AJIE - Asian Journal of Innovation and Entrepreneurship
(e-ISSN: 2477-0574; p-ISSN: 2477-3824)
Vol. 09, Issue. 02, May 2025
DOI: 10.20885/ajie.vol9.iss2.art4

A Review of Leaching and Abrasion Behavior of Pervious Concrete

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ABSTRACT

The durability of pervious concrete is threatened by the phenomena of leaching (chemical dissolution) and abrasion (mechanical wear). This systematic literature review analyzes studies from Scopus (2019–2024), utilizing keywords such as “pervious concrete” or “porous concrete”, “leaching”, and “abrasion”. Articles were selected based on open access, peer-review status, and relevance to experimental/theoretical data. Leaching, primarily driven by the dissolution of calcium from portlandite and C-S-H phases, weakens the cement matrix and increases porosity. Meanwhile, abrasion is physical wear resulting from mechanical forces that erode the cement paste and lead to aggregate dislodgement. Critically, leaching and abrasion interact synergistically in a self-reinforcing degradation cycle: leaching weakens the matrix, making it more susceptible to abrasion, while abrasion exposes fresh material, accelerating further leaching. Although material optimization (e.g., angular aggregates and silica fume additives) and controlled carbonation curing can mitigate degradation, significant research gaps persist. Notably, there is a lack of systematic investigation to optimize cement-aggregate ratios for simultaneous leaching and abrasion resistance, as well as a scarcity of standardized coupled degradation test protocols. To address this gap, a systematic investigation is needed to optimize the sand-to-cement ratio in concrete filters, balancing durability (including resistance to fluid friction during backwashing) with sustained filtration capacity. This is crucial for developing pervious concrete as a sustainable and durable urban solution.

Keywords: Abrasion, Durability, Leaching, Pervious Concrete, Sustainability

1. Introduction

Pervious concrete is characterized by high permeability and reduced compressive strength compared to conventional structural concrete and has gained recognition as a sustainable urban drainage solution due to its ability to mitigate stormwater runoff (Akkaya & Çağatay, 2021; El-Hassan et al., 2019). Recent advancements in pervious concrete technology have demonstrated its efficacy in water quality enhancement through the adsorption and retention of particulate contaminants within its interconnected void network (Yogafanny et al., 2023, 2024).

However, the porous structure faces durability challenges, notably leaching and abrasion. Leaching occurs when dissolved cementitious compounds, such as calcium hydroxide, are progressively solubilized under continuous hydraulic exposure, leading to material degradation and environmental contamination (Hua et al., 2021; Yogafanny et al., 2023). Concurrently, mechanical abrasion—induced by surface friction or impact forces—weakens the bond between aggregates and cement paste, compromising structural integrity and accelerating mass loss (Guo et al., 2020; Mikami et al., 2020).

Over the past five years, innovations to mitigate these issues have focused on mix design optimization. These include partial aggregate replacement with recycled or high-strength materials (Fei et al., 2024; Hua et al., 2021; Zhang & Gao, 2019), aggregate surface coatings to enhance interfacial bonding (Yu et al., 2022), and the adoption of alternative binders such as geopolymers and limestone calcined clay (Furkan Ozel et al., 2022; Lee et al., 2024). Additionally, the incorporation of micro-fillers (e.g., silica fume) or fibers (e.g., polypropylene, steel) has been explored to improve mechanical resilience (El-Hassan et al., 2019; Guo et al., 2019), while hybrid strategies combining multiple approaches have shown synergistic benefits in durability enhancement (El-Hassan et al., 2019; Fei et al., 2024).

Through a systematic literature review, the compositional and mechanical factors influencing leaching and abrasion in pervious concrete were analyzed. The degradation mechanisms—including chemical dissolution kinetics, abrasive wear patterns, and environmental interactions—were critically evaluated to establish a comprehensive understanding of material behavior. These findings are expected to provide a roadmap for researchers to address existing gaps and anticipate emerging challenges in porous concrete durability.

2. Research Method

This review employed a Systematic Literature Review (SLR) framework, utilizing the Scopus database as the primary source due to its multidisciplinary coverage of high-impact journals, advanced search precision, and quality assurance via peer-review exclusivity. Scopus was prioritized over alternatives like Web of Science (limited engineering-environmental overlap) and Google Scholar (includes non-peer-reviewed sources) for three reasons: comprehensive coverage, advanced search precision, and quality assurance.

A keyword search strategy combining *"pervious concrete" OR "porous concrete"*, *"abrasion"*, and *"leaching"* was implemented to retrieve relevant articles. Initial results were filtered by publication year (2019 to early 2024) to prioritize recent advancements. Duplicate entries were removed, and only open-access articles or those accessible via Universitas Gadjah Mada's institutional network, published in English, were retained.

Abstracts were evaluated against predefined eligibility criteria (see Table 1), focusing on studies that explicitly addressed leaching/abrasion mechanisms, included experimental or theoretical data, and examined pervious or filter concrete. Articles unrelated to degradation mechanisms or focused on non-porous concrete were excluded.

Table 1. Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Focuses on abrasion or leaching in pervious concrete	Does not specifically address abrasion/leaching
Includes experimental or theoretical data	Lacks experimental/theoretical data
Published in peer-reviewed journals	Focuses on irrelevant aspects (e.g., structural compressive strength, general permeability)
Examines pervious or filter concrete	Studies non-porous or conventional concrete

Following this process, 35 articles were retained for analysis: 27 primary studies addressing leaching/abrasion mechanisms and 8 secondary studies providing theoretical context or historical benchmarks. The temporal distribution of these publications, spanning 1992 to 2025, is illustrated in Figure 1.

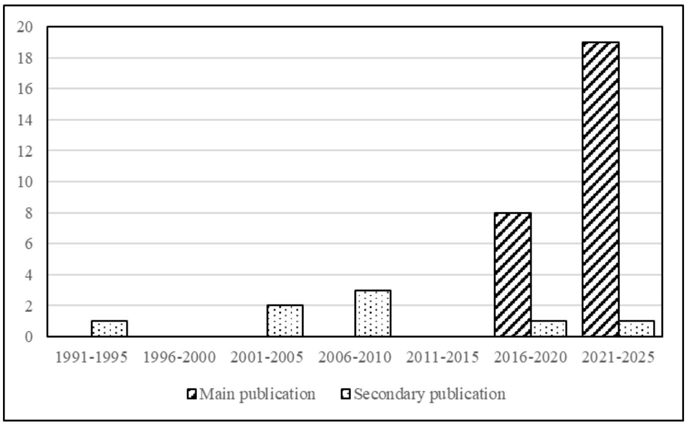

Figure 1. Temporal Distribution of Selected Articles (1992–2025)

Relevant data—including authors, publication year, methodology, and key findings—were systematically extracted from the selected articles. Thematic analysis was conducted to identify trends in material composition, environmental influences, and degradation mechanisms. Secondary studies were integrated to address knowledge gaps and ensure a comprehensive synthesis of findings.

3. Results and Discussion

3.1. Material Composition and Material Preparation Effect on Leaching dan Abrasion Behavior

Leaching in pervious concrete is governed by its hydraulic characteristics, where interconnected pores facilitate extended exposure between infiltrating water and dissolved calcium hydroxide compounds. These reactions occur both at the surface and within internal voids, which form due to heterogeneous aggregate distribution during compaction and water evaporation during curing. Critical hydraulic properties such as porosity and permeability are directly influenced by aggregate size, aggregate gradation, cement-to-aggregate ratio, compaction methods, and curing conditions.

3.1.1. Leaching Indicators and Effluent Analysis

Parameters including pH, Total Dissolved Solids (TDS), calcium ions (Ca^{2+}), and Total Hardness (TH) serve as key indicators for assessing leaching potential in pervious concrete. Following hydraulic permeation through pervious concrete, effluent streams exhibited elevated levels of these parameters. Baseline influent water characteristics were documented as follows: pH 6.7 – 7.5, TDS 87 – 119.5 mg/L, Ca2+ 15.84 – 25.6 mg/L, dan TH 27.72 – 69.3 mg/L (Yogafanny et al., 2024).

As illustrated in Table 2, sand-cement weight ratios showed negligible correlation with leaching intensity, whereas specimen thickness critically influenced effluent alkalinity due to higher cement content in thicker specimens promoting hydration product dissolution (Yogafanny et al., 2024).

Table 2. Leaching indicators in effluent under varying sand-cement ratios.
Source: (Yogafanny et al., 2024)

Sand – cement ratio	pH	TDS (mg/L)	Ca^{2+} (mg/L)	TH ($CaCO_3$) (mg/L)
4	7.5 – 8.5	109.3 – 119.5	25.6 – 32.77	46.08 – 61.44
5	7.1 – 9	109.4 – 133.6	24.58 – 40.96	43.52 – 66.56

3.1.2. Carbonation Curing: Dual Effects on Durability

Carbonation curing requires optimal water proportions to stabilize hydration products, as hydration quality depends on curing duration and carbonation levels (T. Chen & Gao, 2020). Experimental studies have demonstrated that 6-hour carbonation curing in a carbonation reactor maximizes pore stability in pervious concrete, particularly under combined leaching and freeze-thaw cycling (T. Chen & Gao, 2020). However, prolonged carbonation (24 hours) increases cement paste brittleness, especially during extended leaching exposure (10–15 days) across 56 freeze-thaw cycles, indicating C-S-H matrix destabilization due to synergistic chemical-mechanical degradation (T. Chen & Gao, 2020).

Chemically, carbonation curing transforms water-soluble calcium hydroxide (CH) into insoluble calcium carbonate ($CaCO_3$). This conversion densifies the cement paste by filling micropores, reducing permeability, and inhibiting water diffusion—key factors in mitigating leaching (T. Chen & Gao, 2020). Despite enhancing durability through pore stabilization, excessive carbonation disrupts hydration equilibrium, accelerating structural degradation.

3.1.3. Aggregate Characteristics and Abrasion Resistance

Pumice aggregate exhibited relatively inferior abrasion resistance compared to basalt, limestone, and travertine aggregates due to their porous and structurally weak composition (Furkan Ozel et al., 2022). By comparison, pervious concrete specimens incorporating limestone and travertine aggregates demonstrated superior wear resistance, achieving the lowest volumetric loss during abrasion testing (Furkan Ozel et al., 2022). Aggregate size also significantly influenced abrasion resistance, with smaller, uniformly graded fractions (5–12 mm) outperforming larger or mixed-size aggregates (Furkan Ozel et al., 2022; Spoorthy et al., 2023).

Notably, aggregate size critically influences mass loss during abrasion, with larger aggregates (8–16 mm) experiencing up to 22% greater mass reduction than smaller fractions (5–12 mm) (Ferić et al., 2023). Specimens combining natural aggregates (smallest fraction) and high binder intensity achieved a 15.4% mass loss at 300 abrasion cycles, whereas hybrid natural-recycled aggregate mixes exhibited accelerated wear (25% mass loss at 150 cycles) (Bai et al., 2024; Ferić et al., 2023). Abrasion resistance was further modulated by compaction methods. Specimens compacted using a 25-drop mechanical compactor showed 18% lower mass loss than those manually tamped, attributable to enhanced aggregate-cement paste bonding and reduced void heterogeneity (Ferić et al., 2023).

3.1.4. Cement-Aggregate Ratio: Dual Impact on Leaching and Abrasion

While the cement-aggregate ratio showed negligible correlation with leaching intensity, it critically affected abrasion resistance. Lower ratios (e.g., 1:5) reduced volumetric loss by 12–15% compared to higher ratios (1:3), though this effect diminished with increasing aggregate size (Akkaya & Çağatay, 2021).

3.1.5. Key Variables in Leaching and Abrasion

Leaching in pervious concrete was predominantly governed by specimen thickness and curing conditions, as evidenced by effluent parameter analysis (pH, TDS, Ca^{2+}, TH) (T. Chen & Gao, 2020; Yogafanny et al., 2024). Conversely, abrasion resistance depended on aggregate hardness, gradation, compaction method, and cement-aggregate ratio (Akkaya & Çağatay, 2021; Bai et al., 2024; Ferić et al., 2023; Furkan Ozel et al., 2022; Spoorthy et al., 2023). Although individual aspects of mix design influencing leaching (T. Chen & Gao, 2020; Yogafanny et al., 2024) and abrasion (Akkaya & Çağatay, 2021; Ferić et al., 2023; Furkan Ozel et al., 2022) have been explored, a comprehensive and systematic investigation into the proportional cement-aggregate ratios specifically aimed at optimizing both concurrent leaching and abrasion resistance is lacking. This highlights a critical research gap.

3.2. Environmental Effect on Leaching and Abrasion Behavior

The durability and microstructural stability of pervious concrete are critically influenced by external environmental factors. Leaching is governed by wet-dry cycles, influent characteristics, and atmospheric carbonation, while abrasion is exacerbated by mechanical friction from vehicular traffic.

3.2.1. Wet-Dry Cycling and Mechanical Degradation

Wet-dry cycles exhibited negligible impact on crack propagation but significantly reduced compressive strength in pervious concrete (Zhang et al., 2022). Mass loss peaked at 2.36% during cycles 5–12, with marginal losses (0.98–2.36%) observed over a 44-day testing period, indicating progressive material degradation under cyclic hydraulic exposure (Zhang et al., 2022).

3.2.2. Influent Characteristics and Leaching Dynamics

Influent water quality directly modulates leaching behavior. Comparative analysis of effluent parameters from pervious concrete filters (sand-cement weight ratio: 4; thickness: 5 cm) under different influents is summarized in Table 3. Leaching tests conducted via filtration column methods revealed that effluent alkalinity (pH 7.5–9.33), TDS (9–119.5 mg/L), and Ca^{2+} concentrations (1.4–32.77 mg/L) varied significantly across influent sources, including irrigation water (Kalitirto), urban drainage (Selokan Mataram), and deionized water (Yogafanny et al., 2023, 2024).

Table 3. Effluent water quality under varying influent sources.
Source: (Yogafanny et al., 2023, 2024).

Aggregate size (mm)	Influent water sources	pH	TDS (mg/L)	Ca^{2+} (mg/L)	TH ($CaCO_3$) (mg/L)
0.6 – 0.85	Selokan Mataram	7.5 – 8.5	109.3 – 119.5	25.6 – 32.77	46.08 – 61.44
0.425 – 0.85	Irrigation water Kalitirto	7.09 – 8.62	98 – 107	12.86 – 19.3	68.34 – 75.38
0.425 – 0.85	Distilled water	8.54 – 9.33	9 – 18	1.4 – 2.6	4.5 – 8

Notably, leaching efficiency in irrigation water was hindered by impurities (TDS: 98 mg/L; Ca^{2+}: 16.08 mg/L), whereas deionized water—a potent decalcifying agent—induced severe calcium dissolution (Ca^{2+}: 1.4–2.6 mg/L) due to its purity (Adenot & Buil, 1992; Yogafanny et al., 2023).

3.2.3. Behavior Atmospheric Carbonation and Chemical Degradation

Atmospheric carbonation drives the reaction of CO_2 with cement hydration products, converting portlandite ($Ca(OH)_2$) and calcium silicate hydrate (C-S-H) into calcite ($CaCO_3$) (Garrabrants et al., 2004; Van Gerven et al., 2007). The consumption of calcium hydroxide by carbonic acid lowers the pH of the cement paste (Muthu et al., 2019), which promotes the dissolution of unhydrated cement phases and leaching of carbonate compounds and alkalis (Na and K) from the concrete filter (Fernández Bertos et al., 2004; Muthu et al., 2019; Yin et al., 2018). This pH reduction, combined with the dissolution of hydration products, increases porosity and permeability, accelerating water infiltration and ion transport (Huang et al., 2025; Yin et al., 2018).

Environmental factors like humidity, temperature, and moisture availability intensify carbonation rates, further enhancing leaching (Vivek et al., 2023). The resulting porosity not only weakens the concrete's structural integrity—leading to cracks and surface peeling—but also creates pathways for aggressive agents to penetrate deeper layers, perpetuating a cycle of degradation (Huang et al., 2025). These combined effects underscore how atmospheric carbonation exacerbates leaching, compromising both the durability and functional performance of pervious concrete in stormwater applications (Muthu et al., 2019; Yin et al., 2018).

3.2.4. Mechanical Abrasion: Mechanisms and Traffic-Induced Wear

Abrasion in pervious concrete refers to the physical wear of its surface due to cyclically recurring dynamic forces and friction (Lenka et al., 2020). Friction gradually erodes the cement paste layer enveloping aggregates, exposing aggregate fractions to direct mechanical stress and eventual dislodgement. Specimen edges exhibited initial wear after 150 wheel-tracking cycles, with significant aggregate segregation observed as cycle counts increased (Bai et al., 2024).

3.2.5. Integrated Environmental Impact on Degradation

Leaching and abrasion in pervious concrete are demonstrably influenced by environmental exposure. Leaching is driven by wet-dry cycles, atmospheric carbonation, and influent water quality, with long-term cumulative effects necessitating consideration despite minimal short-term damage. Conversely, abrasion is predominantly governed by mechanical factors such as vehicular traffic volume, which dictates the frequency and intensity of surface wear.

3.3. Synergistic Mechanisms of Leaching, Abrasion, and Their Interplay in Pervious Concrete

3.3.1. Leaching Mechanisms

Leaching, a critical degradation mechanism in pervious concrete, is fundamentally a decalcification process driven by the dissolution of calcium-rich phases such as portlandite ($Ca(OH)_2$) and calcium-silicate-hydrate (C-S-H). This chemical degradation occurs when water or low-pH solutions infiltrate the permeable porous structure of pervious concrete, dissolving calcium ions and destabilizing the cementitious matrix over time (J. J. Chen et al., 2006; Youssari et al., 2023). The process begins with hydrolysis, where water or acidic agents react with cement hydrates, releasing soluble Ca^{2+} ions through a series of reactions (Equations 1 – 4) (Overmann et al., 2021; Yogafanny et al., 2023; Youssari et al., 2023).

Formation of carbonic acid

$$H_2O + CO_2 \leftrightarrow H_2CO_3 \tag{1}$$

Dissolved calcium hydroxide

$$2H_2CO_3 + Ca(OH)_2 \leftrightarrow Ca(HCO_3)_2 + 2H_2 \tag{2}$$

Calcium carbonate is formed

$$Ca(HCO_3)_2 + Ca(OH)_2 \leftrightarrow 2CaCO_3 + 2H_2O \tag{3}$$

Dissolved calcium carbonate

$$2CaCO_3 + H_2CO_3 \leftrightarrow Ca(HCO_3)_2 \tag{4}$$

These reactions propagate through a diffusion-dissolution mechanism: aggressive solutions (e.g., carbonic acid from CO_2) penetrate the concrete surface (Equation 1), while dissolved calcium diffuses outward, leaving behind a porous, weakened structure (Overmann et al., 2021). Over time, calcium depletion reduces the Ca/Si ratio in C-S-H gels below 1.2, triggering irreversible shrinkage and transforming stable hydrates into fragile silica gel (J. J. Chen et al., 2006). The resultant porosity not only accelerates further leaching but also primes the surface for mechanical degradation.

The interplay between leaching and abrasion exacerbates structural degradation. As leaching strips calcium from the cement paste (Equations 2 – 4), the matrix loses cohesion, exposing aggregates and increasing surface roughness. This weakened surface becomes highly susceptible to mechanical abrasion from traffic or environmental forces, which further erodes the material and exposes fresh layers to leaching.

Simultaneously, leaching-induced porosity facilitates deeper water infiltration, accelerating calcium dissolution and creating a self-reinforcing cycle of decay (J. J. Chen et al., 2006; Youssari et al., 2023). The combined effects compromise load-bearing capacity, reduce durability, and amplify shrinkage—phenomena akin to carbonation-induced degradation (J. J. Chen et al., 2006). Such synergies underscore the vulnerability of pervious concrete to environmental and mechanical stressors, necessitating strategies to mitigate leaching while preserving its permeable functionality.

3.3.2. Abrasion Mechanisms

Abrasion manifests as physical wear caused by cyclic mechanical forces, such as vehicular traffic, which erode the cement paste layer binding aggregates. Continuous abrasion weakens the interfacial transition zone (ITZ), leading to aggregate dislodgement and mass loss. Experimental studies using wheel-tracking tests demonstrated that specimens subjected to 150 cycles exhibited surface pitting and elliptical pore deformation, with aggregate segregation intensifying at higher cycle counts (Bai et al., 2024). While short-term abrasion rates may decline due to the loss of unstable surface aggregates, long-term structural integrity is compromised. For instance, high-binder mixes incorporating angular aggregates and polypropylene fibers (0.5% by volume) showed 20–35% lower mass loss compared to conventional mixes, underscoring the role of material composition in mitigating abrasion (Bai et al., 2024; Ferić et al., 2023).

3.3.3. Synergistic Mechanisms of Leaching, Abrasion, and Their Interplay in Pervious Concrete

Leaching and abrasion in pervious concrete interact synergistically, creating a self-reinforcing degradation cycle. Leaching weakens the cement matrix through calcium dissolution from portlandite ($Ca(OH)_2$) and calcium-silicate-hydrate (C-S-H), increasing surface roughness and aggregate exposure. This weakened surface becomes susceptible to mechanical abrasion, as observed in studies where leached specimens exhibited accelerated aggregate dislodgement under vehicular traffic simulations (Bai et al., 2024; Youssari et al., 2023)

Conversely, abrasion erodes the protective cement paste layer, exposing fresh, unweathered hydrates to infiltrating water and carbonic acid. This exposure intensifies calcium dissolution and promotes the formation of brittle calcite ($CaCO_3$) through carbonation (Cao et al., 2023). While calcite temporarily densifies the matrix, prolonged exposure to acidic environments dissolves these deposits (Equation 4), further increasing porosity and permeability (Ma et al., 2023).

The equilibrium shift caused by calcium leaching triggers continuous dissolution of portlandite to replenish pore solution Ca^{2+} levels, as confirmed by long-term leaching experiments (Bilal et al., 2021). Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS) analysis of specimens exposed to hydraulic flow revealed significant calcium depletion and textural changes, exposing underlying calcium-alumina-silicate-hydrate (C-A-S-H) layers (Banevičienė et al., 2022). This synergy compromises structural integrity through mass loss and pore clogging by calcite and abrasion debris, reducing both load-bearing capacity and permeability. The cyclic degradation underscores the need for material designs that address coupled chemical-mechanical resilience.

4. Conclusions

This study systematically reviewed the current understanding of pervious concrete degradation, focusing on leaching and abrasion. Leaching is primarily governed by the material's hydraulic properties and characterized as a decalcification process that destabilizes the cementitious matrix, leading to porosity and increased susceptibility to further degradation. Key material and preparation parameters, such as aggregate characteristics, cement-to-aggregate ratio, compaction, and curing conditions, directly influence these hydraulic properties and thus leaching behavior.

Beyond inherent material properties, external environmental factors significantly impact durability. Wet-dry cycling causes strength reduction and mass loss, while influent water quality directly modulates leaching, with purer water inducing more severe calcium dissolution. Atmospheric carbonation critically contributes to chemical degradation by transforming cement hydration products, reducing pH, and increasing porosity, thereby compromising structural integrity. Mechanical abrasion, driven by cyclic forces like vehicular traffic, physically wears the surface, eroding cement paste, weakening the interfacial transition zone, and causing aggregate dislodgement. Collectively, distinct environmental factors govern both leaching and abrasion, necessitating long-term consideration.

Critically, leaching and abrasion operate through a self-reinforcing degradation cycle. Leaching-induced weakening increases susceptibility to abrasion, while abrasion exposes fresh material to further leaching, intensifying dissolution. This complex interplay results in compromised structural integrity, mass loss, pore clogging, and reduced load-bearing capacity, underscoring the need for material designs addressing coupled chemical-mechanical degradation.

Despite these advancements, significant research gaps persist. Notably, a comprehensive and systematic investigation into optimizing proportional cement-aggregate ratios for pervious concrete filters, specifically balancing durability (including resistance to fluid friction during backwashing) with sustained filtration capacity, remains largely unexplored. Furthermore, the absence of standardized coupled degradation tests highlights a critical need for integrated methodologies. Addressing these gaps is essential to advance pervious concrete as a more durable and sustainable solution for urban stormwater management, balancing hydraulic performance with long-term resilience.

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