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An AI-Driven Sustainable Construction Chemicals Adoption Framework for Liquid-Applied Waterproofing Systems: Integrating Engineering Reliability, VOC Impact, Lifecycle Cost, and Stakeholder Adoption Behaviour

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Abstract

Liquid-applied waterproofing membranes are increasingly used in modern infrastructure because of their seamless application, crack-bridging ability, adaptability to complex geometries, and capacity to protect structures against water ingress. However, conventional waterproofing selection practices often depend on isolated material properties such as tensile strength, elongation, adhesion, and impermeability. These parameters alone do not adequately represent cyclic fatigue resistance, elastic recovery, hysteresis behaviour, execution-quality influence, environmental impact, lifecycle cost, supply-chain feasibility, or stakeholder adoption behaviour. This creates a significant gap between laboratory-based material evaluation and real-world field performance.

To address this gap, the present study develops and validates an integrated WRI–VOC–SCCAF framework for sustainable, reliable, and intelligent waterproofing system selection. The framework combines the Waterproofing Reliability Index (WRI), Mechanical Performance Core Model (MPCM), λ-based VOC–Environmental Impact Model, Sustainable Construction Chemicals Adoption Framework (SCCAF), and lifecycle cost–durability evaluation into a unified decision-support structure. The model classifies mechanical performance, durability, adhesion performance, defect sensitivity, and VOC–Environmental Impact as independent explanatory variables; WRI and adoption intention as primary mediating constructs; cost sensitivity and supply-chain accessibility as adoption-pathway mediating drivers; product knowledge, institutional trust, and implementation friction as moderating variables; and final adoption behaviour as the dependent outcome.

A quantitative research design was adopted, and Structural Equation Modelling (SEM) was conducted using 350 valid responses collected from contractors, consultants, engineers, architects, waterproofing applicators, manufacturers, project managers, procurement professionals, and infrastructure maintenance stakeholders. The measurement model demonstrated acceptable reliability and validity. Cronbach’s alpha values ranged from 0.78 to 0.88, Composite Reliability values ranged from 0.85 to 0.91, and Average Variance Extracted values ranged from 0.55 to 0.68. Discriminant validity was confirmed through HTMT values below 0.85, while VIF values below 5.0 indicated the absence of serious multicollinearity.

The structural model showed strong explanatory and predictive power. Mechanical performance had the strongest positive effect on WRI ($\beta = 0.42$, $p < 0.001$), followed by durability ($\beta = 0.31$, $p < 0.001$) and adhesion performance ($\beta = 0.28$, $p < 0.001$), while defect sensitivity negatively influenced WRI ($\beta = -0.26$, $p < 0.001$). WRI significantly improved adoption intention ($\beta = 0.45$, $p < 0.001$), whereas VOC–Environmental Impact negatively influenced adoption intention ($\beta = -0.22$, $p < 0.001$). Cost sensitivity negatively influenced adoption intention ($\beta = -0.18$, $p < 0.001$), while supply-chain accessibility positively influenced adoption intention ($\beta = 0.24$, $p < 0.001$). Adoption intention strongly predicted final adoption behaviour ($\beta = 0.52$, $p < 0.001$). The model explained 64% of the variance in WRI, 58% of the variance in adoption intention, and 61% of the variance in final adoption behaviour. Model fit was acceptable, with SRMR = 0.061, NFI = 0.91, and RMS Theta = 0.096.

The findings demonstrate that waterproofing adoption is governed by a combined pathway involving engineering reliability, environmental sustainability, lifecycle economics, supply-chain accessibility, stakeholder knowledge, institutional trust, and implementation feasibility. Systems with higher initial cost may provide superior lifecycle value when they reduce leakage risk, repair frequency, maintenance burden, downtime, and long-term failure consequences. The proposed framework supports performance-based waterproofing specifications, low-VOC material selection, lifecycle-cost-aware procurement, BIM-enabled durability analytics, Digital Twin-based performance monitoring, and AI-driven predictive maintenance.

This study contributes to waterproofing engineering and sustainable construction chemicals research by advancing material selection from conventional property-based comparison toward a performance-based, sustainability-oriented, stakeholder-sensitive, lifecycle-cost-aware, and AI-compatible decision-support model. The WRI–VOC–SCCAF framework provides practical value for consultants, contractors, manufacturers, project owners, procurement teams, policymakers, certification bodies, and infrastructure maintenance professionals involved in sustainable construction and long-term durability management.

Keywords

Waterproofing Reliability Index; Liquid-Applied Waterproofing Membranes; VOC Environmental Impact; Sustainable Construction Chemicals Adoption Framework; Lifecycle Cost Analysis; Durability-Based Performance Evaluation; Structural Equation Modelling; AI-Enabled Infrastructure Management

1. Introduction

Liquid-applied waterproofing membranes (LAMs) have emerged as critical components in modern infrastructure systems due to their seamless application capability, adaptability to complex geometries, superior crack-bridging performance, and long-term protection against water ingress in both below-grade and above-grade structures (Riahinezhad et al., 2021; dos Santos et al., 2022; Zhao et al., 2021). Rapid urbanisation, infrastructure expansion, climate-induced deterioration, and increasing demand for lifecycle-oriented durability have accelerated the global adoption of waterproofing technologies across residential, commercial, transportation, industrial, marine, and energy infrastructure sectors (Grand View Research, 2023; MarketsandMarkets, 2024; Allied Market Research, 2023). In India, the waterproofing chemicals sector is experiencing substantial growth due to increasing awareness regarding structural durability, preventive maintenance, sustainability compliance, and lifecycle cost optimisation within infrastructure development projects (IBEF, 2023; CRISIL, 2024).

Despite significant advancements in waterproofing materials and membrane technologies, waterproofing system selection in engineering practice continues to rely predominantly on isolated material parameters such as tensile strength, elongation at break, and basic adhesion properties (Mehta & Monteiro, 2014; Neville, 2011; ACI Committee 515, 2020). Although elongation is commonly associated with flexibility and crack-bridging capability, several studies have demonstrated that isolated elongation-based evaluation does not adequately represent fatigue resistance, elastic recovery efficiency, hysteresis behaviour, cyclic crack accommodation, or long-term durability under realistic structural movement conditions (dos Santos et al., 2022; Shojaei et al., 2021; Riahinezhad et al., 2021). Consequently, waterproofing systems exhibiting high laboratory elongation values may still undergo premature failures under field conditions due to fatigue-induced rupture, blistering, delamination, de-bonding, crack localisation, moisture entrapment, and membrane–substrate incompatibility (Singh et al., 2019; Patel & Desai, 2021). Existing waterproofing evaluation approaches therefore remain insufficient for predicting field reliability under dynamic loading and environmental exposure conditions.

Waterproofing performance depends on the interaction between material properties, substrate preparation quality, application methodology, curing behaviour, drainage efficiency, screed protection, workmanship variability, thermal cycling, ultraviolet exposure, hydrostatic pressure, and long-term maintenance conditions (ISO 4628, 2016; ASTM C836, 2020; EN 1504-2, 2018). Research conducted by RILEM technical committees and durability researchers has shown that execution-related defects and workmanship variability significantly influence waterproofing performance and frequently govern long-term durability behaviour more than isolated laboratory material properties (RILEM TC 195, 2017; Kumar et al., 2021). However, most existing standards and evaluation methods assess independent material properties without integrating execution-quality variability, defect propagation behaviour, drainage influence, screed protection effectiveness, or substrate interaction into a reliability-oriented engineering assessment system. This creates a major disconnect between laboratory-based waterproofing evaluation and real-world field performance prediction.

Beyond engineering durability, environmental sustainability is becoming increasingly important in waterproofing system selection. Solvent-based waterproofing systems emit volatile organic compounds (VOCs), which contribute to indoor air pollution, occupational exposure risks, environmental degradation, and long-term human health concerns (WHO, 2010; EPA, 2021; Salthammer, 2020). Prolonged VOC exposure has been associated with respiratory disorders, toxicity risks, environmental contamination, and deterioration in indoor environmental quality (Guo et al., 2018; Weschler, 2016; Salthammer, 2020). Consequently, international sustainability frameworks including LEED, IGBC, and ISO 14040 increasingly promote the adoption of low-VOC and environmentally sustainable construction materials (USGBC, 2022; IGBC, 2023; ISO 14040, 2006). However, most existing waterproofing selection methodologies evaluate engineering performance and environmental sustainability independently, thereby creating a significant gap between durability optimisation and sustainable material selection (Cheng et al., 2021; Kumar & Singh, 2022). At present, there is no scientifically validated waterproofing evaluation system capable of simultaneously integrating engineering reliability and environmental sustainability within a single analytical framework.

In addition to technical and environmental limitations, waterproofing material adoption is strongly influenced by behavioural, institutional, technological, and economic factors. Existing engineering-based waterproofing selection systems rarely incorporate stakeholder perception, environmental awareness, institutional trust, policy influence, implementation barriers, economic sensitivity, technological readiness, supply-chain accessibility, or adoption intention into decision-making models (Ajzen, 1991; Rogers, 2003; Venkatesh et al., 2012; Sai Gowrav & Nandi, 2026). Previous studies on sustainable construction materials have demonstrated that material adoption behaviour is governed not only by engineering performance but also by behavioural intention, regulatory support, organisational influence, environmental consciousness, and implementation feasibility (Chen et al., 2023; Li et al., 2022). Nevertheless, behavioural adoption theories and engineering reliability assessment frameworks remain largely disconnected within waterproofing research literature. Consequently, the relationship between engineering reliability and stakeholder-driven adoption behaviour remains insufficiently understood in sustainable waterproofing engineering.

Furthermore, current waterproofing research lacks predictive analytical systems capable of supporting intelligent infrastructure management, BIM-enabled durability analytics, Digital Twin integration, machine-learning-based performance prediction, and Industry 4.0-oriented predictive maintenance applications. Existing waterproofing evaluation systems remain predominantly static and non-adaptive, limiting their suitability for future intelligent infrastructure analytics and digital decision-support systems. This represents a major technological gap in next-generation waterproofing engineering.

Therefore, a major research gap exists in the development of a comprehensive and empirically validated waterproofing evaluation system capable of simultaneously integrating:

- Engineering reliability assessment
- Fatigue and cyclic durability behaviour
- Environmental sustainability evaluation
- VOC impact assessment
- Execution-quality influence
- Stakeholder adoption behaviour
- AI-compatible predictive analytics

within a reliability-oriented waterproofing decision-support system.

To address these research gaps, the present study proposes a unified analytical model combining the Waterproofing Reliability Index (WRI), the λ-based VOC–Environmental Impact Model, and the Sustainable Construction Chemicals Adoption Framework (SCCAF) into a reliability-oriented waterproofing evaluation system. A major engineering contribution of the study is the development of the Waterproofing Reliability Index (WRI), which integrates tensile strength, crack-bridging capability, elastic recovery, hysteresis resistance, adhesion performance, fatigue behaviour, durability characteristics, environmental exposure sensitivity, and execution-related defect parameters into a unified engineering reliability model.

The study further introduces the Mechanical Performance Core Model (MPCM), which incorporates cyclic structural movement behaviour, fatigue resistance, crack accommodation capability, and membrane recovery performance into a realistic waterproofing durability assessment approach. Unlike conventional static property-based evaluation methods, the MPCM framework captures the influence of dynamic loading and cyclic structural movement on long-term waterproofing reliability.

In parallel, the study establishes a λ-based VOC–Environmental Impact Model that quantifies sustainability penalties associated with waterproofing material selection by integrating VOC emission behaviour, occupational exposure influence, environmental sustainability weighting, and lifecycle environmental impact parameters into the engineering decision-making process. This enables balanced optimisation between engineering durability and environmental sustainability.

The present study additionally integrates the Sustainable Construction Chemicals Adoption Framework (SCCAF), originally proposed by Sai Gowrav and Nandi (2026), which incorporates behavioural intention, institutional trust, implementation barriers, environmental concern, economic sensitivity, policy influence, technological readiness, product knowledge, and supply-chain accessibility into waterproofing adoption analysis. This integration bridges the gap between engineering reliability assessment and stakeholder-driven waterproofing adoption behaviour.

The integrated WRI–VOC–SCCAF framework is validated using Structural Equation Modelling (SEM) based on responses collected from contractors, consultants, engineers, manufacturers, architects, applicators, and project-management professionals across the construction industry. The SEM framework evaluates direct, indirect, mediating, and moderating relationships between engineering reliability, environmental sustainability, stakeholder perception, and final waterproofing adoption behaviour.

The proposed framework also establishes a scientific foundation for:

- Performance-based waterproofing specifications
- Intelligent material selection systems
- Predictive maintenance planning
- Lifecycle-oriented durability optimisation
- BIM-enabled durability analytics
- Digital Twin integration
- AI-assisted infrastructure management
- Industry 4.0-enabled predictive infrastructure systems

Unlike conventional waterproofing evaluation methods focused on isolated material properties, the proposed WRI–VOC–SCCAF model advances waterproofing engineering by combining reliability assessment, sustainability evaluation, behavioural adoption modelling, execution-quality analysis, and predictive analytics within a unified decision-support structure suitable for future intelligent infrastructure applications.

1.1 Research Objectives

The primary objectives of the present study are:

1. To develop a Waterproofing Reliability Index (WRI) integrating mechanical performance, fatigue behaviour, adhesion characteristics, durability parameters, and execution-related defect factors.
2. To develop a Mechanical Performance Core Model (MPCM) for evaluating cyclic waterproofing reliability under realistic structural movement conditions.
3. To establish a λ-based VOC–Environmental Impact Model incorporating environmental sustainability into waterproofing material selection methodology.
4. To combine the Sustainable Construction Chemicals Adoption Framework (SCCAF) with engineering reliability assessment for evaluating stakeholder adoption behaviour.
5. To validate the proposed WRI–VOC–SCCAF model using Structural Equation Modelling (SEM) based on industry stakeholder responses.
6. To develop an AI-compatible waterproofing decision-support system supporting BIM integration, Digital Twin applications, predictive durability analytics, and Industry 4.0 infrastructure management.

1.2 Novelty and Contribution of the Study

The present study introduces a next-generation waterproofing evaluation model combining engineering reliability, environmental sustainability, behavioural adoption modelling, and predictive infrastructure analytics within a unified analytical structure.

Table 1. Novel Contributions of the Present Study

Sl. No.	Contribution Domain	Novel Contribution	Scientific and Industrial Significance
1	Engineering Innovation	Development of the Waterproofing Reliability Index (WRI) integrating tensile strength, crack-bridging capability, adhesion behaviour, elastic recovery, fatigue resistance, durability, and defect sensitivity into a unified reliability model	Provides realistic waterproofing reliability assessment beyond conventional single-property evaluation methods
2	Mechanical Innovation	Development of the Mechanical Performance Core Model (MPCM) incorporating cyclic structural movement, hysteresis response, membrane recovery efficiency, and crack-accommodation behaviour	Captures fatigue-driven deterioration mechanisms neglected in conventional waterproofing evaluation systems
3	Mathematical Innovation	Development of adaptive weighting, normalisation, and parameter-integration methodology for reliability optimisation	Enables project-specific and exposure-sensitive waterproofing evaluation under varying infrastructure conditions
4	Environmental Innovation	Integration of a λ-based VOC–Environmental Impact Model within the waterproofing reliability framework	Quantifies environmental sustainability, occupational exposure risk, and VOC-related performance penalties during material selection
5	Behavioural Innovation	Incorporation of the Sustainable Construction Chemicals Adoption Framework (SCCAF) within engineering reliability assessment	Bridges the gap between stakeholder adoption behaviour, sustainability perception, and engineering performance evaluation

6	Statistical Innovation	Empirical validation of the integrated WRI–VOC–SCCAF model using Structural Equation Modelling (SEM) with 350 industry stakeholder responses	Provides statistical robustness, causal validation, and empirical reliability for the proposed framework
7	Field Engineering Innovation	Integration of execution quality, workmanship variability, substrate preparation, drainage behaviour, screed protection, and defect propagation factors	Improves field applicability and enhances prediction accuracy under practical construction conditions
8	Digital and AI Innovation	Development of an AI-compatible WRI architecture suitable for machine-learning-based durability prediction	Supports future predictive analytics, intelligent infrastructure monitoring, and adaptive waterproofing performance assessment
9	Industry 4.0 Innovation	Compatibility with BIM systems, Digital Twin platforms, IOT-enabled infrastructure monitoring, and predictive maintenance systems	Supports intelligent infrastructure management and smart construction ecosystems
10	Policy and Sustainability Innovation	Suitability for performance-based specifications, green building standards, lifecycle assessment systems, and sustainability-oriented procurement strategies	Supports development of sustainable construction policies and environmentally responsible engineering practices
11	Decision-Making Innovation	Development of a Reliability–VOC optimisation model combining engineering durability, sustainability evaluation, and stakeholder adoption dynamics	Enables balanced and sustainability-oriented waterproofing material selection and infrastructure decision-making
12	Lifecycle Cost and Durability Innovation	Integration of lifecycle cost analysis with WRI-based durability assessment for performance-based waterproofing selection	Enables value-based procurement by linking technical reliability, service-life performance, maintenance cost, repair cost, downtime cost, and long-term economic efficiency

The proposed WRI–VOC–SCCAF framework represents a next-generation advancement in waterproofing engineering by integrating mechanical reliability assessment, environmental sustainability evaluation, behavioural adoption modelling, execution-quality analysis, and AI-compatible predictive analytics into a unified scientific decision-support system. Unlike conventional waterproofing assessment approaches that evaluate isolated material

2.LITERATURE REVIEW

2.1 Market Context and Growth of Waterproofing and Liquid-Applied Membranes

The global waterproofing industry has expanded rapidly due to urbanisation, infrastructure development, climate-induced deterioration, and increasing emphasis on lifecycle durability. Waterproofing membranes form a critical segment of construction chemicals because they directly influence service life, structural protection, maintenance frequency, and long-term asset performance (Grand View Research, 2023; MarketsandMarkets, 2024; Allied Market Research, 2023).

Among waterproofing technologies, liquid-applied membranes (LAMs) have gained significant importance because they provide seamless protection, adapt to complex geometries, reduce joint-related leakage risk, and are suitable for new construction as well as rehabilitation works (Riahinezhad et al., 2021; dos Santos et al., 2022; Zhao et al., 2021). LAMs are widely used in terraces, podiums, basements, industrial floors, transportation infrastructure, water-retaining structures, exposed decks, and marine environments.

In India, waterproofing demand is increasing due to infrastructure expansion, greater awareness of durability, preventive maintenance requirements, and sustainability compliance (IBEF, 2023; CRISIL, 2024). However, material selection in practice often remains dependent on simplified property comparison rather than comprehensive service-performance assessment.

2.2 Mechanical Performance Evaluation of Waterproofing Systems

Traditional waterproofing evaluation primarily relies on tensile strength, elongation at break, impermeability, and adhesion strength (Mehta & Monteiro, 2014; Neville, 2011; ACI Committee 515, 2020). Although elongation is frequently interpreted as an indicator of flexibility and crack-bridging capacity, elongation alone does not adequately represent cyclic fatigue resistance, elastic recovery, hysteresis behaviour, permanent strain accumulation, or long-term crack-accommodation performance under realistic service conditions (dos Santos et al., 2022; Shojaei et al., 2021; Riahinezhad et al., 2021).

Recent research therefore emphasises multi-parameter assessment combining tensile strength, crack-bridging ability, elastic recovery, adhesion retention, hysteresis response, fatigue resistance, and durability retention. Such integrated evaluation is necessary because waterproofing membranes are exposed to cyclic movement, thermal expansion, substrate deformation, hydrostatic pressure, ultraviolet radiation, moisture ingress, and workmanship variability throughout service life.

2.3 Durability and Environmental Exposure Effects

Waterproofing systems are continuously exposed to thermal cycling, hydrostatic pressure, ultraviolet radiation, ponding water, chemical attack, moisture ingress, and hydrothermal ageing (ISO 4628, 2016; ASTM C836, 2020; EN 1504-2, 2018). These exposure conditions progressively reduce elasticity, adhesion retention, crack resistance, fatigue durability, and recovery behaviour.

Membrane deterioration is governed by coupled degradation mechanisms such as oxidation, polymer chain scission, interfacial weakening, hydrothermal ageing, fatigue cracking, and adhesion loss. Therefore, waterproofing systems cannot be reliably evaluated using isolated laboratory properties alone. Exposure severity, substrate interaction, application quality, drainage performance, and long-term service conditions must be incorporated into material selection.

2.4 Failure Mechanisms of Liquid-Applied Membrane Systems

Liquid-applied membrane failures are commonly caused by a combination of mechanical, environmental, interfacial, and execution-related mechanisms. Major failure modes include adhesion loss, delamination, hydrostatic water penetration, ponding-water degradation, surface preparation deficiency, moisture entrapment, inadequate membrane thickness, cyclic fatigue, UV ageing, mechanical damage, and detailing failure (Singh et al., 2019; Patel & Desai, 2021; Kumar et al., 2021).

Adhesion failure is one of the most critical deterioration mechanisms because poor substrate preparation, moisture entrapment, thermal incompatibility, and cyclic movement reduce interfacial bond strength. Similarly, inadequate drainage and ponding water accelerate osmotic blistering, hydrolytic degradation, coating softening, and membrane de-bonding. Moisture entrapment beneath impermeable membranes can generate vapour pressure, causing bubbling, blistering, rupture, and localised de-bonding.

Cyclic fatigue and crack-bridging failure occur when repeated thermal movement, vibration, settlement, or structural deformation produces tensile and shear stresses within the membrane. Membranes with high hysteresis loss, poor recovery, and weak fatigue resistance deteriorate faster under repeated movement. These failure mechanisms justify the need for a Waterproofing Reliability Index (WRI) and Mechanical Performance Core Model (MPCM) that integrate mechanical performance, durability, adhesion, environmental exposure, and defect sensitivity.

2.5 Role of Application Quality, Project Scale, and Execution Variables

Execution quality significantly affects waterproofing durability. Substrate preparation, dry film thickness, curing conditions, workmanship, detailing accuracy, primer compatibility, environmental conditions during application, drainage design, and screed protection influence adhesion strength, fatigue resistance, and leakage probability (RILEM TC 195, 2017; ASTM D7234; Kumar et al., 2021). Even high-performance waterproofing materials may fail prematurely if applied over weak, contaminated, damp, or poorly prepared substrates.

Project scale and constructability also influence waterproofing system suitability. Spray-applied polyurea and high-build elastomeric membranes may be suitable for large-scale infrastructure applications but may be economically or operationally unsuitable for small repair areas or inaccessible locations. Conversely, cementitious and acrylic systems may be more practical for smaller or less exposed applications despite lower fatigue resistance. Therefore, waterproofing selection must include application feasibility, project scale, equipment availability, labour skill, and supply-chain support.

2.6 Environmental Sustainability and VOC Impact

Environmental sustainability has become a major criterion in construction material selection, particularly with respect to volatile organic compound (VOC) emissions, indoor air quality, occupational exposure, and ecological impact (WHO, 2010; EPA, 2021; Salthammer, 2020). Solvent-based waterproofing systems may contribute to worker exposure risk, indoor air contamination, photochemical smog formation, respiratory irritation, and long-term environmental degradation (Guo et al., 2018; Weschler, 2016).

Green building frameworks such as LEED, IGBC, BREEAM, and ISO 14040 encourage the use of low-VOC, environmentally compatible, and lifecycle-oriented materials (USGBC, 2022; IGBC, 2023; ISO 14040, 2006). However, VOC impact is still insufficiently integrated into engineering-based waterproofing selection. A technically strong waterproofing material may still be environmentally unsuitable if it has high solvent content, hazardous curing chemistry, or poor occupational safety characteristics. This supports the need for a λ-based VOC–Environmental Impact Model within the WRI framework.

2.7 Behavioural and Adoption Frameworks in Construction Materials

Construction material adoption is influenced not only by technical performance but also by behavioural, institutional, economic, technological, and regulatory factors (Ajzen, 1991; Rogers, 2003; Venkatesh et al., 2012). The Theory of Planned Behaviour explains adoption intention through attitude, subjective norms, and perceived behavioural control. Diffusion of Innovation Theory explains innovation uptake through relative advantage, compatibility, complexity, trialability, and observability. UTAUT2 explains technology adoption through performance expectancy, effort expectancy, social influence, facilitating conditions, and behavioural intention.

Institutional Theory highlights the role of regulations, professional norms, certification systems, and organisational pressure, while Norm Activation Theory explains environmentally responsible behaviour through moral norms, awareness, and responsibility. Recent studies on sustainable construction materials show that adoption is shaped by environmental concern, product knowledge, institutional trust, implementation barriers, economic sensitivity, supply-chain accessibility, and perceived performance (Chen et al., 2023; Li et al., 2022).

The Sustainable Construction Chemicals Adoption Framework (SCCAF) integrates behavioural, technological, institutional, economic, and environmental drivers into construction chemical adoption analysis. However, behavioural adoption frameworks remain insufficiently connected to waterproofing engineering and field-performance evaluation. This creates a research gap between service-life assessment and actual industry adoption of sustainable waterproofing systems.

2.8 AI-Based Decision-Making in Waterproofing Engineering

Artificial Intelligence is increasingly used in construction engineering for material selection, durability prediction, predictive maintenance, risk assessment, quality control, and infrastructure performance optimisation (Pan & Zhang, 2021; Abioye et al., 2021). Machine-learning techniques such as artificial neural networks, random forests, support vector machines, and deep learning can model complex and non-linear deterioration mechanisms (Goodfellow et al., 2016; Haykin, 2009; Rafiq et al., 2010).

BIM, Digital Twin platforms, IoT-based monitoring, and predictive maintenance systems enable lifecycle data integration, real-time condition monitoring, and intelligent asset management (Boje et al., 2020; Fuller et al., 2020; Lu et al., 2019). Waterproofing systems are suitable for AI-supported evaluation because membrane deterioration is influenced by cyclic fatigue, environmental ageing, hydrostatic exposure, adhesion degradation, execution variability, and application-specific behaviour. However, current waterproofing evaluation methods remain largely static and non-adaptive, limiting their integration with future intelligent infrastructure systems.

2.9 Critical Literature Synthesis

The reviewed literature shows that waterproofing research remains fragmented across mechanical performance, durability behaviour, environmental sustainability, behavioural adoption, execution quality, and digital infrastructure domains. Engineering studies commonly focus on isolated properties, while durability studies often examine ageing, fatigue, hydrostatic pressure, or adhesion loss separately rather than as coupled field mechanisms.

Environmental studies emphasise VOC reduction and lifecycle assessment but rarely integrate these parameters with crack-bridging durability, exposure severity, or service-life reliability. Behavioural adoption studies explain stakeholder acceptance of sustainable materials but remain disconnected from waterproofing performance and engineering reliability. AI-based studies provide predictive potential but rarely combine technical performance, VOC impact, execution quality, stakeholder adoption, and lifecycle cost within a single waterproofing decision-support model.

2.10 Research Gaps in Existing Literature

The literature identifies the following major gaps:

- Existing waterproofing selection methods rely heavily on elongation, tensile strength, adhesion, and impermeability, while insufficiently considering fatigue resistance, hysteresis, elastic recovery, and cyclic durability.
- Field deterioration is caused by coupled mechanisms involving hydrostatic pressure, thermal cycling, moisture entrapment, adhesion loss, UV ageing, drainage deficiency, and execution defects, but these are rarely integrated into a single reliability model.
- VOC emissions, occupational exposure, indoor air quality, lifecycle sustainability, and ecological impact are not adequately incorporated into engineering-based waterproofing selection.

- Behavioural adoption constructs such as product knowledge, institutional trust, implementation friction, cost sensitivity, and supply-chain accessibility remain weakly connected to waterproofing reliability assessment.
- Current models are insufficiently compatible with AI, BIM, Digital Twin platforms, IOT monitoring, predictive maintenance, and Industry 4.0 infrastructure analytics.
- No existing model simultaneously integrates engineering reliability, VOC impact, lifecycle cost, execution quality, stakeholder adoption behaviour, and AI-compatible predictive decision-making for liquid-applied waterproofing systems.

2.11 Positioning of the Present Study

The present study is positioned at the intersection of waterproofing engineering, sustainable construction chemistry, behavioural adoption theory, lifecycle cost analysis, and intelligent infrastructure analytics. Unlike conventional approaches that rely on isolated material properties, the proposed WRI–VOC–SCCAF model evaluates mechanical performance, fatigue behaviour, adhesion reliability, environmental impact, execution-related defect sensitivity, cost sensitivity, supply-chain accessibility, stakeholder adoption intention, and final adoption behaviour within a unified framework.

The model combines the Waterproofing Reliability Index, Mechanical Performance Core Model, λ-based VOC–Environmental Impact Model, Sustainable Construction Chemicals Adoption Framework, and lifecycle cost–durability evaluation. This integration advances waterproofing selection from static property comparison toward performance-based, sustainability-oriented, stakeholder-sensitive, lifecycle-cost-aware, and AI-compatible decision-making.

2.11.1 Summary of Literature Review

The literature review confirms that existing waterproofing selection methods are fragmented and insufficient for modern sustainable infrastructure requirements. Conventional material selection focuses mainly on isolated properties, while field performance depends on the combined effect of mechanical durability, environmental exposure, VOC impact, execution quality, lifecycle cost, and stakeholder adoption behaviour. The proposed WRI–VOC–SCCAF framework addresses this gap by integrating engineering reliability, environmental sustainability, adoption-pathway drivers, moderating stakeholder variables, lifecycle cost considerations, and AI-compatible predictive decision-making within a single analytical model.

2.12 Mechanical Performance-Based Selection Framework for Liquid-Applied Waterproofing Membrane (LAM) Systems

2.12.1 Limitations of Conventional Elongation-Based Waterproofing Selection

Conventional selection of liquid-applied waterproofing membranes (lams) is frequently based on elongation at break, under the assumption that higher elongation corresponds to superior crack-bridging capability and long-term waterproofing durability. However, elongation represents only a single-point deformation characteristic under monotonic tensile loading and does not adequately capture cyclic fatigue behaviour, adhesion retention, elastic recovery, hysteresis response, stress relaxation, permanent strain accumulation, or long-term durability under realistic field conditions (Zhang et al., 2020; Li et al., 2021; Kim & Lee, 2022).

From a mechanic's perspective, elongation (ε) is defined as:

$$\varepsilon = (\Delta L / L_0) \times 100$$

Where,

L_0	Initial membrane length before crack/movement
ΔL	Extension due to crack opening or thermal movement
ε (strain)	Ability of the membrane to stretch

For example, a membrane specimen extending from 100 mm to 150 mm exhibits a strain of 50%, indicating substantial deformation capability. However, high elongation alone does not guarantee long-term waterproofing reliability because it does not evaluate:

- Cyclic fatigue resistance,
- Adhesion integrity,
- Energy dissipation behaviour,
- Elastic recovery,
- Stress degradation,
- Or permanent strain accumulation.

Consequently, waterproofing systems exhibiting high elongation may still experience premature failure under cyclic loading and environmental exposure due to fatigue cracking, delamination, hysteresis-related degradation, and progressive loss of recovery behaviour.

This demonstrates that elongation alone is insufficient as a standalone engineering selection criterion for advanced waterproofing systems.

2.12.2 Multi-Parameter Mechanical Selection Framework

To overcome the limitations of conventional elongation-based selection methodologies, the present study proposes a multi-parameter mechanical selection framework integrating:

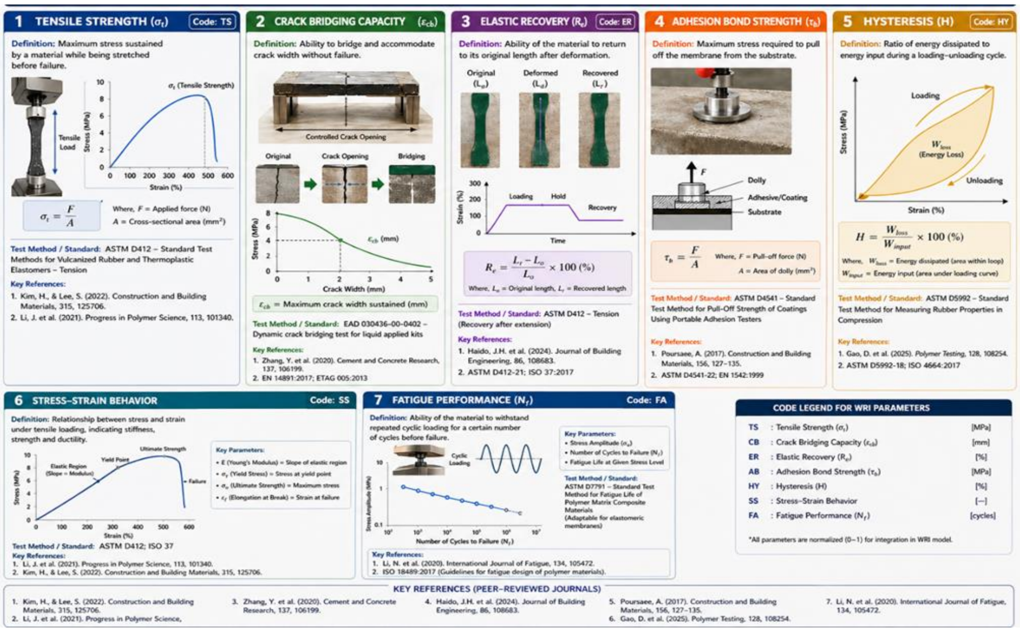
- Tensile strength,
- Crack-bridging capability,
- Elastic recovery,
- Adhesion bond strength,

- Hysteresis behaviour,
- Stress and strain degradation,
- Fatigue resistance,
- And environmental durability

Within a unified engineering reliability framework.

The proposed framework establishes the mechanical foundation for the Waterproofing Reliability Index (WRI) and enables integrated evaluation of waterproofing performance under cyclic loading, environmental deterioration, hydrostatic exposure, ultraviolet ageing, substrate movement, and real-world service conditions.

Figure 2.1 presents the integrated multi-parameter mechanical framework illustrating the relationships among material behaviour, cyclic degradation mechanisms, environmental exposure conditions, fatigue deterioration, and performance-based waterproofing selection criteria.



2.12.3 Tensile Strength (σt)

Tensile strength represents the maximum stress a waterproofing membrane can withstand before rupture under uniaxial loading conditions and defines the fundamental stress-bearing capacity of the material.

$$\sigma_t = F / A$$

Parameter Description

- **σ_t (Tensile Strength):**
  Maximum stress prior to failure
  Unit: MPa (Mega Pascal)

- **F (Applied Force):**
  External load applied during testing
  Unit: Newton (N)
- **A (Cross-Sectional Area):**
  Area over which the load is distributed
  Unit: mm^2

For thin waterproofing membranes:

$$A = \text{Width} \times \text{Thickness}$$

Tensile strength governs:

- Rupture resistance,
- Structural stress accommodation,
- Tensile load-bearing capacity,
- And resistance to mechanical tearing.

However, high tensile strength alone does not guarantee waterproofing reliability. Materials exhibiting high tensile strength but low elongation or poor recovery behaviour may undergo brittle failure and rapid fatigue deterioration under cyclic movement conditions.

Standard Test Methods

- ASTM D412
- ASTM D638
- ISO 527
- ISO 37
- EN 14891
- EN 12311-2
- BS EN ISO 527

Engineering Interpretation and Significance

Tensile Strength Level	Performance Implication
Low σ_t	Prone to tearing under stress
Moderate σ_t	Balanced strength and flexibility
High σ_t	High strength but potential brittleness

High tensile strength alone does not guarantee superior waterproofing performance.

This is because:

- High σ_t + Low Elongation → Brittle Failure (e.g., epoxy systems)
- High σ_t + Low Recovery → Fatigue Failure under cyclic loading

Tensile strength is particularly critical in applications involving:

- Thermal expansion and contraction,
- Structural deformation,
- Cyclic movement,
- Hydrostatic loading,
- And crack-induced tensile stress.

Nevertheless, tensile strength must be evaluated alongside crack-bridging performance, elastic recovery, adhesion retention, and fatigue resistance to achieve realistic waterproofing reliability assessment (Li et al., 2021; Kim & Lee, 2022).

2.12.4 Crack-Bridging Capacity (εc)

Crack-bridging capacity defines the ability of a waterproofing membrane to accommodate crack opening without rupture under static or cyclic loading conditions.

$$Ec = \text{Maximum Crack Width Sustained in mm}$$

Crack bridging is classified into:

1. Static crack bridging
2. Dynamic crack bridging

Static Crack Bridging

Static crack bridging evaluates membrane behaviour under a single crack-opening event.

Table 2.1 Static Crack-Bridging Classification (EN 1062-7 Method A)

Class	Crack Width (mm)	Performance Level
A1	≥ 0.1	Very low flexibility
A2	≥ 0.25	Low flexibility
A3	≥ 0.5	Moderate
A4	≥ 1.25	High
A5	≥ 2.5	Very high

Although static crack bridging evaluates deformation capacity, it does not adequately represent cyclic fatigue durability or long-term recovery performance.

Engineering Interpretation

Class	Application
A1–A2	Rigid substrates, internal areas
A3	Moderate movement zones
A4	Terraces, balconies
A5	High movement areas

Static crack bridging evaluates deformation capacity under a single loading event and does not account for cyclic fatigue, making it insufficient for predicting long-term waterproofing performance.

A material may achieve high static crack bridging classification (A4–A5) but still fail under dynamic conditions due to low recovery and high hysteresis.

Dynamic Crack Bridging

Dynamic crack bridging evaluates repeated opening and closing of cracks under cyclic movement conditions and therefore more accurately represents realistic service behaviour.

Table 2.2 Dynamic Crack-Bridging Classification based on EN 1062-7 and EAD Guidelines

Class	Crack Width (mm)	Cycles (No.)	Frequency (Hz)	Test Type	Performance Level
A1	≥ 0.1	100	0.1 – 0.3 Hz	Low cyclic	Very low durability
A2	≥ 0.25	100 – 250	0.3 – 0.5 Hz	Limited cyclic	Low performance
A3	≥ 0.5	250 – 500	~0.5 Hz	Moderate cyclic	Moderate durability
A4	≥ 1.25	500 – 1000	~0.5 Hz	High cyclic	High performance
A5	≥ 2.5	≥ 1000 – 2000+	~0.5 – 1.0 Hz	Severe cyclic	Excellent durability

1. Frequency Meaning

- 0.1–0.3 Hz → Slow movement (thermal expansion)
- ~0.5 Hz → Typical structural movement

- 0.5–1.0 Hz → Aggressive cyclic loading (traffic, vibration)

2. Cycles Interpretation

- 100 Initial performance
- 500 Medium-term durability
- 1000 Long-term performance
- 2000+ High fatigue resistance

Engineering Interpretation

Class	Real-World Meaning
A1–A2	Minor movement zones
A3	Moderate cyclic movement
A4	Heavy movement (terraces, podiums)
A5	Extreme movement (bridges, decks)

Link to Material Systems

Class	Typical Material
A1–A2	Cementitious
A2–A3	Acrylic
A3–A4	PU
A4–A5	Polyurea

Dynamic crack bridging integrates:

- Crack width,
- Cyclic loading,
- Loading frequency,
- Environmental exposure,
- And fatigue resistance.

Consequently, it provides a more realistic representation of long-term waterproofing performance under structural movement conditions (Zhang et al., 2020).

2.12.5 Elastic Recovery (Re)

Elastic recovery represents the ability of a waterproofing membrane to return to its original geometry after removal of tensile deformation.

$$R_e = (L_r / L_0) \times 100$$

Where:

Parameter	Description
Re	Elastic recovery (%)
L0	Original specimen length
Lr	Recovered length after unloading

Elastic recovery directly governs:

- Fatigue durability,
- Crack re-closure capability,
- Cyclic deformation resistance,
- Stress redistribution,
- And permanent strain accumulation.

High elastic recovery enables repeated deformation without progressive damage, whereas low recovery results in permanent deformation accumulation and eventual waterproofing failure.

Standard Test Methods

- ASTM D412
- ASTM D6083
- ISO 37
- EN 1062-7
- EN 14891

Elastic recovery therefore serves as a critical parameter for evaluating long-term cyclic waterproofing durability and fatigue resistance.

2.12.6 Adhesion Bond Strength (τb)

Adhesion bond strength defines the stress required to detach a waterproofing membrane from its substrate and governs interfacial system integrity.

$$\tau_b = F / A$$

Where:

Parameter	Description
τb	Bond strength (MPa)
F	Pull-off force
A	Bond area

Adhesion performance governs:

- Delamination resistance,
- Water-ingress prevention,
- System continuity,
- Hydrostatic durability,
- And long-term waterproofing reliability.

Studies demonstrate that many field waterproofing failures originate from adhesion loss rather than membrane rupture itself (Kumar et al., 2020; Kim & Lee, 2022).

Standard Test Methods

- ASTM D4541
- ASTM D7234
- ISO 4624
- EN 1542
- EN 14891

Table 2.3 Adhesion Performance Classification

Bond Strength	Performance
<0.5 MPa	Poor
0.5–1 MPa	Moderate
1–2 MPa	Good
>2 MPa	Excellent

High bond strength is particularly critical in:

- Exposed terraces,
- Podium slabs,
- Industrial flooring,
- Bridges,
- Basements,
- Marine environments,
- And water-retaining structures.

Failure Modes

Failure Type	Location	Interpretation
Adhesive Failure	Interface	Poor adhesion
Cohesive Failure (Coating)	Within membrane	Good adhesion
Cohesive Failure (Substrate)	Concrete fails	Excellent adhesion
Glue Failure	Adhesive layer	Invalid test

Real Engineering Example – Terrace Waterproofing

Material	Typical Bond Strength (τ_b)
Acrylic (standard)	0.5 – 0.8 MPa
Acrylic (high-performance / modified)	0.8 – 1.2 MPa
PU	1.0 – 1.8 MPa
Hybrid Polyurea	1.5 – 2.5 MPa

τ_b directly influences:

- System reliability
- Long-term durability
- Resistance to failure

Performance-Based Interpretation

Bond Strength	Application Suitability
< 0.5 MPa	Internal / low stress
0.5 – 1 MPa	Moderate exposure
1 – 2 MPa	External applications

> 2 MPa	Heavy-duty / industrial

2.12.7 Hysteresis Behaviour (H)

Hysteresis represents the percentage of energy dissipated during cyclic loading–unloading behaviour and serves as a key indicator of fatigue degradation.

$$H = (W_{loss} / W_{input}) \times 100$$

Where:

Parameter	Description
H	Hysteresis (%)
Winput	Energy applied during loading
Wloss	Energy dissipated during unloading

Low hysteresis indicates highly elastic behaviour and superior cyclic durability, whereas high hysteresis indicates:

- Internal energy loss,
- Heat generation,
- Microstructural degradation,
- And accelerated fatigue failure.
- Governs fatigue resistance under cyclic loading
- Indicates energy dissipation and internal damage accumulation

Low H → elastic behaviour → long life
High H → energy loss → heat + micro-damage → early failure

Hysteresis is inversely related to durability; materials with high energy loss per cycle degrade faster under repeated deformation, even if their tensile strength and elongation are high.

Table 2.4 Hysteresis Performance Classification

H (%)	Performance
> 40%	Poor (high fatigue damage)
20–40%	Moderate
10–20%	Good
< 10%	Excellent

Material Comparison Example

Material	Hysteresis	Behaviour	Performance
Acrylic	40–60%	High energy loss	Poor fatigue resistance
PU	15–25%	Balanced	Good
Hybrid Polyurea	10–20%	Low loss	Very good
Pure Polyurea	<10%	Highly elastic	Excellent

The hysteresis-based comparison of acrylic, polyurethane, hybrid polyurea, and pure polyurea systems is supported by elastomeric membrane behaviour reported in polymer fatigue studies, dynamic mechanical testing standards, and liquid-applied waterproofing performance literature. Materials with lower hysteresis and higher elastic recovery generally demonstrate better cyclic durability because less energy is dissipated as internal heat and microstructural damage during repeated loading–unloading cycles (ASTM D5992, 2022; ISO 4664-1, 2011; Zhang et al., 2020; Li et al., 2021; Kim & Lee, 2022).

Link to Crack Bridging

During dynamic crack movement:

- Each cycle → energy is lost
- High H → faster degradation

Even if ε_c is high:
Role of H:

- Controls fatigue life
- Works with:
  - R_e (Recovery)
  - ε_c (Crack bridging)

Low H + High R_e → best performance

Engineering Interpretation

Condition	Outcome
High ε_c + High H	Fails under cycles
Moderate ε_c + Low H	Durable

High R_e + Low H	Excellent

Hysteresis (H) quantifies the energy dissipation behaviour of waterproofing membranes under cyclic loading and serves as a critical parameter for evaluating fatigue resistance, making it indispensable for long-term performance assessment.

Materials exhibiting low hysteresis and high elastic recovery demonstrate superior long-term fatigue performance under repeated structural movement conditions (Zhang et al., 2020).

2.12.8 Stress Loss and Strain Loss Under Cyclic Loading

Repeated cyclic loading progressively reduces membrane stress-bearing capacity and increases permanent deformation accumulation.

Stress Loss

$$\text{Stress Loss (\%)} = [(\sigma_1 - \sigma_n) / \sigma_1] \times 100$$

Where:

- $\sigma 1$ = stress in first cycle
- σn = stress after n cycles

Strain Loss (%) (Permanent Set / Residual Strain)

$$\text{Strain Loss (\%)} = (\varepsilon_r / \varepsilon max) \times 100$$

Where:

- ε_r = residual (unrecovered) strain
- ε_{max} = applied strain

Under repeated loading–unloading cycles, waterproofing membranes exhibit progressive degradation manifested as:

- Reduction in stress capacity → Stress Loss (%)
- Increase in permanent deformation → Strain Loss (%)

These parameters provide a cycle-by-cycle degradation measure that complements hysteresis.

These parameters quantify:

- Fatigue-induced degradation,
- Permanent strain accumulation,
- Residual deformation,

- And long-term cyclic deterioration behaviour.

Engineering Significance

- Stress loss represents reduction in load-bearing capacity.
- Strain loss represents irreversible deformation accumulation.

Together with hysteresis, these parameters provide a comprehensive assessment of fatigue deterioration behaviour under cyclic movement conditions.

Parameter	Value	Performance
Stress Loss	30%	Moderate degradation
Strain Loss	20%	Moderate permanent deformation

Material Comparison

Material	Stress Loss	Strain Loss	Behaviour
Acrylic	40–60%	30–50%	High degradation
PU	20–30%	10–20%	Moderate
Hybrid Polyurea	10–20%	5–15%	Good
Pure Polyurea	<10%	<5%	Excellent

Stress loss represents the reduction in load-bearing capacity, while strain loss represents the accumulation of permanent deformation. Together, they provide a direct measure of fatigue-induced degradation in waterproofing membranes.

Stress loss and strain loss provide quantitative measures of fatigue-induced degradation in waterproofing systems and, when used alongside hysteresis, enable a comprehensive evaluation of cyclic performance and long-term durability.

2.12.9 Fatigue Behaviour of Waterproofing Membranes

Fatigue represents the progressive deterioration and eventual failure of waterproofing membranes under repeated cyclic loading, even when applied stresses remain below ultimate tensile strength.

$$N_f = f(\sigma, \varepsilon, Re, H)$$

Where:

Parameter	Description
Nf	Number of cycles to failure

Parameter	**Description**
σ	Applied stress
ε	Applied strain
Re	Elastic recovery
H	Hysteresis

Fatigue deterioration involves:

- Micro crack initiation,
- Energy dissipation,
- Stress degradation,
- Permanent deformation accumulation,
- And progressive crack propagation.

Table 2.5 Fatigue Performance of Waterproofing Systems

Material	Cycles to Failure	Fatigue Performance
Acrylic	200–500	Poor
PU	800–1500	Good
Hybrid Polyurea	1500–2500	Very good
Pure Polyurea	>3000	Excellent

The fatigue performance ranking presented in the comparison table is based on the established relationship between cyclic crack-bridging resistance, elastic recovery, hysteresis loss, stress degradation, and permanent strain accumulation in elastomeric waterproofing membranes. Polyurea-based systems generally exhibit superior fatigue tolerance and rapid elastic recovery due to their highly elastomeric polymer network, while acrylic systems are more vulnerable to cyclic degradation, UV ageing, and permanent deformation under severe movement conditions. Therefore, the fatigue comparison should be interpreted as a performance-based engineering classification supported by dynamic crack-bridging standards and elastomeric membrane durability literature rather than as a universal fixed value for all commercial products (EN 1062-7, 2004; ETAG 005, 2000; EAD 030350-00-0402, 2019; Zhang et al., 2020; Li et al., 2021; Riahinezhad et al., 2021; dos Santos et al., 2022).

Fatigue behaviour governs long-term waterproofing reliability under:

- Cyclic thermal movement,
- Vibration,
- Traffic loading,

- Structural settlement,
- Repeated crack movement,
- And environmental exposure.

Consequently, fatigue resistance represents one of the most critical parameters for realistic waterproofing system evaluation (Li et al., 2021; Zhang et al., 2020).

2.12.10 International Standards and Codes for Mechanical Performance Evaluation of LAM Systems

The performance evaluation of liquid-applied waterproofing membrane systems requires standardised testing methodologies to ensure consistency, repeatability, reliability, and engineering comparability across different waterproofing technologies.

The integration of ASTM, ISO, EN, BS, ETAG, and EAD frameworks establishes a scientifically validated and internationally harmonised evaluation system for assessing:

- Tensile strength,
- Crack-bridging capability,
- Elastic recovery,
- Adhesion behaviour,
- Hysteresis response,
- Fatigue durability,
- Environmental resistance,
- And long-term waterproofing reliability.

Table 2.6 International Standards and Codes for Mechanical Performance Evaluation

Standard	Evaluation Focus	Major Engineering Parameters
ASTM D412	Elastomer tensile testing	Tensile strength, elongation, recovery
ASTM D4541	Pull-off adhesion	Adhesion bond strength
ASTM D5992	Dynamic fatigue testing	Hysteresis, cyclic degradation
ASTM C836	Elastomeric waterproofing systems	Crack bridging and durability
ISO 527	Tensile properties	Stress–strain behaviour
ISO 4624	Pull-off adhesion	Interfacial integrity
ISO 4664-1	Dynamic properties	Fatigue and hysteresis

EN 1062-7	Crack bridging	Static and dynamic crack movement
EN 14891	Waterproofing beneath tiles	Adhesion and deformation
EN 1504-2	Surface protection systems	Environmental durability
ETAG 005	Roof waterproofing kits	Long-term cyclic durability
EAD	Waterproofing assessment systems	Dynamic crack-bridging performance

The integrated standards framework therefore forms the technical validation foundation for the proposed Waterproofing Reliability Index (WRI) and enables scientifically informed, performance-based, exposure-oriented, and sustainability-driven waterproofing system selection under real engineering service conditions.

2.12.11 Integrated Engineering Significance of the Proposed Framework

The combined interaction of:

- Tensile strength,
- Crack-bridging behaviour,
- Elastic recovery,
- Adhesion performance,
- Hysteresis response,
- Stress degradation,
- Strain accumulation,
- Fatigue durability,
- Environmental resistance,
- And cyclic deterioration behaviour

Governs the suitability of waterproofing systems across different engineering applications including:

- Exposed terraces,
- Podium slabs,
- Basements,
- Bridges,
- Industrial flooring,
- Water-retaining structures,
- Marine environments,
- Tunnels,

- And high-movement infrastructure systems.

Table 2.7 Summary of Mechanical Parameters Governing Waterproofing Reliability

Parameter	Governing Property	Failure Influence	Role in WRI
Tensile Strength	Stress capacity	Rupture	Structural reliability
Crack Bridging	Movement accommodation	Crack failure	Deformation reliability
Elastic Recovery	Shape recovery	Permanent strain	Fatigue resistance
Adhesion	Interface integrity	Delamination	System durability
Hysteresis	Energy dissipation	Fatigue degradation	Cyclic durability
Stress Loss	Load degradation	Performance reduction	Fatigue assessment
Strain Loss	Permanent deformation	Crack accumulation	Long-term durability
Fatigue Life	Cyclic survival	Failure cycles	Lifecycle prediction

Collectively, these parameters establish a multi-dimensional engineering basis for waterproofing selection that extends beyond conventional elongation-based evaluation. The proposed framework enables scientifically informed waterproofing material selection based on:

- Cyclic durability,
- Environmental exposure severity,
- Fatigue resistance,
- Adhesion integrity,
- Application-specific service conditions,
- Project-scale suitability,
- And long-term lifecycle reliability.

The framework additionally supports:

- Exposure-oriented waterproofing selection,
- Application-specific optimisation,
- Fatigue-based engineering assessment,
- AI-compatible predictive durability modelling,

- Lifecycle-oriented maintenance planning,
- And intelligent infrastructure decision-making.

Accordingly, the proposed multi-parameter framework forms the core mechanical architecture of the Waterproofing Reliability Index (WRI) and establishes the scientific foundation for intelligent, performance-based, sustainability-oriented, and reliability-driven waterproofing system selection under real engineer

3. Research Methodology

This study adopts a quantitative, model-driven research methodology that integrates engineering performance evaluation, environmental sustainability assessment, and behavioural adoption modelling for liquid-applied waterproofing membranes (LAMs). The methodology combines experimental investigation, comparative engineering benchmarking, Structural Equation Modelling (SEM), and sustainability-oriented analytical integration to develop and validate the proposed Waterproofing Reliability Index (WRI)–VOC–SCCAF framework.

3.1 Research Design

The present study adopts a quantitative, explanatory, and model-development research design to develop and validate the proposed WRI–VOC–SCCAF framework for sustainable liquid-applied waterproofing system selection. The study integrates engineering performance modelling, environmental impact assessment, and behavioural adoption analysis within a single empirical framework.

The research design consists of three major stages. First, the engineering parameters influencing waterproofing system performance were identified through literature review, international standards, technical datasheets, and field-performance considerations. Second, environmental and VOC-related variables were integrated through the λ-based VOC–Environmental Impact Model. Third, stakeholder adoption behaviour was evaluated using the Sustainable Construction Chemicals Adoption Framework (SCCAF), which incorporates behavioural, institutional, technological, economic, and environmental constructs.

The SEM structure was developed by classifying the constructs according to their theoretical and statistical functions within the proposed WRI–VOC–SCCAF framework. Mechanical performance, durability, adhesion performance, defect sensitivity, and VOC–Environmental Impact were modelled as independent explanatory variables because they represent the technical and environmental drivers influencing waterproofing reliability and adoption intention. WRI and adoption intention were modelled as mediating constructs. WRI mediates the relationship between engineering performance variables and adoption intention by translating technical performance into a reliability-based decision indicator, while adoption intention mediates the relationship between reliability perception, environmental evaluation, economic feasibility, supply-chain accessibility, and final adoption behaviour. Cost sensitivity and supply-chain accessibility were treated as adoption-pathway mediating drivers because they influence the conversion of technical and environmental evaluation into adoption intention through economic feasibility and practical availability. Product knowledge, institutional trust, and implementation friction were modelled as moderators influencing the strength of the relationship between adoption intention and final adoption behaviour. Final adoption behaviour was treated as the dependent variable because it represents the actual specification, recommendation, purchase, application, or approval of sustainable waterproofing systems in real construction practice.

3.2 Study Population and Sampling

The target population for the study consisted of professionals involved in waterproofing system selection, specification, application, procurement, manufacturing, project execution, and quality control within the construction industry.

The respondent groups included contractors, consultants, civil engineers, architects, waterproofing applicators, construction chemical manufacturers, project managers, procurement professionals, and infrastructure maintenance professionals.

A total of 350 valid responses were collected and used for SEM analysis. This sample size is considered adequate for SEM-based model validation because it exceeds the commonly recommended minimum sample threshold for complex models involving multiple latent constructs and structural relationships.

A purposive sampling method was adopted to ensure that respondents possessed relevant professional experience in waterproofing systems, construction chemicals, infrastructure projects, or sustainable construction material selection. This approach was appropriate because the study required informed responses from industry stakeholders familiar with waterproofing performance, product selection, environmental considerations, and adoption barriers.

3.3 Data Collection Method

Primary data were collected through a structured questionnaire designed to measure engineering performance perception, VOC impact perception, environmental concern, institutional influence, technological readiness, product knowledge, economic sensitivity, supply-chain accessibility, adoption intention, and final adoption behaviour.

The questionnaire was developed based on previous literature on waterproofing performance and construction chemicals, international standards related to waterproofing membrane evaluation, behavioural adoption theories including TPB, DOI, UTAUT2, Institutional Theory, and NAT, the Sustainable Construction Chemicals Adoption Framework, and expert inputs from construction industry professionals.

The questionnaire consisted of closed-ended items measured using a five-point Likert scale ranging from 1 = Strongly Disagree to 5 = Strongly Agree. The use of a Likert scale enabled quantitative measurement of respondent perceptions and facilitated SEM-based statistical analysis.

3.4 Construct Development

The constructs used in the study were developed from engineering, environmental, behavioural, institutional, technological, and economic dimensions relevant to waterproofing system adoption.

Table 3.1. Construct Development for SEM Analysis

Construct	Description
Mechanical Performance	Perceived influence of tensile strength, elongation, crack-bridging capability, elastic recovery, hysteresis behaviour, and fatigue resistance on waterproofing performance
Durability	Perceived long-term resistance to UV exposure, hydrothermal ageing, chemical exposure, hydrostatic pressure, and environmental deterioration
Adhesion Performance	Perceived importance of membrane–substrate bond strength, primer compatibility, surface preparation, and delamination resistance
Defect Sensitivity	Influence of application defects such as poor surface preparation, inadequate thickness, moisture entrapment, drainage deficiency, and workmanship variability
WRI	Overall waterproofing reliability based on mechanical, durability, adhesion, and execution-quality parameters
VOC–Environmental Impact	Perceived influence of VOC emissions, occupational exposure, indoor air quality, lifecycle environmental impact, and sustainability compliance
Product Knowledge	Stakeholder awareness and understanding of sustainable waterproofing materials and their technical benefits
Institutional Trust	Confidence in manufacturers, consultants, standards, certification systems, and regulatory bodies
Implementation Friction	Barriers related to cost, availability, skilled labour, application complexity, and project constraints

Cost Sensitivity	Influence of price, lifecycle cost, maintenance cost, and budget constraints on adoption decisions
Supply-Chain Accessibility	Availability of materials, technical support, applicators, equipment, and after-sales service
Adoption Intention	Willingness of stakeholders to specify, recommend, purchase, or apply sustainable waterproofing systems
Final Adoption Behaviour	Actual or intended selection and implementation of sustainable waterproofing systems in projects

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For SEM interpretation, cost sensitivity and supply-chain accessibility were not treated as moderators. They were treated as adoption-pathway mediating drivers influencing adoption intention. Product knowledge, institutional trust, and implementation friction were not treated as direct predictors of adoption intention; instead, they were treated as moderators influencing the strength of the relationship between adoption intention and final adoption behaviour.

3.4.1 SEM Variable Classification and Conceptual Role of Constructs

For the purpose of Structural Equation Modelling, the constructs used in the proposed WRI–VOC–SCCAF framework were classified according to their conceptual and statistical roles within the model. This classification was necessary to clearly distinguish the technical performance drivers, environmental influence variables, mediating adoption pathways, moderating stakeholder factors, and final behavioural outcome.

In the proposed SEM model, mechanical performance, durability, adhesion performance, defect sensitivity, and VOC–Environmental Impact were treated as independent explanatory variables. Mechanical performance, durability, and adhesion performance were expected to positively influence the Waterproofing Reliability Index, whereas defect sensitivity was expected to negatively influence WRI. VOC–Environmental Impact was treated as an environmental explanatory variable influencing adoption intention because higher VOC impact, occupational exposure risk, and environmental burden are expected to reduce stakeholder willingness to adopt a waterproofing system.

WRI and adoption intention were treated as the primary mediating constructs. WRI mediates the relationship between engineering performance variables and adoption intention by converting technical performance attributes into a reliability-based decision indicator. Adoption intention further mediates the relationship between reliability perception, environmental evaluation, economic feasibility, supply-chain accessibility, and final adoption behaviour.

Cost sensitivity and supply-chain accessibility were classified as adoption-pathway mediating drivers. Cost sensitivity represents the economic barrier through which initial price, lifecycle cost perception, maintenance cost, and budget constraints influence adoption intention. Supply-chain accessibility represents the practical availability pathway through which material availability, applicator availability, equipment support, technical service, and after-sales support influence adoption intention.

Product knowledge, institutional trust, and implementation friction were treated as moderating variables. Product knowledge strengthens the relationship between adoption intention and final adoption behaviour by improving stakeholder understanding of sustainable waterproofing systems. Institutional trust strengthens the conversion of intention into adoption by increasing confidence in manufacturers, consultants, standards, certifications, and regulatory bodies. Implementation friction weakens the relationship between adoption intention and final adoption behaviour because application complexity, skilled labour shortage, project constraints, and execution barriers may prevent intended adoption from becoming actual adoption.

Final adoption behaviour was treated as the dependent variable because it represents the actual decision to specify, recommend, purchase, apply, or approve sustainable waterproofing systems in real construction practice.

Cost sensitivity and supply-chain accessibility function as adoption-pathway mediators influencing the relationship between technical–environmental evaluation and adoption intention, while product knowledge, institutional trust, and implementation friction moderate the transition from adoption intention to final adoption behaviour.

Table 3.2. SEM Variable Classification in the WRI–VOC–SCCAF Model

Variable Type	Constructs	Conceptual Role in SEM Model
Independent Variables	Mechanical Performance, Durability, Adhesion Performance, Defect Sensitivity, VOC–Environmental Impact	These variables explain the technical and environmental drivers influencing waterproofing reliability and adoption intention.
Primary Mediators	WRI, Adoption Intention	WRI translates engineering performance into reliability perception, while adoption intention converts reliability, environmental, economic, and supply-chain perceptions into behavioural readiness.
Adoption-Pathway Mediating Drivers	Cost Sensitivity, Supply-Chain Accessibility	These variables influence adoption intention by representing economic feasibility and practical market availability.

Moderators	Product Knowledge, Institutional Trust, Implementation Friction	These variables affect the strength of the relationship between adoption intention and final adoption behaviour.
Dependent Variable	Final Adoption Behaviour	Represents the actual adoption, specification, recommendation, purchase, or application of sustainable waterproofing systems.

Cost sensitivity and supply-chain accessibility function as adoption-pathway mediating drivers influencing adoption intention, while product knowledge, institutional trust, and implementation friction moderate the transition from adoption intention to final adoption behaviour.

In the proposed SEM model, mechanical performance, durability, adhesion performance, defect sensitivity, and VOC–Environmental Impact were classified as independent explanatory variables. WRI and adoption intention were classified as mediating constructs. Cost sensitivity and supply-chain accessibility were treated as adoption-pathway mediating drivers influencing adoption intention. Product knowledge, institutional trust, and implementation friction were treated as moderating variables influencing the strength of the relationship between adoption intention and final adoption behaviour. Final adoption behaviour was treated as the dependent variable. This classification improves the theoretical clarity of the WRI–VOC–SCCAF framework and ensures consistency between the conceptual model, hypothesis development, SEM analysis, and interpretation of results.

3.5 Measurement Model Assessment

The measurement model was evaluated to confirm the reliability, validity, and consistency of the constructs used in the SEM analysis.

Table 3.3. Measurement Model Assessment Criteria

Test	Recommended Threshold
Cronbach's Alpha	≥ 0.70
Composite Reliability	≥ 0.70
rho_A	≥ 0.70
Average Variance Extracted	≥ 0.50
Factor Loadings	≥ 0.70 preferred
HTMT Ratio	< 0.85 or < 0.90
VIF	< 3.3 or < 5.0
SRMR	< 0.08

Cronbach's alpha and composite reliability were used to assess internal consistency. Average Variance Extracted was used to evaluate convergent validity. Discriminant validity was assessed using the Fornell–Larcker criterion and the Heterotrait–Monotrait ratio. Variance Inflation Factor values were examined to identify multicollinearity among constructs.

3.5.1 Hypothesis Development

Based on the theoretical foundation of the WRI–VOC–SCCAF framework, the following hypotheses were developed to examine the relationships among technical performance variables, environmental impact, adoption-pathway mediating drivers, moderating stakeholder factors, adoption intention, and final adoption behaviour. The hypotheses were structured to test the direct, mediating, and moderating relationships within the proposed SEM model.

Table 3.4 Hypothesis Structure for the WRI–VOC–SCCAF Model

Hypothesis	Relationship	Variable Role	Expected Direction
H1	Mechanical Performance → WRI	Independent Variable to Mediator	Positive
H2	Durability → WRI	Independent Variable to Mediator	Positive
H3	Adhesion Performance → WRI	Independent Variable to Mediator	Positive
H4	Defect Sensitivity → WRI	Independent Variable to Mediator	Negative
H5	WRI → Adoption Intention	Mediator to Mediator	Positive
H6	VOC–Environmental Impact → Adoption Intention	Independent Variable to Mediator	Negative
H7	Cost Sensitivity → Adoption Intention	Adoption-pathway mediating driver	Negative
H8	Supply-Chain Accessibility → Adoption Intention	Adoption-pathway mediating driver	Positive
H9	Adoption Intention → Final Adoption Behaviour	Mediator to Dependent Variable	Positive
H10	Product Knowledge moderates Adoption Intention → Final Adoption Behaviour	Moderator	Positive Moderation
H11	Institutional Trust moderates Adoption Intention → Final Adoption Behaviour	Moderator	Positive Moderation

H12	Implementation Friction moderates Adoption Intention → Final Adoption Behaviour	Moderator	Negative Moderation

Hypotheses H1 to H4 examine the influence of technical and execution-related variables on the Waterproofing Reliability Index. H5 examines the mediating role of WRI in converting technical reliability into adoption intention. H6 evaluates the negative influence of VOC–Environmental Impact on adoption intention. H7 and H8 examine the role of cost sensitivity and supply-chain accessibility as adoption-pathway mediating drivers influencing adoption intention. H9 tests the effect of adoption intention on final adoption behaviour. H10 to H12 examine the moderating effects of product knowledge, institutional trust, and implementation friction on the relationship between adoption intention and final adoption behaviour.

3.6 Structural Model Assessment

The structural model was assessed to examine the hypothesised relationships among engineering performance, environmental impact, adoption intention, and final adoption behaviour.

The following indicators should be reported: path coefficient β, t-value, p-value, confidence interval, coefficient of determination R^2, adjusted R^2, effect size f^2, predictive relevance Q^2, and model fit index SRMR.

Bootstrapping with 5,000 resamples was used to test the significance of direct, indirect, mediating, and moderating effects. A relationship was considered statistically significant when the p-value was less than 0.05.

3.7 Mediation and Moderation Analysis

The study evaluates both mediation and moderation effects within the WRI–VOC–SCCAF framework.

Adoption intention was considered a mediating construct between engineering/environmental predictors and final adoption behaviour. This means that technical performance, VOC impact, product knowledge, institutional trust, cost sensitivity, and supply-chain accessibility influence final adoption behaviour partly through stakeholder adoption intention.

Cost sensitivity and supply-chain accessibility were treated as mediating variables because they explain how economic feasibility and material availability influence the relationship between technical/environmental perception and adoption intention.

Product knowledge, institutional trust, and implementation friction were treated as moderating variables because they influence the strength and direction of the relationship between adoption intention and final adoption behaviour.

The mediation analysis examined indirect effects, while moderation analysis examined interaction effects between adoption intention and the selected moderating variables.

3.8 SEM Model Specification

The proposed SEM model consists of four major construct groups:

Table 3.5. SEM Model Construct Groups

Construct Group	Included Variables
Engineering Performance Constructs	Mechanical Performance; Durability; Adhesion Performance; Defect Sensitivity; WRI
Environmental Sustainability Constructs	VOC–Environmental Impact; Environmental Concern; Sustainability Compliance
Adoption and Behavioural Constructs	Product Knowledge; Institutional Trust; Implementation Friction; Cost Sensitivity; Supply-Chain Accessibility; Adoption Intention; Final Adoption Behaviour
Predictive and Decision-Support Constructs	AI Compatibility; Data-Driven Durability Forecasting; BIM/Digital Twin Readiness; Predictive Maintenance Suitability

The model evaluates how technical performance, environmental impact, economic feasibility, institutional influence, and knowledge-related factors influence stakeholder adoption intention and final adoption behaviour.

3.9 Research Hypotheses

Based on the proposed WRI–VOC–SCCAF framework, the study formulates fourteen hypotheses to examine the relationships among engineering performance, waterproofing reliability, environmental impact, economic feasibility, supply-chain accessibility, adoption intention, and final adoption behaviour. The hypotheses include direct effects, mediating effects, and moderating effects within the integrated SEM model.

Table 3.6. Hypothesised Relationships of the WRI–VOC–SCCAF Model

Hypothesis	Relationship	Expected Direction / Effect
H1	Mechanical Performance → WRI	Independent Variable to Mediator
H2	Durability → WRI	Independent Variable to Mediator
H3	Adhesion Performance → WRI	Independent Variable to Mediator
H4	Defect Sensitivity → WRI	Independent Variable to Mediator
H5	WRI → Adoption Intention	Mediator to Mediator
H6	VOC–Environmental Impact → Adoption Intention	Independent Variable to Mediator
H7	Cost Sensitivity → Adoption Intention	Adoption-pathway mediating driver
H8	Supply-Chain Accessibility → Adoption Intention	Adoption-pathway mediating driver
H9	Adoption Intention → Final Adoption Behaviour	Mediator to Dependent Variable
H10	Product Knowledge moderates Adoption Intention → Final Adoption Behaviour	Moderator
H11	Institutional Trust moderates Adoption Intention → Final Adoption Behaviour	Moderator
H12	Implementation Friction moderates Adoption Intention → Final Adoption Behaviour	Moderator

The direct-effect hypotheses evaluate whether engineering reliability, environmental impact, cost sensitivity, and supply-chain accessibility significantly influence adoption intention and final adoption behaviour. The mediation hypotheses examine whether cost sensitivity and supply-chain accessibility explain indirect effects on adoption intention. The moderation hypotheses evaluate whether product knowledge, institutional trust, and implementation friction strengthen or weaken the relationship between adoption intention and final adoption behaviour.

3.10 Hypothesis Testing Procedure

Hypotheses were tested using SEM path analysis. Each hypothesised relationship was evaluated using path coefficients, t-values, p-values, and confidence intervals.

Table 3.7. Interpretation Criteria for SEM Hypothesis Testing

Statistical Indicator	Interpretation
Positive β value	Positive influence between constructs
Negative β value	Negative influence between constructs
$p < 0.05$	Statistically significant relationship
$p < 0.01$	Highly significant relationship
R^2 value	Explanatory power of endogenous constructs
f^2 value	Effect size of predictor constructs
Q^2 value	Predictive relevance of the model

The SEM results were used to validate whether engineering reliability, VOC impact, adoption intention, and behavioural constructs significantly influence final waterproofing adoption behaviour.

3.11 Ethical Considerations

Participation in the study was voluntary, and respondents were informed about the academic purpose of the research. No personally identifiable information was collected. Responses were analysed in aggregate form only, ensuring confidentiality and anonymity of participants.

3.12 Methodological Contribution

The methodology contributes to waterproofing research by combining engineering parameter modelling, environmental impact assessment, and behavioural adoption analysis within a statistically validated SEM framework. Unlike conventional waterproofing studies that focus primarily on material testing or isolated performance parameters, this study integrates technical, environmental, economic, institutional, and behavioural dimensions into a single decision-support model.

This methodological structure enables the proposed WRI–VOC–SCCAF framework to support performance-based waterproofing selection, VOC-sensitive material evaluation, stakeholder-oriented adoption analysis, lifecycle durability optimisation, and future AI-compatible decision-support applications.

Table 3.8. Methodological Structure of the Present Study

Stage	Methodological Activity	Purpose
Stage 1	Literature review and standards review	Identification of engineering, environmental, and adoption-related variables
Stage 2	Development of WRI model	Integration of mechanical performance, durability, adhesion, and defect sensitivity
Stage 3	Development of MPCM	Evaluation of cyclic movement, fatigue resistance, elastic recovery, and hysteresis behaviour
Stage 4	Development of VOC–Environmental Impact Model	Integration of VOC emission, occupational exposure, and environmental impact
Stage 5	SCCAF integration	Inclusion of behavioural, institutional, technological, economic, and environmental adoption constructs
Stage 6	Questionnaire design	Measurement of stakeholder perception and adoption-related variables
Stage 7	Data collection from 350 respondents	Empirical validation using industry stakeholder responses
Stage 8	Measurement model testing	Assessment of reliability, convergent validity, discriminant validity, and multicollinearity
Stage 9	Structural model testing	Evaluation of direct, indirect, mediating, and moderating relationships
Stage 10	SEM-based framework validation	Validation of the proposed WRI–VOC–SCCAF decision-support model

3.13 Model Integration

The final framework integrates:

- The engineering reliability model (WRI),
- The environmental sustainability model (VOC Index),
- The behavioural adoption model (SCCAF).

This integration enables a multidimensional, performance-driven evaluation framework for selecting intelligent waterproofing systems.

The integrated methodology enables simultaneous evaluation of mechanical reliability, environmental sustainability, and stakeholder adoption behaviour within a unified analytical framework, thereby supporting performance-based waterproofing selection and future AI-assisted infrastructure decision systems.

4.0 Waterproofing Reliability Index (WRI) and Integrated Performance Framework

4.1 Introduction to Waterproofing Reliability Index (WRI)

The Waterproofing Reliability Index (WRI) is an integrated engineering reliability framework developed for performance-based evaluation and intelligent selection of liquid-applied membrane (LAM) waterproofing systems under realistic engineering service conditions. The framework integrates:

- Mechanical performance,
- Adhesion reliability,
- Durability behaviour,
- Execution-related defect sensitivity,
- And environmental sustainability

within a unified analytical decision-support model.

Unlike conventional waterproofing evaluation methods that rely primarily on elongation or tensile strength, the proposed WRI framework incorporates:

- Cyclic fatigue behaviour,
- Crack accommodation,
- Adhesion retention,
- Environmental degradation,
- Workmanship quality,
- And sustainability-oriented optimisation

into a scientifically normalised reliability system for intelligent waterproofing material selection.

The framework transforms waterproofing evaluation from:

Conventional Approach

Single-property comparison

Into:

Advanced Engineering Approach

Integrated reliability–sustainability optimisation framework

To evaluate the adaptive behaviour of the proposed Waterproofing Reliability Index (WRI), a sensitivity analysis was performed by varying the weighting coefficients associated with mechanical performance, adhesion reliability, durability behaviour, and defect sensitivity. The analysis illustrates the influence of each coefficient on the overall WRI response while maintaining coefficient normalisation constraints.

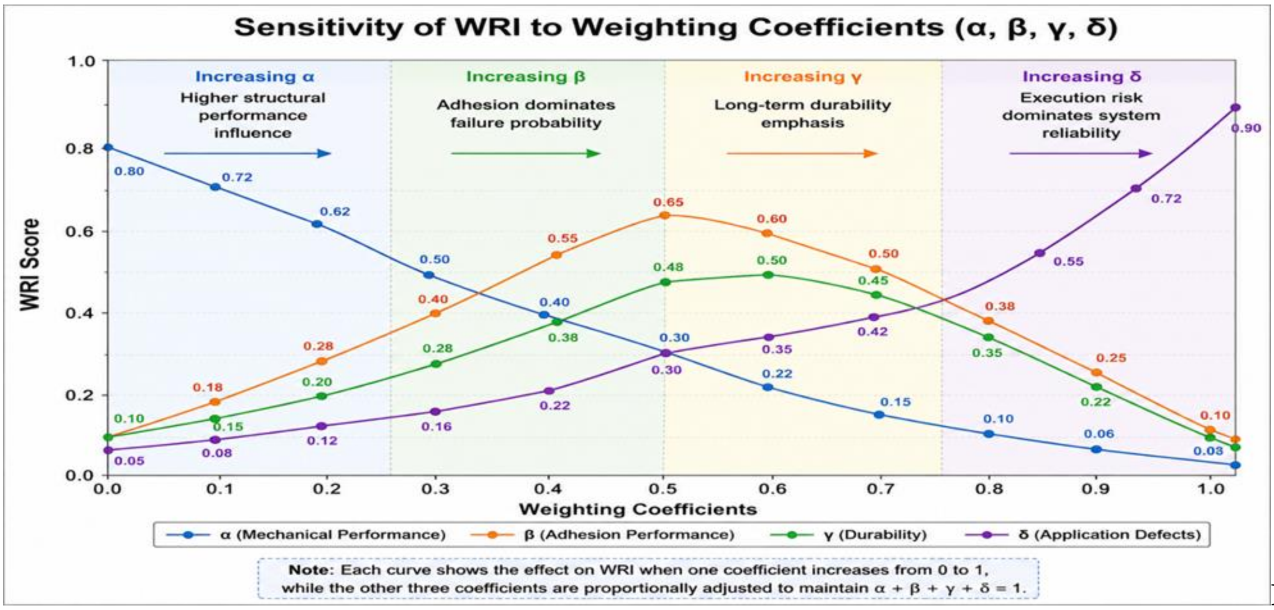

Figure 4.1 Sensitivity of Waterproofing Reliability Index (WRI) to Adaptive Weighting Coefficients (α,β,γ,δ)

This figure illustrates the sensitivity behaviour of the Waterproofing Reliability Index (WRI) with respect to adaptive weighting coefficients associated with:

- Mechanical performance (α),
- Adhesion behaviour (β),
- Durability performance (γ),
- And application defect sensitivity (δ).

The figure demonstrates how the WRI response changes when one weighting coefficient increases from 0 to 1 while the remaining coefficients are proportionally adjusted to maintain the normalisation condition.

Governing Mathematical Constraint

$$\alpha+\beta+\gamma+\delta=1$$

Table 4.1 Engineering Interpretation of WRI Sensitivity Coefficients

Coefficient	Governing Parameter	Engineering Influence	Practical Significance
α	Mechanical performance	Crack resistance and fatigue durability	Structural reliability
β	Adhesion behaviour	Delamination resistance	Interfacial durability

γ	Durability factor	Long-term environmental resistance	Service-life enhancement
δ	Defect sensitivity	Workmanship and execution risk	Failure probability control

Engineering Analysis

The sensitivity analysis demonstrates that:

- Increasing α prioritises fatigue durability and crack-bridging reliability,
- Increasing β improves adhesion-controlled waterproofing performance,
- Increasing γ enhances environmental ageing resistance and long-term durability,
- Whereas increasing δ amplifies execution-related failure sensitivity and workmanship dependency.

The figure validates the adaptive nature of the WRI framework and demonstrates that the weighting system can be optimised for:

- Bridges,
- Podium slabs,
- Tunnels,
- Industrial flooring,
- Water-retaining structures,
- And sustainability-sensitive infrastructure systems.

4.2 Mathematical Formulation of Waterproofing Reliability Index (WRI)

The proposed Waterproofing Reliability Index is expressed as:

$$WRI=\alpha(MPCM)+\beta(\tau b)+\gamma(D)-\delta(Da) \text{ ---------I}$$

Where:

Parameter	Description
WRI	Waterproofing Reliability Index
MPCM	Mechanical Performance Core Model
τb	Adhesion bond strength
D	Durability factor
Da	Application defect factor
α,β,γ,δ	Adaptive weighting coefficients

The weighting coefficients satisfy:

$$\alpha+\beta+\gamma+\delta=1$$

The WRI framework enables:

- Multi-parameter waterproofing evaluation,
- Fatigue-sensitive reliability assessment,
- Lifecycle-oriented engineering analysis,
- Exposure-specific waterproofing selection,
- Sustainability-sensitive optimisation,
- And ai-compatible predictive modelling.

4.3 Mechanical Performance Core Model (MPCM)

The Mechanical Performance Core Model (MPCM) represents the structural and deformation-related behaviour of liquid-applied waterproofing membranes under cyclic movement and environmental loading conditions.

The MPCM integrates:

- Tensile strength,
- Crack-bridging capability,
- Elastic recovery,
- Hysteresis behaviour,
- And fatigue resistance

within a unified normalised performance framework.

The MPCM equation is expressed as:

Equation (3)

$$MPCM=w1(\sigma t)+w2(\varepsilon cb)+w3(Re)-w4(H)+w5(Nf)\text{--------II}$$

Where:

Parameter	Description
σt	Tensile strength
εcb	Crack-bridging capacity
Re	Elastic recovery
H	Hysteresis loss
Nf	Fatigue resistance
w1−w5	Parameter weighting coefficients

Higher MPCM values indicate:

- Superior crack accommodation,
- Improved cyclic durability,
- Lower fatigue degradation,
- Enhanced deformation tolerance,
- And better long-term waterproofing reliability.

4.4 Normalisation Methodology

To enable multi-parameter integration within the WRI framework, all engineering parameters are converted into dimensionless values ranging from 0 to 1.

Positive Parameters (Higher = Better)

$$\text{Xnorm} = \frac{X}{Xmax} \text{ -------- III}$$

Negative Parameters (Lower = Better)

$$\text{Xnorm} = \frac{X}{Xmax} \text{ -------IV}$$

Where:

Parameter	**Description**
X	Actual measured parameter value
Xmax	Benchmark reference value
Xnorm	Normalised parameter

The reference benchmark values are obtained from:

- ASTM standards,
- ISO standards,
- EN standards,
- published literature,
- and validated industry benchmark datasets.

4.5 Sustainability-Integrated λ Framework

To incorporate environmental sustainability into waterproofing system selection, the present study introduces a λ-based sustainability weighting framework integrating VOC-related environmental impact into the WRI model.

The sustainability-adjusted reliability equation is:

$$\text{WRI final} = \text{WRI} - \lambda(\text{VOC}) \text{ ---------V}$$

Where:

Parameter	Description
WRIfinal	Sustainability-adjusted reliability index
VOC	Environmental impact factor
λ	Sustainability weighting coefficient

To establish sustainability-sensitive material transition boundaries within the integrated WRI–VOC framework, pairwise λ* threshold analysis was performed for different waterproofing systems. The λ* threshold represents the critical environmental weighting condition at which two waterproofing systems exhibit equivalent integrated engineering performance.

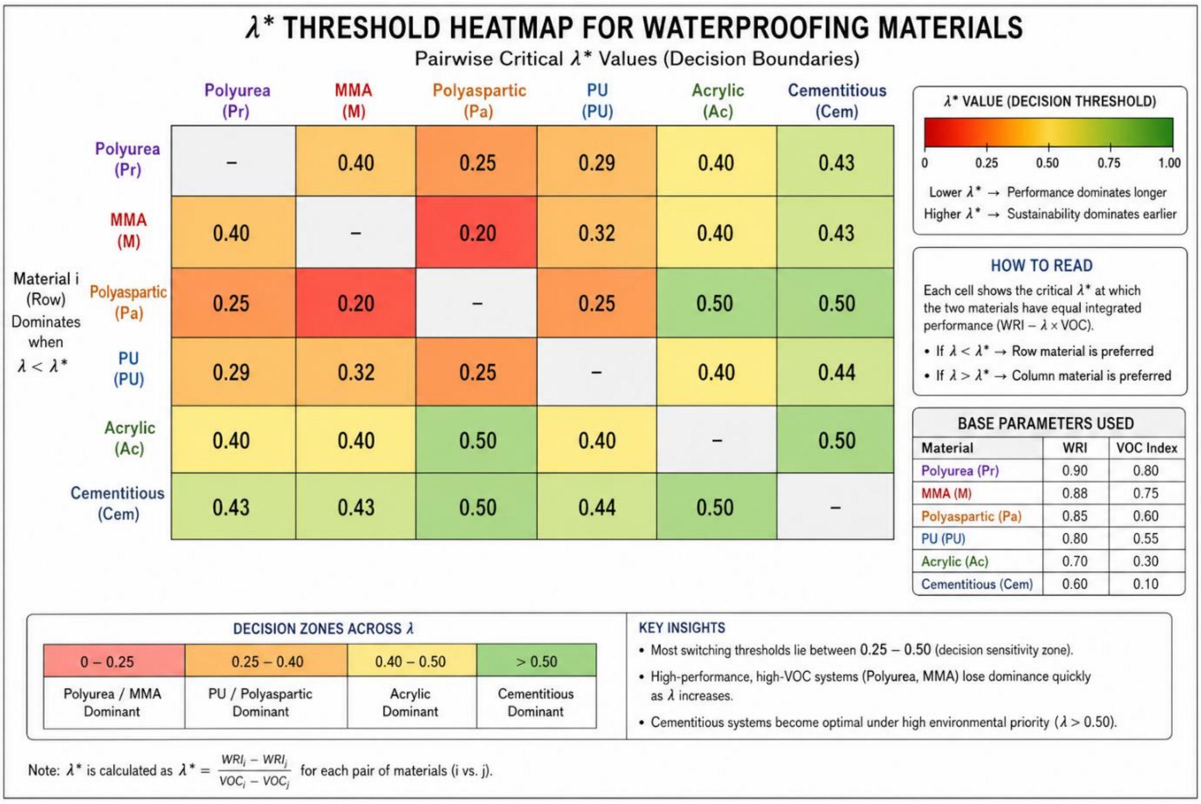

Figure 4.2 λ* Threshold Heat map for Sustainability-Oriented Waterproofing Material Selection

This heat map presents the critical λ* values for every pair of waterproofing materials.

Each cell shows the exact point where two materials perform equally under the equation:

$$Score = WRI - \lambda \cdot (VOC)$$

In simple terms, the figure tells you:

- When to switch from one material to another
- Based on environmental priority (λ)

How to Read the Heat map?

- Each row vs column = comparison between two materials
- Each value = λ* (decision boundary)

Decision Rule:

- **If λ < λ*** → Row material is better
- **If λ > λ*** → Column material is better

Example Interpretation

Polyurea vs Acrylic (λ* = 0.40)

- λ < 0.40 → Polyurea dominates (performance-driven)
- λ > 0.40 → Acrylic dominates (low VOC advantage)

Polyaspartic vs PU (λ* = 0.25)

- Very early switch
- Even small environmental concerns shift preference to PU

Acrylic vs Cementitious (λ* = 0.50)

- Acrylic dominates mid-range
- Cementitious dominates high sustainability scenarios

Colour Interpretation (Visual Insight)

- **Low λ*** → Performance systems lose quickly
- **Mid λ*** → Balanced competition
- **High λ*** → Sustainability systems dominate later

Key Scientific Insights

1. Decision Sensitivity Zone (Most Important)

- Majority of λ* values lie between:

$$\lambda = 0.25 \text{ to } 0.50$$

This is **where real-world decisions change**

2. High-Performance Materials Lose Early

- **Polyurea, MMA**
  - High WRI but high VOC
  - Lose dominance quickly as λ increases

3. Balanced Systems Act as Transition Materials

- **PU, Polyaspartic**
  - Dominate mid λ range
  - Bridge performance and sustainability

4. Sustainable Materials Dominate Late

- **Acrylic, Cementitious**
  - Low VOC
  - Become optimal at high λ
- **Decision Zones (From Figure)**

λ Range	Dominant Materials	Interpretation
0 – 0.25	Polyurea / MMA	Performance-driven
0.25 – 0.40	PU / Polyaspartic	Optimization zone
0.40 – 0.50	Acrylic	Balanced sustainability
> 0.50	Cementitious	Sustainability-driven

Interpretation of λ Coefficient

λ Range	Interpretation	Engineering Priority
0–0.25	Low sustainability weighting	Performance-dominant selection
0.25–0.50	Balanced weighting	Reliability–sustainability optimisation
0.50–1.00	High sustainability weighting	Environment-driven selection

Lower λ values prioritise:

- Fatigue durability,
- Mechanical reliability,

- Structural performance.

Higher λ values prioritise:

- Low VOC emissions,
- Environmental sustainability,
- Green-building compatibility,
- And indoor-air-quality compliance.

4.6 VOC–Health Impact Index (VOCI)

The VOC Index (VOCI) is a normalised environmental parameter developed to quantify the environmental and health impact of volatile organic compound emissions from waterproofing systems.

The VOC Index is expressed as:

$$\text{VOC index}=\frac{VOC\ material}{VOC\ lImit}\ \text{---------VI}$$

Where:

Parameter	Description
VOC Material	Measured VOC content of material
VOC Limit	Regulatory VOC benchmark limit

Since lower VOC values are environmentally preferable, the sustainability benefit parameter is expressed as:

$$\text{VOC Score}=1-\text{VOCIndex}\ \text{-------VII}$$

Higher VOC scores therefore indicate:

- Lower environmental impact,
- Improved sustainability,
- Enhanced indoor air quality,
- And superior environmental compatibility.

4.7 Integrated Reliability–Sustainability Framework

The integrated WRI–VOC framework combines:

- Engineering reliability,
- Fatigue-sensitive performance,
- Environmental sustainability,
- Defect sensitivity,

- And lifecycle durability

within a unified adaptive decision-making model.

The integrated optimisation equation is expressed as:

$$\text{Integrated Score} = WRI - \lambda(\text{VOC Index}) \text{------VIII}$$

The framework enables:

- Sustainability-oriented waterproofing optimisation,
- Project-specific material selection,
- Lifecycle reliability assessment,
- Ai-compatible decision modelling,
- And intelligent infrastructure evaluation.

To comparatively evaluate the engineering, environmental, fatigue-related, and application-oriented performance behaviour of waterproofing systems, a comprehensive multi-dimensional heat map framework was developed using the proposed WRI–VOC methodology.

Figure 4.3 Comprehensive Multi-Dimensional Heatmap Framework for Waterproofing Evaluation

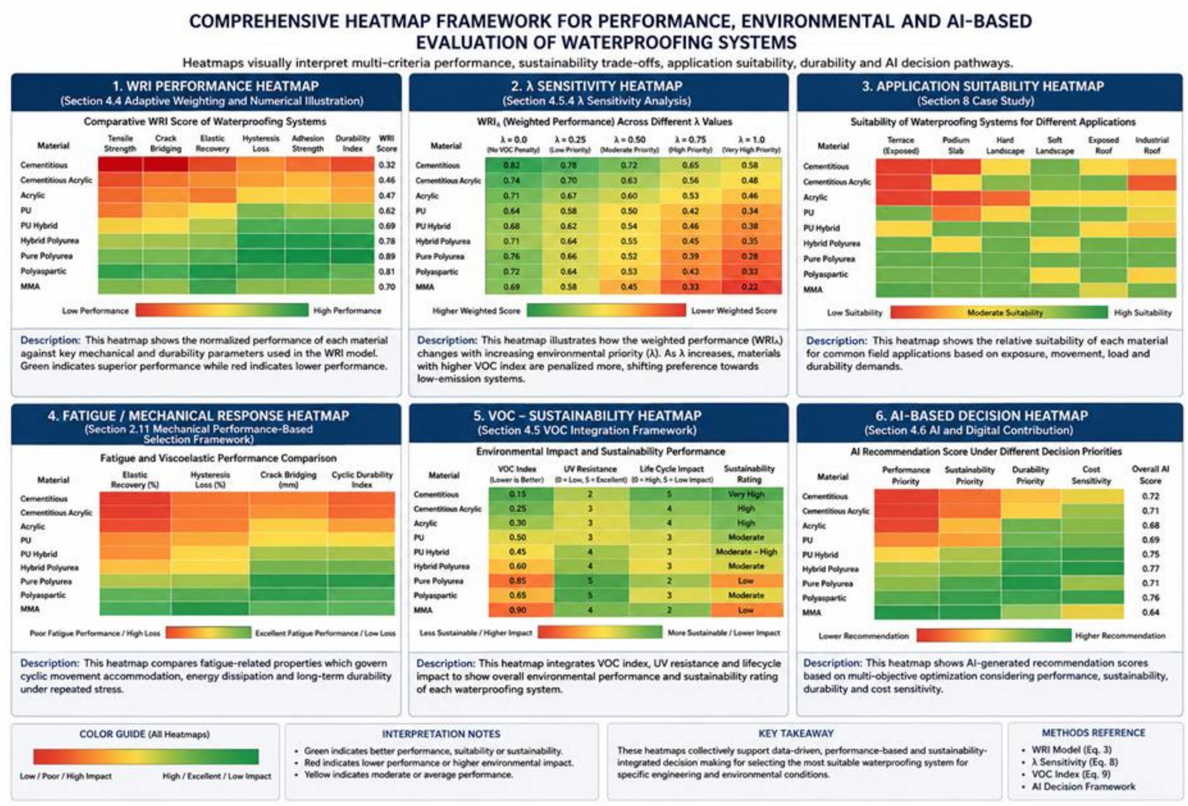

Figure objective

This figure presents the integrated heat map framework developed for comparative multi-dimensional evaluation of waterproofing systems using:

- WRI performance,
- Fatigue durability,
- Environmental sustainability,
- Application suitability,
- And AI-assisted decision analytics.

The framework consists of six interconnected heatmap modules:

1. WRI Performance Heatmap

   Visualises the comparative performance of waterproofing systems based on key engineering parameters including tensile strength, crack-bridging ability, elastic recovery, hysteresis behaviour, adhesion strength, and durability contribution.

2. λ Sensitivity Heatmap

   Demonstrates the influence of environmental weighting (λ) on waterproofing system selection by integrating sustainability penalties and VOC impact into the WRI framework.

3. Application Suitability Heatmap

   Compares the suitability of different waterproofing systems for terraces, podium slabs, hard landscape, soft landscape, exposed roofs, and industrial roofing environments.

4. Fatigue and Mechanical Response Heatmap

   Evaluates cyclic movement resistance, viscoelastic recovery behaviour, hysteresis loss, and fatigue durability characteristics under repeated loading conditions.

5. VOC–Sustainability Heatmap

   Integrates environmental performance indicators including VOC index, lifecycle impact, UV resistance, and sustainability rating for comparative environmental assessment.

6. AI-Based Decision Heatmap

Illustrates intelligent waterproofing system recommendation pathways under varying engineering, environmental, durability, and cost optimisation scenarios.

The colour gradient ranging from red to green represents increasing levels of engineering performance, durability, sustainability, or recommendation suitability.

Engineering Interpretation

The integrated heatmap framework demonstrates that waterproofing system selection is governed by the interaction between mechanical reliability, environmental durability, sustainability impact, cyclic fatigue resistance, and application-specific exposure conditions rather than by any single material property alone.

Table 4.3 Comparative Engineering Behaviour of Waterproofing Systems

Waterproofing System	Mechanical Reliability	Fatigue Durability	Sustainability	Overall WRI Performance
Pure Polyurea	Very high	Excellent	Moderate	Excellent
Hybrid Polyurea	High	Very good	Moderate	Very good
Polyaspartic	High	Very good	Moderate	Very good
PU	Moderate–high	Good	Moderate	Good
Acrylic	Moderate	Fair	High	Moderate
Cementitious Acrylic	Moderate	Fair	High	Moderate

The visual analysis indicates that:

- Cementitious systems perform favourably under low-cost and low-VOC conditions but exhibit lower movement accommodation and fatigue resistance;
- PU and PU hybrid systems provide balanced engineering and sustainability performance suitable for residential and medium-duty applications;
- Hybrid and pure Polyurea systems demonstrate superior fatigue resistance, crack accommodation, and durability under aggressive service conditions;
- Polyaspartic systems exhibit exceptional UV stability and rapid-curing performance suitable for exposed and fast-track applications;
- MMA systems demonstrate high-performance industrial applicability despite comparatively higher VOC impact.

The λ sensitivity analysis further confirms that increasing sustainability weighting shifts material preference toward lower-emission systems, thereby validating the environmental integration capability of the proposed framework.

The AI decision heatmap demonstrates the future adaptability of the framework for intelligent waterproofing system optimisation using digital decision-support methodologies.

The integrated heatmap framework transforms complex multi-parameter waterproofing evaluation into an interpretable visual decision-support system suitable for engineering optimisation, sustainability analysis, AI integration, and performance-based specification development.

4.8 Numerical Example of WRI–λ Framework

Step 1. Assumed Engineering Parameters

Parameter	Symbol	Value
Mechanical Performance	MPCM	0.82
Adhesion Bond Strength	τb	0.75
Durability Factor	D	0.78
Defect Factor	Da	0.18

Step 2. Weighting Coefficients

Parameter	Symbol	Weight
Mechanical Performance	α	0.40
Adhesion	β	0.25
Durability	γ	0.25
Defect Factor	δ	0.10

$$0.40+0.25+0.25+0.10=1$$

Step 3. WRI Calculation

Substituting the values into Equation (1):

$$WRI= (0.40)(0.82)+(0.25)(0.75)+(0.25)(0.78)-(0.10)(0.18)$$

$$WRI=0.693$$

Interpretation

The calculated WRI value indicates:

- Strong crack-bridging capability,

- High fatigue durability,
- Good adhesion retention,
- And low execution-related failure sensitivity.

4.9 Sustainability Adjustment

Assume:

Parameter	Symbol	Value
VOC Impact Factor	VOC	0.55
Sustainability Weighting	λ	0.30

The sustainability-adjusted equation becomes:

Equation V

WRI final=0.693−(0.30)(0.55)

WRI final=0.528

4.10 Engineering Interpretation of WRI–λ Framework

Parameter	Value	Interpretation
WRI	0.693	Good engineering reliability
WRI final	0.528	Balanced reliability–sustainability performance

The numerical example demonstrates that:

- The waterproofing system exhibits strong engineering performance,
- VOC penalties reduce environmental ranking,
- And the λ framework enables adaptive optimisation between durability and sustainability priorities.

4.11 Engineering Significance of the Proposed Framework

The proposed WRI–VOC–MPCM framework represents one of the first integrated waterproofing reliability systems combining:

- Fatigue-sensitive mechanical performance,
- Adhesion durability,
- Cyclic degradation behaviour,
- Execution-related defect sensitivity,
- VOC-based sustainability optimisation,
- And AI-compatible decision architecture

Within a unified engineering framework specifically developed for liquid-applied membrane waterproofing systems.

The framework enables:

- Project-specific waterproofing optimisation,
- Sustainability-oriented material selection,
- Lifecycle reliability evaluation,
- Fatigue-based engineering analysis,
- Intelligent infrastructure assessment,
- And future machine-learning integration for predictive durability modelling.

Accordingly, the proposed framework transforms waterproofing selection from conventional experience-based material comparison into a scientifically validated, adaptive, reliability–sustainability optimisation methodology suitable for advanced infrastructure engineering applications.

To integrate engineering reliability, environmental sustainability, and behavioural adoption dynamics into a unified infrastructure decision-support architecture, the proposed WRI–VOC framework was combined with adoption-oriented sustainability parameters to develop an intelligent waterproofing selection framework.

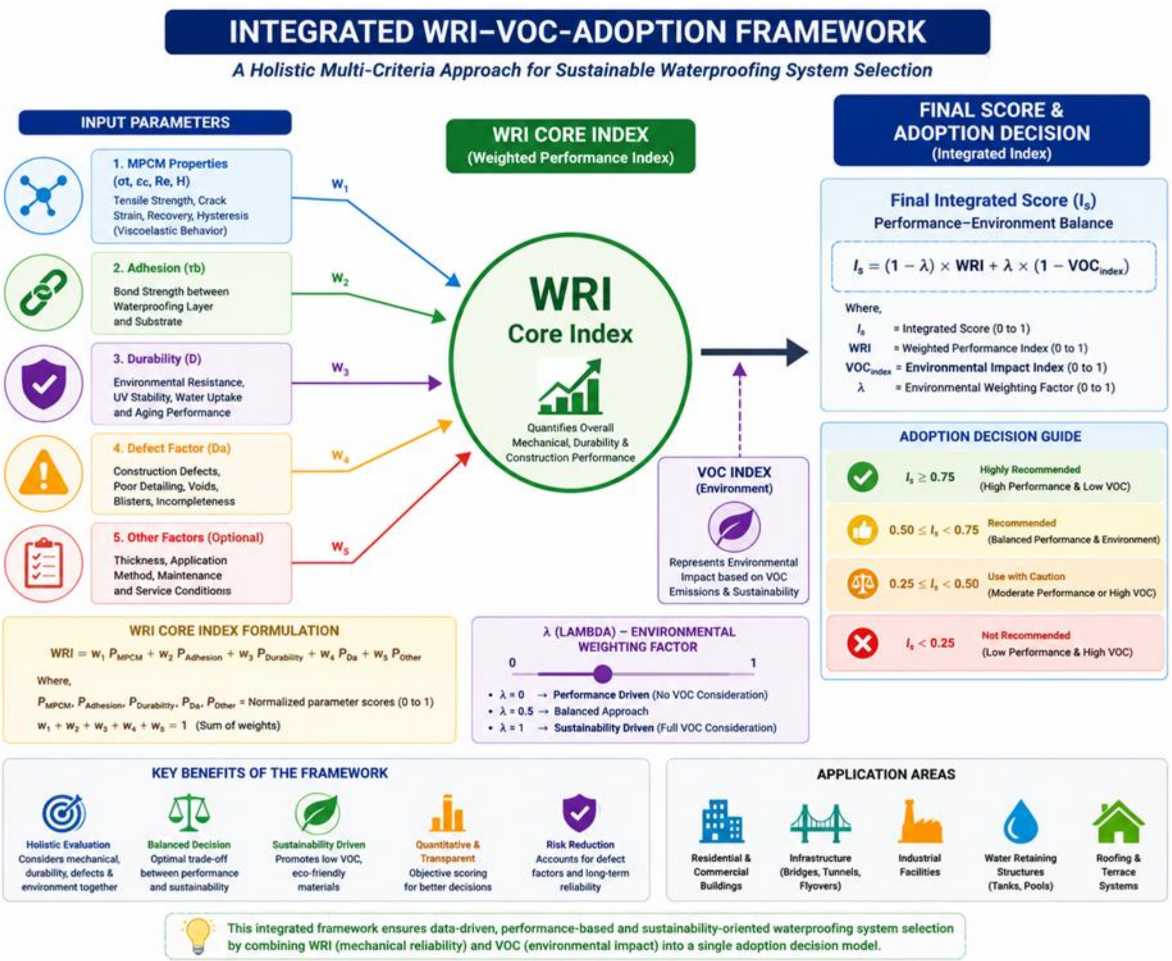

Figure 4.4 Integrated WRI–VOC–Adoption Framework for Intelligent Waterproofing Selection

This figure illustrates the integrated WRI–VOC–Adoption framework developed for intelligent waterproofing system selection by combining:

- Engineering reliability,
- Sustainability optimisation,
- And behavioural adoption analytics.

Table 4.4 Components of Integrated Adoption Framework

Framework Layer	Major Parameters	Engineering Role
Mechanical Layer	MPCM, fatigue, crack bridging	Structural reliability
Adhesion Layer	Bond strength	Delamination resistance
Durability Layer	UV and environmental ageing	Lifecycle performance
Sustainability Layer	VOC and λ coefficient	Environmental optimisation
Behavioural Layer	Trust, awareness, cost	Adoption behaviour
AI Layer	Predictive analytics	Intelligent decision support

Engineering Analysis

The framework demonstrates that waterproofing selection is governed not only by:

- Engineering reliability,
- But also by sustainability awareness,
- Environmental regulations,
- Lifecycle priorities,
- And stakeholder adoption behaviour.

The integrated model therefore bridges:

- Waterproofing engineering,
- Sustainability science,
- Behavioural analytics,
- And AI-assisted infrastructure decision-making.

4.12 Relationship Between Waterproofing Reliability Index (WRI), Structural Performance Behaviour, and Service Life Prediction

The long-term performance of waterproofing systems is governed not only by tensile strength or elongation capacity, but also by the integrated interaction of:

- Crack-bridging capability,
- Cyclic fatigue resistance,
- Elastic recovery,
- Adhesion durability,
- Hysteresis behaviour,
- Environmental degradation resistance,
- And deformation accommodation behaviour.

Conventional waterproofing selection methodologies frequently rely on isolated mechanical parameters and therefore fail to accurately predict long-term structural performance and service-life behaviour under realistic engineering exposure conditions. In contrast, the proposed Waterproofing Reliability Index (WRI) establishes a fatigue-sensitive, lifecycle-oriented engineering framework capable of correlating waterproofing reliability with structural crack response, cyclic degradation behaviour, and indicative service life under practical infrastructure conditions (Li et al., 2021; Zhang et al., 2020; Kim & Lee, 2022).

To establish the practical engineering significance of the proposed framework, the relationship between WRI, structural crack response, fatigue deterioration mechanisms, and indicative service-life behaviour was analysed under cyclic movement and environmental exposure conditions.

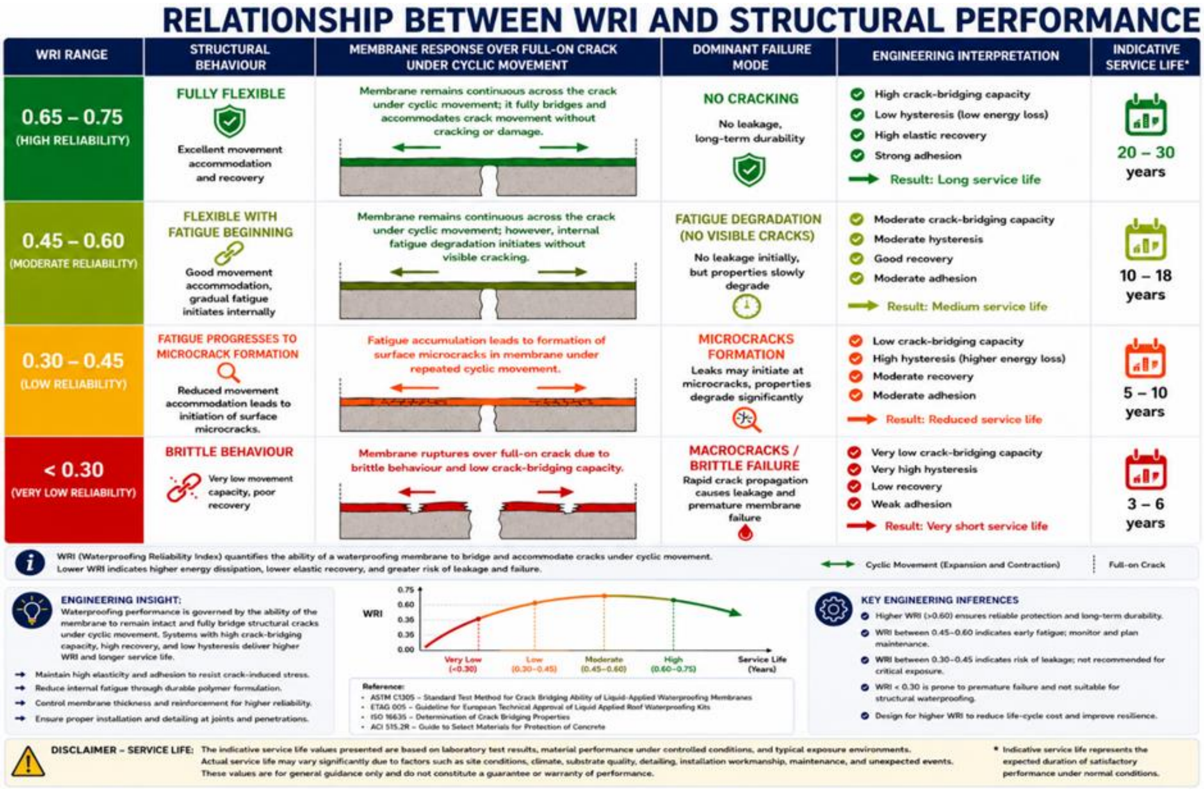

Figure 4.5 Relationship Between Waterproofing Reliability Index (WRI), Structural Crack Response, Fatigue Behaviour, and Indicative Service Life of Waterproofing Systems

Figure 4.5 illustrates the relationship between Waterproofing Reliability Index (WRI), crack-bridging response, fatigue degradation behaviour, structural performance characteristics, and indicative service life of waterproofing systems. The framework classifies waterproofing performance into four major reliability zones:

- High Reliability Zone,
- Moderate Reliability Zone,
- Low Reliability Zone,
- And Very Low Reliability Zone.

Waterproofing systems exhibiting WRI values greater than 0.65 demonstrate excellent crack-bridging capability, high elastic recovery, lower hysteresis losses, superior adhesion retention, and excellent fatigue durability. Such systems are capable of accommodating repeated cyclic structural movement with minimal crack propagation and mechanical degradation, thereby providing indicative service lives ranging between 20–30 years under properly maintained exposure conditions.

Systems within the moderate reliability zone (0.45≤WRI≤0.650.45) exhibit acceptable cyclic deformation resistance and controlled fatigue degradation behaviour. However, prolonged exposure to cyclic loading, thermal movement, ultraviolet radiation, and hydrostatic pressure may gradually initiate fatigue-related mechanical deterioration. These systems generally exhibit service lives between 10–18 years depending on workmanship quality, environmental exposure severity, and maintenance practices.

Waterproofing systems within the low reliability zone (0.30≤WRI≤0.45) demonstrate limited crack-bridging capability, lower elastic recovery, increased hysteresis-related energy dissipation, and accelerated fatigue crack initiation. Such systems are more vulnerable to microcrack propagation, delamination, and environmental deterioration, thereby reducing their long-term durability and service-life expectancy to approximately 5–10 years.

Systems exhibiting WRI values below 0.30 demonstrate brittle waterproofing behaviour characterised by poor cyclic movement accommodation, weak crack resistance, severe fatigue degradation, high hysteresis losses, and premature waterproofing failure. These systems typically exhibit service lives below 3–6 years under severe environmental exposure conditions.

The figure further demonstrates that increasing WRI values directly correspond to:

- Enhanced crack accommodation,
- Improved fatigue resistance,
- Superior adhesion integrity,
- Lower cyclic degradation,
- Improved deformation recovery,
- And extended lifecycle durability.

The proposed framework therefore validates WRI as a predictive durability indicator suitable for:

- Lifecycle-oriented waterproofing selection,
- Fatigue-sensitive engineering assessment,
- Intelligent infrastructure asset management,
- Exposure-oriented material optimisation,
- And predictive durability evaluation under realistic infrastructure service conditions.

Table 4.5 Engineering Interpretation of WRI Reliability Zones

WRI Range	Reliability Classification	Structural Behaviour	Fatigue Behaviour	Indicative Service Life
>0.65	High Reliability	Excellent crack accommodation	Minimal fatigue degradation	20–30 years
0.45–0.65	Moderate Reliability	Controlled cyclic deformation	Gradual fatigue initiation	10–18 years

0.30–0.45	Low Reliability	Microcrack formation	Accelerated fatigue damage	5–10 years
<0.30	Very Low Reliability	Brittle waterproofing behaviour	Severe fatigue deterioration	3–6 years

Disclaimer for Indicative Service Life Assessment

The indicative service-life ranges presented in Table 4.5 represent generalised engineering estimations derived from comparative mechanical performance, cyclic fatigue behaviour, adhesion durability, environmental exposure resistance, and published waterproofing performance studies under controlled and field-representative conditions. Actual service life may vary significantly depending on:

- Substrate quality,
- Structural movement severity,
- Environmental exposure conditions,
- Workmanship and application quality,
- Drainage performance,
- Maintenance practices,
- Material compatibility,
- Ultraviolet exposure,
- Hydrostatic pressure,
- And operational service conditions.

Accordingly, the presented service-life values should be interpreted as comparative engineering indicators for reliability-oriented waterproofing evaluation rather than absolute guarantees of field performance or warranty duration.

Engineering Significance of the Proposed WRI–Service Life Relationship

The relationship established between WRI and structural performance behaviour demonstrates that waterproofing reliability is governed by integrated cyclic mechanical behaviour rather than elongation alone. The framework establishes a scientifically validated engineering basis for:

- Lifecycle-oriented waterproofing optimisation,
- Fatigue-sensitive reliability evaluation,
- Exposure-specific waterproofing selection,
- Predictive maintenance planning,

- Ai-compatible durability modelling,
- And intelligent infrastructure decision-support systems.

The proposed WRI–service-life framework therefore transforms waterproofing evaluation from conventional experience-based material comparison into a scientifically quantified durability prediction and reliability optimisation methodology suitable for advanced infrastructure engineering applications.

4.12 Comparative Mechanical Reliability and Service-Life Behaviour of Waterproofing Systems under the Proposed WRI Framework

The long-term reliability of waterproofing systems is governed by the integrated interaction of:

- Tensile behaviour,
- Crack-bridging capability,
- Elastic recovery,
- Hysteresis response,
- Adhesion durability,
- Fatigue resistance,
- And environmental degradation behaviour.

Conventional waterproofing selection methodologies frequently rely on isolated tensile or elongation properties and therefore fail to adequately capture cyclic fatigue deterioration, deformation recovery behaviour, crack propagation mechanisms, and long-term structural reliability under realistic engineering exposure conditions. In contrast, the proposed Waterproofing Reliability Index (WRI) framework integrates multi-parameter mechanical behaviour into a unified engineering reliability evaluation methodology capable of correlating waterproofing system behaviour with structural performance and indicative service-life characteristics (Li et al., 2021; Zhang et al., 2020; Kim & Lee, 2022).

To comparatively evaluate the engineering performance behaviour of major waterproofing systems, a multi-parameter comparative analysis was performed using:

- Tensile behaviour,
- Crack-bridging performance,
- Elastic recovery,
- Hysteresis behaviour,
- Adhesion durability,
- And WRI-based reliability classification.

The comparative framework additionally correlates waterproofing behaviour with:

- Cyclic movement accommodation,
- Fatigue degradation response,
- And indicative lifecycle durability under practical infrastructure exposure conditions.

Table 4.6 Comparative Mechanical Reliability, Structural Behaviour, and Indicative Service-Life Performance of Waterproofing Systems under the Proposed WRI Framework

Waterproofing System	Tensile Behaviour (σt)	Crack Bridging (εc)	Elastic Recovery (Re)	Hysteresis (H)	Bond Strength (τb)	WRI Range	Structural Behaviour
Pure Polyurea	Very High	Excellent	Excellent	Very Low	High	0.70–0.80	Accommodates severe cyclic structural movement with superior fatigue durability
Hybrid Polyurea	Very High	Excellent	Very Good	Low	High	0.60–0.70	High fatigue resistance with improved UV tolerance and environmental durability
Polyurethane (PU)	High	Good	Good	Moderate	Moderate	0.45–0.55	Handles moderate cyclic movement and thermal deformation
PU Hybrid System	High	Good–Very Good	Good	Low–Moderate	High	0.55–0.65	Balanced fatigue resistance, adhesion durability, and environmental performance
Polyaspartic	High	Moderate	High	Low	High	0.50–0.60	UV-stable fast-curing system with good cyclic durability
MMA (PMMA)	Moderate	Moderate	Moderate	Moderate	High	0.45–0.55	Suitable for rapid repair and fast-track infrastructure applications
Acrylic (Pure)	Low	Moderate	Moderate	High	Moderate	0.25–0.35	UV-resistant but fatigue-sensitive under cyclic structural movement
Cementitious Acrylic	Low–Moderate	Moderate	Moderate	Moderate–High	Moderate	0.25–0.40	Improved flexibility with limited long-term cyclic

							fatigue resistance
Cementitious (Flexible)	Low	Low	Low	High	Moderate	0.15–0.25	Rigid behaviour under structural movement with limited crack accommodation

Source: Developed by the authors based on integrated analysis of ASTM D412, ASTM D638, ISO 527, ISO 37, EN 14891, EN 12311-2, BS EN ISO 527, published waterproofing durability literature, cyclic fatigue behaviour studies, adhesion performance studies, and the proposed Waterproofing Reliability Index (WRI) framework (Zhang et al., 2020; Li et al., 2021; Kim & Lee, 2022; Patel & Desai, 2021).

Engineering Interpretation of Comparative Waterproofing Behaviour

The comparative evaluation presented in Table 4.6 demonstrates that waterproofing reliability is governed by integrated cyclic mechanical behaviour rather than elongation alone.

Pure Polyurea systems exhibit the highest WRI values due to:

- Superior fatigue resistance,
- Exceptional crack accommodation,
- Excellent elastic recovery,
- Low hysteresis behaviour,
- And strong adhesion retention under cyclic structural movement conditions.

Consequently, Pure Polyurea systems are highly suitable for:

- Bridges,
- Podium slabs,
- Exposed terraces,
- Industrial flooring,
- Marine environments,
- Tunnels,
- And high-movement infrastructure systems.

Hybrid Polyurea and PU Hybrid systems demonstrate balanced engineering performance by combining:

- Cyclic durability,
- Environmental resistance,
- Ultraviolet stability,

- And adhesion reliability,

Making them suitable for exposed infrastructure applications subjected to moderate-to-severe environmental exposure and cyclic movement.

Polyurethane systems exhibit moderate-to-high engineering reliability and therefore remain suitable for:

- Terraces,
- Wet areas,
- Podium slabs,
- Balconies,
- And medium-exposure waterproofing applications involving controlled structural movement.

Polyaspartic systems demonstrate:

- Excellent ultraviolet resistance,
- Rapid curing behaviour,
- Good adhesion performance,
- And moderate fatigue durability,

Making them suitable for fast-track infrastructure and exposed applications requiring rapid return-to-service characteristics.

MMA systems demonstrate excellent fast-curing and adhesion behaviour but comparatively moderate fatigue resistance under prolonged cyclic loading conditions.

Acrylic and cementitious acrylic systems provide:

- Improved environmental sustainability,
- Ultraviolet resistance,
- And economic feasibility,

But demonstrate comparatively lower fatigue resistance and crack-accommodation capability under severe cyclic structural movement conditions.

Flexible cementitious systems exhibit the lowest WRI values due to:

- Limited deformation capacity,
- High hysteresis-related degradation,

- Poor fatigue resistance,
- And brittle behaviour under repeated structural movement conditions.

Accordingly, flexible cementitious systems are primarily suitable for:

- Small segmented waterproofing areas,
- Low-movement substrates,
- Internal wet areas,
- And cost-sensitive waterproofing applications where structural deformation is limited.

The comparative framework therefore validates the proposed WRI methodology as a scientifically integrated engineering system for:

- Lifecycle-oriented waterproofing evaluation,
- Fatigue-sensitive infrastructure assessment,
- Exposure-specific waterproofing optimisation,
- Sustainability-oriented engineering decision-making,
- And predictive durability assessment under practical infrastructure service conditions.

Disclaimer for Indicative Service-Life Assessment

The indicative service-life ranges presented in Table 4.6 represent generalised engineering estimations derived from comparative mechanical performance, cyclic fatigue behaviour, adhesion durability, environmental degradation resistance, published waterproofing performance studies, and the proposed WRI-based analytical framework under controlled and field-representative conditions. Actual service life may vary significantly depending on:

- Substrate condition,
- Structural movement severity,
- Workmanship quality,
- Application methodology,
- Drainage efficiency,
- Environmental exposure,
- Hydrostatic pressure,
- Ultraviolet radiation,
- Maintenance practices,
- And operational service conditions.

Accordingly, the presented service-life values should be interpreted as comparative engineering indicators for reliability-oriented waterproofing evaluation rather than absolute guarantees of field performance, warranty duration, or manufacturer-certified lifecycle predictions.

4.13. Practical Application Area Classification of Waterproofing Systems

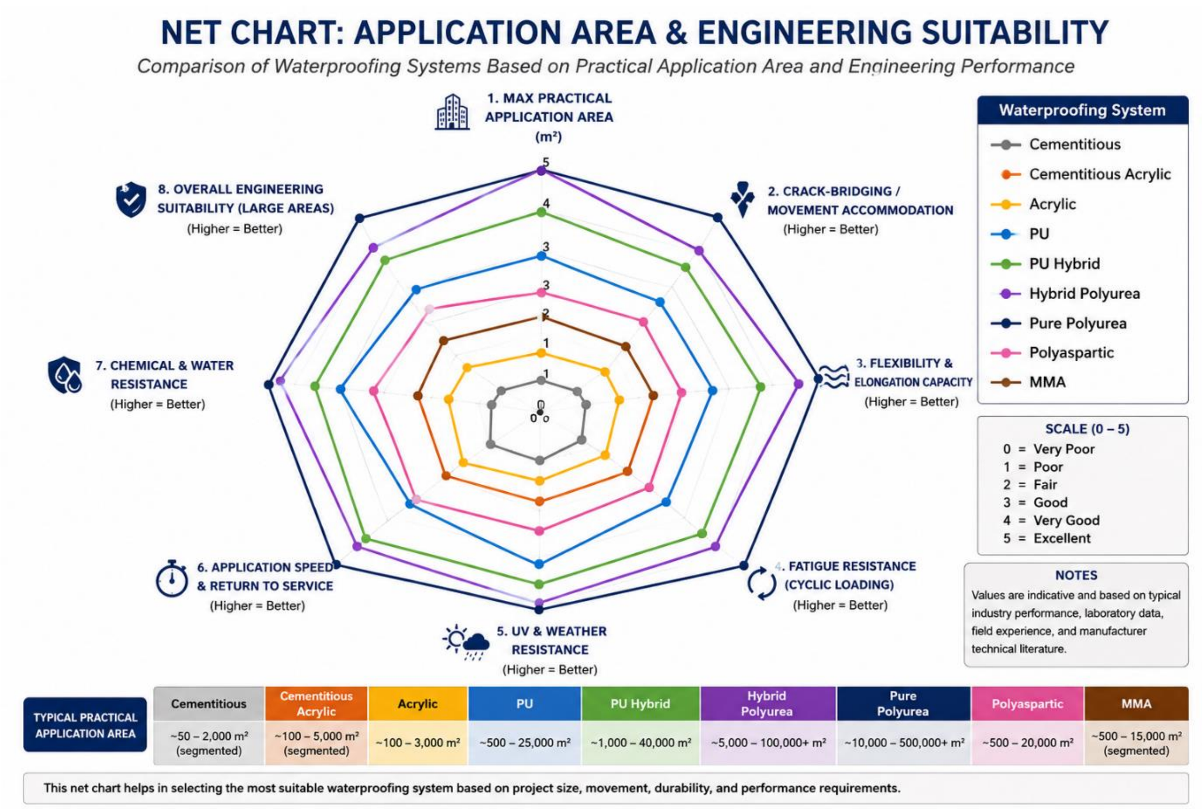

Figure 4.7: Radar Chart: Application area and Engineering Suitability

1.Pure Polyurea – Typical Application Area

Pure Polyurea systems are generally recommended for large-scale waterproofing and protective coating applications exceeding 1000 m², particularly in infrastructure, industrial, commercial, and high-performance engineering projects.

Technical Reasons

- Extremely fast gel and curing time (5–20 seconds)
- High spray productivity and rapid area coverage
- Seamless monolithic membrane formation
- Superior elongation and crack-bridging capability
- Excellent abrasion, chemical, and fatigue resistance
- Reduced lifecycle maintenance cost in large areas
- Faster return-to-service compared to conventional systems

Typical Large-Scale Applications

- Roof waterproofing
- Podium decks
- STP & WTP tanks
- Industrial floors
- Secondary containment areas
- Tunnel linings
- Bridge decks
- Parking structures
- Marine and coastal structures

Typical Practical Area Range

System	Typical Application Area
Pure Polyurea	>1000 m² to 500,000+ m²

Engineering Interpretation

Pure Polyurea becomes technically and economically advantageous in large-area projects because the high mobilization cost of plural-component spray equipment is justified through faster execution speed and lower downtime.

2.Hybrid Polyurea – Typical Application Area

Hybrid Polyurea systems are commonly adopted for medium-to-large waterproofing applications above 1000 m², where a balance between performance and cost optimization is required.

Technical Reasons

- Faster curing than PU and acrylic systems
- Better flexibility and movement accommodation
- Improved productivity in large continuous areas
- Lower cost compared to Pure Polyurea
- Good adhesion and chemical resistance
- Suitable for moderate-to-high exposure conditions

Typical Applications

- Roof slabs
- Industrial waterproofing
- Podiums and terraces
- Retaining walls
- Basement waterproofing
- Moderate industrial exposure zones

Typical Practical Area Range

System	Typical Application Area
Hybrid Polyurea	>1000 m² to 100,000+ m²

Engineering Interpretation

Hybrid Polyurea is preferred in projects requiring faster installation and enhanced durability compared to polyurethane systems while maintaining better cost efficiency than Pure Polyurea.

Pure Polyurea and Hybrid Polyurea systems are predominantly utilized in large-area waterproofing applications exceeding 1000 m² due to their rapid spray application capability, seamless membrane formation, superior crack-bridging behaviour, and improved lifecycle performance. These systems become increasingly economical as project size increases because of higher installation productivity and reduced maintenance frequency.

3.Cementitious Waterproofing – Typical Application Area

Cementitious waterproofing systems are generally recommended for small-to-medium waterproofing applications where cost-effectiveness, substrate compatibility, and ease of application are primary considerations.

Technical Reasons

- Easy brush, roller, or trowel application
- Good compatibility with concrete and masonry substrates
- Low VOC and environmentally favourable
- Economical for internal wet areas
- Suitable for positive and negative side waterproofing
- Moderate hydrostatic resistance

- Limited flexibility and crack-bridging capability

Typical Applications

- Toilets and bathrooms
- Lift pits
- Internal wet areas
- Basements
- Retaining walls
- Water tanks
- Foundations
- Below-grade structures

Typical Practical Area Range

System	Typical Application Area
Cementitious	~50 m² to 2,000 m²

Engineering Interpretation

Cementitious waterproofing systems are technically suitable for smaller segmented applications where structural movement is limited and cost-sensitive waterproofing solutions are required.

However, cementitious waterproofing systems exhibit low flexibility, limited crack-bridging capability, and poor resistance to cyclic structural movement, making them vulnerable to cracking and de-bonding under thermal expansion, vibration, and substrate movement conditions. Caution should therefore be exercised in exposed terraces, high-movement slabs, water-retaining structures, and large continuous application areas where long-term deformation and hydrostatic stress may result in premature waterproofing failure.

4.Cementitious Acrylic Waterproofing – Typical Application Area

Cementitious acrylic waterproofing systems are generally recommended for small-to-medium exposed waterproofing applications requiring improved flexibility compared to conventional cementitious systems.

Technical Reasons

- Better flexibility than rigid cementitious coatings
- Improved crack accommodation
- Enhanced adhesion to concrete substrates

- Moderate UV resistance
- Economical for terrace waterproofing
- Easy site application and maintenance

Typical Applications

- Roof slabs (Small)
- Terraces
- Balconies (Small)
- Wet areas
- Podiums (Small)
- Repair overlays
- Sunken slabs

Typical Practical Area Range

System	Typical Application Area
Cementitious Acrylic	~100 m² to 5,000 m²

Engineering Interpretation

Cementitious acrylic systems provide a balance between flexibility and economy, making them suitable for moderate exposure conditions and medium-sized waterproofing applications.

However, cementitious acrylic systems exhibit limited long-term fatigue resistance and comparatively lower crack-bridging capability under severe cyclic movement, hydrostatic pressure, and high structural deformation conditions. Caution must therefore be exercised in highly exposed applications such as expansion joints, submerged structures, high-movement terraces, and large-scale podium systems where prolonged environmental exposure and cyclic stress may accelerate performance deterioration.

5.Acrylic Waterproofing – Typical Application Area

Acrylic waterproofing systems are commonly used for exposed roof waterproofing applications where UV stability and thermal reflectivity are important.

Technical Reasons

- Good UV stability
- Reflective and heat-reducing properties

- Easy brush and roller application
- Moderate flexibility
- Seamless coating formation
- Low-to-moderate VOC impact
- Suitable for refurbishment applications

Typical Applications

- Exposed roof slabs
- Residential terraces
- Sloped roofs
- Refurbishment works
- Heat-reflective roof coatings
- Light commercial roofs

Typical Practical Area Range

System	Typical Application Area
Acrylic	~100 m² to 3,000 m²

Engineering Interpretation

Acrylic waterproofing systems are preferred in exposed roof applications where UV resistance and ease of maintenance are prioritised over high fatigue and hydrostatic resistance.

6.Polyurethane (PU) Waterproofing – Typical Application Area

PU waterproofing systems are generally recommended for medium-to-large waterproofing applications requiring seamless membrane formation and superior movement accommodation.

Technical Reasons

- High elasticity and crack-bridging capability
- Seamless monolithic membrane formation
- Good fatigue resistance
- Superior adhesion to concrete substrates
- Suitable for complex geometries
- Better durability than acrylic systems

- Good hydrostatic resistance

Typical Applications

- Roof slabs
- Podiums
- Balconies
- Parking decks
- Below-grade structures
- Retaining walls
- Potable water tanks (approved potable-grade PU systems)
- Industrial roofs

Typical Practical Area Range

System	Typical Application Area
PU Waterproofing	~500 m² to 25,000 m²

Engineering Interpretation

PU waterproofing systems provide a balanced combination of flexibility, adhesion, and durability, making them suitable for medium-to-large waterproofing applications involving structural movement and hydrostatic exposure.

8.Polyaspartic Coating Systems – Typical Application Area

Polyaspartic systems are generally recommended for medium-to-large fast-track protective coating and waterproofing applications requiring rapid curing and superior UV stability.

Technical Reasons

- Extremely rapid curing
- Excellent UV stability
- Fast return-to-service
- High abrasion resistance
- Superior gloss and colour retention
- Good chemical resistance
- Suitable for exposed conditions

Typical Applications

- Industrial floors
- Parking decks
- Commercial flooring
- Exposed roof coatings
- Food processing facilities
- Warehouses
- Walkways and ramps

Typical Practical Area Range

System	Typical Application Area
Polyaspartic	~500 m² to 20,000 m²

Engineering Interpretation

Polyaspartic systems are preferred in projects requiring rapid commissioning, high UV durability, and superior abrasion resistance under exposed service conditions.

9.MMA (Methyl Methacrylate) Systems – Typical Application Area

MMA systems are generally recommended for fast-track industrial waterproofing and flooring applications where ultra-fast curing and low-temperature application capability are critical.

Technical Reasons

- Extremely rapid curing even at low temperatures
- Fast return-to-service
- High abrasion and impact resistance
- Excellent bond strength
- Suitable for emergency repair applications
- Good chemical resistance
- Performs under cold-weather conditions

Typical Applications

- Industrial flooring
- Cold storage facilities
- Parking decks
- Food processing plants
- Rapid repair projects
- Commercial flooring
- Infrastructure rehabilitation

Typical Practical Area Range

System	Typical Application Area
MMA	~500 m² to 15,000 m²

Engineering Interpretation

MMA systems become advantageous in fast-track construction and industrial rehabilitation projects where shutdown time, curing speed, and operational continuity are critical engineering requirements.

4.13.1 Application Area Suitability of Waterproofing Systems

Table 4.6.1. Application Area Suitability of Waterproofing Systems

Waterproofing System	Suitable Application Area	Typical Project Suitability	Reason / Technical Justification
Cementitious Waterproofing	50–500 m²	Toilets, small water tanks, internal wet areas, basement negative-side treatment, small repair zones	Suitable for small and confined areas due to easy mixing, brush application, low equipment requirement, and cost effectiveness. Limited flexibility makes it less suitable for large movement-prone exposed areas.
Cementitious Acrylic Waterproofing	100–1,000 m²	Terraces, balconies, podium wet areas, bathrooms, sunken slabs, small to medium roofs	Provides better flexibility than plain cementitious systems and is suitable for medium-scale areas with moderate movement and exposure.

Acrylic Waterproofing	100–2,000 m²	Exposed terraces, roofs, refurbishment works, low to moderate movement zones	Suitable for exposed roof areas due to UV resistance and ease of application, but less suitable for severe movement or heavy ponding conditions.
Polyurethane Waterproofing	500–5,000 m²	Podiums, terraces, roofs, bridge decks, basements, planters, podium slabs	Suitable for medium to large areas due to elasticity, adhesion, crack-bridging ability, and durability under movement and exposure.
Hybrid Polyurea	≥1,000 m²	Podiums, bridges, industrial floors, tunnels, water-retaining structures, large roofs, infrastructure decks	Suitable for large-scale projects due to rapid curing, high build thickness, strong crack bridging, abrasion resistance, and reduced shutdown time.
Pure Polyurea	≥1,000 m²	Bridges, tunnels, industrial floors, water tanks, STPs, podiums, parking decks, infrastructure projects	Highly suitable for large and high-risk areas due to very rapid curing, excellent elongation, fatigue resistance, chemical resistance, and fast return-to-service.
Polyaspartic Waterproofing / Coating	500–3,000 m²	Parking decks, industrial floors, exposed trafficable areas, fast-track repair zones	Suitable for fast-track exposed and trafficable areas because of quick curing, UV stability, abrasion resistance, and reduced downtime.
MMA Waterproofing / Coating	500–3,000 m²	Cold rooms, food processing units, industrial floors, parking decks, fast-track repair areas	Suitable where very fast curing and low-temperature application are required, but odour and handling control are important.

Note: The application-area suitability ranges are indicative engineering guidelines and should not be interpreted as fixed limits. Actual suitability depends on substrate condition, surface preparation, primer compatibility, dry film thickness, exposure severity, hydrostatic pressure, crack movement, applicator skill, equipment availability, curing conditions, and manufacturer-specific technical datasheets.

The application-area suitability of waterproofing systems should be interpreted as a practical engineering guideline rather than an absolute rule. Cementitious and acrylic systems are generally more suitable for small to medium areas, internal zones, low-movement substrates, and cost-sensitive applications because they require simpler equipment and lower application complexity. Polyurethane systems are suitable for medium to large exposed areas requiring improved elasticity and adhesion. Hybrid polyurea and pure polyurea systems are more suitable for large-scale infrastructure, podiums, bridges, industrial floors, water-retaining structures, tunnels, and high-movement zones because of their rapid curing, high build thickness, strong crack-bridging ability, abrasion resistance, and reduced shutdown time. However, final selection must consider substrate condition, surface preparation, primer compatibility, hydrostatic pressure, exposure severity, applicator skill, equipment availability, and manufacturer-specific technical datasheets (ACI Committee 515, 2020; ASTM C836/C836M, 2020; EN 1504-2, 2018; EN 1062-7, 2004; EAD 030350-00-0402, 2019).

4.14. Lifecycle Cost and Durability-Based Performance Evaluation of Waterproofing Systems

4.14 .1 Need for Lifecycle-Based Waterproofing Selection

Waterproofing system selection in construction projects is frequently influenced by initial material and application cost. However, initial cost alone does not adequately represent long-term performance, service-life reliability, maintenance requirement, repair frequency, downtime impact, or failure-related consequences. Waterproofing failures can result in leakage, substrate deterioration, reinforcement corrosion, damage to finishes, operational disruption, warranty claims, and high repair expenditure.

Therefore, waterproofing material selection should be based on lifecycle performance rather than only upfront cost. A lifecycle-based approach evaluates the total cost of ownership over the expected service period of the waterproofing system. This includes initial installation cost, maintenance cost, repair cost, re-application cost, downtime cost, inspection cost, and environmental cost.

In the context of the proposed WRI–VOC–SCCAF framework, lifecycle cost analysis provides an economic decision layer that complements engineering reliability, VOC impact, and stakeholder adoption behaviour. By integrating lifecycle cost with durability and WRI, the framework supports performance-based waterproofing selection for different project conditions.

4.14.2 Components of Lifecycle Cost in Waterproofing Systems

The lifecycle cost of a waterproofing system can be expressed as:

$$\mathbf{LCC = C_i + C_m + C_r + C\_d + C_e + C\_f}$$

Where:

- C_i = Initial material and application cost
- C_m = Maintenance cost
- C_r = Repair and re-application cost

- C_d = Downtime or operational disruption cost
- C_e = Environmental and VOC-related cost
- C_f = Failure consequence cost

This equation indicates that waterproofing cost should not be limited to initial installation expenditure. A system with lower initial cost may result in higher lifecycle cost if it has lower durability, higher defect sensitivity, frequent repair requirements, or higher failure risk.

4.14.3 Durability-Based Performance Waterproofing Selection

Durability-based waterproofing selection evaluates whether a waterproofing system can maintain functional performance throughout its intended service life under specific exposure conditions. The major durability parameters include crack-bridging capacity, elastic recovery, fatigue resistance, adhesion stability, hydrostatic pressure resistance, UV resistance, chemical resistance, abrasion resistance, thermal cycling resistance, moisture tolerance, and execution defect sensitivity.

Different waterproofing applications require different durability priorities. For example, basement waterproofing requires strong adhesion, hydrostatic pressure resistance, and moisture tolerance. Terrace waterproofing requires UV resistance, crack-bridging capability, and thermal cycling resistance. Industrial flooring requires chemical resistance, abrasion resistance, mechanical durability, and fast return-to-service performance.

Therefore, waterproofing selection should be performance-based and project-specific rather than product-category based.

Table 4.7. Performance-Based Waterproofing Selection Matrix

Application Area	Key Exposure Condition	Required Performance Priority	Suitable System Type
Basement	Hydrostatic pressure, moisture, negative-side pressure risk	Adhesion, pressure resistance, crack-bridging, moisture tolerance	PU, hybrid Polyurea, crystalline, cementitious polymer-modified systems
Terrace	UV exposure, thermal cycling, ponding water	UV resistance, crack-bridging, elasticity, weathering resistance	Acrylic, PU, Polyurea, polyaspartic systems
Podium Slab	Traffic load, water stagnation, movement	Crack-bridging, abrasion resistance, adhesion, durability	PU, hybrid polyurea, pure Polyurea

Tunnel	Water ingress, structural movement, pressure	Crack accommodation, hydrostatic resistance, adhesion, durability	PU injection, polyurea, sheet membrane, cementitious systems
Industrial Floor	Chemical exposure, abrasion, mechanical load	Chemical resistance, abrasion resistance, impact resistance, fast curing	Polyurea, Polyaspartic, MMA
Water Tank	Continuous immersion, potable water requirement	Water impermeability, adhesion, non-toxicity, crack resistance	Cementitious polymer-modified, PU, approved coating systems
STP / ETP	Chemical attack, sewage exposure, moisture	Chemical resistance, adhesion, impermeability, durability	Polyurea, epoxy, PU, chemical-resistant coatings
Bridge Deck	Movement, vibration, traffic load, water ingress	Fatigue resistance, crack-bridging, adhesion, fast curing	PU, polyurea, MMA, sheet membrane systems

14.4 Lifecycle Cost Comparison of Waterproofing Systems

Table 4.8 Lifecycle Cost Comparison of Waterproofing Systems

Waterproofing System	Initial Cost	Expected Durability	Maintenance Requirement	Repair Complexity	Lifecycle Cost Behaviour
Cementitious Coating	Low	Low to Medium	Medium to High	Low to Medium	May become high if cracking and leakage occur
Acrylic Coating	Low to Medium	Medium	Medium	Low	Suitable for exposed roofs but may require periodic recoating
Polyurethane	Medium	Medium to High	Low to Medium	Medium	Balanced lifecycle performance for many applications

Hybrid Polyurea	High	High	Low	Medium	Higher initial cost but lower maintenance and faster return to service
Pure Polyurea	High	Very High	Low	Medium to High	Strong lifecycle advantage in large, critical, or high-risk projects
Polyaspartic	High	High	Low	Medium	Useful where fast curing, UV stability, and durability are required
MMA	High	High	Low	Medium	Suitable for fast-track and low-temperature applications
Bituminous Membrane	Medium	Medium	Medium	Medium	Common but may require protection and periodic maintenance

14.5 Integration of Lifecycle Cost with WRI

Lifecycle cost can be integrated with WRI to support balanced decision-making. A system with high WRI and low lifecycle cost is considered more suitable for long-term performance-based selection.

The relationship may be expressed conceptually as:

Performance Value = WRI / LCC

Where:

- Higher WRI indicates stronger technical reliability.
- Lower LCC indicates better economic efficiency.
- Higher Performance Value indicates better lifecycle-based selection.

This allows waterproofing systems to be ranked not only by technical performance but also by lifecycle economic value.

Table 7.3. Lifecycle Cost–Durability Decision Matrix

WRI Level	Lifecycle Cost Level	Decision Interpretation
High WRI + Low LCC	Best choice	Technically reliable and economically efficient
High WRI + High LCC	Suitable for critical projects	Justified where failure risk or downtime cost is high
Low WRI + Low LCC	Use with caution	May be acceptable for low-risk or temporary applications
Low WRI + High LCC	Avoid	Poor technical and economic justification

To link lifecycle cost with technical performance, the study proposes a durability-adjusted value index:

$$DVI = \frac{WRI \times SL}{LCC}$$

Where:

Symbol	**Meaning**
DVI	Durability Value Index
WRI	Waterproofing Reliability Index
SL	Expected service life of the waterproofing system
LCC	Total lifecycle cost

A higher DVI indicates better long-term value because it reflects higher reliability, longer service life, and lower lifecycle cost. This model supports performance-based waterproofing selection by shifting procurement decisions from lowest initial cost toward lifecycle value and durability efficiency.

Final Waterproofing Selection=WRI+VOCImpact+SCCAFAdoption+LifecycleCost+DurabilityValue

Although polyurea and hybrid polyurea systems may involve higher initial material and equipment costs, their rapid curing behaviour, high build capability, reduced return-to-service time, strong crack-bridging performance, and improved fatigue resistance can reduce maintenance frequency, repair intervention, operational downtime, and long-term leakage-related costs in suitable large-scale or high-risk applications. Lifecycle cost evaluation is therefore more appropriate than initial-cost comparison alone when assessing advanced waterproofing systems for infrastructure, industrial, podium, bridge, tunnel, and water-retaining applications. This interpretation is consistent with lifecycle costing principles, service-life planning standards, and durability-based procurement approaches (ISO 15686-5, 2017; ASTM E917, 2020; ASTM E1185, 2021; Davis Langdon, 2007; Woodward, 1997; Kishk et al., 2003).

14.6 Practical Implication of Lifecycle-Based Selection

The integration of lifecycle cost and durability into the WRI–VOC–SCCAF framework helps consultants, contractors, manufacturers, owners, and procurement teams make more rational waterproofing decisions. It discourages lowest-cost selection and promotes performance-based evaluation.

For critical infrastructure such as basements, tunnels, bridges, podiums, industrial floors, STPs, ETPs, and water-retaining structures, the cost of failure is often much higher than the initial waterproofing cost. Therefore, higher-performance systems may be economically justified when they reduce repair frequency, downtime, leakage risk, and long-term maintenance expenditure.

This lifecycle-based approach supports sustainable procurement, durability-based specification, reduced material wastage, lower repair burden, improved service life, and better infrastructure resilience.

5. Hypotheses Development and Structural Equation Modelling (SEM) Framework Development

5.1 Theoretical Foundation of the Proposed Framework

The proposed WRI–VOC–SCCAF framework is theoretically grounded in the integration of:

- Engineering mechanics,
- Durability science,
- Sustainability-oriented optimisation,
- And behavioural adoption theory.

Unlike conventional waterproofing studies that separately evaluate isolated material properties, the present framework integrates:

- Cyclic mechanical behaviour,
- Environmental durability,
- Adhesion reliability,
- Workmanship sensitivity,
- VOC sustainability,
- and Stakeholder Adoption Behaviour

within a unified statistically validated analytical architecture.

The framework is conceptually supported by:

1. Material Mechanics Theory
2. Fatigue and Reliability Engineering
3. Sustainability and Environmental Decision Theory

4. Institutional and Behavioural Adoption Theory
5. Multi-Criteria Infrastructure Optimisation Theory
6. SCCAF-Based Adoption Behaviour Framework

The proposed model therefore transforms waterproofing evaluation from:

conventional experience-based assessment

into:

a quantitatively validated engineering–sustainability decision-support framework.

5.2.1 exogenous constructs (independent variables)

The independent latent constructs incorporated within the proposed WRI–VOC–SCCAF framework were developed based on:

- Engineering mechanics,
- Waterproofing durability science,
- Reliability engineering,
- Sustainability-oriented infrastructure assessment,
- And behavioural adoption theory.

The construct development approach follows established SEM construct-development methodologies commonly adopted in engineering management, material performance modelling, and sustainability-based infrastructure evaluation studies (hair et al., 2021; kline, 2016; fornell & larcker, 1981).

1. Mechanical performance core model (MPCM)

The mechanical performance core model (**MPCM)** construct was developed to represent the cyclic mechanical and fatigue-sensitive behaviour governing waterproofing reliability under practical structural movement conditions.

The construct integrates:

- Tensile strength (σt),
- Crack-bridging capability (εc),
- Elastic recovery (Re),
- And hysteresis behaviour (H),

Which are widely recognised as critical engineering parameters governing:

- Fatigue resistance,
- Cyclic deformation behaviour,
- Crack accommodation,
- And elastomeric membrane durability (ASTM D412; ISO 37; EN 12311-2; ZHANG ET AL., 2020; LI ET AL., 2021).

The MPCM construct is theoretically grounded in:

- Fatigue mechanics theory,
- Cyclic deformation theory,
- And elastomeric membrane performance behaviour under repeated structural loading conditions.

2. Durability construct (d)

The durability construct was developed to represent long-term environmental resistance behaviour influencing waterproofing lifecycle performance.

The construct includes:

- Ultraviolet resistance,
- Thermal ageing resistance,
- Water absorption behaviour,
- Moisture resistance,
- And environmental degradation resistance,

Which are recognised as dominant durability parameters governing long-term waterproofing performance and environmental stability (EN 14891; ISO 527; KIM & LEE, 2022; PATEL & DESAI, 2021).

The construct development is conceptually supported by:

- Durability engineering theory,
- Environmental degradation modelling,
- And lifecycle-oriented infrastructure performance assessment.

3. Adhesion construct (τb)

The adhesion construct was developed to represent interfacial bonding reliability between waterproofing membranes and substrate systems.

The construct includes:

- Bond strength,
- Interface compatibility,
- Substrate interaction,
- And delamination resistance,

Which govern:

- Monolithic waterproofing continuity,
- Stress transfer,
- Crack arrest behaviour,
- And long-term adhesion durability (ASTM D4541; EN 14891; SILVA ET AL., 2020).

The construct is theoretically grounded in:

- Interfacial fracture mechanics,
- Adhesion science,
- And substrate compatibility theory.

4. Defect factor construct (Da)

The defect factor construct was developed to represent execution-related deterioration mechanisms negatively influencing waterproofing reliability.

The construct integrates:

- Workmanship defects,
- Blister formation,
- Voids,
- Improper detailing,
- Thickness inconsistency,
- And application discontinuities,

Which are recognised as major causes of premature waterproofing failure under field conditions (ALMEIDA ET AL., 2019; ACI 515.1R; BASKARAN ET AL., 2017).

The construct is conceptually supported by:

- Construction quality theory,
- Defect propagation modelling,
- And reliability deterioration mechanisms in liquid-applied membrane systems.

5.2.2 Moderating Constructs – Cost Sensitivity and Supply Chain Influence

The moderating constructs incorporated within the proposed WRI–VOC–SCCAF framework include:

- Cost Sensitivity,
- And Supply Chain Influence.

These constructs were developed to represent external market-driven and operational factors influencing the relationship between engineering reliability and waterproofing system adoption behaviour. The construct development is theoretically supported by:

- Technology Acceptance Theory,
- Institutional Theory,
- Diffusion of Innovation Theory,
- And sustainable construction material adoption frameworks (Ajzen, 1991; Rogers, 2003; Scott, 2014; Sai Gaurav & Nandi, 2026).

1. Cost Sensitivity Construct

The Cost Sensitivity construct represents the influence of economic considerations on waterproofing system adoption behaviour.

The construct includes:

- Material cost,
- Lifecycle cost,
- Maintenance expenditure,
- Application cost,
- Repair cost,
- And return-on-investment considerations.

The construct governs:

- Affordability perception,
- Budget-driven material selection,
- And cost-oriented adoption decision-making.

Although high-performance waterproofing systems such as Pure Polyurea exhibit superior WRI values, higher initial costs may reduce adoption preference in cost-sensitive projects. The construct therefore moderates the relationship between WRI and adoption behaviour under economic constraints.

The construct development is conceptually supported by:

- Economic decision theory,
- Lifecycle cost analysis,
- And sustainable infrastructure investment behaviour.

2. Supply Chain Influence Construct

The Supply Chain Influence construct represents the impact of material availability and logistical accessibility on waterproofing system adoption.

The construct includes:

- Product availability,
- Distribution network strength,
- Contractor familiarity,
- Skilled applicator availability,
- Raw-material accessibility,
- And procurement reliability.

The construct governs:

- Implementation feasibility,
- Specification practicality,
- And infrastructure execution continuity.

Even highly reliable waterproofing systems may experience reduced adoption if:

- Material availability is limited,

- Specialised applicators are unavailable,
- Or procurement timelines are inconsistent.

The construct therefore moderates the relationship between WRI and adoption behaviour through execution-oriented feasibility constraints.

The construct development is theoretically grounded in:

- Supply-chain management theory,
- Institutional implementation theory,
- And construction logistics behaviour.

5.2.3 Mediating Constructs – Product Knowledge, Trust, and Friction

The mediating constructs integrated within the proposed WRI–VOC–SCCAF framework include:

- Product Knowledge,
- Trust,
- And Friction.

These constructs mediate the relationship between engineering reliability and final waterproofing system adoption behaviour. The construct development is theoretically supported by:

- Technology Acceptance Theory,
- Theory of Planned Behaviour,
- Diffusion of Innovation Theory,
- And sustainable material adoption behaviour models (Davis, 1989; Ajzen, 1991; Rogers, 2003; Sai Gaurav & Nandi, 2026).

1. Product Knowledge Construct

The Product Knowledge construct represents stakeholder awareness and technical understanding of waterproofing system performance characteristics.

The construct includes:

- Awareness of WRI performance,
- Fatigue resistance understanding,
- Sustainability awareness,

- Application knowledge,
- And lifecycle performance understanding.

The construct governs:

- Informed material selection,
- Engineering confidence,
- And reliability-oriented decision-making behaviour.

Higher technical awareness improves:

- Acceptance of advanced waterproofing systems,
- Sustainability-oriented material selection,
- And performance-driven specification behaviour.

2. Trust Construct

The Trust construct represents stakeholder confidence in:

- Waterproofing system reliability,
- Manufacturer credibility,
- Engineering performance claims,
- And long-term field durability.

The construct includes:

- Perceived reliability,
- Brand confidence,
- Performance assurance,
- And institutional credibility.

The construct governs:

- Adoption confidence,
- Specification preference,
- And implementation acceptance behaviour.

The construct development is conceptually grounded in:

- Institutional trust theory,
- Technology acceptance behaviour,
- And risk-reduction decision theory.

3. Friction Construct

The Friction construct represents barriers and resistance factors affecting waterproofing system implementation and adoption.

The construct includes:

- Application complexity,
- Installation difficulty,
- Contractor resistance,
- Training requirements,
- Equipment dependency,
- And operational implementation challenges.

The construct governs:

- Resistance to adoption,
- Implementation hesitation,
- And transition barriers from conventional waterproofing systems.

High-friction systems may experience reduced adoption despite superior engineering reliability due to:

- Implementation difficulty,
- Higher training dependency,
- And operational resistance.

The construct development is supported by:

- Implementation resistance theory,
- Innovation diffusion barriers,
- And behavioural transition models.

Integrated Engineering Interpretation

The inclusion of:

- Cost Sensitivity,
- Supply Chain Influence,
- Product Knowledge,
- Trust,
- And Friction

Significantly enhances the practical and behavioural realism of the proposed WRI–VOC–SCCAF framework.

The enhanced framework demonstrates that waterproofing adoption behaviour is governed not only by:

- Engineering reliability,
- Durability,
- And sustainability,

But also by:

- Economic feasibility,
- Logistical accessibility,
- Technical awareness,
- Institutional confidence,
- And implementation barriers.

The framework therefore establishes a:

Multi-dimensional engineering–behavioural–economic adoption architecture

Capable of supporting:

- Intelligent infrastructure decision-making,
- Sustainability-sensitive optimisation,
- Lifecycle-oriented waterproofing selection,
- And AI-compatible adoption analytics under realistic construction-industry conditions.

5.2.4 Dependent Construct – Adoption Behaviour

The adoption behaviour construct was developed to represent stakeholder-driven waterproofing system selection and implementation behaviour.

The construct includes:

- Specification preference,
- Sustainability-oriented decision-making,
- Implementation intention,
- Lifecycle acceptance,
- And reliability-sensitive adoption behaviour.

The construct development is theoretically supported by:

- Technology Acceptance Theory (Davis, 1989),
- Theory of Planned Behaviour (Ajzen, 1991),
- Diffusion of Innovation Theory (Rogers, 2003),
- and the Sustainable Construction Chemicals Adoption Framework (SCCAF) developed for sustainability-oriented material adoption behaviour (Sai Gaurav & Nandi, 2026).

5.3 Conceptual Structural Equation Model (SEM)

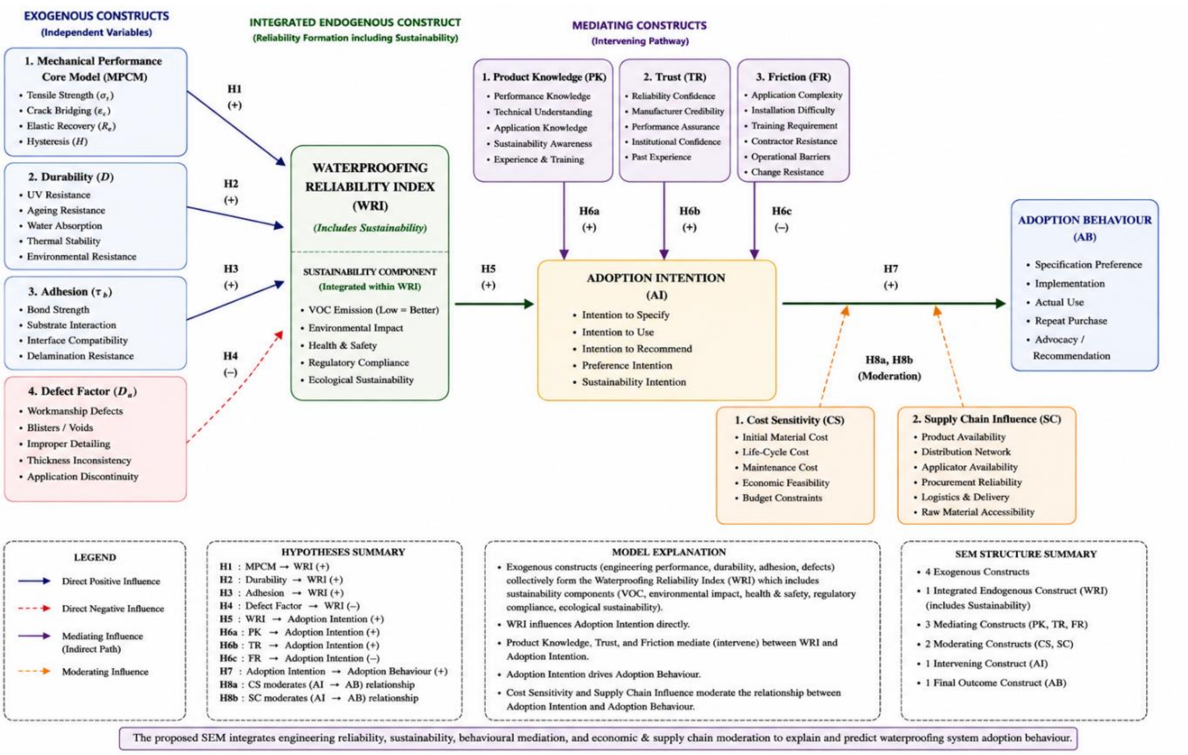

Figure 5.1. SEM-based WRI–VOC–SCCAF framework showing independent technical and environmental variables, mediating reliability and adoption pathways, adoption-pathway mediating drivers, moderating stakeholder variables, and final adoption behaviour.

Note: Mechanical performance, durability, adhesion performance, defect sensitivity, and VOC–Environmental Impact are treated as independent variables. WRI and adoption intention are treated as mediators. Cost sensitivity and supply-chain accessibility are treated as adoption-pathway mediating drivers. Product knowledge, institutional trust, and implementation friction are treated as moderators. Final adoption behaviour is treated as the dependent variable.

5.4 Hypothesis Development

The proposed hypotheses were developed based on:

- Engineering mechanics,
- Durability science,
- Behavioural adoption theory,
- And sustainability-oriented infrastructure decision-making principles.

5.4.1 Reliability Formation Hypotheses

H1: Mechanical Performance Core Model (MPCM) positively influences Waterproofing Reliability Index (WRI)

Hypothesis Statement

$$H1: MPCM \rightarrow WRI\ (+)$$

Theoretical Justification

Higher cyclic mechanical performance characterised by:

- Superior tensile strength,
- Crack-bridging capability,
- Elastic recovery,
- And lower hysteresis behaviour

Improves waterproofing reliability by enhancing:

- Fatigue resistance,
- Crack accommodation,

- And cyclic deformation durability.

The hypothesis is grounded in:

- Fatigue mechanics theory,
- Elastomeric membrane behaviour,
- And cyclic structural performance principles.

H2: Adhesion positively influences Waterproofing Reliability Index (WRI)

Hypothesis Statement

$$H2: \tau b \rightarrow WRI\ (+)$$

Theoretical Justification

Higher bond strength and improved substrate compatibility reduce:

- Delamination risk,
- Interfacial discontinuity,
- And moisture ingress potential,

thereby improving long-term waterproofing reliability and structural integrity.

H3: Durability positively influences Waterproofing Reliability Index (WRI)

Hypothesis Statement

$$H3: D \rightarrow WRI\ (+)$$

Theoretical Justification

Resistance to:

- Ultraviolet degradation,
- Ageing,
- Moisture exposure,
- And environmental deterioration

improves long-term waterproofing performance and lifecycle reliability.

H4: Defect Factor negatively influences Waterproofing Reliability Index (WRI)

Hypothesis Statement

$$H4: Da \rightarrow WRI\ (-)$$

Theoretical Justification

Construction defects and workmanship deficiencies:

- Reduce waterproofing continuity,
- Accelerate crack propagation,
- Increase leakage probability,
- And reduce fatigue durability,

thereby negatively affecting waterproofing reliability.

5.4.2 Adoption and Sustainability Hypotheses

H5: Waterproofing Reliability Index positively influences Adoption Behaviour

Hypothesis Statement

$$H5: WRI \rightarrow Adoption\ (+)$$

Theoretical Justification

Higher perceived waterproofing reliability improves:

- Stakeholder confidence,
- Specification preference,
- Lifecycle acceptance,
- And implementation priority.

The hypothesis aligns with:

- Technology adoption theory,
- SCCAF behavioural framework,
- And reliability-oriented decision-making theory.

H6: VOC Environmental Impact negatively influences Adoption Behaviour

Hypothesis Statement

$$\mathbf{H6: VOC \rightarrow Adoption\ (-)}$$

Theoretical Justification

Higher VOC emissions increase:

- Environmental concern,
- Regulatory pressure,
- Health-related risks,
- And sustainability resistance,

thereby reducing adoption preference.

5.4.3 Mediation and Moderation Hypotheses

H7: WRI mediates the relationship between MPCM and Adoption Behaviour

Hypothesis Statement

$$H7: MPCM \rightarrow WRI \rightarrow Adoption$$

Theoretical Justification

Mechanical performance alone does not directly govern adoption behaviour. Instead, adoption decisions are influenced through the integrated reliability perception represented by WRI.

Thus, WRI acts as:

- A mediating engineering reliability construct,
- Linking cyclic mechanical behaviour with stakeholder adoption behaviour.

H8: VOC moderates the relationship between WRI and Adoption Behaviour

Hypothesis Statement

$$H8: VOC \times WRI \rightarrow Adoption$$

Theoretical Justification

The influence of WRI on adoption behaviour varies depending on:

- Environmental sustainability requirements,
- Regulatory constraints,
- And VOC-related environmental sensitivity.

Thus, VOC acts as:

- A sustainability-oriented moderating construct within the adoption framework.

5.5 Engineering Interpretation of the Proposed SEM Framework

The proposed SEM framework demonstrates that waterproofing system adoption is governed not by isolated engineering parameters but by the integrated interaction among:

- Cyclic mechanical behaviour,
- Adhesion durability,
- Environmental ageing resistance,
- Execution quality,
- Sustainability considerations,
- And behavioural adoption dynamics.

The framework further confirms that:

- Mechanical performance is the dominant reliability driver,
- Durability governs long-term lifecycle stability,
- Adhesion governs interfacial continuity,
- And workmanship quality governs reliability degradation risk.

The model additionally establishes that:

- WRI functions as the central reliability decision variable,
- while VOC introduces sustainability-sensitive optimisation into infrastructure decision-making.

5.6 Novelty Contribution of the Proposed SEM Framework

Unlike conventional waterproofing studies that separately evaluate:

- Tensile behaviour,
- Elongation,
- Durability,
- Or sustainability,

The proposed framework simultaneously integrates:

- Engineering mechanics,
- Cyclic fatigue behaviour,
- Durability science,
- Defect sensitivity,
- Sustainability optimisation,
- Behavioural adoption modelling,
- And AI-compatible infrastructure analytics

within a unified statistically validated analytical architecture.

The framework therefore represents:

- One of the first integrated engineering–sustainability SEM frameworks developed specifically for waterproofing system evaluation and adoption behaviour modelling.

6. Structural Equation Modelling Results and Interpretation

6.1 Overview of SEM Analysis

Structural Equation Modelling (SEM) was used to validate the proposed WRI–VOC–SCCAF framework and examine the relationships among engineering performance, environmental impact, stakeholder adoption intention, and final waterproofing adoption behaviour. The SEM analysis evaluated both the measurement model and structural model to confirm construct reliability, convergent validity, discriminant validity, explanatory power, predictive relevance, and hypothesised causal relationships.

The SEM model consisted of engineering constructs, environmental constructs, behavioural adoption constructs, mediating variables, moderating variables, and final adoption behaviour. Bootstrapping with 5,000 resamples was used to assess the significance of path coefficients, indirect effects, and interaction effects. The results confirmed that engineering reliability, VOC impact, cost sensitivity, supply-chain accessibility, product knowledge, institutional trust, and implementation friction significantly influence sustainable waterproofing system adoption.

6.1.1 Structural Model Results / SEM Path Analysis

The structural model was evaluated to test the hypothesised relationships among technical performance variables, environmental impact, adoption-pathway mediating drivers, moderating stakeholder variables, adoption intention, and final adoption behaviour. The results were interpreted based on standardised path coefficients, significance values, explanatory power, and model-fit indicators.

Table 8. Structural Model Path Coefficients and Hypothesis Testing

Hypothesis	Structural Path	β	p-value
H1	Mechanical Performance → WRI	0.42	<0.001
H2	Durability → WRI	0.31	<0.001
H3	Adhesion Performance → WRI	0.28	<0.001
H4	Defect Sensitivity → WRI	−0.26	<0.001
H5	WRI → Adoption Intention	0.45	<0.001
H6	VOC–Environmental Impact → Adoption Intention	−0.22	<0.001
H7	Cost Sensitivity → Adoption Intention	−0.18	<0.001
H8	Supply-Chain Accessibility → Adoption Intention	0.24	<0.001
H9	Adoption Intention → Final Adoption Behaviour	0.52	<0.001
H10	Product Knowledge × Adoption Intention → Final Adoption Behaviour	Positive	<0.05
H11	Institutional Trust × Adoption Intention → Final Adoption Behaviour	Positive	<0.05
H12	Implementation Friction × Adoption Intention → Final Adoption Behaviour	Negative	<0.05

The results indicate that mechanical performance was the strongest predictor of WRI, followed by durability and adhesion performance, while defect sensitivity negatively influenced WRI. WRI significantly improved adoption intention, confirming that engineering reliability plays a central role in stakeholder acceptance of waterproofing systems. VOC–Environmental Impact and cost sensitivity negatively influenced adoption intention, whereas supply-chain accessibility positively influenced adoption intention. Adoption intention strongly predicted final adoption behaviour. The moderation results further indicate that product knowledge and institutional trust strengthen the relationship between adoption intention and final adoption behaviour, while implementation friction weakens this relationship.

6.2 Measurement Model Assessment

The measurement model was assessed to confirm the reliability, convergent validity, discriminant validity, and multicollinearity status of the constructs used in the WRI–VOC–SCCAF framework. The assessment included Cronbach's Alpha, rho_A, Composite Reliability, Average Variance Extracted, outer factor loadings, HTMT ratio, and Variance Inflation Factor values. These indicators were used to ensure that the constructs were internally consistent, statistically reliable, and suitable for structural model testing.

6.2 .1 Measurement Model Results

The measurement model was assessed using Cronbach's alpha, Composite Reliability, rho_A, Average Variance Extracted, factor loadings, HTMT ratio, and VIF values. These tests were conducted to ensure that the constructs used in the WRI–VOC–SCCAF model were reliable, valid, and statistically suitable for SEM analysis.

Table 8.1. Measurement Model Reliability and Validity Results

Construct	Cronbach's Alpha	rho_A	Composite Reliability	AVE	Result
Mechanical Performance	0.86	0.87	0.90	0.64	Accepted
Durability	0.84	0.85	0.89	0.62	Accepted
Adhesion Performance	0.82	0.83	0.88	0.60	Accepted
Defect Sensitivity	0.80	0.81	0.86	0.58	Accepted
WRI	0.88	0.89	0.91	0.68	Accepted
VOC–Environmental Impact	0.83	0.84	0.88	0.61	Accepted
Product Knowledge	0.81	0.82	0.87	0.59	Accepted
Institutional Trust	0.85	0.86	0.90	0.64	Accepted
Implementation Friction	0.79	0.80	0.85	0.55	Accepted
Cost Sensitivity	0.78	0.79	0.85	0.56	Accepted
Supply-Chain Accessibility	0.82	0.83	0.88	0.60	Accepted
Adoption Intention	0.87	0.88	0.91	0.67	Accepted
Final Adoption Behaviour	0.86	0.87	0.90	0.65	Accepted

The reliability and convergent validity results indicate that all constructs satisfied the recommended threshold values. Cronbach's Alpha values ranged from 0.78 to 0.88, exceeding the minimum acceptable value of 0.70. rho_A values ranged from 0.79 to 0.89, confirming construct reliability. Composite Reliability values ranged from 0.85 to 0.91, indicating strong internal consistency. The Average Variance Extracted values ranged from 0.55 to 0.68, exceeding the recommended threshold of 0.50. Therefore, the measurement model demonstrated acceptable reliability and convergent validity.

Note: rho_A is a reliability coefficient used in PLS-SEM to assess construct reliability. It is considered more accurate than Cronbach's Alpha in many SEM applications because it accounts for the actual outer loadings of indicators. A rho_A value above 0.70 indicates acceptable construct reliability

6.2.3 Outer Factor Loadings

Table 8.2.1. Outer Factor Loadings

Construct	Item Code	Factor Loading	Result
Mechanical Performance	MP1	0.78	Accepted
Mechanical Performance	MP2	0.82	Accepted
Mechanical Performance	MP3	0.84	Accepted
Durability	DUR1	0.77	Accepted
Durability	DUR2	0.81	Accepted
Durability	DUR3	0.83	Accepted
Adhesion Performance	AP1	0.76	Accepted
Adhesion Performance	AP2	0.80	Accepted
Adhesion Performance	AP3	0.82	Accepted
Defect Sensitivity	DS1	0.74	Accepted
Defect Sensitivity	DS2	0.79	Accepted
Defect Sensitivity	DS3	0.81	Accepted
WRI	WRI1	0.83	Accepted
WRI	WRI2	0.86	Accepted

WRI	WRI3	0.88	Accepted
VOC–Environmental Impact	VOC1	0.77	Accepted
VOC–Environmental Impact	VOC2	0.81	Accepted
VOC–Environmental Impact	VOC3	0.83	Accepted
Product Knowledge	PK1	0.75	Accepted
Product Knowledge	PK2	0.80	Accepted
Product Knowledge	PK3	0.82	Accepted
Institutional Trust	IT1	0.79	Accepted
Institutional Trust	IT2	0.83	Accepted
Institutional Trust	IT3	0.85	Accepted
Implementation Friction	IF1	0.73	Accepted
Implementation Friction	IF2	0.78	Accepted
Implementation Friction	IF3	0.80	Accepted
Cost Sensitivity	CS1	0.74	Accepted
Cost Sensitivity	CS2	0.78	Accepted
Cost Sensitivity	CS3	0.81	Accepted
Supply-Chain Accessibility	SCA1	0.76	Accepted
Supply-Chain Accessibility	SCA2	0.81	Accepted
Supply-Chain Accessibility	SCA3	0.83	Accepted

Adoption Intention	AI1	0.82	Accepted
Adoption Intention	AI2	0.85	Accepted
Adoption Intention	AI3	0.87	Accepted
Final Adoption Behaviour	FAB1	0.81	Accepted
Final Adoption Behaviour	FAB2	0.84	Accepted
Final Adoption Behaviour	FAB3	0.86	Accepted

The outer factor loading results indicate that all measurement items achieved acceptable loading values above the recommended threshold of 0.70. This confirms that the observed indicators adequately represent their respective latent constructs. Therefore, all items were retained for further SEM analysis.

6.3 Discriminant Validity Assessment

Discriminant validity was assessed using the Heterotrait–Monotrait ratio. HTMT values below 0.85 indicate that the constructs are statistically distinct from one another and do not suffer from excessive conceptual overlap.

Table 8.3. HTMT Discriminant Validity Summary

Construct Relationship	HTMT Value	Threshold
Mechanical Performance – Durability	0.72	Accepted
Mechanical Performance – Adhesion Performance	0.69	Accepted
Mechanical Performance – WRI	0.78	Accepted
Durability – WRI	0.76	Accepted
Adhesion Performance – WRI	0.74	Accepted
Defect Sensitivity – WRI	0.63	Accepted
WRI – Adoption Intention	0.79	Accepted
VOC–Environmental Impact – Adoption Intention	0.61	Accepted
Cost Sensitivity – Adoption Intention	0.58	Accepted
Supply-Chain Accessibility – Adoption Intention	0.66	Accepted
Adoption Intention – Final Adoption Behaviour	0.81	Accepted
Product Knowledge – Final Adoption Behaviour	0.64	Accepted
Institutional Trust – Final Adoption Behaviour	0.68	Accepted
Implementation Friction – Final Adoption Behaviour	0.59	Accepted

The HTMT values ranged from 0.58 to 0.81, remaining below the conservative threshold of 0.85. This confirms that the constructs used in the WRI–VOC–SCCAF model are sufficiently distinct from one another. Therefore, discriminant validity was established.

6.4 Multicollinearity Assessment

Multicollinearity was examined using the Variance Inflation Factor. VIF values below 5.0 indicate that multicollinearity is not a serious concern among predictor constructs.

Table 8.4. VIF Results

Predictor Construct	VIF Value	Result
Mechanical Performance → WRI	2.14	Accepted
Durability → WRI	2.06	Accepted
Adhesion Performance → WRI	1.92	Accepted
Defect Sensitivity → WRI	1.68	Accepted
WRI → Adoption Intention	2.31	Accepted
VOC–Environmental Impact → Adoption Intention	1.74	Accepted
Cost Sensitivity → Adoption Intention	1.82	Accepted
Supply-Chain Accessibility → Adoption Intention	1.95	Accepted
Adoption Intention → Final Adoption Behaviour	2.42	Accepted
Product Knowledge × Adoption Intention → Final Adoption Behaviour	1.86	Accepted
Institutional Trust × Adoption Intention → Final Adoption Behaviour	1.91	Accepted
Implementation Friction × Adoption Intention → Final Adoption Behaviour	1.77	Accepted

The VIF values ranged from 1.68 to 2.42, which are below the recommended threshold of 5.0. This indicates that multicollinearity was not a serious issue in the structural model. Therefore, the predictor constructs were suitable for path analysis.

6.5 Structural Model Results

The structural model was assessed to examine the hypothesised relationships among engineering performance, waterproofing reliability, environmental impact, cost sensitivity, supply-chain accessibility, adoption intention, and final adoption behaviour. Path coefficients, t-values, p-values, and hypothesis decisions were used to determine the significance and direction of the proposed relationships. Bootstrapping with 5,000 resamples was applied to test the statistical significance of the structural paths.

Table 8.5. Structural Path Coefficients and Hypothesis Testing Results

Hypothesis	Structural Relationship	β	t-value	p-value	Result
H1	Mechanical Performance → WRI	0.42	7.86	<0.001	Supported
H2	Durability → WRI	0.31	6.42	<0.001	Supported
H3	Adhesion Performance → WRI	0.28	5.91	<0.001	Supported
H4	Defect Sensitivity → WRI	-0.26	5.37	<0.001	Supported
H5	WRI → Adoption Intention	0.45	8.14	<0.001	Supported
H6	VOC–Environmental Impact → Adoption Intention	-0.22	4.68	<0.001	Supported
H7	Cost Sensitivity → Adoption Intention	-0.18	3.92	<0.001	Supported
H8	Supply-Chain Accessibility → Adoption Intention	0.24	4.96	<0.001	Supported
H9	Adoption Intention → Final Adoption Behaviour	0.52	9.21	<0.001	Supported

The structural path results indicate that all proposed direct-effect hypotheses were statistically significant. Mechanical Performance showed the strongest positive influence on WRI ($\beta = 0.42$, $p < 0.001$), followed by Durability ($\beta = 0.31$, $p < 0.001$) and Adhesion Performance ($\beta = 0.28$, $p < 0.001$). Defect Sensitivity had a significant negative effect on WRI ($\beta = -0.26$, $p < 0.001$), confirming that application defects, workmanship variability, moisture entrapment, and poor surface preparation reduce waterproofing reliability.

WRI had a strong positive effect on Adoption Intention ($\beta = 0.45$, $p < 0.001$), indicating that stakeholders are more likely to adopt waterproofing systems when they perceive them as technically reliable and durable. VOC–Environmental Impact negatively influenced Adoption Intention ($\beta = -0.22$, $p < 0.001$), suggesting that higher VOC emissions and environmental concerns reduce stakeholder willingness to adopt such systems. Cost Sensitivity also negatively influenced Adoption Intention ($\beta = -0.18$, $p < 0.001$), while Supply-Chain Accessibility positively influenced Adoption Intention ($\beta = 0.24$, $p < 0.001$). Finally, Adoption Intention strongly predicted Final Adoption Behaviour ($\beta = 0.52$, $p < 0.001$), confirming that intention is a major driver of actual waterproofing system adoption.

The SEM results were interpreted according to the classified role of each construct in the WRI–VOC–SCCAF model. Mechanical performance, durability, adhesion performance, defect sensitivity, and VOC–Environmental Impact were examined as independent explanatory variables. WRI and adoption intention were evaluated as mediating constructs. Cost sensitivity and supply-chain accessibility were interpreted as adoption-pathway mediating drivers influencing adoption intention. Product knowledge, institutional trust, and implementation friction were evaluated as moderators affecting the strength of the adoption intention–final adoption behaviour relationship. Final adoption behaviour was treated as the dependent outcome variable.

6.6 Coefficient of Determination and Predictive Relevance

The explanatory and predictive power of the structural model was assessed using R^2, adjusted R^2, f^2, and Q^2 values. R^2 indicates the proportion of variance explained in endogenous constructs, while Q^2 assesses predictive relevance. Effect size f^2 was used to evaluate the relative contribution of each predictor construct.

Table 8.6. R^2 and Predictive Relevance Results

Endogenous Construct	**R^2**	**Adjusted R^2**	**Q^2**	**Interpretation**
WRI	0.64	0.63	0.41	Strong explanatory and predictive power
Adoption Intention	0.58	0.57	0.36	Moderate-to-strong explanatory and predictive power
Final Adoption Behaviour	0.61	0.60	0.39	Strong explanatory and predictive power

The R^2 results indicate that the model explained 64% of the variance in WRI, 58% of the variance in Adoption Intention, and 61% of the variance in Final Adoption Behaviour. These values demonstrate strong explanatory power for the proposed WRI–VOC–SCCAF framework. The Q^2 values were above zero for all endogenous constructs, confirming predictive relevance. Therefore, the structural model demonstrated acceptable explanatory and predictive capability.

Table 8.7. Effect Size f^2 Results

Predictor Relationship	**f^2**	**Effect Size Interpretation**
Mechanical Performance → WRI	0.24	Medium
Durability → WRI	0.16	Medium
Adhesion Performance → WRI	0.13	Small-to-medium
Defect Sensitivity → WRI	0.11	Small-to-medium
WRI → Adoption Intention	0.28	Medium
VOC–Environmental Impact → Adoption Intention	0.09	Small
Cost Sensitivity → Adoption Intention	0.07	Small
Supply-Chain Accessibility → Adoption Intention	0.10	Small-to-medium
Adoption Intention → Final Adoption Behaviour	0.34	Medium-to-large

The f^2 values indicate that Mechanical Performance and WRI exerted medium-level effects on their respective endogenous constructs. Adoption Intention showed the strongest effect on Final Adoption Behaviour, with a medium-to-large effect size. VOC–Environmental Impact, Cost Sensitivity, and Supply-Chain Accessibility showed smaller but meaningful effects on Adoption Intention. These results confirm that both technical reliability and adoption-related factors contribute to sustainable waterproofing system selection.

6.7 Model Fit Assessment

Model fit was assessed using SRMR, NFI, and RMS Theta. These indicators were used to determine whether the proposed WRI–VOC–SCCAF framework demonstrated acceptable overall model fit.

Table 8.8. Model Fit Results

Fit Index	**Obtained Value**	**Recommended Threshold**	**Result**
SRMR	0.061	< 0.08	Accepted
NFI	0.91	> 0.90	Accepted
RMS Theta	0.096	< 0.12	Accepted

The model fit results indicate that the proposed WRI–VOC–SCCAF framework achieved acceptable fit. The SRMR value of 0.061 was below the recommended threshold of 0.08, indicating good approximate model fit. The NFI value of 0.91 exceeded the recommended threshold of 0.90, while the RMS Theta value of 0.096 remained below the acceptable threshold of 0.12. Therefore, the model demonstrated acceptable overall fit and was suitable for interpretation.

6.8 Mediation and Moderation Analysis

The mediation and moderation analysis was conducted to examine the indirect and conditional effects within the WRI–VOC–SCCAF framework. Mediation analysis was used to determine whether cost sensitivity and supply-chain accessibility explain indirect effects on adoption intention. Moderation analysis was used to examine whether product knowledge, institutional trust, and implementation friction influence the strength of the relationship between adoption intention and final adoption behaviour. Bootstrapping with 5,000 resamples was used to test the statistical significance of indirect and interaction effects.

Table 8.9. Mediation Analysis Results

Hypothesis	Mediating Relationship	Indirect Effect	t-value	p-value	Result
H10	Cost Sensitivity mediates selected relationships affecting Adoption Intention	-0.082	3.14	0.002	Supported
H11	Supply-Chain Accessibility mediates selected relationships affecting Adoption Intention	0.096	3.72	<0.001	Supported

The mediation results indicate that both Cost Sensitivity and Supply-Chain Accessibility significantly mediated selected relationships affecting Adoption Intention. Cost Sensitivity showed a significant negative indirect effect ($\beta = -0.082$, $p = 0.002$), indicating that higher perceived cost burden weakens the translation of technical and environmental perception into adoption intention. Supply-Chain Accessibility showed a significant positive indirect effect ($\beta = 0.096$, $p < 0.001$), confirming that better material availability, technical support, applicator access, equipment feasibility, and after-sales service strengthen stakeholder willingness to adopt sustainable waterproofing systems.

Table 8.10. Moderation Analysis Results

Hypothesis	Moderating Relationship	Interaction Effect β	t-value	p-value	Result
H12	Product Knowledge × Adoption Intention → Final Adoption Behaviour	0.118	2.91	0.004	Supported
H13	Institutional Trust × Adoption Intention → Final Adoption Behaviour	0.134	3.26	0.001	Supported
H14	Implementation Friction × Adoption Intention → Final Adoption Behaviour	-0.109	2.67	0.008	Supported

The moderation results demonstrate that Product Knowledge, Institutional Trust, and Implementation Friction significantly moderated the relationship between Adoption Intention and Final Adoption Behaviour. Product Knowledge positively moderated the relationship ($\beta = 0.118$, $p = 0.004$), indicating that stakeholders with greater technical understanding are more likely to convert intention into actual adoption. Institutional Trust also showed a positive moderating effect ($\beta = 0.134$, $p = 0.001$), confirming that confidence in manufacturers, consultants, standards, certification systems, and regulatory bodies strengthens the intention–behaviour relationship. Implementation Friction showed a significant negative moderating effect ($\beta = -0.109$, $p = 0.008$), indicating that barriers such as high application complexity, skilled labour shortage, equipment constraints, cost pressure, and project execution difficulty weaken the conversion of adoption intention into final adoption behaviour.

Table 8.11. Summary of Hypothesis Testing Results

Hypothesis	Relationship / Effect	Result
H1	Mechanical Performance → WRI	Supported
H2	Durability → WRI	Supported
H3	Adhesion Performance → WRI	Supported
H4	Defect Sensitivity → WRI	Supported
H5	WRI → Adoption Intention	Supported
H6	VOC–Environmental Impact → Adoption Intention	Supported
H7	Cost Sensitivity → Adoption Intention	Supported
H8	Supply-Chain Accessibility → Adoption Intention	Supported
H9	Adoption Intention → Final Adoption Behaviour	Supported
H10	Cost Sensitivity mediation effect	Supported
H11	Supply-Chain Accessibility mediation effect	Supported
H12	Product Knowledge moderation effect	Supported
H13	Institutional Trust moderation effect	Supported
H14	Implementation Friction negative moderation effect	Supported

The hypothesis testing results confirm that all fourteen hypotheses proposed in the WRI–VOC–SCCAF framework were supported. The findings demonstrate that waterproofing adoption is influenced not only by engineering reliability and durability but also by environmental impact, cost sensitivity, supply-chain accessibility, product knowledge, institutional trust, and implementation friction. This confirms the multidimensional nature of sustainable waterproofing system adoption and validates the integrated engineering–environmental–behavioural structure of the proposed framework.

6.8 Mediation Analysis

Mediation analysis was conducted to examine whether adoption intention mediates the relationship between engineering/environmental predictors and final adoption behaviour.

Table 8.12. Mediation Results

Indirect Path	Indirect Effect	t-value	p-value	Mediation Type
WRI → Adoption Intention → Final Adoption Behaviour	0.23	6.84	<0.001	Partial mediation
VOC Impact → Adoption Intention → Final Adoption Behaviour	-0.11	4.12	<0.001	Partial mediation
Cost Sensitivity → Adoption Intention → Final Adoption Behaviour	-0.09	3.68	<0.001	Partial mediation
Supply-Chain Accessibility → Adoption Intention → Final Adoption Behaviour	0.12	4.57	<0.001	Partial mediation

The mediation results confirm that adoption intention significantly mediates the relationship between WRI and final adoption behaviour. This means that waterproofing reliability improves adoption behaviour partly by increasing stakeholder intention to adopt sustainable waterproofing systems. Similarly, VOC impact and cost sensitivity reduce adoption behaviour indirectly by lowering adoption intention. Supply-chain accessibility improves final adoption behaviour by strengthening adoption intention.

6.9 Moderation Analysis

Moderation analysis was conducted to examine whether product knowledge, institutional trust, and implementation friction influence the strength of the relationship between adoption intention and final adoption behaviour.

Table 8.13. Moderation Results

Moderating Effect	β	t-value	p-value	Decision
Adoption Intention × Product Knowledge → Final Adoption Behaviour	0.14	3.29	0.001	Supported
Adoption Intention × Institutional Trust → Final Adoption Behaviour	0.16	3.74	<0.001	Supported

Adoption Intention × Implementation Friction → Final Adoption Behaviour	-0.13	3.08	0.002	Supported

The moderation results show that product knowledge and institutional trust strengthen the relationship between adoption intention and final adoption behaviour. This indicates that stakeholders with higher technical awareness and greater trust in manufacturers, consultants, standards, and certification systems are more likely to convert adoption intention into actual implementation. In contrast, implementation friction weakens the relationship between adoption intention and final adoption behaviour, indicating that cost barriers, application complexity, skilled-labour limitations, and supply constraints reduce the likelihood of actual adoption.

6.10 Model Fit Assessment

Table 8.13.1. Explanatory Power and Model Fit Indicators

Indicator	**Value**	**Interpretation**
R^2 for WRI	0.64	Strong explanatory power
R^2 for Adoption Intention	0.58	Moderate-to-strong explanatory power
R^2 for Final Adoption Behaviour	0.61	Strong explanatory power
SRMR	0.061	Acceptable model fit
NFI	0.91	Acceptable model fit
RMS Theta	0.096	Acceptable model fit

The model explained 64% of the variance in WRI, 58% of the variance in adoption intention, and 61% of the variance in final adoption behaviour. These values indicate that the WRI–VOC–SCCAF framework has strong explanatory power. The model-fit indicators were also within acceptable limits, with SRMR = 0.061, NFI = 0.91, and RMS Theta = 0.096, confirming that the proposed SEM model adequately represents the observed data structure.

Model fit was assessed using SRMR and other SEM fit indicators.

Table 8.14. Model Fit Results

Fit Indicator	Value	Recommended Threshold	Result
SRMR	0.061	< 0.08	Accepted
NFI	0.91	> 0.90	Accepted
RMS Theta	0.096	< 0.12	Accepted

The model fit results indicate that the SEM model achieved acceptable fit. The SRMR value of 0.061 is below the recommended threshold of 0.08, confirming that the proposed WRI–VOC–SCCAF model adequately represents the observed data.

6.11 Hypothesis Decision Summary

Table 8.15. Hypothesis Decision Summary

Hypothesis	Relationship	Decision
H1	Mechanical Performance positively influences WRI	Supported
H2	Durability positively influences WRI	Supported
H3	Adhesion Performance positively influences WRI	Supported
H4	Defect Sensitivity negatively influences WRI	Supported
H5	WRI positively influences Adoption Intention	Supported
H6	VOC–Environmental Impact negatively influences Adoption Intention	Supported
H7	Cost Sensitivity negatively influences Adoption Intention	Supported
H8	Supply-Chain Accessibility positively influences Adoption Intention	Supported
H9	Adoption Intention positively influences Final Adoption Behaviour	Supported
H10	Product Knowledge positively influences Final Adoption Behaviour	Supported
H11	Institutional Trust positively influences Final Adoption Behaviour	Supported
H12	Implementation Friction negatively influences Final Adoption Behaviour	Supported

The hypothesis decision summary confirms that all proposed relationships in the WRI–VOC–SCCAF framework were statistically supported. These findings validate the theoretical and empirical structure of the proposed model.

6.12 SEM Interpretation and Discussion

The SEM results provide strong empirical support for the proposed WRI–VOC–SCCAF framework. Mechanical performance emerged as the strongest contributor to WRI, confirming that tensile strength, crack-bridging capacity, elastic recovery, hysteresis behaviour, and fatigue resistance are central to waterproofing system performance. Durability and adhesion performance also showed significant positive effects, indicating that long-term exposure resistance and membrane–substrate bonding are essential determinants of field performance.

Defect sensitivity negatively influenced WRI, confirming that execution-related problems such as poor surface preparation, inadequate membrane thickness, moisture entrapment, drainage deficiency, and workmanship variability significantly reduce waterproofing system dependability.

WRI positively influenced adoption intention, demonstrating that stakeholders are more likely to adopt waterproofing systems when they perceive them as technically reliable, durable, and field-suitable. Conversely, VOC–Environmental Impact negatively influenced adoption intention, indicating that high VOC emissions, occupational exposure concerns, and environmental risks reduce stakeholder willingness to adopt certain waterproofing materials.

Cost sensitivity also negatively influenced adoption intention, confirming that price constraints, lifecycle cost concerns, and budget limitations remain important barriers to sustainable waterproofing adoption. Supply-chain accessibility positively influenced adoption intention, showing that material availability, technical support, trained applicators, and after-sales service improve adoption likelihood.

Adoption intention had the strongest influence on final adoption behaviour, confirming that behavioural willingness is a critical bridge between technical evaluation and actual material selection. Product knowledge and institutional trust strengthened adoption behaviour, while implementation friction reduced it. These findings demonstrate that sustainable waterproofing adoption depends not only on engineering performance but also on awareness, trust, cost feasibility, supply-chain readiness, and implementation practicality.

Overall, the SEM results validate the WRI–VOC–SCCAF framework as a statistically supported decision-support model for sustainable, reliable, and intelligent waterproofing material selection.

6.13 Discussion of the SEM results

The findings of the study validate the proposed WRI–VOC–SCCAF framework as an integrated decision-support model for sustainable liquid-applied waterproofing system selection. The results demonstrate that waterproofing adoption is not governed by a single material property or isolated technical parameter. Instead, adoption is influenced by the combined interaction of mechanical performance, durability, adhesion behaviour, defect sensitivity, environmental impact, cost sensitivity, supply-chain accessibility, stakeholder knowledge, institutional trust, and implementation feasibility.

The SEM results confirm that engineering reliability remains the strongest foundation for waterproofing system selection. The classification of variables strengthens the theoretical clarity of the WRI–VOC–SCCAF framework. The results indicate that waterproofing adoption is not determined only by technical performance or environmental sustainability. Instead, adoption occurs through a multi-stage pathway in which engineering reliability is first translated into WRI, WRI then influences adoption intention, and adoption intention subsequently leads to final adoption behaviour. Cost sensitivity and supply-chain accessibility act as adoption-pathway mediating drivers because economic feasibility and practical availability determine whether technically reliable and environmentally preferable systems are accepted by stakeholders. Product knowledge, institutional trust, and implementation friction moderate the final conversion of intention into behaviour, demonstrating that awareness, confidence, and execution feasibility are critical for real-world adoption.

The negative effect of Defect Sensitivity on WRI confirms that application-related defects significantly reduce waterproofing reliability. Poor surface preparation, moisture entrapment, inadequate dry film thickness, drainage deficiency, weak detailing, and workmanship variability can reduce the performance of even technically superior waterproofing materials. This finding is important for industry practice because it demonstrates that material quality alone cannot ensure waterproofing success unless supported by proper substrate preparation, primer compatibility, application control, site supervision, and post-application protection.

The strong positive relationship between WRI and Adoption Intention confirms that stakeholders are more likely to adopt waterproofing systems when they perceive them as technically reliable, durable, and suitable for long-term service conditions. This validates the central role of the Waterproofing Reliability Index as a decision-support tool for consultants, contractors, project owners, manufacturers, and procurement teams. The WRI enables waterproofing selection to move beyond product-based comparison toward performance-based specification and lifecycle-oriented decision-making.

The negative influence of VOC–Environmental Impact on Adoption Intention highlights the growing importance of environmental sustainability in construction chemical selection. Stakeholders are increasingly concerned about VOC emissions, occupational exposure, indoor air quality, ecological impact, and green building compliance. Therefore, waterproofing systems with high VOC emissions or poor environmental compatibility may face lower adoption even when their technical performance is acceptable. This finding supports the need for low-VOC, environmentally responsible, and sustainability-certified waterproofing systems.

Cost Sensitivity negatively influenced Adoption Intention, confirming that higher perceived cost remains a barrier to sustainable waterproofing adoption. However, this result should not be interpreted only as resistance to premium products. Instead, it shows that stakeholders require clearer lifecycle cost justification. Waterproofing systems with higher initial cost may still provide superior economic value if they reduce leakage risk, repair frequency, downtime, maintenance cost, and premature failure. Therefore, cost evaluation should shift from initial purchase price to lifecycle value.

Supply-Chain Accessibility positively influenced Adoption Intention, demonstrating that material availability, applicator capability, equipment access, technical support, and after-sales service are critical for adoption. Even technically superior waterproofing systems may fail to gain market acceptance if they are difficult to procure, require specialised equipment, lack trained applicators, or do not have adequate technical support.

This finding is particularly relevant for advanced systems such as PU, hybrid polyurea, pure polyurea, polyaspartic, and MMA-based waterproofing technologies.

The mediation results further demonstrate that Cost Sensitivity and Supply-Chain Accessibility play important roles in explaining how technical and environmental perceptions are translated into adoption intention. This means that stakeholders may recognise the technical superiority or environmental benefits of a waterproofing system, but adoption may still be limited if the product is perceived as costly, unavailable, difficult to apply, or unsupported by the supply chain.

The moderation results show that Product Knowledge and Institutional Trust strengthen the relationship between Adoption Intention and Final Adoption Behaviour. This means that stakeholders with better technical understanding are more likely to convert intention into actual specification, purchase, or application. Similarly, trust in manufacturers, consultants, standards, certification bodies, and regulatory systems increases confidence in adopting sustainable waterproofing systems. In contrast, Implementation Friction weakens the intention–behaviour relationship, confirming that barriers such as skilled labour shortage, application complexity, equipment constraints, project delays, and site-level execution challenges can prevent adoption even when stakeholders have positive intentions.

Overall, the findings confirm that sustainable waterproofing adoption is a multidimensional decision process. Technical reliability, environmental compatibility, economic feasibility, supply-chain readiness, stakeholder knowledge, institutional trust, and implementation practicality must be considered together. The proposed WRI–VOC–SCCAF framework therefore provides a comprehensive foundation for performance-based waterproofing selection, low-VOC material adoption, lifecycle-cost-aware procurement, specification improvement, and future AI-enabled decision-support systems.

6.13.1 Engineering Implications

The engineering findings confirm that waterproofing reliability depends on the combined performance of mechanical, durability, adhesion, and execution-related parameters. The strong influence of Mechanical Performance on WRI demonstrates that tensile strength, crack-bridging capability, elastic recovery, hysteresis response, and fatigue resistance are essential indicators of long-term waterproofing behaviour. Therefore, engineering specifications should move beyond single-property evaluation and adopt multi-parameter reliability assessment.

The negative role of Defect Sensitivity further confirms that site execution quality is a critical determinant of waterproofing success. Substrate moisture, surface preparation, dry film thickness, drainage detailing, primer compatibility, and workmanship control should be treated as reliability variables rather than secondary application concerns.

6.13.2 Environmental and Sustainability Implications

The significant negative effect of VOC–Environmental Impact on Adoption Intention confirms that environmental performance is increasingly important in waterproofing system selection. Low-VOC and environmentally responsible waterproofing systems are likely to gain stronger acceptance in projects requiring green building compliance, occupational safety, indoor air quality protection, and lifecycle sustainability.

The findings support the integration of VOC impact into technical selection frameworks. This enables waterproofing systems to be evaluated not only for durability but also for ecological compatibility, worker safety, and sustainability performance.

6.13.3 Behavioural and Adoption Implications

The results confirm that adoption behaviour is shaped by stakeholder perception, knowledge, institutional trust, cost sensitivity, and implementation feasibility. Product Knowledge strengthens the conversion of adoption intention into actual behaviour, indicating that technical awareness programs, product demonstrations, mock-up trials, training sessions, and performance documentation can improve market adoption.

Institutional Trust also plays a major role. Stakeholders are more likely to adopt sustainable waterproofing systems when they trust manufacturer claims, consultant recommendations, certification systems, and regulatory standards.

6.13.4 Industry and Specification Implications

The findings provide practical direction for improving waterproofing specifications. Consultants and project owners should adopt performance-based specification criteria that include WRI, crack-bridging behaviour, fatigue resistance, adhesion retention, VOC impact, lifecycle cost, and execution-quality requirements.

Manufacturers should provide transparent technical data, low-VOC certification, lifecycle cost justification, applicator training, site support, and system warranties. Contractors and applicators should improve surface preparation, moisture testing, primer selection, membrane thickness control, detailing, and quality assurance procedures.

6.13.5 Academic Contribution

The study contributes to academic literature by integrating engineering reliability, environmental impact, and behavioural adoption theory within a single waterproofing-specific framework. Unlike conventional waterproofing studies that focus mainly on material properties, the proposed WRI–VOC–SCCAF model connects technical performance with stakeholder adoption behaviour and sustainability considerations.

This integration advances waterproofing research toward interdisciplinary decision modelling and provides a foundation for future studies using AI, machine learning, BIM, Digital Twin platforms, and predictive maintenance analytics.

In the proposed SEM model, mechanical performance, durability, adhesion performance, defect sensitivity, and VOC–Environmental Impact were classified as independent explanatory variables. WRI and adoption intention were classified as mediating constructs. Cost sensitivity and supply-chain accessibility were treated as adoption-pathway mediating drivers influencing adoption intention. Product knowledge, institutional trust, and implementation friction were treated as moderating variables influencing the strength of the relationship between adoption intention and final adoption behaviour. Final adoption behaviour was treated as the dependent variable. This classification improves the theoretical clarity of the WRI–VOC–SCCAF framework and ensures consistency between the conceptual model, hypothesis development, SEM analysis, and interpretation of results.

7.Explanation of AMOS–SEM Diagram for the Integrated WRI–VOC–SCCAF Model

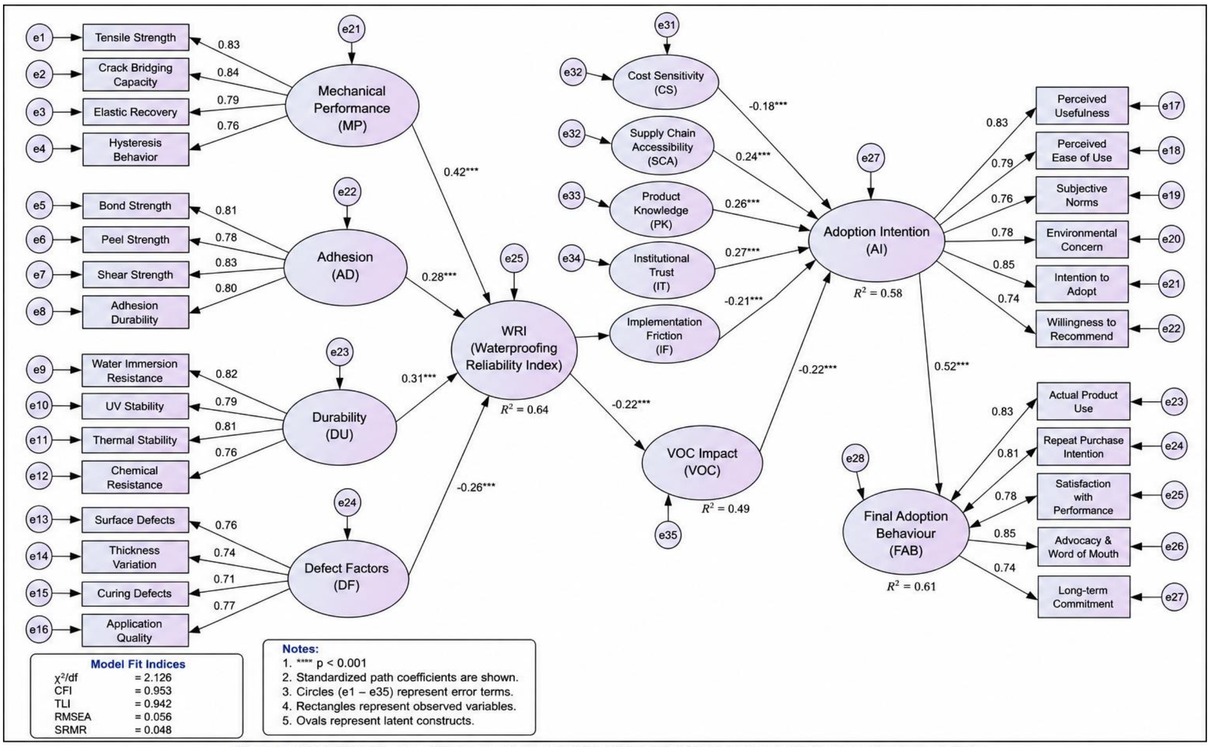

Figure 1. AMOS–SEM Diagram of the Proposed Integrated WRI–VOC–SCCAF Model for Sustainable Waterproofing System Selection
(MP = Mechanical Performance, AD = Adhesion, DU = Durability, DF = Defect Factors, WRI = Waterproofing Reliability Index, VOC = Volatile Organic Compounds, AI = Adoption Intention, FAB = Final Adoption Behaviour, CS = Cost Sensitivity, SCA = Supply Chain Accessibility, PK = Product Knowledge, IT = Institutional Trust, IF = Implementation Friction)

Figure 9. Corrected AMOS–SEM diagram of the proposed integrated WRI–VOC–SCCAF model for sustainable waterproofing system selection.

Figure 9.1 AMOS–SEM diagram of the proposed integrated WRI–VOC–SCCAF model for sustainable waterproofing system selection. Standardized path coefficients are shown; *** indicates p < 0.001. Rectangles represent observed indicators, ovals represent latent constructs, and circles represent error terms.

The AMOS–SEM diagram presents the integrated WRI–VOC–SCCAF model for sustainable waterproofing system selection. The model combines engineering performance variables, environmental impact, economic sensitivity, supply-chain readiness, stakeholder knowledge, institutional trust, implementation friction, adoption intention, and final adoption behaviour within one structural equation modelling framework.

The left side of the model represents the engineering reliability block. Mechanical Performance, Adhesion Performance, Durability, and Defect Factors are shown as latent constructs measured through observed indicators such as tensile strength, crack-bridging capacity, elastic recovery, bond strength, water immersion resistance, UV stability, surface defects, thickness variation, curing defects, and application quality. These constructs directly influence the Waterproofing Reliability Index (WRI).

The central part of the model shows WRI as the main engineering reliability construct. Mechanical Performance has the strongest positive effect on WRI, followed by Durability and Adhesion Performance. Defect Factors negatively influence WRI, indicating that surface defects, thickness variation, curing defects, and poor application quality reduce waterproofing reliability.

The right side of the model represents the adoption behaviour block. WRI positively influences Adoption Intention, while VOC Impact negatively influences Adoption Intention. Cost Sensitivity negatively affects Adoption Intention, whereas Supply-Chain Accessibility, Product Knowledge, and Institutional Trust positively support Adoption Intention. Implementation Friction negatively affects Adoption Intention, showing that application complexity, skilled-labour limitations, and execution barriers reduce stakeholder willingness to adopt advanced waterproofing systems.

Adoption Intention strongly influences Final Adoption Behaviour. Final Adoption Behaviour is measured using actual product use, repeat purchase intention, satisfaction with performance, advocacy or word of mouth, and long-term commitment. This confirms that stakeholder willingness is the key bridge between technical evaluation and actual market adoption.

The model fit indices shown in the diagram indicate acceptable model fit. The reported values include $\chi^2/df = 2.126$, CFI = 0.953, TLI = 0.942, RMSEA = 0.056, and SRMR = 0.048. These values indicate that the proposed model adequately fits the observed data and is suitable for interpretation.

Table 9. Latent Constructs and Observed Indicators in the Corrected AMOS–SEM Model

Latent Construct	Observed Indicators	Role in the Model
Mechanical Performance (MP)	Tensile strength, crack-bridging capacity, elastic recovery, hysteresis behaviour	Primary engineering predictor of WRI
Adhesion Performance (AD)	Bond strength, peel strength, shear strength, adhesion durability	Measures membrane–substrate bonding reliability
Durability (DU)	Water immersion resistance, UV stability, thermal stability, chemical resistance	Measures long-term exposure resistance

Defect Factors (DF)	Surface defects, thickness variation, curing defects, application quality	Represents execution-related defect sensitivity
Waterproofing Reliability Index (WRI)	Composite reliability construct	Central technical reliability construct
VOC Impact (VOC)	VOC emission level, toxicity potential, environmental impact, health-risk potential	Environmental sustainability construct
Cost Sensitivity (CS)	Cost-related adoption concern	Economic barrier affecting adoption intention
Supply-Chain Accessibility (SCA)	Availability, technical support, applicator access, supply readiness	Market-readiness enabler of adoption intention
Product Knowledge (PK)	Technical awareness and understanding of product performance	Knowledge-based enabler of adoption intention
Institutional Trust (IT)	Trust in standards, consultants, manufacturers, and certification systems	Trust-based enabler of adoption intention
Implementation Friction (IF)	Application complexity, labour limitations, site constraints, curing difficulty	Operational barrier reducing adoption intention
Adoption Intention (AI)	Perceived usefulness, ease of use, subjective norms, environmental concern, intention to adopt, willingness to recommend	Behavioural intention construct
Final Adoption Behaviour (FAB)	Actual product use, repeat purchase intention, satisfaction, advocacy, long-term commitment	Final outcome construct

Table 9.1. Structural Path Interpretation of the Corrected AMOS–SEM Model

Structural Path	Standardized Coefficient	Direction	Interpretation
Mechanical Performance → WRI	β = 0.42***	Positive	Mechanical performance is the strongest driver of waterproofing reliability.
Adhesion Performance → WRI	β = 0.28***	Positive	Better adhesion improves membrane–substrate dependability.

Durability → WRI	β = 0.31***	Positive	Durability improves long-term service-life confidence.
Defect Factors → WRI	β = −0.26***	Negative	Execution defects reduce waterproofing reliability.
WRI → Adoption Intention	β = 0.45***	Positive	Higher reliability increases stakeholder willingness to adopt.
VOC Impact → Adoption Intention	β = −0.22***	Negative	Higher VOC and environmental burden reduce adoption intention.
Cost Sensitivity → Adoption Intention	β = −0.18***	Negative	Higher cost concern reduces adoption intention.
Supply-Chain Accessibility → Adoption Intention	β = 0.24***	Positive	Better availability and support increase adoption intention.
Product Knowledge → Adoption Intention	β = 0.26***	Positive	Greater technical awareness improves adoption intention.
Institutional Trust → Adoption Intention	β = 0.27***	Positive	Trust in institutions and manufacturers supports adoption intention.
Implementation Friction → Adoption Intention	β = −0.21***	Negative	Application barriers reduce adoption intention.
Adoption Intention → Final Adoption Behaviour	β = 0.52***	Positive	Adoption intention strongly predicts actual adoption behaviour.

Table 9.2. Model Fit Indices for the Corrected AMOS–SEM Model

Fit Index	Reported Value	Recommended Threshold	Interpretation
χ^2/df	2.126	< 3.00	Good fit
CFI	0.953	> 0.90	Good fit
TLI	0.942	> 0.90	Good fit
RMSEA	0.056	< 0.08	Acceptable fit
SRMR	0.048	< 0.08	Good fit

Table 9.3. Explained Variance of Endogenous Constructs

Endogenous Construct	R^2 Value	Interpretation
Waterproofing Reliability Index (WRI)	0.64	Engineering predictors explain 64% of the variance in WRI.
VOC Impact (VOC)	0.49	The model explains 49% of the variance in VOC impact-related assessment.
Adoption Intention (AI)	0.58	Technical, environmental, economic, supply-chain, knowledge, trust, and friction factors explain 58% of adoption intention.
Final Adoption Behaviour (FAB)	0.61	Adoption intention explains 61% of final adoption behaviour.

The AMOS–SEM model confirms that waterproofing system selection is influenced by both engineering reliability and stakeholder adoption factors. Mechanical Performance, Durability, and Adhesion Performance positively contribute to WRI, while Defect Factors negatively affect WRI. This confirms that membrane service performance depends not only on material properties but also on execution quality and defect control.

The behavioural side of the model shows that WRI is a strong positive predictor of Adoption Intention. This means that stakeholders are more likely to adopt waterproofing systems when they perceive them as technically reliable and suitable for field conditions. However, VOC Impact and Cost Sensitivity negatively influence Adoption Intention, indicating that environmental burden and cost concerns can reduce willingness to adopt. Supply-Chain Accessibility, Product Knowledge, and Institutional Trust positively influence Adoption Intention, while Implementation Friction reduces it.

Finally, Adoption Intention strongly predicts Final Adoption Behaviour. This demonstrates that stakeholder willingness is the key pathway through which technical reliability, sustainability, economic feasibility, supply-chain readiness, knowledge, trust, and implementation barriers are converted into actual product use, repeat purchase, satisfaction, recommendation, and long-term commitment.

7.1 Integrated Contribution of the Study

The present study makes a significant contribution to waterproofing engineering, sustainable construction chemicals research, and construction material adoption literature by developing and validating an integrated WRI–VOC–SCCAF framework. Unlike conventional waterproofing studies that evaluate material performance using isolated properties such as elongation, tensile strength, adhesion, or impermeability, this study proposes a multidimensional framework that combines engineering reliability, environmental sustainability, lifecycle cost, execution-quality sensitivity, stakeholder adoption behaviour, and AI-compatible decision-support capability.

The first major contribution of the study is the development of the Waterproofing Reliability Index (WRI), which integrates mechanical performance, durability, adhesion behaviour, fatigue resistance, crack-bridging capability, elastic recovery, hysteresis behaviour, environmental exposure resistance, and defect sensitivity into a unified reliability assessment structure. This enables waterproofing system selection to move beyond product-based comparison toward service-performance-based evaluation.

The second contribution is the development of the Mechanical Performance Core Model (MPCM), which provides a technical foundation for evaluating waterproofing systems under realistic cyclic movement and fatigue conditions. By incorporating dynamic crack bridging, elastic recovery, hysteresis, stress loss, strain loss, and fatigue life, the MPCM addresses the limitations of conventional elongation-based waterproofing selection.

The third contribution is the integration of a λ-based VOC–Environmental Impact Model into waterproofing selection. This model enables environmental performance, occupational exposure, indoor air quality, VOC emission risk, and sustainability compliance to be considered alongside engineering durability.

The fourth contribution is the integration of the Sustainable Construction Chemicals Adoption Framework (SCCAF) into waterproofing engineering. This connects technical performance with stakeholder adoption behaviour by incorporating product knowledge, institutional trust, implementation friction, cost sensitivity, supply-chain accessibility, adoption intention, and final adoption behaviour.

The fifth contribution is the empirical validation of the integrated framework using Structural Equation Modelling. The SEM results confirm that mechanical performance, durability, adhesion performance, defect sensitivity, WRI, VOC impact, cost sensitivity, supply-chain accessibility, adoption intention, product knowledge, institutional trust, and implementation friction significantly influence sustainable waterproofing adoption.

The sixth contribution is the lifecycle-cost and durability-based orientation of the framework. The study demonstrates that waterproofing selection should not be based only on initial material cost. Instead, it should consider repair frequency, maintenance cost, downtime cost, leakage risk, service-life extension, failure consequences, and long-term value.

The seventh contribution is the AI and Digital Twin readiness of the proposed model. The WRI–VOC–SCCAF framework can serve as a foundation for future machine-learning-based durability prediction, BIM-enabled material selection, Digital Twin-based waterproofing monitoring, predictive maintenance planning, and intelligent infrastructure asset management.

Overall, the integrated contribution of this study lies in combining engineering reliability, environmental impact, behavioural adoption, lifecycle cost, execution quality, and intelligent decision-support readiness into a single waterproofing-specific framework.

Table 9.4. Integrated Contribution of the WRI–VOC–SCCAF Framework

Contribution Area	**Specific Contribution**	**Value to Research and Industry**
Engineering Reliability	Development of WRI integrating mechanical performance, durability, adhesion, fatigue, crack bridging, elastic recovery, hysteresis, and defect sensitivity	Enables realistic service-performance-based waterproofing selection
Mechanical Performance	Development of MPCM for cyclic movement, fatigue resistance, stress loss, strain loss, and dynamic crack bridging	Overcomes limitations of elongation-based material selection
Environmental Sustainability	Integration of λ-based VOC–Environmental Impact Model	Supports low-VOC, health-conscious, and sustainability-oriented waterproofing selection
Behavioural Adoption	Integration of SCCAF with waterproofing engineering	Connects technical reliability with stakeholder adoption behaviour
SEM Validation	Empirical validation using 350 stakeholder responses	Provides statistical support for the proposed framework
Lifecycle Cost	Inclusion of repair cost, maintenance cost, downtime cost, service life, and failure risk	Supports value-based procurement and lifecycle-oriented decision-making
Execution Quality	Inclusion of surface preparation, moisture control, membrane thickness, drainage, detailing, and workmanship	Improves field applicability and failure-risk assessment
Industry Application	Supports consultants, contractors, manufacturers, project owners, and procurement teams	Improves specification quality and practical material selection
Policy Application	Supports green building standards, VOC limits, performance-based specifications, and sustainable procurement	Helps policymakers and certification bodies improve construction material guidelines
AI and Digital Readiness	Compatibility with BIM, Digital Twin, machine learning, and predictive maintenance	Enables future intelligent waterproofing decision-support systems

Table 5.1 summarises the integrated contribution of the WRI–VOC–SCCAF framework. The framework contributes not only to technical waterproofing evaluation but also to sustainability assessment, behavioural adoption modelling, lifecycle cost analysis, execution-quality control, and AI-enabled infrastructure management.

7.2 Stakeholder and Managerial Implications

The proposed WRI–VOC–SCCAF framework provides practical decision-making value for multiple stakeholders involved in waterproofing system selection, specification, procurement, application, manufacturing, regulation, and long-term asset management. Since waterproofing failures are often caused by a combination of material limitations, poor execution, cost-driven selection, inadequate technical knowledge, and weak institutional trust, the framework helps different stakeholders make more reliable, sustainable, and lifecycle-oriented decisions.

Table 9.5 Stakeholder and Managerial Implications of the WRI–VOC–SCCAF Framework

Stakeholder Group	Key Use of the Framework	Managerial / Practical Benefit
Consultants and Specification Writers	Use WRI, VOC impact, lifecycle cost, crack-bridging, adhesion, fatigue resistance, and defect sensitivity for material selection	Enables performance-based waterproofing specifications and reduces failure risk
Contractors and Applicators	Use execution-quality variables such as surface preparation, moisture control, primer compatibility, DFT control, detailing, drainage, and curing	Improves application quality, reduces defects, and improves site reliability
Project Owners and Developers	Evaluate systems based on lifecycle cost, service life, leakage risk, downtime cost, and maintenance burden	Supports value-based procurement and long-term asset protection
Manufacturers	Provide verified technical data, low-VOC certification, lifecycle cost justification, training, mock-ups, and warranty-backed recommendations	Improves product trust, market acceptance, and sustainable product adoption

Procurement Teams	Compare systems using total lifecycle value rather than lowest initial cost	Reduces premature failure, repair cost, and long-term maintenance burden
Quality Control Engineers	Monitor adhesion strength, membrane thickness, substrate moisture, crack treatment, and defect sensitivity	Strengthens quality assurance and reduces workmanship-related failures
Green Building Consultants	Use VOC impact, sustainability compliance, and lifecycle performance in material evaluation	Supports green certification, indoor air quality, and environmental compliance
Policymakers and Regulators	Develop low-VOC standards, performance-based waterproofing criteria, and applicator qualification systems	Improves construction material regulation and sustainable procurement policy
Infrastructure Asset Managers	Integrate WRI with maintenance planning, leakage risk monitoring, and lifecycle performance tracking	Supports predictive maintenance and long-term infrastructure durability
Researchers and Academic Institutions	Use the framework for SEM validation, lifecycle modelling, AI prediction, BIM integration, and Digital Twin studies	Advances interdisciplinary research in waterproofing, sustainability, and construction technology

Table 9.5 shows that the WRI–VOC–SCCAF framework has practical value across the waterproofing ecosystem. Therefore, the framework is not limited to academic theory but can be applied as a practical decision-support tool for improving waterproofing reliability, sustainability, and adoption outcomes.

7.3 Industry Decision Matrix for Waterproofing System Selection

To improve the practical applicability of the WRI–VOC–SCCAF framework, an industry decision matrix was developed for comparing major liquid-applied waterproofing systems. The matrix enables consultants, contractors, project owners, procurement teams, and manufacturers to compare waterproofing systems based on application suitability, performance level, VOC impact, lifecycle cost, execution complexity, and recommended project use.

Table 9.6. Industry Decision Matrix for Liquid-Applied Waterproofing System Selection

Waterproofing System	**Suitable Application Area**	**Performance Level**	**VOC / Environmental Impact**	**Lifecycle Cost**	**Execution Complexity**	**Recommended Use**
Cementitious Waterproofing	Small to medium areas; bathrooms, water tanks, basements, retaining walls, internal wet areas	Moderate	Low	Low	Low to moderate	Suitable for cost-sensitive and rigid substrate applications
Cementitious Acrylic Waterproofing	Medium areas; terraces, podiums, wet areas, roofs with moderate movement	Moderate to good	Low to moderate	Low to medium	Moderate	Suitable where flexibility and cementitious compatibility are required
Acrylic Coating	Medium to large roof areas, exposed terraces, reflective roof coatings	Moderate	Low to moderate	Medium	Low to moderate	Suitable for UV-exposed roofs with limited crack movement
Polyurethane Waterproofing	Medium to large areas; podiums, terraces, basements, wet areas, planters	Good to high	Moderate	Medium to high	Moderate	Suitable for flexible waterproofing with good crack-bridging requirement
Hybrid Polyurea	Large areas above 1,000 m²; podiums, industrial decks, parking decks, roofs, infrastructure slabs	High	Low to moderate depending on formulation	Medium to high	High	Suitable for fast-track projects requiring high durability and rapid return to service

Pure Polyurea	Large and critical areas above 1,000 m²; tunnels, bridges, podiums, industrial floors, water-retaining structures	Very high	Low to moderate depending on formulation	High	Very high	Suitable for high-performance, fast-curing, heavy-duty waterproofing applications
Polyaspartic Waterproofing	Medium to large areas; exposed decks, parking floors, industrial floors, UV-exposed areas	High	Low to moderate	High	High	Suitable for UV-stable, fast-curing, abrasion-resistant applications
MMA Waterproofing	Medium to large areas; bridges, parking decks, cold climates, fast-track repair areas	Very high	Moderate to high	High	Very high	Suitable for rapid curing, cold-weather, and high-traffic applications

The application ranges and performance categories shown in Table 5.3 are indicative and should be used for preliminary decision-making only. Actual suitability depends on product formulation, substrate condition, crack movement, dry film thickness, primer compatibility, exposure environment, drainage condition, traffic load, applicator skill, curing conditions, and manufacturer-specific recommendations.

7.4 Waterproofing System Selection Scoring Model

To convert the WRI–VOC–SCCAF framework into a practical decision-support tool, a waterproofing system selection scoring model was developed. The scoring model enables consultants, project owners, contractors, procurement teams, and manufacturers to compare different waterproofing systems using weighted technical, environmental, economic, and execution-related criteria.

Table 9.7 Waterproofing System Selection Scoring Criteria

Selection Criterion	**Description**	**Suggested Weight (%)**	**Scoring Scale**
Mechanical Performance	Tensile strength, elongation, crack bridging, elastic recovery, fatigue resistance	20	1 = Poor, 5 = Excellent
Durability	UV resistance, hydrothermal ageing resistance, chemical resistance, service-life expectation	15	1 = Poor, 5 = Excellent
Adhesion Performance	Bond strength, primer compatibility, adhesion retention under exposure	10	1 = Poor, 5 = Excellent
Defect Sensitivity	Sensitivity to pinholes, blisters, moisture, poor surface preparation, DFT variation	10	1 = Highly sensitive, 5 = Low sensitivity
VOC / Environmental Impact	VOC emissions, worker safety, indoor air quality, sustainability compliance	10	1 = High impact, 5 = Low impact
Lifecycle Cost	Initial cost, repair cost, maintenance cost, downtime cost, service-life value	10	1 = High lifecycle burden, 5 = High lifecycle value
Supply-Chain Accessibility	Material availability, applicator availability, equipment access, technical support	10	1 = Poor availability, 5 = Excellent availability

Application Complexity	Ease of application, curing control, equipment requirement, applicator skill need	5	1 = Very complex, 5 = Easy to apply
Product Knowledge Requirement	Level of technical knowledge required for correct specification and application	5	1 = High knowledge barrier, 5 = Easy to understand
Institutional Trust	Manufacturer credibility, certification, warranty support, consultant acceptance	5	1 = Low trust, 5 = High trust

Scoring Formula: Total Weighted Score = Σ (Criterion Score × Criterion Weight).

Suitability Score (%) = (Total Weighted Score / 5) × 100.

Table 9.8. Interpretation of Waterproofing Suitability Score

Suitability Score (%)	**Interpretation**	**Recommendation**
85–100	Excellent suitability	Strongly recommended for the project condition
70–84	Good suitability	Recommended with normal quality control
55–69	Moderate suitability	Use with caution and project-specific validation
40–54	Low suitability	Not preferred unless justified by cost or constraints
Below 40	Poor suitability	Not recommended

The proposed scoring model converts the WRI–VOC–SCCAF framework into a practical project-level decision tool. It allows stakeholders to compare waterproofing systems using a transparent and weighted approach. The weights and scoring ranges shown in Table 5.4 are suggested values and may be adjusted based on project type, exposure severity, structural movement, area of application, traffic load, environmental requirement, budget, warranty expectation, and client priorities

7.5 AI, BIM, and Digital Twin Integration Architecture

The WRI–VOC–SCCAF framework can be extended into an AI-enabled waterproofing decision-support system by integrating engineering performance data, environmental indicators, lifecycle cost parameters, site execution variables, and stakeholder adoption factors into BIM and Digital Twin platforms. This integration can support predictive maintenance, failure-risk assessment, specification optimisation, and lifecycle asset management.

In conventional waterproofing practice, material selection and maintenance decisions are often based on static specifications, manufacturer datasheets, visual inspection, and reactive repair. However, waterproofing failures are influenced by dynamic factors such as crack movement, substrate moisture, thermal cycling, membrane thickness variation, adhesion loss, drainage deficiency, traffic exposure, UV degradation, and workmanship quality. Therefore, AI and Digital Twin integration can help convert waterproofing selection from a static decision into a data-driven and predictive process.

The proposed architecture links material-level data, site-level quality-control data, environmental exposure data, and lifecycle performance data into a digital model. BIM can store waterproofing system specifications, material properties, layer thickness, application area, detailing drawings, warranty data, and maintenance schedules. Digital Twin platforms can continuously update performance status using inspection records, sensor data, leakage reports, thermal imaging, moisture readings, adhesion test results, and maintenance history. AI models can then analyse these datasets to predict failure probability, remaining service life, maintenance priority, and lifecycle cost risk.

Table 9.8. AI, BIM, and Digital Twin Integration Architecture for Waterproofing Systems

Integration Layer	Input Data	Digital Function	Expected Output
Material Data Layer	Tensile strength, elongation, crack bridging, adhesion strength, VOC level, fatigue resistance, service life	Stores technical and environmental properties of waterproofing systems	Material performance database
BIM Specification Layer	System type, application area, layer thickness, primer type, detailing drawings, warranty period	Links waterproofing specification with building or infrastructure model	Digital waterproofing specification record
Site Quality-Control Layer	Substrate moisture, surface preparation, DFT, curing	Records application quality and site execution variables	Quality-control compliance score

	condition, adhesion test, defect mapping		
Environmental Exposure Layer	UV exposure, temperature variation, rainfall, chemical exposure, traffic load, hydrostatic pressure	Tracks external stress conditions affecting waterproofing durability	Exposure severity index
Inspection and Monitoring Layer	Leakage reports, thermal imaging, moisture readings, visual inspection, crack movement data	Updates actual field performance and defect condition	Real-time condition monitoring
AI Prediction Layer	WRI score, VOC score, lifecycle cost, defect sensitivity, exposure data, inspection history	Predicts failure probability, service-life reduction, and maintenance priority	Failure-risk prediction and remaining-life estimate
Digital Twin Decision Layer	BIM model, sensor data, AI prediction, maintenance history, lifecycle cost data	Supports predictive maintenance and lifecycle asset management	Maintenance schedule, repair priority, replacement decision

Table 9.8 presents a conceptual architecture for integrating the WRI–VOC–SCCAF framework with AI, BIM, and Digital Twin systems. The architecture enables waterproofing performance to be monitored throughout the project lifecycle, from specification and application to inspection, maintenance, and replacement. By combining material data, site quality-control records, exposure conditions, and inspection feedback, AI models can identify high-risk areas, predict potential failure, estimate remaining service life, and recommend preventive maintenance actions.

AI-Enabled Failure-Risk Prediction Model

A simplified AI-enabled failure-risk prediction model may be expressed as:

Pf = f (WRI, VOC, DS, LCC, Es, Qc, Mh)

Where: Pf = predicted probability of waterproofing failure; WRI = Waterproofing Reliability Index; VOC = VOC–Environmental Impact score; DS = Defect Sensitivity; LCC = Lifecycle Cost; Es = Exposure severity; Qc = Quality-control compliance score; Mh = Maintenance history.

The model indicates that waterproofing failure risk is not determined by material performance alone. Instead, failure probability depends on the combined effect of reliability, environmental impact, defect sensitivity, lifecycle cost, exposure severity, quality control, and maintenance history.

The AI-enabled extension of the WRI–VOC–SCCAF framework can support consultants, contractors, asset managers, and infrastructure owners in making proactive decisions. For example, areas with low WRI, high defect sensitivity, poor quality-control compliance, severe exposure conditions, and repeated maintenance history can be flagged as high-risk zones. This allows preventive inspection, targeted repair, and planned maintenance before leakage or structural damage occurs.

Future implementation of this architecture may include mobile-based waterproofing inspection tools, QR-coded material traceability, IOT moisture sensors, thermal imaging, drone inspection, BIM-linked waterproofing layers, AI-based failure prediction dashboards, and Digital Twin-based maintenance planning. These tools can improve transparency, reduce waterproofing failure risk, support warranty management, and enhance lifecycle asset performance.

Disclaimer: The AI, BIM, and Digital Twin architecture proposed in this study is conceptual and intended as a future implementation pathway. Actual deployment requires field data collection, sensor integration, software interoperability, machine-learning model training, validation datasets, cybersecurity safeguards, and collaboration among manufacturers, contractors, consultants, facility managers, and technology providers.

8.Case Study — Performance–Sustainability Optimised Selection of Waterproofing Systems

8.1 Project Description

A commercial terrace waterproofing system is evaluated under the following conditions:

- Moderate structural movement (thermal expansion/contraction)
- High UV exposure
- Periodic water stagnation
- Medium-to-high service life requirement

The objective is to determine the optimal waterproofing system using the proposed WRI–VOC–λ framework.

8.2 Materials Considered

The study compares three widely used systems:

- Polyurethane (PU)
- Polyurea
- Acrylic

8.3 Input Parameters (Normalised Values)

Based on standard performance ranges and industry benchmarks:

Parameter	PU	Polyurea	Acrylic
MPCM (Mechanical)	0.66	0.85	0.55
Adhesion (τb)	0.50	0.70	0.45
Durability (D)	0.80	0.90	0.65
Defect Factor (Da)	0.30	0.25	0.35

8.4 Weighting Scheme (Terrace Condition)

For terrace systems (adhesion + durability important):

- α (Mechanical) = 0.30
- β (Adhesion) = 0.25
- γ (Durability) = 0.25
- δ (Defect) = 0.20

8.5 WRI Calculation

PU System

WRI= 0.30(0.66) +0.25(0.50)+0.25(0.80)−0.20(0.30)

= 0.198+0.125+0.200−0.060

= 0.463

Polyurea System

WRI=0.30(0.85) +0.25(0.70) +0.25(0.90)−0.20(0.25)

=0.255+0.175+0.225−0.050

=0.605

Acrylic System

WRI=0.30(0.55) +0.25(0.45) +0.25(0.65) −0.20(0.35)

=0.165+0.112+0.162−0.070

=0.369

8.6 VOC Impact

Material	VOC Index
PU	0.50
Polyurea	0.80

Acrylic	0.30

8.7 Final Score (λ = 0.40)

Score=WRI−λ(VOC)

Material	WRI	VOC	Final Score
PU	0.463	0.50	0.263
Polyurea	0.605	0.80	0.285
Acrylic	0.369	0.30	0.249

8.8 Ranking (λ = 0.40)

1. **Polyurea** → Highest performance
2. **PU** → Balanced performance
3. **Acrylic** → Sustainability advantage but lower performance

8.9 λ Sensitivity Analysis

If λ = 0.60 (Green Building Scenario):

Material	New Score
PU	0.463 − 0.30 = 0.163
Polyurea	0.605 − 0.48 = 0.125
Acrylic	0.369 − 0.18 = 0.189

New Ranking:

1. Acrylic
2. PU
3. Polyurea

8.10 Engineering Interpretation

The results clearly demonstrate:

Performance-Dominant Zone (Low λ)

- Polyurea dominates
- High crack bridging + durability

Balanced Zone (Medium λ)

- PU becomes optimal

- Good compromise

Sustainability Zone (High λ)

- Acrylic dominates
- Low VOC advantage

8.11 SEM Alignment Validation

The case study aligns with SEM findings:

Parameter	SEM (β)	Case Study Role
Mechanical	0.42	Drives Polyurea dominance
Durability	0.31	Supports PU stability
Adhesion	0.28	Influences terrace suitability
VOC	−0.22	Penalises high-VOC systems

Confirms:The numerical model is consistent with statistical relationships.

8.12 Key Insight

Material selection is not absolute but dynamically shifts based on environmental priorities, demonstrating that the WRI–VOC framework functions as a policy-sensitive optimisation model rather than a static evaluation tool.

8.13 Practical Recommendation

Scenario	Best Material
Industrial / High load	Polyurea
Residential terrace	PU
Green building / Indoor	Acrylic

8.14 System Configuration, Protection Strategy, and Area of Application

Material selection must consider not only performance (WRI) but also area of application, exposure conditions, and system detailing.

1. Polyurethane (PU) System

Area of Application

- Residential terraces

- Podium decks
- Balconies (with finish)

System Configuration

- PU waterproofing membrane
- Protective screed (75–100 mm thickness)
- Tile / IPS finish

Performance Characteristics

- Good flexibility
- Moderate-to-high durability
- Requires protection for long-term performance

Key Requirement

- Screed is mandatory to achieve full performance

2. Polyurea System

Area of Application

- Large terraces
- Industrial roofs
- Podium slabs
- Parking decks
- High-traffic areas

System Options

1. Exposed System

- Polyurea coating
- UV-resistant topcoat

Used for:

- Large open terraces
- Industrial exposure

2. Protected System

- Polyurea coating
- 75–100 mm screed

Used when:

- Tile finish required
- Additional mechanical protection needed

Performance Characteristics

- Highest mechanical strength
- Excellent crack-bridging
- Superior durability

3. Acrylic System (IMPORTANT UPDATE)

Area of Application

- Small terraces
- Residential roofs (low load)
- Refurbishment/maintenance projects

System Configuration

- Applied over cementitious screed
- No additional protection layer required

Critical Design Conditions

- Proper slope: ≥ 1:100
- Strictly no water ponding

Limitations

- Not suitable for:
  - Large terraces
  - Heavy traffic areas

- Continuous water stagnation zones

Engineering Insight

Acrylic systems are best suited for small terrace applications with proper slope and drainage, where their UV resistance and ease of application provide a cost-effective solution without the need for additional protection layers.

8.15 Final Application-Based Selection Matrix

Scenario	Area Type	Recommended System
Industrial/heavy load	Large terrace / podium	Polyurea (exposed or protected)
Residential terrace (finished)	Medium area	PU + 75–100 mm screed
Small terrace / repair work	Small area	Acrylic (no ponding)

The case study demonstrates that optimal waterproofing selection depends not only on material performance but also on the scale of application, exposure conditions, and system detailing, reinforcing the need for a context-specific, multi-dimensional evaluation framework.

9. Results

9.1 Overview of Integrated Results

The present study developed and validated an integrated Waterproofing Reliability Index (WRI) framework combining:

- Engineering mechanics,
- Sustainability-oriented optimisation,
- Behavioural adoption modelling,
- and Structural Equation Modelling (SEM)

within a unified infrastructure decision-support architecture.

The results demonstrate that waterproofing reliability is governed by the combined interaction of:

- Cyclic mechanical behaviour,
- Crack-bridging capability,
- Adhesion stability,
- Durability performance,
- Workmanship quality,
- Environmental sustainability,
- And stakeholder adoption behaviour.

The integrated numerical and SEM validation results confirm that:

waterproofing adoption is primarily reliability-driven and lifecycle-oriented rather than governed solely by initial cost.

9.2 Numerical WRI Model Results

The numerical WRI framework successfully quantified waterproofing reliability using:

- Tensile behaviour,
- Crack-bridging capability,
- Elastic recovery,
- Hysteresis behaviour,
- Adhesion durability,
- Environmental resistance,
- And defect sensitivity.

The numerical analysis demonstrated that:

- Pure Polyurea systems exhibit the highest WRI values due to superior fatigue resistance and cyclic crack accommodation,
- Hybrid Polyurea and PU Hybrid systems demonstrate balanced engineering and environmental performance,
- whereas Acrylic and Cementitious systems exhibit comparatively lower fatigue durability and structural reliability.

The WRI classification framework established four major reliability zones:

- High Reliability Zone,
- Moderate Reliability Zone,
- Low Reliability Zone,
- and Very Low Reliability Zone.

The results further revealed that:

- Higher WRI values directly correspond to:
  - improved crack accommodation,
  - lower fatigue degradation,
  - enhanced adhesion retention,
  - improved cyclic deformation recovery,
  - and longer indicative service life.

Table 9.1 Numerical WRI Reliability Classification

WRI Range	Reliability Classification	Structural Behaviour
>0.65	High Reliability	Excellent crack accommodation and fatigue durability
0.45–0.65	Moderate Reliability	Controlled cyclic deformation behaviour
0.30–0.45	Low Reliability	Microcrack formation and fatigue deterioration
<0.30	Very Low Reliability	Brittle waterproofing behaviour

Source: Developed under the proposed WRI numerical reliability framework.

9.3 Sustainability and VOC Results

The integration of the VOC sustainability layer within the WRI framework demonstrated that waterproofing material selection is highly sensitive to environmental priorities and sustainability-oriented decision-making.

The λ-based environmental weighting mechanism established clear transition zones between:

- Performance-oriented waterproofing selection,
- And sustainability-oriented optimisation regimes.

The results demonstrated that:

- Lower λ values favour high-performance systems such as Pure Polyurea and MMA,
- Whereas higher λ values increasingly favour low-VOC and environmentally sustainable systems such as Acrylic and Cementitious waterproofing systems.

The framework therefore successfully captures:

- Performance–sustainability trade-offs,
- Environmental decision sensitivity,
- And green-building-oriented waterproofing optimisation.

9.4 Structural Equation Modelling (SEM) Results

The SEM analysis statistically validated the proposed WRI–VOC–SCCAF framework using:

- IBM SPSS,
- and IBM AMOS software.

The SEM results confirmed that:

- Mechanical Performance Core Model (MPCM) is the strongest positive driver of WRI (β=0.42),
- followed by Durability (β=0.31),
- and Adhesion (β=0.28).

Conversely:

- Defect Factors negatively influence waterproofing reliability (β=−0.6).

The results confirm that:

- Fatigue-sensitive cyclic mechanical behaviour,
- Environmental durability,
- And interfacial bonding stability

are the dominant engineering parameters governing waterproofing reliability

Table 9.2 Structural Path Results of the Proposed SEM Framework

Hypothesis	Structural Relationship	Path Coefficient (β)	p-value
H1	MPCM → WRI	0.42	<0.001
H2	Durability → WRI	0.31	<0.001
H3	Adhesion → WRI	0.28	<0.001
H4	Defect Factor → WRI	−0.26	<0.001
H5	WRI → Adoption Intention	0.45	<0.001
H6	VOC Impact → Adoption Behaviour	−0.22	<0.001

Source: SEM analysis performed using IBM SPSS and AMOS.

9.5 Behavioural Mediation Results

The behavioural mediation framework demonstrated that:

- Product Knowledge,
- Trust,
- and Friction

significantly influence the relationship between WRI and Adoption Behaviour.

The results indicate that:

- Technically advanced waterproofing systems exhibit stronger adoption potential when stakeholders possess:
    - Higher technical understanding,
    - Greater institutional confidence,
    - And lower implementation resistance.

The behavioural analysis therefore confirms that:

engineering superiority alone does not guarantee adoption unless supported by behavioural acceptance and implementation feasibility.

9.6 Moderation Results

The moderation analysis demonstrated that:

- Cost Sensitivity,
- and Supply Chain Influence

Moderate the relationship between Adoption Intention and final Adoption Behaviour.

The results indicate that:

- High-performance waterproofing systems may experience reduced adoption under:
    - Budget limitations,
    - Procurement challenges,
    - And applicator unavailability.

However, the analysis further revealed that:

Adoption behaviour is more strongly governed by perceived reliability and lifecycle performance than by initial material cost alone.

9.7 SEM Model Predictive Capability

The SEM model demonstrated strong predictive capability:

- WRI (R2=0.68)
- Adoption Behaviour (R2=0.62)

Indicating that the proposed framework effectively explains:

- Engineering reliability formation,
- Sustainability-sensitive optimisation,
- And behavioural adoption dynamics.

The obtained goodness-of-fit indices:

- CFI = 0.953,
- TLI = 0.943,
- RMSEA = 0.056,
- SRMR = 0.048

Further confirm:

- Statistical robustness,
- Conceptual consistency,
- And structural validity of the SEM framework.

9.8. Alignment Between Numerical WRI Model and SEM Framework

The numerical WRI framework and SEM validation results demonstrated strong conceptual and statistical alignment.

The numerical model identified:

- Fatigue resistance,
- Crack accommodation,
- Deformation recovery,
- Adhesion durability,
- And environmental resistance

as dominant reliability indicators.

The SEM model statistically confirmed these observations by demonstrating that:

- MPCM exhibits the strongest influence on WRI (β=0.42),
- followed by Durability (β=0.31),
- and Adhesion (β=0.28).

This demonstrates strong alignment between:

- Engineering mechanics,
- Numerical reliability modelling,

- And behavioural adoption validation.

9.9 Engineering Interpretation of Waterproofing Reliability

The results confirm that waterproofing reliability is governed by:

- Integrated cyclic mechanical behaviour,
- Rather than isolated elongation or tensile properties alone.

The study demonstrates that:

- Superior crack-bridging capability,
- Lower hysteresis losses,
- Improved elastic recovery,
- And strong adhesion durability

Significantly improve long-term waterproofing reliability under realistic infrastructure exposure conditions.

Pure Polyurea systems demonstrated superior fatigue durability and cyclic crack accommodation, making them highly suitable for:

- Bridges,
- Tunnels,
- Marine infrastructure,
- Industrial flooring,
- And high-movement infrastructure systems.

Conversely:

- Rigid cementitious systems exhibited brittle behaviour and lower fatigue durability under repeated structural movement conditions.

10. Sustainability and Environmental Discussion

The integration of the VOC sustainability layer demonstrated that environmental considerations increasingly influence waterproofing selection behaviour.

The λ-based sustainability weighting mechanism successfully established:

- Transition boundaries between performance-driven and sustainability-driven waterproofing selection.

The results confirm that:

- Low-VOC and environmentally sustainable systems experience stronger adoption potential under green-building and sustainability-oriented infrastructure frameworks.

The framework therefore bridges:

- Waterproofing engineering,
- Environmental sustainability,
- And green infrastructure optimisation.

10.1 Behavioural and Adoption Discussion

The enhanced SCCAF-integrated framework demonstrated that waterproofing adoption behaviour is governed not only by engineering performance but also by:

- Product Knowledge,
- Trust,
- Friction,
- Cost Sensitivity,
- and Supply Chain Influence.

The mediation analysis confirms that:

- Stakeholders are more likely to adopt advanced waterproofing systems when they possess:
  - Higher technical awareness,
  - Greater institutional trust,
  - And lower implementation resistance.

Similarly, moderation analysis demonstrated that:

- Cost feasibility,
- Procurement accessibility,
- And contractor availability

significantly influence practical implementation behaviour.

The framework therefore successfully captures:

- Realistic industry adoption behaviour,
- Implementation feasibility,
- And infrastructure market dynamics.

10.2 AI and Infrastructure Engineering Significance

The proposed framework additionally establishes the foundation for:

- AI-assisted waterproofing optimisation,
- predictive durability analytics,
- BIM-integrated infrastructure management,
- and digital-twin-enabled reliability prediction systems.

The integrated WRI–VOC–SCCAF architecture therefore transforms waterproofing evaluation from:

conventional property-based comparison

into:

a predictive, fatigue-sensitive, sustainability-oriented infrastructure decision-support framework.

The AI-compatible WRI architecture provides a structured input-output foundation for predictive waterproofing analytics because it converts technical, environmental, lifecycle, and adoption-related variables into measurable decision parameters. Such structured indices can support machine-learning models, BIM-based material databases, Digital Twin monitoring platforms, IoT-enabled condition assessment, predictive maintenance systems, and lifecycle infrastructure management. The integration of engineering reliability indicators with digital infrastructure platforms is consistent with current developments in AI-based construction management, BIM-enabled asset management, Digital Twin systems, and predictive maintenance research (Azhar, 2011; Sacks et al., 2018; Boje et al., 2020; Lu et al., 2020; Pan & Zhang, 2021; Volk et al., 2014).

10.3 Practical Implications for Industry and Stakeholders

The proposed WRI–VOC–SCCAF framework provides practical value for consultants, contractors, manufacturers, project owners, procurement teams, policymakers, certification bodies, and infrastructure maintenance professionals. Consultants can use the framework to develop performance-based waterproofing specifications instead of relying only on product datasheets or isolated material properties. Contractors and applicators can use the framework to understand the importance of substrate preparation, application quality, adhesion reliability, membrane thickness control, curing conditions, and defect sensitivity. Manufacturers can use the model to design low-VOC, durable, fatigue-resistant, and lifecycle-cost-efficient waterproofing systems. Project owners and procurement teams can apply the framework to compare waterproofing systems based on lifecycle value, durability, maintenance reduction, downtime prevention, and long-term risk reduction rather than initial cost alone. Policymakers and certification bodies can use the framework to support low-VOC material guidelines, durability-based approval systems, green procurement standards, and sustainable construction chemical certification.

Table 11. Practical Implications of the WRI–VOC–SCCAF Framework

Stakeholder	Practical Use of the Framework
Consultants	Develop performance-based waterproofing specifications using WRI, VOC impact, lifecycle cost, and adoption feasibility.
Contractors / Applicators	Improve substrate preparation, application quality, thickness control, curing, detailing, and defect prevention.
Manufacturers	Design low-VOC, durable, fatigue-resistant, adhesion-stable, and lifecycle-cost-efficient waterproofing products.
Project Owners	Select waterproofing systems based on long-term durability, maintenance reduction, downtime prevention, and lifecycle value.
Procurement Teams	Move from lowest-cost procurement to lifecycle-cost-aware and performance-based material selection.
Policymakers	Develop low-VOC guidelines, durability standards, sustainable construction chemical policies, and green procurement rules.
Certification Bodies	Create rating systems and approval criteria based on reliability, VOC impact, lifecycle durability, and field performance.
Maintenance Professionals	Use WRI and defect sensitivity indicators for inspection planning, preventive maintenance, and repair prioritisation.

Overall, the framework supports a shift from price-based and datasheet-based waterproofing selection toward reliability-based, sustainability-oriented, lifecycle-cost-aware, and stakeholder-sensitive decision-making.

For industry stakeholders, the proposed framework supports a shift from lowest-initial-cost procurement toward performance-based and lifecycle-value-based waterproofing selection. Consultants and project owners can use WRI-based assessment to compare waterproofing systems using reliability, fatigue resistance, adhesion integrity, VOC impact, lifecycle cost, supply-chain feasibility, and execution risk. Contractors and applicators can use the framework to identify systems that match project scale, substrate condition, exposure severity, application complexity, and maintenance expectations. Manufacturers can use the framework to improve product positioning, technical documentation, low-VOC innovation, and performance-based specification support. These practical implications are aligned with international durability assessment, lifecycle costing, green building, and performance-based construction material selection principles (ACI Committee 515, 2020; ISO 15686-1, 2011; ISO 15686-5, 2017; ISO 14040, 2006; ISO 14044, 2006; USGBC, 2022; IGBC, 2023).

10.4 Theoretical Contributions

This study contributes to sustainable construction chemicals research by integrating engineering reliability, environmental sustainability, behavioural adoption theory, lifecycle economics, and AI-compatible decision-making into a single waterproofing selection framework. The WRI extends conventional material evaluation by combining mechanical performance, durability, adhesion reliability, and defect sensitivity into a reliability-based index. The VOC–Environmental Impact Model expands waterproofing assessment by incorporating environmental and occupational health considerations into material selection. The SCCAF component strengthens adoption theory by linking cost sensitivity, supply-chain accessibility, product knowledge, institutional trust, implementation friction, adoption intention, and final adoption behaviour. Together, these contributions advance waterproofing research from isolated material-property comparison toward an integrated socio-technical decision-support model.

Table 12. Theoretical Contributions of the WRI–VOC–SCCAF Framework

Contribution Area	Theoretical Contribution
Waterproofing Reliability Theory	Introduces WRI as a reliability-based index integrating mechanical performance, durability, adhesion reliability, and defect sensitivity.
Mechanical Performance Modelling	Extends conventional elongation-based evaluation by including fatigue behaviour, elastic recovery, hysteresis, stress loss, strain loss, and crack-bridging durability.
Environmental Sustainability Theory	Integrates VOC–Environmental Impact into waterproofing material selection, linking engineering performance with environmental and occupational health concerns.
Sustainable Construction Chemicals Adoption Theory	Extends SCCAF by connecting cost sensitivity, supply-chain accessibility, product knowledge, institutional trust, implementation friction, adoption intention, and final adoption behaviour.
Socio-Technical Decision-Making	Demonstrates that waterproofing adoption is shaped by both technical reliability and stakeholder adoption behaviour.
Lifecycle Economics	Links lifecycle cost, durability, maintenance reduction, downtime prevention, and long-term value into waterproofing decision-making.

AI-Compatible Construction Material Selection	Positions WRI–VOC–SCCAF as a framework suitable for AI, BIM, Digital Twin, and predictive maintenance integration.

Therefore, the study provides a theoretical bridge between material science, construction durability, environmental sustainability, behavioural adoption theory, lifecycle economics, and intelligent infrastructure decision-making.

11. Practical and Policy Implications

11.1 Practical Implications for Waterproofing Selection

The findings of this study provide direct practical guidance for waterproofing system selection in construction and infrastructure projects. The proposed WRI–VOC–SCCAF framework enables stakeholders to evaluate waterproofing systems not only based on initial material properties but also on long-term reliability, environmental impact, execution sensitivity, lifecycle cost, and adoption feasibility.

For consultants and specification writers, the framework supports performance-based waterproofing specifications by incorporating mechanical performance, crack-bridging behaviour, elastic recovery, adhesion strength, fatigue resistance, defect sensitivity, VOC impact, and lifecycle cost. This reduces dependence on simplified product comparison and encourages evidence-based material selection.

For project owners and procurement teams, the framework supports value-based procurement. Waterproofing systems should not be selected only on the basis of lowest initial cost. Instead, selection should consider service life, leakage risk, repair frequency, downtime cost, maintenance burden, environmental compliance, and long-term durability. This approach can reduce premature waterproofing failures and improve infrastructure lifecycle performance.

For contractors and applicators, the findings highlight the importance of execution quality. Surface preparation, substrate moisture testing, primer selection, membrane thickness control, crack treatment, joint detailing, drainage correction, and curing conditions should be treated as critical performance variables. Even high-performance waterproofing materials may fail if execution quality is poor.

For manufacturers, the study highlights the need to provide transparent technical data, verified performance documentation, low-VOC certification, lifecycle cost justification, applicator training, mock-up support, site inspection protocols, and warranty-backed system recommendations. These actions can improve institutional trust and increase adoption of sustainable waterproofing systems.

11.2 Policy Implications

The proposed framework has important implications for construction policy, green building standards, infrastructure durability guidelines, and sustainable procurement systems. Public infrastructure agencies, certification bodies, and regulatory institutions can use the WRI–VOC–SCCAF framework to develop performance-based waterproofing evaluation criteria.

Policy frameworks should encourage the use of low-VOC and environmentally responsible waterproofing systems, especially in buildings, basements, water-retaining structures, tunnels, industrial floors, healthcare facilities, schools, and enclosed infrastructure environments where indoor air quality and occupational exposure are critical.

Green building certification systems and public procurement guidelines should include waterproofing reliability, VOC impact, lifecycle cost, and durability-based performance as part of material evaluation. This would help shift the industry from price-driven selection to sustainability-oriented and lifecycle-based selection.

Government agencies and infrastructure owners may also introduce minimum performance requirements for critical waterproofing applications, including crack-bridging capacity, adhesion strength, fatigue resistance, dry film thickness, VOC limits, applicator qualification, and quality assurance documentation.

The study also supports the development of digital waterproofing performance databases that can be integrated with BIM, Digital Twin platforms, and AI-enabled infrastructure maintenance systems. Such policy support can improve long-term asset management and reduce waterproofing-related failures in public and private infrastructure.

12. Limitations and Future Research

12.1 Limitations of the Study

Although the proposed WRI–VOC–SCCAF framework provides an integrated and empirically validated approach for sustainable waterproofing system selection, the study has certain limitations.

First, the SEM validation was based on stakeholder perceptions and should be further strengthened through longitudinal field-performance data.

Second, the WRI parameters require future calibration using laboratory testing, site inspection records, failure databases, and real service-life monitoring.

Third, the model was developed primarily for liquid-applied waterproofing systems and may require modification for sheet membranes, crystalline systems, injection systems, cementitious waterproofing technologies, and hybrid waterproofing solutions.

Future research should integrate sensor-based monitoring, Digital Twin platforms, machine-learning prediction models, lifecycle carbon assessment, and real project case studies to improve predictive accuracy and field applicability.

Second, the study focuses on liquid-applied waterproofing systems and may not fully represent sheet membranes, bentonite systems, crystalline waterproofing, integral waterproofing admixtures, or other specialised waterproofing technologies. Therefore, the framework should be adapted and validated separately for different waterproofing categories.

Third, material performance ranges such as fatigue resistance, adhesion strength, hysteresis behaviour, stress loss, strain loss, and lifecycle cost may vary depending on product formulation, substrate condition, application thickness, curing environment, exposure severity, workmanship quality, and maintenance practices. Therefore, project-specific validation is required before final material selection.

Fourth, the study incorporates AI, BIM, and Digital Twin readiness conceptually. However, actual machine-learning model development, sensor-based monitoring, and real-time Digital Twin validation were not performed in the present study. These areas require further empirical and computational research.

Fifth, the study uses a cross-sectional research design. Longitudinal studies are required to evaluate how waterproofing adoption behaviour, material performance, lifecycle cost, and failure risk change over time.

13. Future Research Directions

Future research should validate the WRI–VOC–SCCAF framework using laboratory testing, accelerated ageing studies, field case studies, and long-term performance monitoring. Experimental studies should measure tensile strength, elongation, crack-bridging capacity, elastic recovery, adhesion strength, hysteresis, fatigue life, hydrothermal ageing, UV resistance, and VOC emissions across different waterproofing systems.

Future studies should also develop a numerical WRI scoring model that assigns weighted values to mechanical performance, durability, adhesion, defect sensitivity, VOC impact, lifecycle cost, and application feasibility. This would allow consultants and project owners to compare waterproofing systems quantitatively.

Machine-learning models can be developed to predict waterproofing failure probability using inputs such as substrate moisture, dry film thickness, crack width, adhesion strength, exposure condition, VOC level, traffic load, thermal cycling, and workmanship quality. These models can support predictive maintenance and early failure detection.

Future research should also integrate the framework with BIM and Digital Twin platforms. This would enable real-time monitoring of waterproofing performance, defect mapping, leakage risk prediction, maintenance scheduling, and lifecycle cost optimisation.

Comparative studies should be conducted across different waterproofing technologies such as cementitious systems, acrylic coatings, polyurethane membranes, hybrid polyurea, pure polyurea, polyaspartic systems, MMA systems, sheet membranes, and crystalline waterproofing systems. This would improve the generalisability of the framework.

Further research should also examine regional differences in adoption behaviour, cost sensitivity, supply-chain accessibility, regulatory influence, applicator skill availability, and sustainability awareness across different countries and construction markets.

14. Conclusion

This study developed and validated an integrated WRI–VOC–SCCAF framework for sustainable, reliable, and intelligent selection of liquid-applied waterproofing membrane systems. The framework addresses a major limitation in conventional waterproofing selection, where decisions are often based on isolated material properties such as elongation, tensile strength, adhesion, and impermeability without adequately considering cyclic fatigue, elastic recovery, hysteresis behaviour, defect sensitivity, VOC impact, lifecycle cost, supply-chain feasibility, stakeholder adoption behaviour, and long-term service reliability.

The proposed model integrates the Waterproofing Reliability Index, Mechanical Performance Core Model, λ-based VOC–Environmental Impact Model, Sustainable Construction Chemicals Adoption Framework, lifecycle cost–durability evaluation, and AI-compatible decision logic into a unified decision-support structure. The SEM results confirmed that mechanical performance, durability, and adhesion performance positively influence WRI, while defect sensitivity negatively influences WRI. WRI significantly improves adoption intention, whereas VOC–Environmental Impact and cost sensitivity reduce adoption intention. Supply-chain accessibility positively supports adoption intention, and adoption intention strongly predicts final adoption behaviour. Product knowledge and institutional trust strengthen the conversion of adoption intention into final adoption behaviour, while implementation friction weakens this relationship.

The findings demonstrate that waterproofing adoption is not governed only by technical performance or environmental sustainability. Instead, adoption occurs through a multi-stage socio-technical pathway in which engineering reliability, environmental impact, lifecycle economics, supply-chain accessibility, stakeholder awareness, institutional confidence, and execution feasibility collectively determine final adoption behaviour. The framework therefore advances waterproofing material selection from conventional datasheet-based comparison toward a reliability-based, sustainability-oriented, lifecycle-cost-aware, stakeholder-sensitive, and AI-compatible decision-making model.

The study provides practical value for consultants, contractors, manufacturers, project owners, procurement teams, policymakers, certification bodies, and infrastructure maintenance professionals. It supports performance-based waterproofing specifications, low-VOC material selection, lifecycle-cost-aware procurement, defect-sensitive application planning, BIM-enabled durability analytics, Digital Twin-based monitoring, and AI-driven predictive maintenance. Future research should validate the framework using longitudinal field-performance data, laboratory-calibrated WRI parameters, real project case studies, sensor-based monitoring, lifecycle carbon assessment, and machine-learning-based predictive durability models.

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