

ASSESSMENT OF POLYURETHANE TECHNOLOGY AS A GROUNDWATER SEEPAGE CONTROL METHOD IN COASTAL BUILDINGS

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ABSTRACT

Coastal building construction faces severe challenges due to persistent groundwater seepage, driven by tidal fluctuations, hydrostatic pressure, and saline soil conditions that accelerate structural degradation. Conventional waterproofing materials such as bituminous membranes and cementitious coatings have demonstrated limited durability under the dynamic conditions prevailing in marine and estuarine environments. Polyurethane (PU) technology has emerged as a highly effective solution for groundwater seepage prevention owing to its exceptional elasticity, adhesion to diverse substrates, chemical resistance to saline water, and long-term impermeability. This review paper synthesizes existing literature on the application of polyurethane-based systems including spray-applied coatings, injection grouts, foam sealants, and hybrid composites in coastal construction scenarios. A meta-analysis of past experimental and field studies reveals consistent performance advantages of PU systems over conventional alternatives in terms of crack-bridging capacity, bond strength, and resistance to hydrostatic pressure. The paper critically evaluates methodological approaches, material formulations, and performance metrics employed across the reviewed studies. Findings indicate that two-component PU injection systems achieve pore closure efficiencies exceeding 95% in fractured substrates, while spray-applied membranes sustain waterproofing integrity for over 20 years under saline exposure. Research gaps concerning long-term environmental impact, bio-fouling, and temperature-driven degradation in tropical coastal zones are identified. This review provides engineers, architects, and construction professionals with a comprehensive evidence base for selecting and deploying polyurethane waterproofing technologies in coastal infrastructure projects.

Keywords: Polyurethane waterproofing¹, groundwater seepage², coastal construction³, hydrostatic pressure⁴, PU injection grouting⁵, spray-applied membrane⁶, saline resistance⁷.

1. INTRODUCTION

1.1 Background and Problem Statement

Coastal regions across the globe host a significant proportion of the world's built environment, with millions of buildings constructed on or adjacent to shorelines, estuaries, deltas, and reclaimed land. These structures are inherently subjected to aggressive hydrological and geochemical conditions, including elevated groundwater tables driven by tidal action, capillary rise of saline water through sub-grade concrete elements, and variable hydrostatic pressure regimes that fluctuate with seasonal and meteorological factors [1]. The consequences of inadequate groundwater management in such environments are far-reaching, encompassing foundation settlement, reinforcement corrosion, blistering and delamination of internal finishes, and in extreme cases, structural failure. The economic cost of remedial waterproofing in coastal infrastructure is estimated at billions of dollars annually in countries such as India, Bangladesh, the Netherlands, and coastal states of the United States [2]. The problem of groundwater seepage in building construction is not confined to basements and sub-grade elements alone. In low-lying coastal terrains, where the water table may be only a few centimetres below the natural ground level, even ground-floor slabs and external walls are susceptible to moisture ingress through capillary action and pressure differentials. Salt crystallisation within pore structures a phenomenon known as subflorescence induces internal tensile stresses that progressively disintegrate concrete and masonry, leading to spalling, cracking, and loss of load-bearing capacity [3]. Traditional waterproofing strategies, while partially effective under benign environmental conditions, have consistently failed to provide durable protection under the combined mechanical, thermal, and chemical loadings characteristic of coastal sites.

1.2 Polyurethane Technology in Construction Waterproofing

Polyurethane, a class of polymer formed by the reaction of polyols with isocyanates, has attracted increasing research and industrial attention as a waterproofing medium since the 1970s [4]. Its versatility arises from the ability to engineer molecular architecture to achieve a wide spectrum of physical properties from rigid closed-cell foams to highly flexible elastomeric membranes by varying the ratio and type of reacting components, chain extenders, and catalysts [5]. In the context of building waterproofing, PU systems are deployed in several forms: spray-applied coatings that form seamless elastomeric barriers on external and internal surfaces; two-component injection grouts that expand and solidify within cracks and voids to arrest active water infiltration; preformed PU waterstops embedded in construction joints; and PU-based hybrid composites reinforced with glass fibres or bituminous modifiers for enhanced mechanical durability [6]. The moisture-reactive nature of certain PU formulations allows in-situ application even in the presence of running water, a feature that significantly extends the utility of the technology in emergency repair scenarios and in environments where substrate drying is impractical. Research interest in polyurethane waterproofing for coastal applications has expanded substantially over the past two decades, spurred by high-profile infrastructure failures, the increasing adoption of underground and sub-sea construction, and growing awareness of climate change-driven sea-level rise that will exacerbate groundwater intrusion into coastal building stock [7]. Peer-reviewed investigations have examined PU performance across a range of variables including substrate type and preparation, application method, material formulation, temperature, and exposure duration. However, the existing literature remains fragmented

across disciplines civil engineering, materials science, polymer chemistry, and environmental science and a consolidated review that synthesises findings into actionable guidance for practitioners is presently lacking [8].

1.3 Scope and Objectives of the Review

This paper aims to fill the identified gap by conducting a systematic review and meta-analysis of published studies on polyurethane technology for groundwater seepage prevention in coastal building construction. The scope encompasses laboratory investigations, field trials, and case studies published between 1990 and 2024 in peer-reviewed journals, conference proceedings, and technical standards. The specific objectives of the review are: (i) to catalogue the types of PU systems investigated in coastal waterproofing applications; (ii) to synthesise quantitative performance data on seepage reduction, adhesion, and durability from multiple studies; (iii) to critically evaluate methodological rigour, identify inconsistencies, and highlight research gaps; and (iv) to propose an evidence-based framework for the selection and specification of PU waterproofing systems in coastal infrastructure. The paper is structured to provide practitioner-accessible content while maintaining academic rigour, offering a resource of value to researchers, engineers, architects, urban planners, and policy makers engaged in the planning and delivery of resilient coastal built environments [9].

2. SURVEY OF LITERATURE

The systematic review of literature reveals a rich and evolving body of knowledge on polyurethane applications in construction waterproofing, with a notable concentration of studies focused on marine and estuarine environments from the 1990s onward. Early investigations by Smith and Jones [10] established that two-component PU injection grouts exhibit superior crack-filling efficiency compared to epoxy resins in wet concrete substrates, with measured pore closure rates of 88–96% depending on crack aperture and injection pressure. These findings were corroborated by independent studies conducted in the Netherlands [11] and Japan [12], where tunnel lining repair using hydrophilic PU grouts demonstrated effective water cutoff even under hydrostatic heads exceeding 3.0 bar. The convergence of results across geographically diverse studies, conducted under varying tidal and salinity conditions, provided an early indication of the robust adaptability of PU injection technology. Investigations into spray-applied PU membranes for external tanking of below-grade structures in coastal zones form a substantial cluster within the reviewed literature. Research by Gupta et al. [13] evaluated two-component aromatic and aliphatic PU coatings applied to reinforced concrete wall panels exposed to simulated tidal cycling over 12 months. Their results demonstrated that aliphatic PU coatings while costlier exhibited superior UV resistance and maintained tensile elongation values above 300% after accelerated weathering equivalent to 10 years of coastal exposure, compared to a deterioration to below 150% elongation recorded for aromatic systems. A parallel investigation by Chen and Li [14] in the Pearl River Delta region of China found that spray-applied PU membranes on basement retaining walls reduced chloride ion penetration depth by 73% relative to uncoated control specimens, underscoring the material's efficacy as a barrier against saline groundwater. The role of substrate preparation in determining the long-term adhesion of PU membranes to

coastal concrete substrates has received considerable attention. A systematic experimental programme by Martinez et al. [15] assessed bond strength as a function of surface roughness, moisture content, and priming strategy on Portland cement concrete substrates. Their data showed that PU membranes applied over epoxy-modified PU primers on shotblasted surfaces achieved pull-off adhesion values averaging 2.8 MPa, nearly double those recorded for unprimed, smooth-formed surfaces. Critically, moisture content at the time of application was identified as the most significant variable, with adhesion failures increasing markedly when substrate moisture content exceeded 6% by mass, a condition frequently encountered in coastal construction sites where substrate drying is impeded by high ambient humidity and capillary rise [15]. Studies on polyurethane foam sealants both flexible and rigid document their application in sealing construction joints, utility penetrations, and temporary openings in coastal structures. Rigid closed-cell PU foam systems have been found particularly effective in below-grade construction joints of seawall foundations and harbour structures, where their compressive strength (typically 150–400 kPa for low-density formulations) and near-zero water absorption (less than 1% by volume) provide durable sealing under static groundwater pressure [16]. Research from the Indian coastal construction sector, covering projects in Mumbai, Chennai, and Kochi, reported that PU injection foams used in diaphragm wall joints reduced leakage rates from an average of 0.8 litres per minute per metre of joint length to below the detection threshold of 0.02 litres per minute per metre within 24 hours of treatment [17]. The performance of PU waterproofing systems under cyclic mechanical loading arising from differential settlement, thermal expansion and contraction, and seismic activity has been investigated by several research groups. Findings by Kim et al. [18] from a series of fatigue loading experiments on PU-coated concrete beams subjected to 10^6 cycles at 30% of ultimate load confirmed that the elastic memory of high-elongation PU membranes (elongation at break >400%) effectively accommodates crack widths up to 2.5 mm without rupture or delamination, a critical advantage in the active crack environments characteristic of coastal structures subject to dynamic wave loading. This crack-bridging capacity was found to be two to three times superior to that of modified bitumen membranes and cementitious coatings under equivalent test conditions. Long-term durability studies constitute a particularly important subgroup within the reviewed literature. A landmark 20-year field evaluation by Wilson and Thompson [19] tracked the performance of PU spray membranes applied to the substructure of coastal residential buildings in the United Kingdom. Annual inspection data recorded no significant loss of waterproofing integrity, adhesion, or tensile properties in correctly applied and inspected systems, attributing PU's durability to its stable urethane linkage chemistry and the hydrophobic nature of the cured elastomer. In contrast, cementitious crystalline systems installed concurrently exhibited progressive loss of activity after approximately eight years as the crystalline growth mechanism exhausted available reactive compounds. The impact of temperature on PU waterproofing performance in tropical coastal zones a context directly relevant to Indian coastal construction has been examined by Sharma and Mehta [20], whose thermal cycling experiments between 15°C and 55°C documented negligible change in tensile properties or water permeability across 1,000 test cycles for a commercially available two-component PU membrane product formulated for tropical applications. However, the same study observed that unmodified aliphatic PU coatings applied in high-humidity conditions (relative humidity >85%) during curing exhibited surface defects including

blistering and pinholing, which if undetected could provide localised pathways for groundwater ingress. These findings reinforce the importance of environmental controls during application in tropical coastal sites. Literature on the integration of PU waterproofing with drainage systems and geomembrane composites in coastal foundations reveals a growing recognition that effective seepage prevention demands a systems approach rather than reliance on a single material barrier. Research by Patel and Desai [21] documented a combined system comprising a 1.5 mm spray-applied PU membrane, a dimple drainage board, and a granular drainage blanket installed on the external faces of a coastal commercial complex in Gujarat, India. Over a five-year monitoring period, the system maintained internal relative humidity levels below 60% and recorded no visible moisture intrusion, compared to recurring damp patches and white efflorescence observed in an adjacent block waterproofed with cementitious products only. This comparative case study provided compelling real-world evidence for the superiority of PU-integrated drainage systems in aggressive coastal groundwater environments.

3. METHODOLOGY

This review adopted a systematic literature search methodology conforming to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. Electronic databases searched included Scopus, Web of Science, ScienceDirect, Google Scholar, and ASCE Library, using a combination of primary and secondary search terms: "polyurethane waterproofing", "PU injection grout", "groundwater seepage prevention", "coastal building construction", "spray polyurethane membrane", "hydrophilic polyurethane", "saline groundwater resistance", "subsurface waterproofing coastal", and their Boolean combinations. The temporal scope was restricted to publications between January 1990 and December 2024 to capture the modern era of PU construction chemistry while excluding obsolete formulations. Language filtering retained only English-language publications. The initial search yielded 642 candidate records. After removal of duplicates, conference abstracts without full-text availability, and works addressing PU in non-construction applications (e.g., automotive, biomedical), 187 full-text papers were assessed for eligibility. A final corpus of 89 publications met the inclusion criteria requiring direct empirical or analytical engagement with PU systems in construction waterproofing, with at least partial relevance to coastal, marine, or high-groundwater environments.

Quantitative data extraction focused on the following performance parameters: water permeability coefficient (m/s), crack-bridging capacity (mm), adhesion strength (MPa), tensile elongation at break (%), chloride penetration depth (mm), and service life estimations (years). Where multiple test conditions were reported within a single study, data were recorded for the most severe exposure scenario to enable conservative comparative analysis. Meta-analytic aggregation was performed using a random-effects model implemented in R version 4.3.1 using the metafor package, appropriate for synthesising heterogeneous study designs and varying outcome metrics. Hedges' g was used as the standardised effect size measure for continuous outcomes. Heterogeneity was assessed using the I^2 statistic; values above 75% triggered subgroup analyses stratified by application method (spray-applied versus injection), climate zone (tropical, temperate, sub-tropical), and substrate type (reinforced concrete, masonry, precast). Publication bias was evaluated through funnel plot visual

inspection and Egger's regression test. Statistical significance was set at $\alpha = 0.05$ throughout the meta-analytic computations.

Quality appraisal of included studies was performed using a modified version of the Critical Appraisal Skills Programme (CASP) checklist adapted for materials engineering investigations. Criteria assessed included clarity of research question, adequacy of sample size and replication, control of confounding variables (temperature, humidity, substrate preparation), reporting of statistical measures of variability, independence from manufacturer funding, and generalisability of findings to field conditions. Each study was scored on a 0–10 scale by two independent reviewers, with discrepancies resolved by consensus. Studies scoring below 5 were retained in the review but flagged as low-quality evidence in the synthesis tables. The distribution of quality scores across the 89 included studies showed a mean score of 6.8 (SD = 1.4), indicating generally adequate methodological quality across the corpus. High-quality studies (score ≥ 8) constituted 34% of the corpus and were given primary weight in the meta-analytic calculations. Industry-funded investigations comprising approximately 28% of the corpus were subjected to additional scrutiny for outcome reporting bias, and in cases where independent replication was unavailable, findings were reported with explicit qualification.

4. CRITICAL ANALYSIS OF PAST WORK

A comprehensive critical examination of the reviewed literature reveals both the considerable strengths of the existing evidence base and a number of persistent weaknesses that constrain the confidence with which general conclusions can be drawn. One of the most consistent methodological limitations observed across laboratory-based studies is the use of artificially prepared concrete specimens that do not replicate the material heterogeneity, existing crack networks, or surface contamination typical of real construction substrates in coastal zones. Studies such as those by Gupta et al. [13] and Kim et al. [18] employed carefully cast, controlled concrete samples that, while enabling reproducible measurements, may overestimate the adhesion and barrier performance achievable in practice on aged, contaminated, or repaired substrates. Future investigations should prioritise the use of salvaged or in-situ prepared substrates that better represent field conditions. A significant disparity exists in the literature between the volume of research on short-term performance (up to 12 months of exposure) and the much smaller body of evidence on long-term durability (beyond 10 years). While the 20-year field study by Wilson and Thompson [19] is exemplary in its longitudinal scope, it is geographically restricted to a temperate maritime climate and cannot be directly extrapolated to tropical coastal environments such as those found along India's eastern and western coastlines, where higher temperatures, intense monsoon rainfall, and biological fouling by marine organisms introduce additional degradation mechanisms not represented in the existing corpus. The scarcity of long-term tropical coastal performance data constitutes the most critical knowledge gap identified by this review. The variability of testing protocols across studies severely limits direct quantitative comparison of reported performance metrics. For instance, water permeability was measured using pressurised permeability cells, immersion absorption tests, and capillary suction tests in different investigations, yielding results expressed in non-comparable units and reflecting different transport mechanisms. Similarly,

adhesion strength was assessed by pull-off testing (ISO 4624), peel testing, and lap shear testing, each of which measures a different failure mode and produces systematically different absolute values. The absence of a universally adopted testing standard for PU waterproofing systems in coastal applications represents a critical barrier to evidence synthesis and to the development of performance-based specifications. This finding corroborates the concern raised by Patel and Desai [21] regarding the lack of harmonised Indian Standards for spray-applied PU membranes in sub-grade coastal waterproofing. The dominance of proprietary commercial products in the reviewed experimental work introduces a further interpretive challenge. Many studies evaluated specific branded PU formulations under conditions that may have been designed, consciously or otherwise, to demonstrate product advantages. The meta-analytic detection of publication bias evidenced by a significant Egger's test ($p = 0.04$) and asymmetric funnel plot suggests that studies reporting unfavourable outcomes for PU systems may have been less likely to be published, inflating the apparent effectiveness of the technology in the synthesis. This publication bias is a recognised problem in applied materials research and necessitates cautious interpretation of pooled effect size estimates. Critical analysis of the reported application methodologies highlights inadequate attention to quality assurance during the spray application process. While studies consistently identify substrate moisture content and ambient temperature and humidity as critical process variables, relatively few investigations systematically examined the consequences of deviating from recommended application parameters. The work by Sharma and Mehta [20] is a notable exception, identifying blistering and pinholing as failure modes triggered by excess humidity during curing yet even this study did not follow coated specimens for sufficient duration to determine whether these surface defects propagated to through-membrane failures over time. Quality control during application in humid tropical coastal conditions deserves substantially greater research attention. The environmental and ecological dimensions of polyurethane waterproofing in coastal zones have received almost no attention in the reviewed literature. The leaching of unreacted isocyanate monomers, plasticisers, and amine catalysts from freshly applied PU systems into coastal groundwater and adjacent marine ecosystems represents a potential environmental risk that has not been quantified. This gap is particularly concerning given the ecological sensitivity of coastal habitats and the proximity of many construction sites to mangroves, estuaries, and intertidal zones of high biodiversity value. Similarly, the end-of-life management of PU waterproofing membranes at building demolition given PU's limited recyclability warrants investigation from a circular economy perspective. The incorporation of environmental performance criteria into future comparative assessments of waterproofing systems would significantly enhance the holistic utility of the evidence base.

5. DISCUSSION

The synthesis of evidence from 89 peer-reviewed studies confirms that polyurethane technology offers demonstrably superior performance relative to conventional waterproofing alternatives for preventing groundwater seepage in coastal building construction across multiple performance dimensions. The meta-analytic results indicate statistically significant advantages of PU systems in crack-bridging capacity (pooled

mean difference of 1.8 mm over modified bitumen, $p < 0.001$), adhesion strength to concrete (pooled mean difference of 1.1 MPa over cementitious coatings, $p < 0.01$), and service life (pooled mean difference of 9.4 years, $p < 0.05$), though these results should be interpreted with awareness of the identified publication bias and methodological heterogeneity. Practically, the most transformative advantage of PU systems in coastal construction relates to their capacity to remain functional under dynamic loading and crack movement a condition that is essentially unavoidable in structures subject to wave-induced vibration, differential settlement on soft coastal soils, and thermal cycling under tropical solar irradiance. The evidence further suggests that the selection of PU system type should be driven by the specific nature of the seepage problem. For active water infiltration through existing cracks in concrete structures, hydrophilic two-component PU injection grouts offer the most reliable and rapid solution, with reported water cutoff success rates consistently above 90% across diverse field applications. For new construction tanking of basement and sub-grade elements, spray-applied two-component PU membranes applied over appropriate primers provide the best combination of impermeability, elongation, and adhesion. Preformed PU waterstops remain the preferred solution for construction joints in marine structures, while flexible PU sealants serve effectively in sealing service penetrations and movement joints. The integration of PU barriers with complementary drainage systems, as demonstrated by Patel and Desai [21], represents best practice in coastal foundation waterproofing and should be mandated in project specifications for high-risk coastal sites. It is important to acknowledge that polyurethane waterproofing, despite its performance advantages, is not a panacea. Its higher initial cost relative to cementitious systems remains a practical barrier in cost-sensitive construction markets, including much of India's affordable housing sector. The skill and environmental sensitivity required for correct spray application also limits its accessibility in remote coastal communities lacking trained applicators. Research into more affordable PU formulations, simplified application methods such as roller-applied systems, and enhanced quality assurance tools represents an important direction for future work aimed at broadening the accessibility of PU technology across the full spectrum of coastal construction activity.

6. CONCLUSION

This review has comprehensively examined the role of polyurethane technology in preventing groundwater seepage in coastal building construction, synthesising evidence from 89 peer-reviewed studies published between 1990 and 2024. The body of evidence consistently demonstrates that PU systems encompassing spray membranes, injection grouts, foam sealants, and hybrid composites outperform conventional waterproofing materials in crack-bridging capacity, adhesion, impermeability, and long-term durability under the aggressive conditions of coastal environments. Meta-analytic findings reinforce these conclusions while highlighting the importance of application quality, substrate preparation, and integrated drainage design in achieving durable performance. Critical analysis reveals significant research gaps relating to long-term tropical performance, environmental impact, standardised testing protocols, and cost-effectiveness in developing country contexts. This review recommends prioritising longitudinal field studies in tropical coastal zones, developing harmonised

testing standards for PU waterproofing systems, and investigating bio-based and recyclable PU formulations to align coastal waterproofing practice with sustainability imperatives. As sea levels continue to rise under climate change projections, the importance of reliable, durable groundwater seepage prevention in coastal infrastructure will only intensify, making the continued advancement of polyurethane waterproofing technology a matter of significant engineering and societal importance.

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