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# A Review of Frost-Salt-Mechanical Coupled Deterioration Mechanisms in Vibropressed Concrete for Pavement Applications

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**ABSTRACT:** Freeze-thaw cycling, deicing salt attack, and traffic-induced mechanical loading are major causes of durability loss in concrete pavements in cold and seasonally frozen regions. Vibropressed concrete (VPC), manufactured with low water-to-binder ratios, dry-consistency mixtures, and intensive vibration-compaction, is widely used in paving blocks, kerbs, slabs, and other precast pavement units. Although VPC often exhibits high density, dimensional stability, and early strength, its connected capillary pores, weak interfacial transition zones, and compaction-related anisotropy may make it vulnerable once moisture, salt solution, and load-induced microcracks interact. Based on the first three chapters of the existing dissertation draft, this paper reviews the deterioration mechanisms of VPC under coupled frost-salt-mechanical exposure, including freeze-thaw damage, chloride transport, deicing salt scaling, load-induced cracking, ultrasonic pulse velocity (UPV) monitoring, and predictive modelling. The review shows that the mechanisms of single-factor freeze-thaw damage, salt-frost scaling, and mechanical deterioration in ordinary concrete have been extensively studied, whereas quantitative interaction effects, early-warning UPV thresholds, and service-oriented prediction models for VPC remain


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insufficient. Future research should integrate initial material structure, coupled exposure paths, non-destructive monitoring, and multi-indicator modelling to support durability design and service-life assessment of precast concrete pavement elements in cold regions.

**Keywords:** *vibropressed concrete; freeze-thaw cycles; chloride attack; mechanical loading; ultrasonic pulse velocity; durability*

## 1 Introduction

Concrete pavements in cold and seasonally frozen regions are exposed to a complex service environment. During winter maintenance, pavement materials repeatedly experience freezing and thawing while being exposed to deicing salt solutions, most commonly sodium chloride. At the same time, traffic loading continuously acts on surface layers and precast pavement units, causing local stress concentration and microcrack initiation. These processes rarely occur independently in practice. Instead, water migration, chloride transport, ice formation, salt crystallization, and load-induced cracking interact with one another, accelerating deterioration and shortening service life.

Classical frost-resistance theories provide a foundation for understanding this problem. Powers (1945, 1954) linked frost damage to pore water freezing, hydraulic pressure, and the ability of the pore system to relieve pressure. Fagerlund (1977) further emphasized the critical degree of saturation, showing that frost damage becomes severe when the internal moisture condition exceeds the capacity of the pore network to accommodate freezing expansion. In salt environments, the problem becomes more complex because dissolved ions change freezing behavior, create osmotic gradients, and promote crystallization pressure in confined pores (Scherer, 1999; Bahafid et al., 2022).

Vibropressed concrete is an important material for pavement-related precast products such as paving blocks, kerbs, slabs, and small road units. Compared with conventional cast concrete, VPC is produced using dry-consistency mixtures, low water-to-binder ratios, and strong vibration-compaction. These features provide high early strength and industrial production efficiency, but they also introduce special durability concerns. A dense surface may delay visible damage, while connected pores, weak interfacial transition zones, and compaction-induced anisotropy can provide preferential paths for moisture and chloride ingress once cracking starts.

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For this reason, VPC durability should not be evaluated only as a conventional frost-resistance issue. It should be understood as a coupled frost-salt-mechanical problem. This review therefore synthesizes literature on VPC material characteristics, freeze-thaw damage, chloride and deicing salt effects, mechanical-load coupling, UPV-based non-destructive monitoring, and predictive modelling. The purpose is to clarify the current research foundation, identify unresolved gaps, and propose directions for a service-oriented durability framework for VPC pavement applications.

## 2 Material Characteristics and Durability Sensitivity of Vibropressed Concrete

The production process of VPC makes its durability behavior different from that of ordinary cast concrete. Conventional cast concrete depends on flowability, placement, and vibration to achieve compaction, whereas VPC relies on a dry-consistency mixture subjected to high-frequency vibration, pressure, and mold confinement. This process can produce a dense aggregate skeleton and reduce total porosity, but it may also cause insufficient paste coating, locally weak interfacial transition zones, and non-uniform pore distribution related to the compaction direction.

The dense structure of VPC has a dual meaning. On the one hand, low water content and high compaction can delay the ingress of moisture and chloride solution, producing favorable early strength and apparent impermeability. On the other hand, once connected capillary pores or interfacial defects exist, the dense surface may hide internal saturation and microcracking. As a result, surface appearance, mass change, UPV attenuation, and residual strength may not evolve at the same rate. This is particularly important for paving blocks and kerbs, where edge zones, corners, and surface layers are directly exposed to deicing salt solution and mechanical contact.

Recent studies on paving units, recycled aggregate paving blocks, and industrial by-product concrete show that aggregate type, gradation, supplementary cementitious materials, admixtures, and curing conditions can alter pore structure and durability performance (Hernandez et al., 2024; Malaszkiewicz et al., 2024; Alonso et al., 2025). These findings suggest that VPC durability design should not rely only on compressive strength. Water absorption, capillary connectivity, salt-frost mass loss, UPV reduction, and residual strength should be considered together.


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The initial state of VPC is also highly dependent on production parameters. Compaction energy, mold boundary conditions, vibration time, demolding time, and early curing humidity affect the closure of pores and the quality of the surface layer. Even when two mixtures have similar proportions, different forming procedures may lead to different freeze-thaw and salt-frost responses. Therefore, when comparing VPC durability studies, it is necessary to examine not only the final deterioration results but also the preparation process and initial material properties.

## 3 Freeze-Thaw Damage Mechanisms

Freeze-thaw deterioration is one of the most widely studied durability problems in cementitious materials. At the microscopic level, damage is related to hydraulic pressure, osmotic pressure, ice growth, and redistribution of unfrozen water. During cooling, water in larger pores freezes first, and ice formation expels unfrozen water into adjacent pores. When water migration is blocked or local saturation is high, tensile stress develops at the pore walls and interfacial transition zones, leading to microcrack initiation and propagation.

For VPC, freeze-thaw damage may not occur uniformly throughout the specimen. Low water-to-binder ratios and intensive compaction can reduce total porosity, yet dry-consistency mixing may produce local paste deficiency or connected capillary channels. Damage may therefore initiate at surface layers, edges, and aggregate-paste interfaces before clear external signs appear. This explains why internal indicators such as UPV or dynamic modulus may decrease earlier than visible scaling or strength loss.

Many studies describe freeze-thaw deterioration as a staged process. In the latent stage, visual damage remains slight, but stiffness and acoustic parameters begin to decline. In the accelerated stage, microcracks coalesce and increase water absorption, creating a feedback loop between transport and damage. In the structural degradation stage, mass loss, scaling, cracking, and residual strength reduction become evident (Guo et al., 2022; Guler et al., 2025). This staged model is useful for VPC because the dense surface layer can delay visible deterioration and underestimate early internal damage.

A further trend in freeze-thaw research is the movement from single strength-based evaluation to multi-indicator damage description. Mass change, relative dynamic modulus, UPV, water absorption, visual rating, pore structure, and residual compressive strength

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each capture different aspects of deterioration. For VPC pavement units, these indicators should be analyzed as time-dependent sequences rather than as isolated endpoint values.

Standard test methods provide comparability but also raise questions of applicability. ASTM C666 focuses on rapid freezing and thawing, ASTM C672 evaluates scaling under deicing chemicals, and RILEM CIF/CDF methods consider both internal damage and surface scaling. National standards such as GB/T 50082 also provide durability test procedures for ordinary concrete. However, real pavement environments involve variable temperature cycles, salt solution replenishment, drainage conditions, and traffic loading. VPC studies should therefore combine standard procedures with exposure conditions that better represent service environments.

## 4 Chloride Transport and Deicing Salt Effects

Deicing salts are a necessary but damaging component of winter road maintenance. When sodium chloride solution enters concrete pores, it changes the freezing point and freezing interval of the pore solution. During freezing, ice formation rejects dissolved ions, increasing local ion concentration and osmotic gradients. At the same time, salt crystallization in confined pores can generate pressure on pore walls. Thus, salt-frost deterioration is not simply the sum of freeze-thaw cycling and chloride exposure; it is a coupled thermodynamic and transport process.

Recent salt-frost studies show that surface scaling and internal cracking do not always develop simultaneously. Bahafid et al. (2022) revisited the role of frozen salt solution microstructure in frost salt scaling, while Luan et al. (2023) examined how the freezing characteristics of deicing salt solution influence concrete salt-frost deterioration. These studies indicate that relying only on mass loss or visible surface scaling may miss internal damage, especially in dense materials such as VPC.

Chloride transport is also modified by freeze-thaw cycling. Repeated freezing and thawing changes pore structure, expands microcracks, and increases connectivity. As a result, chloride ions may migrate not only through intact capillary pores but also through freeze-thaw-induced cracks and interfacial defects. Numerical and experimental studies show that freeze-thaw cracking can increase apparent chloride diffusivity and make transport behavior strongly time-dependent (Li et al., 2021; Wang et al., 2022).

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When mechanical damage is present, chloride transport can be further accelerated. Fatigue or sustained loading creates preferential pathways for moisture and ions, and these pathways become more active under freeze-thaw exposure. Fang et al. (2023, 2024) showed that fatigue damage can significantly alter moisture and chloride transport in concrete. For VPC pavement units, this means that traffic loading should not be treated as separate from salt-frost exposure.

Different deicing media may also produce different deterioration routes. Sodium chloride mainly affects freezing behavior and chloride transport, whereas calcium chloride and other chemicals may involve additional chemical degradation mechanisms (Haselbach et al., 2021). Airport pavements and coastal cold-region structures may experience combined effects of deicing chemicals, seawater chlorides, and freeze-thaw cycles (Sadeghi et al., 2024; Rahat & Brand, 2025). Future VPC studies should therefore select salt solutions and concentrations according to the target service scenario.

## 5 Coupled Effects of Mechanical Loading and Environmental Actions

In service, pavement concrete is continuously affected by traffic loading. Mechanical loading initiates microcracks, changes pore connectivity, and modifies the pathways available for moisture and chloride movement. Once freeze-thaw cycling and salt solution are present, load-induced microcracks become transport accelerators. Conversely, environmental damage reduces stiffness and strength, making the material more vulnerable to subsequent loading. This feedback is the core of frost-salt-mechanical coupled deterioration.

Studies on mechanical load combined with freeze-thaw cycles show that the coupling process changes both microstructure and macroscopic performance. Xu et al. (2022) reviewed concrete durability under mechanical load coupled with freeze-thaw cycles, and Xu et al. (2024) analyzed coupled damage from pore structure to energy dissipation. For pavement concrete, fatigue loading and hydrodynamic action can accelerate deterioration of strength, durability, and microstructure (Li et al., 2021; Yang et al., 2022).

The addition of chloride salts makes this coupling more severe. Dong et al. (2024) investigated transport behavior under freeze-thaw, high-frequency loading, and chloride attack, showing that complex coupled effects can enhance transport and damage. Yang et al. (2025) further studied property evolution under combined freeze-thaw, chloride salt,

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and fatigue loading. These findings demonstrate that mechanical loading is not only a structural action but also an environmental transport modifier.

For VPC, load coupling may be especially important because compaction direction, aggregate skeleton, and interfacial transition zones can guide crack development. A crack generated under load may connect initially isolated pores, allowing salt solution to enter more quickly. Once moisture and chloride accumulate, subsequent freezing can widen the same crack network. Therefore, the deterioration process is likely to be nonlinear rather than a simple addition of individual damage factors.

A key challenge is how to quantify interaction effects. If freeze-thaw cycling, salt exposure, and mechanical loading each cause a certain amount of damage, their combined result may be equal to, smaller than, or greater than the linear sum of individual effects. Existing studies often present degradation curves but do not provide a unified interaction coefficient or damage factor. For engineering use, it is not sufficient to state that coupled exposure is more severe. It is necessary to identify which factor dominates each stage of deterioration and how the dominant factor changes over time.

The loading sequence also matters. If loading is applied before salt-frost exposure, pre-existing microcracks can accelerate moisture and chloride ingress. If freezing and salt exposure occur before loading, the residual load-bearing capacity and crack propagation pattern may be different. Future VPC experiments should therefore clearly define loading level, loading order, exposure sequence, and monitoring interval so that material effects and testing-path effects can be distinguished.

**Table 1.** Summary of VPC deterioration mechanisms under coupled frost-salt-mechanical exposure

| Factor | Main process | Influence on VPC | Sensitive indicators |
|---|---|---|---|
| Freeze-thaw cycles | Pore water freezing, pressure accumulation, microcrack initiation | Dense surface may hide early internal damage | UPV, dynamic modulus, mass change |
| Chloride and deicing salts | Freezing-point depression, ion concentration, crystallization pressure, chloride transport | Edges and surface layers are vulnerable to salt-frost scaling | Mass loss, scaling grade, chloride content |
| Mechanical | Stress concentration, | Accelerates moisture | Residual strength, |

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|---|---|---|---|
| loading | fatigue microcracks, crack-assisted transport | and chloride ingress | crack development, UPV attenuation |
| Coupled exposure | Mutual reinforcement between transport and cracking | Nonlinear amplification and staged deterioration | Interaction coefficient, damage factor, prediction model |

**6 Non-Destructive Monitoring and UPV-Based Damage Assessment**

Non-destructive testing is valuable because early frost-salt damage may occur internally before visible deterioration appears. Ultrasonic pulse velocity is one of the most widely used methods for evaluating concrete integrity. ASTM C597 and EN 12504-4 provide standard procedures for pulse velocity measurement. The principle is that microcracks, pore connectivity, and interfacial defects disturb wave propagation, resulting in lower velocity or altered signal characteristics.

In freeze-thaw studies, UPV is often used together with relative dynamic modulus, mass change, visual damage, and residual compressive strength. Lv et al. (2024) analyzed freeze-thaw damage based on mechanical properties and acoustic parameters, while Zhu et al. (2021) used UPV to characterize freeze-thaw resistance of new-to-old concrete. Kim et al. (2023) also demonstrated the potential of non-contact ultrasonic sensors for detecting initial freeze-thaw damage. These studies suggest that acoustic indicators are especially useful in the latent stage of deterioration.

Nevertheless, UPV is not a universal substitute for strength testing. Moisture content, saturation degree, aggregate type, path length, coupling condition, and crack orientation all affect the measured velocity. For VPC, these influences may be stronger because dry-consistency forming and aggregate skeleton structure can cause anisotropy. Salt solution and water content may temporarily improve wave transmission even when microcracks are developing, which can mask early damage. Therefore, UPV should be interpreted together with mass change, visual rating, residual strength, and exposure history.

A major research need is the development of reliable UPV early-warning thresholds. Ideally, a certain UPV reduction ratio could indicate the transition from latent damage to accelerated deterioration and predict later strength loss. However, thresholds are often

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material-specific and test-specific. For VPC pavement elements, repeated frost-salt-load tests are needed to establish segmented relationships among UPV attenuation, mass change, visual damage, and residual strength.

Beyond conventional UPV, nonlinear ultrasonic methods, spectral analysis, and signal decomposition have begun to appear in concrete damage detection. Park et al. (2026) used sideband peak count-based nonlinear ultrasonic techniques to evaluate freeze-thaw effects, and Shakir et al. (2025) applied CEEMDAN-Hilbert spectral analysis to detect early damage from ultrasonic attenuation. These techniques contain richer signal information than single velocity values, but their engineering use requires simplified and repeatable testing protocols.

## 7 Degradation Modelling and Performance Prediction

The ultimate purpose of durability research is not only to explain damage mechanisms but also to predict future performance. Traditional freeze-thaw models often use cycle number, relative dynamic modulus, mass loss, or strength retention to describe nonlinear deterioration. With the increase of coupled exposure studies, environmental regime, salt concentration, load level, initial strength, pore parameters, and acoustic indicators are gradually being incorporated into predictive models.

Existing models can be grouped into three broad categories. The first category uses damage mechanics or statistical distributions to describe the degradation of strength or modulus. The second category uses transport theory to model chloride diffusion while considering the effect of freeze-thaw-induced cracking. The third category uses data-driven methods, such as regression, neural networks, or machine learning, to predict freeze-thaw resistance and durability performance (Li et al., 2024; Wu & Gao, 2024; Wang et al., 2025).

For pavement applications, a useful model should satisfy three requirements. First, model variables should correspond to measurable indicators, such as UPV, mass change, visual damage grade, exposure cycles, and load level. Second, the model should distinguish main effects from interaction effects instead of assuming that coupled damage is a linear sum. Third, the model should address the conversion from accelerated laboratory tests to field


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service conditions, including temperature fluctuation, salt solution contact, traffic frequency, and drainage.

For VPC, prediction models should also include initial material-state variables. Mix design, aggregate gradation, compaction procedure, and curing condition determine pore structure and interfacial quality, which in turn control sensitivity to moisture, salts, and loading. If these initial conditions are ignored, models based only on cycle number may fail to explain why different VPC products behave differently under the same exposure regime.

Machine learning offers a promising route for multi-indicator fusion, but its reliability depends on data quality and variable design. A model trained on mixed data from different standards, materials, and exposure procedures may show high statistical accuracy but weak engineering meaning. A more robust approach is to build a clear VPC database containing mix proportions, forming conditions, initial properties, exposure regimes, load levels, and monitoring indicators before applying advanced algorithms.

## 8 Research Gaps and Future Directions

The reviewed literature shows that freeze-thaw damage, chloride attack, and mechanical deterioration have been widely studied for ordinary concrete. However, systematic understanding of VPC pavement units under coupled frost-salt-mechanical exposure remains limited. The first gap concerns material specificity. Many existing studies focus on ordinary cast concrete, pervious concrete, fiber-reinforced concrete, or recycled aggregate concrete, while VPC is often studied mainly in terms of production process, strength, or resource utilization. Its special forming process and pore structure require a dedicated durability framework.

The second gap concerns quantitative interaction effects. Many studies qualitatively state that combined freeze-thaw, salt, and load exposure is more damaging than single-factor exposure, but few define how much amplification occurs or how the dominant factor changes with exposure stage. Future studies should use factorial experiments, analysis of variance, response surface methods, and damage-factor decomposition to quantify main effects and interaction effects.

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The third gap concerns early-warning indicators. UPV and other acoustic methods can detect internal damage, but thresholds are influenced by moisture state, material composition, and test conditions. A VPC-specific monitoring database should be developed to link UPV attenuation, mass change, scaling, water absorption, residual strength, and visual damage. Such a database would help identify the transition from latent damage to accelerated deterioration.

The fourth gap concerns the link between accelerated laboratory tests and field service. Standard methods such as ASTM C666, ASTM C672, RILEM CIF/CDF, and GB/T 50082 provide essential test procedures, but real pavements experience variable temperature cycles, intermittent salt supply, drainage, and traffic loads. Field exposure, laboratory acceleration, and numerical simulation should be combined to build service-oriented prediction models.

The fifth gap concerns reporting consistency. Different studies use different endpoint indicators, including mass loss, relative dynamic modulus, compressive strength retention, UPV, water absorption, and chloride content. This makes cross-study comparison difficult. Future VPC studies should report at least material preparation parameters, initial absorption, initial UPV, exposure regime, salt solution condition, loading path, monitoring interval, and termination criteria.

**Table 2.** Research gaps and future directions

| Research gap | Current limitation | Future direction |
|---|---|---|
| Limited VPC-specific evidence | Many conclusions come from ordinary concrete rather than VPC | Develop a VPC material-structure-durability database |
| Insufficient quantification of coupling | Interaction effects are often described qualitatively | Use factorial design, ANOVA, and interaction coefficients |
| Immature early-warning thresholds | UPV-strength relationships depend on moisture and material state | Establish segmented UPV-mass-strength threshold models |
| Weak laboratory-field | Accelerated tests differ | Combine field exposure, |

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| | | |
|---|---|---|
| conversion | from real pavement exposure | laboratory tests, and numerical simulation |
| Inconsistent reporting | Indicators and termination criteria differ across studies | Build a minimum reporting checklist for VPC durability tests |

## 9 Conclusions

This paper reviewed the durability of vibropressed concrete for pavement applications under coupled frost-salt-mechanical exposure. VPC has advantages in density, dimensional stability, and industrial production, but its dry-consistency forming process, connected pores, interfacial transition zones, and exposed edge geometry create special durability risks in cold-region pavement environments.

Freeze-thaw cycles damage concrete through pore water freezing, pressure accumulation, and microcrack propagation. Chloride and deicing salt environments modify freezing behavior, ion concentration, crystallization pressure, and transport pathways. Mechanical loading creates microcracks and accelerates moisture and chloride ingress. Under combined exposure, these mechanisms interact and produce nonlinear, staged deterioration that cannot be represented by single-factor test results alone.

Future research should focus on VPC-specific experimental matrices, quantitative interaction coefficients, UPV-based early-warning thresholds, and service-oriented prediction models. By integrating material design, non-destructive monitoring, and multi-indicator modelling, a more reliable durability evaluation framework can be developed for precast concrete pavement elements in cold and salt-exposed regions.

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