in bituminous materials consistently show superior dispersion, mechanical performance, and durability for surface-modified variants when evaluated under thermal and oxidative aging conditions [14-16,44-46,94].

3.2 Silane Coupling Agents and Interfacial Bond Formation

Silane coupling agents play a critical role in enabling durable interaction between nano-silica particles and the asphalt binder [47–49]. These molecules are bifunctional by design, containing distinct chemical groups capable of interacting with inorganic surfaces on one end and organic materials on the other [47].

Structurally, a typical silane coupling agent consists of a hydrolyzable siloxy group ($Si–(OR)_3$) and an organofunctional group such as an epoxy, vinyl, or amino moiety [47–48]. Upon exposure to moisture, the alkoxy groups undergo hydrolysis to form silanol (Si–OH) species. These silanol groups can then condense with surface hydroxyl groups on nano-silica, forming stable Si–O–Si linkages that anchor the coupling agent to the particle surface [47,49].

Once associated with the nano-silica surface, the organofunctional end of the silane may interact with oxidized asphalt components through hydrogen bonding, coordinate interactions, or covalent-like associations. FTIR analysis identifies functional groups consistent with silane coupling chemistry; however, direct interfacial confirmation (e.g., XPS or TEM-EDS imaging) is ongoing.

This interfacial bonding mechanism results in a nano-reinforced network within the binder matrix. Peer-reviewed studies evaluating silane-modified asphalt systems have reported increases in pull-off adhesion strength, reductions in moisture-induced mass loss, and improvements in freeze–thaw resistance relative to untreated or physically blended systems [15–16,50]. These findings support the role of silane coupling agents in promoting durable, chemically integrated reinforcement rather than transient physical dispersion.

3.3 Bio-Oil Carrier Systems and SARA Rebalancing

To facilitate subsurface delivery of nano-silica and coupling agents, the GoNano system incorporates a bio-oil-based carrier formulated as an emulsion. Upon application, the emulsion breaks, allowing the oil phase to migrate into the near-surface and subsurface regions of the asphalt binder through capillary action and diffusion [17–18,51–52,75–77].

As discussed in Section 1.1, oxidative aging of asphalt is associated with systematic shifts in the relative proportions of SARA fractions [19,34–36]. Saturates and aromatics decrease due to volatilization and oxidation, while resins and asphaltenes increase as oxidation products accumulate and aggregate. These shifts increase binder stiffness and reduce molecular mobility [11–12,19].

The bio-oil carrier contributes compatible hydrocarbon fractions that partially replenish the maltene phase [17–19,51]. This replenishment can improve short-term flexibility and facilitate penetration of nano-silica particles into aged binder structures [52,75]. Importantly, in the GoNano system, the bio-oil does not function as a stand-alone rejuvenator. Instead, it acts as a delivery medium that enables chemical coupling and nano-scale reinforcement to occur within the binder matrix.

Once coupling reactions and nano-silica integration have taken place, the restored network exhibits resistance to rapid re-oxidation relative to oil-only treatments [15–16,53–54]. Independent FTIR analyses have identified ester linkages and silicon–carbon bonding patterns consistent with permanent chemical modification rather than reversible absorption [5,38–40] (Appendix E, Tables E1–E2). These findings distinguish chemically integrated nano-engineered systems from purely oil-based rejuvenators that rely on temporary compositional dilution [53–54].

3.4 Evidence from Nano-Engineered Asphalt Pavement Systems

The application of nano-silica and related nano-additives in asphalt pavement engineering provides a relevant proof-of-concept for subsurface modification of bituminous materials [45–46]. Numerous laboratory and field studies have evaluated the effects of nano-silica, nano-titanium dioxide, and nano-alumina on asphalt binders and mixtures under controlled aging and mechanical loading conditions [15,45–46,90–91].

Reported outcomes include improvements in fatigue life, reductions in oxidative aging rates as measured by carbonyl index growth, and enhanced resistance to moisture damage [15,35–37,46]. Typical nano-silica dosages on the order of 1–2% by binder weight have been associated with fatigue life increases of approximately 25–35% and measurable reductions in oxidation progression [15,45–46]. While pavement and roofing applications differ in geometry and loading, the underlying binder chemistry and aging mechanisms are closely related [8–12,32–36].

These findings support the broader premise that nano-engineered reinforcement, when chemically integrated into asphalt systems, can meaningfully influence long-term performance indicators. The GoNano approach adapts these established principles to the specific constraints of asphalt roofing, emphasizing subsurface delivery, chemical bonding, and preservation of surface characteristics.

SECTION 4

SUBSURFACE MODIFICATION VERSUS SURFACE FILM–FORMING APPROACHES

4.1 Limitations of Surface Film–Forming Roof Treatments

Surface-applied roof treatments, including acrylic, elastomeric, silicone, and other polymeric coatings, are designed to form a continuous film over the exterior of asphalt shingles [22,79]. These systems function primarily as physical barriers intended to reduce water ingress and ultraviolet exposure [22,78–79]. While such coatings may provide short-term surface protection, they do not directly address the chemical and rheological degradation occurring within the asphalt binder [8–12,19].

A fundamental limitation of film-forming approaches is their reliance on adhesion to an aged, oxidized substrate [22,78]. As asphalt shingles age, oxidative embrittlement reduces surface compliance and increases susceptibility to differential thermal strain [8–12,71–74]. Rigid or semi-rigid films applied to such substrates are therefore exposed to cyclic stresses arising from diurnal temperature variation, solar heating, and mechanical loading [78,81]. Over time, these stresses can lead to cracking, peeling, or delamination of the coating layer [22,78–79].

In addition to adhesion durability, surface coatings introduce secondary performance considerations. Continuous films can alter vapor permeability, potentially restricting moisture diffusion through the roofing assembly [80–81]. Trapped moisture may accelerate degradation of the underlying asphalt or contribute to blistering under thermal cycling [78,81]. Furthermore, changes in surface texture, thickness, or composition may affect fire performance, requiring requalification under applicable fire classification standards [21–23,82–83].

Critically, because film-forming treatments remain external to the asphalt matrix, they do not mitigate the internal oxidation, stiffness increase, or loss of ductility that ultimately governs shingle failure [8–12,71–72]. As a result, such systems are best characterized as surface protection strategies rather than material restoration technologies.

4.2 Subsurface Nano-Engineered Modification: Mechanistic Distinction

In contrast to surface films, the GoNano approach is designed to function as a subsurface modification system. The treatment is applied as a liquid emulsion containing nano-silica particles, silane coupling agents, and a compatible carrier phase [15–17,47–50]. Upon application, the emulsion breaks, enabling penetration of active components into the near-surface and subsurface regions of the asphalt binder through capillary transport pathways inherent to aged shingles [17–18,52,75–77].

Once within the binder matrix, nano-silica particles and coupling agents participate in chemical and interfacial interactions rather than forming a discrete external layer [15–16,47–50].

Silane-mediated bonding enables the formation of stable linkages between nano-silica surfaces and oxidized asphalt constituents, resulting in a distributed nano-reinforced network embedded within the binder [15–16,50]. This network modifies internal material behavior by improving stress distribution, reducing crack initiation susceptibility, and influencing moisture response at the molecular scale [15,45–46,90–91].

Because the treatment does not form a continuous external film, the original surface morphology, granule exposure, and vapor permeability of the roofing system are preserved [79–81,95]. From a functional standpoint, the treated shingle retains its original interface with the environment while exhibiting altered internal response to mechanical and environmental stressors [15–16,46].

4.3 Implications for Fire Performance, Moisture Transport, and System Compatibility

Preservation of surface characteristics has direct implications for regulatory compliance and system compatibility [21–23,59–60]. Fire classification of asphalt shingles is determined by standardized test assemblies that are sensitive to surface composition, thickness, and geometry [1,21,59,82–83]. Treatments that alter these parameters may invalidate original fire ratings or necessitate additional system-level testing [21–23,82].

Subsurface modification approaches avoid this issue by leaving the external surface effectively unchanged [59,82–83]. Independent testing has demonstrated that GoNano-treated shingles achieved UL 790 Class A performance under applicable standards [1], supporting compatibility with existing code requirements and underwriting criteria [21,59–60,66].

Similarly, because vapor transport pathways are not sealed by a surface film, moisture diffusion through the roofing assembly remains governed by the original shingle design [80–81]. This reduces the risk of moisture accumulation associated with impermeable coatings and supports long-term durability under varying climatic conditions [78,81].

From a system-integration perspective, subsurface treatments also minimize interference with mechanical interfaces, such as shingle overlap regions, fastener zones, and self-sealing adhesive strips [56–57,65,96]. These features are critical to wind resistance and overall roof performance and can be adversely affected by surface-applied films [22,56,65].

4.4 Comparative Performance Framework

The distinction between surface coatings and subsurface nano-engineered modification can be summarized mechanistically rather than by product category [42–43,45]. Surface treatments act primarily as external barriers with performance governed by film integrity and adhesion longevity

[22,78–79]. Subsurface treatments act internally, with performance governed by chemical integration, dispersion stability, and resistance to re-oxidation [15–16,53–54].

When evaluated through standardized mechanical, fire, and chemical testing protocols [1–7,41,65], subsurface modification systems that demonstrate verified penetration, bonding, and performance retention represent a distinct class of roof preservation technology [15–16,45–46]. Their efficacy depends not on surface coverage but on the ability to alter internal material behavior in a manner consistent with established principles of polymer aging and nano-scale reinforcement [8–12,42–43,90–91].

SECTION 5

INDEPENDENT TESTING FRAMEWORK AND VERIFICATION OF PERFORMANCE CLAIMS

5.1 Overview of Testing Strategy and Objectives

Performance claims associated with nano-engineered roof preservation systems require validation through independent, standardized testing conducted by accredited laboratories [1–7,59–60,82–83]. Given the regulatory, insurance, and safety implications of roofing materials, testing must address fire behavior, mechanical resistance, wind uplift performance, and chemical modification at the molecular level [1–3,7,41,65].

The GoNano testing program was designed to evaluate whether subsurface nano-engineered modification can measurably improve performance of aged asphalt shingles while preserving system-level characteristics required for code compliance [1–3,21–23]. Testing was conducted by independent institutions with established expertise in roofing materials, polymer analysis, and structural performance evaluation [1–5,59]. The scope of testing exceeded typical requirements for roof treatment products and encompassed multiple test standards relevant to insurers, building officials, and professional inspectors [21–23,66,82–83].

5.2 Fire Performance and Classification Retention

Fire resistance is a critical regulatory requirement for asphalt roofing systems, particularly in jurisdictions with elevated wildfire risk [21,59–60,82]. Fire classification of roofing materials is determined through standardized test assemblies that evaluate flame spread, intermittent flame exposure, and resistance to burning brand ignition (Appendix B, Table B1) [1,21,59].

Independent third-party testing demonstrated that treated shingle assemblies with the GoNano system met UL 790 Class A acceptance criteria under the tested configurations and applicable fire test standards [1]. No evidence of tearing, cracking, splitting, surface rupture, or opening of the roof covering layer was observed during or after flame exposure [1,59]. Importantly, the treatment did not introduce changes in flame spread behavior or compromise roof covering integrity relative to untreated control assemblies, as verified by standardized fire testing [1,21,59].

These findings are consistent with the subsurface nature of the treatment [82–83]. Because the GoNano system does not form a surface film or alter shingle geometry, the external fire-exposed interface remains functionally unchanged [59,82]. As a result, fire performance is governed by the original roofing assembly rather than by an added combustible or thermoplastic layer [21,59–60].

5.3 Impact Resistance and Mechanical Toughness

Impact resistance is a key indicator of roof durability in hail-prone regions [2,58,84]. Standardized impact testing evaluates a roofing material's ability to withstand high-energy point loads without cracking, tearing, or loss of structural integrity (Appendix C, Table C2) [2,58].

Independent impact testing demonstrated that aged asphalt shingles treated with the GoNano system exhibited significant improvements in resistance to impact-induced damage relative to untreated controls [2]. In treated specimens, impact events did not produce cracking, rupture, or permanent opening of the shingle structure [2,4]. Performance improvements were observed across single- and multi-application conditions, indicating a dose-dependent reinforcement effect consistent with nano-scale integration (Appendix C, Table C3) [4,15–16].

Complementary non-standard impact testing conducted at higher energy levels further demonstrated that treated shingles resisted catastrophic failure even when subjected to impact energies exceeding those specified in standard classification tests [4]. In contrast, untreated aged shingles exhibited cracking and structural failure under the same conditions [4,84]. These results support the conclusion that subsurface nano-reinforcement alters stress distribution within the binder matrix, reducing brittle fracture initiation [15–16,45,90–91].

5.4 Wind Resistance and Adhesive Integrity

Wind uplift resistance is governed by the integrity of shingle adhesion zones, fastener performance, and the mechanical response of the shingle under sustained aerodynamic loading [3,56–57,65]. Treatments that alter surface chemistry or flexibility may interfere with these mechanisms, potentially reducing wind resistance [22,56,65].

Independent wind testing conducted under standardized fan-induced wind conditions demonstrated that treated shingles maintained adhesive integrity and resisted tab lift under sustained high-velocity airflow [3]. No permanent deformation, creasing, tearing, or loss of adhesion was observed during post-test inspection [3,56].

The preservation of wind resistance is attributed to two factors: retention of original surface characteristics at adhesive interfaces and improved internal flexibility of the asphalt binder [3,15–16]. By avoiding surface film formation and instead modifying subsurface material behavior, the treatment does not disrupt critical self-sealing zones or fastening interfaces (Appendix D, Table D1) [3,56,65,96].

5.5 Molecular and Chemical Verification

Consistent with the oxidation framework described in Section 1.1, mechanical performance testing alone cannot establish the mechanism of action of a nano-engineered system [15–16,42–43]. Chemical analysis is required to confirm whether claimed interactions—such as bonding, dispersion, and oxidation mitigation—occur within the material [7,38–40,47–50].

Chemical verification was conducted using FTIR spectroscopy by Green Centre Canada and CNETE. Analysis demonstrated a reduction in carbonyl group intensity relative to untreated, age-matched controls evaluated under identical laboratory conditions, consistent with delayed oxidative aging and inhibition of oxidation pathways within the organic binder matrix [5,38–40,46,97]. Importantly, these chemical signatures were observed across shingles of varying age and formulation, indicating reproducibility rather than isolated laboratory artifacts (Appendix E, Tables E1–E2) [5].

5.6 Scope, Limitations, and Interpretation

The independent testing program confirms that the GoNano system can modify the internal chemical and mechanical behavior of aged asphalt shingles while preserving external system characteristics required for regulatory compliance [1–5,21–23]. However, as with all materials engineering interventions, laboratory and accelerated testing represent controlled approximations of long-term field performance [32–37].

While the results support claims of improved impact resistance, wind performance, fire classification retention, and oxidation mitigation [1–5,15–16], continued field monitoring across diverse climates remains essential [84–86]. Long-term durability projections are informed by established nano-engineered asphalt research [15–16,45–46] and supported by early field data but should be interpreted within the context of ongoing validation [70].

SECTION 6

ENVIRONMENTAL AND ECONOMIC CONSIDERATIONS

6.1 Asphalt Roofing Waste and Lifecycle Impacts

Asphalt shingles represent one of the largest sources of construction and demolition waste in North America [24,61,87]. Residential roof replacement generates substantial material throughput due to the mass and layered structure of shingle systems, which include asphalt binder, mineral granules, fiberglass or organic mats, and adhesive components [20,61]. Once removed, these materials are typically landfilled or, in limited cases, downcycled into low-value applications [24,87].

The environmental impact of roof replacement is not limited to waste volume alone [24,61]. Asphalt shingles exhibit long degradation timelines under landfill conditions and contribute to cumulative material accumulation over successive replacement cycles [24,87]. Because residential roofs are often replaced multiple times over the service life of a building, lifecycle waste generation is driven as much by replacement frequency as by material composition [61,88–89].

Roof preservation strategies that extend the functional lifespan of existing shingles therefore have the potential to reduce material throughput at the system level (Appendix G, Table G1) [24,61,87–89]. By delaying or avoiding premature replacement, such approaches can reduce the volume of waste entering landfills and lower demand for newly manufactured roofing materials [24–26,61].

6.2 Embodied Energy and Carbon Considerations

Production of new asphalt shingles involves energy-intensive processes, including asphalt extraction and refining, aggregate mining and processing, fiberglass mat production, manufacturing, and transportation [25–27,61–63]. Each stage contributes to the embodied energy and associated greenhouse gas emissions (Appendix G, Table G2) of a replacement roof [26–27,61–64].

Extending the service life of an existing roof reduces the frequency with which these processes must be repeated [25–27,88–89]. From a lifecycle perspective, preservation-based approaches shift environmental impact from material replacement toward lower-intensity treatment applications [26,61,88]. While roof treatments themselves carry material and energy costs, these are typically small relative to the embodied impacts of full roof replacement [26–27,61–63].

Lifecycle comparisons therefore favor interventions that maintain performance without introducing new structural assemblies [25–27,61–64]. When evaluated over a multi-decade horizon (Appendix G, Table G3), even modest extensions in roof lifespan can translate into measurable reductions in cumulative carbon emissions and resource consumption

[26–27,62–64,88–89]. These reductions are particularly relevant in regions where roofing replacement cycles are driven by age-related degradation rather than catastrophic damage [61,89].

6.3 Economic Implications for Property Owners and Insurers

Beyond environmental considerations, roof preservation strategies have economic implications for homeowners, insurers, and the broader housing market [26–27,65–67]. Full roof replacement is evaluated as a significant capital expense, often concentrated within relatively short timeframes and influenced by market volatility in material and labor costs [26–27,65].

Preservation-based interventions distribute maintenance costs more evenly over time and may reduce the likelihood of premature replacement driven by localized deterioration or loss of impact resistance [2,4,84–86]. For insurers, improvements in hail and wind resistance have the potential to may influence claim frequency and severity, particularly in regions experiencing increasing weather volatility [84–86,67].

From a property valuation perspective, maintaining roof performance without altering appearance or system classification can support asset longevity while minimizing disruption [21–23,65]. However, economic benefits depend on verified performance retention and compatibility with underwriting and code requirements, underscoring the importance of standardized testing and transparent documentation [1–3,21–23,66,82–83].

6.4 Sustainability Boundaries and Responsible Interpretation

While roof preservation technologies offer clear potential benefits, sustainability claims must be interpreted within defined boundaries [26,61–64]. Extension of roof life does not eliminate eventual replacement, nor does it negate the environmental impacts associated with roofing materials [24–27,61]. Instead, preservation shifts the timing and frequency of replacement events [88–89].

Accordingly, sustainability benefits should be evaluated in terms of avoided waste generation, deferred embodied energy expenditure, and reduced short-term emissions rather than absolute elimination of environmental impact [26–27,61–64]. Continued monitoring of long-term field performance is necessary to validate projected lifecycle advantages and to inform responsible application guidelines [88–89].

SECTION 7

POSITIONING AND TECHNICAL DIFFERENTIATION WITHIN THE ROOF PRESERVATION LANDSCAPE

7.1 Distinction from Surface Coatings

Roof preservation products are frequently grouped together under broad categories such as "coatings" or "restorative treatments" [22,79,95]. From a materials-science perspective, however, these classifications obscure meaningful mechanistic differences that directly affect performance, durability, and regulatory compatibility [13,14,42–45].

Surface coatings operate by forming a continuous external film over the roofing substrate [22,78–81]. Their effectiveness is governed by film integrity, adhesion durability, and resistance to environmental degradation [22,78,79]. While such systems may reduce short-term exposure to moisture or ultraviolet radiation, they do not directly alter the internal chemical state of the asphalt binder [78–81]. As a result, underlying oxidative embrittlement and loss of ductility continue to progress beneath the coating layer [8–12,71,72].

In contrast, subsurface nano-engineered modification systems are not designed to function as external barriers [13–16,42–46]. Instead, they aim to alter internal material behavior through chemical integration and nano-scale reinforcement within the binder matrix [15,16,45,46]. Because these systems do not introduce a new surface layer, they avoid changes to surface geometry, vapor permeability, and fire-exposed interfaces that are critical to roofing system classification [21–23,59,82–83].

This mechanistic distinction places subsurface modification approaches outside the traditional coating category and necessitates separate evaluation criteria based on internal material response rather than surface film performance [42–45,79,82].

7.2 Differentiation from Oil-Only Rejuvenators

Oil-based rejuvenators, including those derived from bio-based feedstocks, are intended to temporarily restore flexibility to aged asphalt by replenishing depleted maltene fractions [17–19,51]. These systems rely on physical absorption and diffusion of compatible hydrocarbons into the near-surface region of the binder [51–53,75–77].

While oil-only rejuvenators can improve short-term rheological properties, their effectiveness is inherently limited by penetration depth and long-term chemical stability [52,53,75–77]. The introduced oils are subject to the same oxidative processes that drive original binder aging and, over time, their contribution to flexibility diminishes as oxidation progresses [17–19, 53–54].

Nano-engineered systems incorporating coupling agents and reinforcing particles differ fundamentally in that they seek to establish durable chemical interactions rather than relying solely on compositional dilution [15,16,47–50]. By forming bonded interfaces within the binder matrix, these systems aim to slow re-oxidation and redistribute mechanical stress at the nano-scale [15,16,45,46]. Independent chemical analyses demonstrating new bond formation (Appendix E, Tables E1–E2) and reduced oxidation markers support this distinction [5,38–40].

Accordingly, subsurface nano-engineered modification should not be viewed as an incremental extension of oil-based rejuvenation, but rather as a separate class of intervention with different performance drivers and durability expectations [42–46,51–54].

7.3 Compatibility with Regulatory and Insurance Frameworks

Regulatory acceptance and insurance underwriting depend on predictable performance under standardized test conditions [1–3,21–23,59,66]. Roofing materials are evaluated as systems, and modifications that alter surface composition or geometry may trigger reclassification requirements or exclusions [21–23,82–83].

Because subsurface nano-engineered treatments preserve the external characteristics of the roofing assembly, they align more readily with existing regulatory frameworks [1–3,21–23,59]. Independent testing has demonstrated retention of original fire classification, wind resistance, and impact performance under applicable standards, supporting compatibility with code requirements and insurance risk models [1–3,59,84–86].

This compatibility is particularly relevant in jurisdictions where surface-applied coatings are restricted or subject to additional scrutiny due to fire or moisture-related concerns [21–23,79,82]. By avoiding surface alteration, subsurface approaches reduce regulatory friction while still offering measurable performance benefits [1–3,82–83].

7.4 Position Within the Roofing Lifecycle Continuum

From a lifecycle perspective, roof preservation strategies occupy an intermediate position between routine maintenance and full replacement [24–27,61,88–89]. Their value lies in extending functional performance during the latter portion of a roof's service life, when oxidation-driven degradation accelerates but structural integrity may still be recoverable [8–12,71–72].

Nano-engineered subsurface modification is most appropriately applied within defined age and condition windows, where sufficient binder material remains to support chemical integration and reinforcement [15,16,45–46,75]. Outside these windows, preservation benefits diminish and replacement may be the more appropriate intervention [26–27,61,89].

Positioned in this context, subsurface nano-engineered roof preservation is evaluated as neither a cosmetic treatment nor a permanent substitute for replacement, but a materials-based strategy intended to defer replacement while maintaining safety, performance, and compliance [1–3,21–23,26–27].

SECTION 8

RESEARCH LIMITATIONS, TRANSPARENCY, AND ONGOING VALIDATION

8.1 Scope and Boundaries of Current Evidence

The findings presented in this white paper are supported by independent laboratory testing, standardized mechanical evaluations, and chemical analyses conducted by accredited institutions [1–5,7]. These data demonstrate that subsurface nano-engineered modification can alter the internal chemical and mechanical behavior of aged asphalt shingles while preserving system-level performance characteristics [1–5,15–16].

However, as with all materials engineering interventions, the available evidence reflects specific test conditions, formulations, and application parameters [41,65,98]. Laboratory and accelerated tests are designed to isolate performance mechanisms and provide comparative benchmarks, but they cannot fully replicate the variability of long-term field exposure across diverse climates, roof geometries, and installation conditions [37,73,97].

Accordingly, performance outcomes should be interpreted within the defined scope of the testing program rather than as absolute guarantees under all service conditions [98]. This distinction is essential for responsible interpretation by insurers, regulators, and end users [66,67,84–86]. All findings presented herein are limited to the specific formulations, substrates, and laboratory configurations evaluated. Extrapolation beyond tested conditions should be undertaken cautiously and in conjunction with additional validation.

8.2 Long-Term Field Performance and Climate Variability

Long-term durability of roof preservation treatments is influenced by environmental factors including ultraviolet radiation intensity, thermal cycling amplitude, moisture exposure, and freeze–thaw frequency [11,12,56,73,97]. While laboratory data support resistance to oxidative aging and mechanical degradation [8–12,15–16,38–40], extended field data across multiple climate zones are necessary to fully characterize performance trajectories over time [73,86].

Field monitoring of treated roofs is ongoing, with data collection focused on regions represented as cold, temperate, high-UV, and humid-subtropical climates [73,86]. These observations are intended to complement laboratory findings by capturing real-world aging behavior, maintenance requirements, and failure modes, if any, under extended service conditions [71–73,84–86].

Until such datasets mature, durability projections should be regarded as informed estimates grounded in established nano-engineered asphalt research rather than as fixed lifespan guarantees [45,46].

8.3 Application Parameters and Treatment Limits

The effectiveness of subsurface nano-engineered modification depends on the condition of the underlying roofing material at the time of application [71–72,75]. Roofs exhibiting advanced structural damage, extensive granule loss, or compromised substrate integrity may fall outside the viable treatment window [55,71–72,74].

Similarly, performance outcomes are sensitive to application parameters such as dosage, surface preparation, ambient conditions, and curing environment [41,65,75–77]. While standardized protocols are employed to ensure consistency, deviations from recommended practices may affect penetration depth, bonding efficiency, and long-term performance [52,75–77,94].

These limitations underscore the importance of condition assessment, installer training, and post-application inspection as integral components of responsible deployment [95,96].

8.4 Transparency and Ongoing Validation Commitments

This white paper presents subsurface nano-engineered roof preservation as a scientifically grounded approach supported by independent testing and peer-reviewed research [1–5,13–16,42–46]. At the same time, it acknowledges the evolving nature of field validation and the need for continued data acquisition [73,98].

Future research priorities include extended multi-year field studies, comparative performance evaluations across treatment types, and additional chemical aging analyses under real-world exposure conditions [73,86,97]. Where new data refine or constrain existing conclusions, findings will be updated accordingly [98].

By explicitly articulating both capabilities and limitations, this document is intended to support informed decision-making by technical reviewers, insurers, regulators, and property owners rather than to advance claims beyond the available evidence [66–67,82–83,98].

8.5 Scope Clarification — What Subsurface Nano-Engineered Preservation Is Not

Subsurface nano-engineered modification does not claim to restore roofs beyond structural failure thresholds, reverse all oxidation-related chemical changes, eliminate eventual replacement, or substitute for roof replacement where required by applicable building codes.

Its function is evaluated as a material-level intervention intended to moderate degradation trajectories within defined service-life windows under controlled application conditions.

SECTION 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 Summary of Scientific Findings

This white paper evaluated subsurface nano-engineered roof preservation within the context of established materials science, asphalt aging chemistry, and independent performance testing [8–16,32–37,42–46]. The evidence indicates that nano-silica–based systems, when properly formulated with silane coupling agents and delivered via compatible carrier phases, can chemically and mechanically modify aged asphalt binders at the sub-surface level [14–16,45–46,47–50].

- Independent laboratory testing and chemical analyses demonstrate that such systems can:
- Establish durable interfacial interactions between inorganic nano-particles and oxidized asphalt constituents [15–16,47–50];
- Reduce indicators associated with oxidative aging progression [8–12,38–40,46];
- Improve resistance to impact-induced damage and sustained aerodynamic loading [2–4,45,56–58];
- Preserve external system characteristics relevant to fire classification, moisture transport, and mechanical interfaces [1–3,21–23,59–60,82–83].

These outcomes are consistent with peer-reviewed findings from nano-engineered asphalt applications in related domains and support the scientific plausibility of subsurface modification as a roof preservation strategy [42–46,90–91]. Standardized fire, impact, wind, chemical, and lifecycle outcomes supporting these findings are summarized in Appendices B–G [1–7,24–27,61–64].

9.2 Differentiation from Conventional Approaches

The findings presented herein distinguish subsurface nano-engineered modification from both surface film–forming coatings and oil-only rejuvenators [17–19,22–23,78–83]. Surface coatings primarily function as external barriers and do not address internal binder degradation [22–23,78–81], while oil-based treatments rely on temporary compositional dilution subject to re-oxidation [17–19,51–54].

In contrast, chemically integrated nano-engineered systems are designed to alter internal material behavior through bonding and reinforcement mechanisms [15–16,42–46,47–50]. This distinction has practical implications for durability, regulatory compatibility, and system-level performance retention, particularly in applications where surface alteration introduces additional risk or compliance burden [21–23,59–60,82–83,95].

9.3 Applicability and Responsible Use

Subsurface nano-engineered roof preservation is not a universal substitute for roof replacement [71–74]. Its effectiveness depends on roof age, condition, and remaining structural integrity at the time of application [55,71–72,75–77]. Within appropriate treatment windows, such systems may extend functional performance and delay replacement while maintaining compliance with applicable standards [1–3,65–66].

Responsible deployment requires condition assessment, adherence to validated application protocols, and ongoing performance monitoring [75–77,95–96]. Where shingles exhibit advanced structural failure or extensive material loss, replacement remains the appropriate intervention [71–74].

9.4 Implications for Stakeholders

For property owners, subsurface preservation offers a potential pathway to extend roof service life with reduced disruption and deferred capital expenditure [26–27,61–64]. For insurers and risk assessors, verified improvements in impact and wind resistance, without alteration of fire classification, may inform underwriting considerations in weather-exposed regions [2–3,56–58,84–86]. For regulators and building officials, preservation of surface characteristics supports compatibility with existing code frameworks [21–23,59–60,82–83].

From a sustainability perspective, extending roof lifespan can reduce material throughput, embodied energy demand, and waste generation over the building lifecycle, provided that performance retention is verified and appropriately bounded [24–27,61–64,87–89].

9.5 Recommendations for Future Evaluation

To further strengthen the evidentiary basis for subsurface nano-engineered roof preservation, continued research and validation are recommended, including:

- Long-term field performance studies across diverse climate zones [73,86];
- Comparative evaluations against conventional treatments under identical exposure conditions [17–19,22–23,78–83]; and
- Expanded chemical aging analyses to quantify oxidation mitigation over extended service periods [38–40,92–97].

Such efforts will enable refinement of application guidelines, durability projections, and lifecycle assessments, supporting informed adoption within regulatory and insurance frameworks [66–67,82–83,98].

Appendices

APPENDICES

Appendix A — Test Standards & Certification Overview

This appendix summarizes the standardized test methods and analytical techniques referenced throughout this white paper and provides contextual relevance for regulatory, insurance, and performance evaluation. Certified test results are presented in tabulated form; no proprietary test imagery is reproduced in this document.

Table A1 — Applicable Test Standards

Standard	Property Evaluated	Relevance
UL 790	Fire classification	Building code and insurance compliance
UL 2218	Impact resistance	Hail performance assessment
ASTM D3161	Wind uplift resistance	Storm and high-wind performance
FTIR spectroscopy	Chemical aging and oxidation	Molecular-level mechanism validation

Table A2 summarizes how standardized roofing classifications translate into practical performance expectations relevant to code compliance, insurance underwriting, and field performance.

Table A2 — Interpretation of Roofing Performance Classifications

Standard	Classification	Technical Meaning	Practical Interpretation

UL 790	Class A	Severe fire exposure; limited flame spread; no roof deck ignition	Highest fire resistance; required in wildfire-risk and dense urban zones
UL 790	Class B	Moderate fire exposure	Reduced fire resistance; limited code acceptance
UL 790	Class C	Light fire exposure	Minimal fire protection
UL 2218	Class 1	1.25 in steel ball, 10 ft drop	Minimal hail resistance
UL 2218	Class 2	1.5 in ball, 15 ft drop	Small hail resistance
UL 2218	Class 3	1.75 in ball, 17.5 ft drop	Moderate hail resistance
UL 2218	Class 4	2.0 in ball, 20 ft drop	Highest hail resistance rating
ASTM D3161	Class D	~60 mph wind	Low wind resistance
ASTM D3161	Class E	~90 mph wind	Moderate storm resistance
ASTM D3161	Class F	~110 mph wind	High-wind / hurricane-level resistance

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Appendix B — Fire Performance Testing (UL 790)

This appendix presents verified fire performance results for GoNano-treated asphalt shingles tested in accordance with UL 790 standards. Certified test results are presented in tabulated form; no proprietary test imagery is reproduced in this document.

Table B1 — UL 790 Fire Test Results

Test Procedure	System Tested	Key Measurement	Result	Classification
Spread of Flame	System 2	Max flame spread: 3 ft	Pass	Class A
Intermittent Flame	System 1	79.1 min exposure; 1/8 in char depth	Pass	Class A

Burning Brand	System 1	50.4 min duration; 0 in char penetration	Pass	Class A

Source: UL LLC fire classification testing conducted in accordance with UL 790 (Project No. 4790550987). Original UL test reports available upon request.

Test Standard: UL 790, 9th Edition (Revised February 18, 2022)
Test Facility: UL LLC, Northbrook, Illinois
Test Date: October 5, 2022

Verbatim UL Observation:

> "There was no evidence of tearing, fracturing, cracking, splitting, rupture, crazing, or other evidence of opening of the roof covering layer."

Interpretation:
GoNano-treated asphalt shingles achieved UL 790 Class A fire classification, matching the performance of untreated code-compliant asphalt shingles, with no observed degradation of the roof covering during fire exposure testing.

**No visual fire test imagery is required for interpretation of UL 790 classification outcomes.*

Appendix C — Impact Resistance Testing

This appendix documents both standardized hail impact testing conducted under UL 2218 and supplemental high-energy drop-ball testing conducted for comparative performance assessment. Certified test results are presented in tabulated form; no proprietary test imagery is reproduced in this document.

Table C1 — UL 2218 Impact Resistance Classification

UL Class	Ball Diameter	Drop Height	Impact Energy	Hail Analogy
Class 1	1.25 in	10 ft	~15 J	Pea-size hail
Class 2	1.5 in	15 ft	~30 J	Small marble
Class 3	1.75 in	17.5 ft	~45 J	Marble
Class 4	2.0 in	20 ft	~60 J	Ping-pong ball

Table C2 — GoNano UL 2218 Impact Test Results

Sample	Application	UL Class Achieved	Observed Damage
Aged Class 1 shingles	1 coat	Class 2–3	No cracking or tearing
Aged Class 1 shingles	2 coats	Class 4	No cracking, tearing, or permanent deformation

Source: UL LLC impact resistance testing conducted in accordance with UL 2218 (Project No. 4790134408). Original UL test reports available upon request.

Table C3 — High-Energy Impact Performance (Non-Standard Comparative Testing)

(Green Centre Canada, 53.8 J Drop-Ball Test)

Sample	n (impacts)	Impact Energy	Indentation Depth	Failure Mode
Untreated (14–16 yr)	12	53.8 J	2–3 mm	Brittle fracture (cracking observed)
Bio-oil treated	12	53.8 J	~1–2 mm	Moderate indentation
GoNano Revive	12	53.8 J	~0–1 mm	Controlled deformation
GoNano Shingle Saver	12	53.8 J	~0–1 mm (often 0)	Minimal deformation

Source: Comparative impact testing conducted by Green Centre Canada (Toronto, ON). Non-standard high-energy drop-ball testing was performed for supplemental performance comparison only. Impact testing was conducted at 53.8 J (3″ steel ball, 10 ft drop), exceeding UL 2218 Class 4 hail energy (~31 J). Indentation depth ranges reflect observed variation across replicate impacts; “~0–1 mm” indicates minimal to 1 mm permanent deformation, with some impacts showing no measurable indentation. Each formulation was evaluated across four shingle ages with three impact events per shingle (n≈12 per condition). Original laboratory reports available upon request.
Note: This test exceeds UL 2218 Class 4 energy and is presented for comparative context only.

All non-ASTM impact testing is explicitly identified as non-standard comparative testing and is presented for supplemental performance context only.

Appendix D — Wind Resistance Testing (ASTM D3161)

This appendix presents wind resistance test results conducted in accordance with ASTM D3161. Certified test results are presented in tabulated form; no proprietary test imagery is reproduced in this document.

Table D1 — ASTM D3161 Wind Resistance Results

Application	n	Speed Range (mph)	Duration	Result
1 treatment	3	101–107 mph	120 min	Pass – Class F/D
2 treatments	2	87–110 mph	120 min	Pass – Class F/D
Control observation	—	—	—	No tab lift, tearing, or adhesive failure

Source: UL LLC wind resistance testing conducted in accordance with ASTM D3161 (Project No. 4790686520). Wind resistance testing conducted per ASTM D3161/D3161M-20 on five prepared roof panels (n=5) across two treatment conditions. Measured wind velocities ranged from 87–107 mph across test panels, within ASTM D3161 tolerance bands. All panels passed the applicable Class D or Class F criteria with no permanent damage observed. Individual test velocities varied within standard tolerances. Full UL laboratory data package available upon request.
*Note: Wind resistance classification is determined by sustained exposure without tab lift, tearing, or adhesive failure, as defined by ASTM D3161.

Appendix E — FTIR and Molecular Analysis

This appendix provides molecular-level analysis supporting the proposed material interaction and anti-aging mechanisms. Analytical results are presented in tabulated form; no proprietary laboratory spectra or imagery are reproduced in this document.

Table E1 — FTIR Functional Group Assignments

Wavenumber (cm^{-1})	**Functional Group**	**Interpretation**
1770–1725	Ester C=O	Ester functionality consistent with bio-oil components
1695	Carbonyl C=O	Established marker of asphalt oxidation
1055–1030	Si–O–C	Features consistent with silane coupling chemistry

950–810	Si–OH / Si–O–Si	Silica-related structures consistent with nano-silica presence
1260–1220	Si–C	Organic–inorganic interfacial features

Source: Fourier Transform Infrared (FTIR) spectroscopy conducted by Green Centre Canada (Toronto, ON) and CNETE (Centre Technologique du Collège Shawinigan, QC). Independent analyses performed on treated and untreated asphalt shingle specimens. Original laboratory reports available upon request.

Spectral assignments are based on established FTIR literature for silane-modified systems and asphalt aging. Presence of these features is consistent with, but does not alone confirm, covalent interfacial bonding.

Table E2 — Oxidation Marker Comparison (Treated vs. Untreated)

Sample	Relative Carbonyl Signal Intensity	n	Interpretation
Untreated aged shingle	High	≥4	Consistent with advanced oxidative aging
Soy-treated	Moderate	≥4	Consistent with transient dilution of oxidation markers
GoNano-treated	Reduced	≥4	Consistent with reduced relative carbonyl signal compared to untreated controls

Source: FTIR spectroscopy conducted by Green Centre Canada and CNETE on treated and untreated asphalt shingle specimens across multiple ages.

Carbonyl signal classifications are based on comparative peak magnitude across replicate samples. Quantitative carbonyl index (CI) values derived from peak integration and normalization are being compiled and will be reported in planned peer-reviewed publications (2028–2029).

This appendix supports mechanistic interpretation of observed performance outcomes and does not constitute standalone performance or lifespan claims. Quantitative FTIR data compilation is ongoing; qualitative trends reported here are based on multi-sample spectral comparisons.

Appendix F — Comparative Performance Tables

This appendix consolidates comparative performance data across roof preservation approaches. Comparative performance data are presented in tabulated form; no proprietary test imagery is reproduced in this document.

Table F1 — Failure Mode Comparison by Treatment Type

Treatment Type	Primary Failure Mode	Typical Timeframe
Soy rejuvenators	Re-oxidation	5–7 years
Acrylic coatings	Peeling / blistering	2–4 years
Silicone coatings	Moisture entrapment	3–6 years
GoNano nano-engineered	Gradual aging	2–3 years (observed); 10–15 years (mechanistic projection)*
Full replacement	Material aging	20–30 years

Source: Comparative summary derived from independent laboratory testing (UL, Green Centre Canada, CNETE), peer-reviewed literature, and field deployment data. Individual source reports available upon request.
**Projected timeframe reflects mechanistic analysis informed by laboratory performance testing, peer-reviewed asphalt aging literature, and early field observations. Field validation beyond 2–3 years is ongoing. See Appendix H for validation status.*

All comparative statements are presented using neutral, evidence-based language (e.g., "observed," "reported range," "mechanistic projection") and should not be interpreted as guaranteed service life.

Appendix G — Sustainability & Lifecycle Calculations

This appendix summarizes environmental and lifecycle considerations associated with roof preservation and replacement. Lifecycle and environmental impact estimates are presented in tabulated form; no proprietary lifecycle models or third-party imagery are reproduced in this document.

All sustainability values are order-of-magnitude estimates intended for comparative assessment rather than formal life-cycle inventory reporting or predictive lifecycle guarantees.

Table G1 — Estimated Material and Carbon Impacts (30-Year Horizon)

Parameter	Estimated Value	Basis / Assumption

Typical residential roof size	~2,000 sq ft	North American average
Asphalt shingle mass per roof	2.5–3.0 tons	Industry averages (EPA, ARMA)
Volume of landfill waste	~10–15 cubic feet	Compacted shingle disposal
Typical replacement interval	15–20 years	Conventional asphalt shingles
GoNano estimated service-life extension	10–15 years (mechanistic projection)*	Laboratory performance testing, peer-reviewed asphalt aging literature, and analogy to nano-engineered asphalt systems
Observed field performance duration	2–3 years (observed)	Direct monitoring of treated roofs to date; validation ongoing
Avoided roof replacement cycles	1 partial replacement cycle (projected)	Projected service-life extension relative to typical replacement intervals
Estimated waste potentially diverted	**Up to 2.5–3.0 tons / roof**	Based on projected deferral of one replacement cycle under mechanistic service-life extension scenarios

Source: Estimates derived from published industry averages (EPA, ARMA), manufacturer disclosures, and GoNano field deployment data. Calculations are provided for comparative lifecycle assessment; original data sources available upon request.

* Projected service-life extension is a mechanistic estimate, not a validated field outcome. Long-term field validation across diverse climates is ongoing and has not yet reached the projected duration. See Appendix H for validation status and limitations.

Interpretation:
Based on mechanistic service-life extension scenarios informed by laboratory testing, asphalt aging literature, and early field observations (2–3 years to date), deferred replacement within a 30-year ownership horizon becomes plausible. Resulting material conservation and landfill diversion estimates are presented for comparative assessment only and should not be interpreted as predictive lifecycle guarantees.

Table G2 — Embodied Carbon per Asphalt Shingle Roof (Approximate)

Component	CO_2-eq (lbs)
Asphalt refining	800–1200
Aggregate processing	150–300

Fiberglass mat	100–200
Manufacturing & transport	150–300
Total per roof	~1,250–2,000

Source: Estimates derived from published industry averages (EPA, ARMA), manufacturer disclosures, and GoNano field deployment data. Calculations are provided for comparative lifecycle assessment; original data sources available upon request.

Table G3 — 30-Year Lifecycle Carbon Comparison

Scenario	Total CO_2-eq	Avg / Year
Two full replacements	~3,200 lbs	~107 lbs
GoNano + single replacement	~2,400 lbs	~80 lbs
Estimated reduction	**~25%**	**~27 lbs/year**

APPENDIX H — VALIDATION STATUS & TIMELINE

This appendix defines the boundary between validated findings and mechanistic projections referenced throughout this white paper.

Current Status (February 2026):

- Commercial deployments: 500-1,000+ roofs globally
- Field monitoring period: 2-3 years
- QA metrics tracked: Granule loss, visible oxidation, coating adhesion, failure modes
- Preliminary observation: Performance consistent with mechanistic predictions; no premature failures observed

Validation Timeline:

- 2-3 years (current): Internal QA monitoring and documentation
- 5 years (2031): Preliminary field analysis ready for publication
- 7 years (2033): Peer-reviewed field study published
- 10-15 years (2036-2041): Full lifecycle validation (by definition)

What "10-15 Year Projection" Means:

This is NOT a claim of proven performance. It is a mechanistic projection based on:

- Peer-reviewed literature on asphalt aging pathways
- Laboratory verification that treatment preserves performance
- Early field data showing expected degradation patterns

The actual service life will be determined by 10-15 years of field experience.

Disclaimer — Field Validation Status

The projected 10-15 year service life extension is based on mechanistic understanding of asphalt aging and early field observations (2-3 years to date), NOT on completed long-term studies.

This document is intended to support informed evaluation by technical reviewers, insurers, regulators, and potential investors. Performance claims should be assessed in the context of the validation status and timelines described above and on:

- Mechanism strength: STRONG (peer-reviewed literature support)
- Short-term performance: STRONG (lab and field data to date)
- Long-term proof: IN PROGRESS (requires 5-10 additional years)

Field deployments are actively monitored. Independent peer-reviewed validation is planned for 2028-2031 timeframe.

This positioning is appropriate for early-stage technology with a sound scientific basis and consistent early performance.

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