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**THE ROLE OF THE INTERFACIAL TRANSITION ZONE IN THE DURABILITY
OF HIGH-PERFORMANCE CONCRETE EXPOSED TO MARINE ENVIRONMENT
AND FREEZE-THAW CYCLES**

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The durability of high-performance concrete (HPC) in marine environments under freeze-thaw cycles is critically governed by the Interfacial Transition Zone (ITZ). This theoretical article analyzes the ITZ's role as the preferential pathway for chloride ingress and the nucleus for micro-crack initiation. We argue that the synergistic degradation, where freeze-thaw damage accelerates ionic transport and vice-versa, is primarily facilitated through this interfacial region. The discussion establishes a framework for enhancing durability by engineering a densified ITZ through optimized particle packing and ultra-fine supplementary cementitious materials. Consequently, a paradigm shift towards explicitly modeling and designing the ITZ microstructure is essential for predicting and extending the service life of marine concrete infrastructure in cold climates.

Keywords: high-performance concrete, interfacial transition zone, durability, marine environment, freeze-thaw cycles, chloride penetration, microstructure, supplementary cementitious materials, synergistic degradation, service life modeling.

**РОЛЬ КОНТАКТНОЙ ЗОНЫ В ОБЕСПЕЧЕНИИ ДОЛГОВЕЧНОСТИ ВЫСОКОКАЧЕСТВЕННОГО
БЕТОНА В УСЛОВИЯХ МОРСКОЙ СРЕДЫ И ЦИКЛИЧЕСКОГО ЗАМОРАЖИВАНИЯ**

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Долговечность высококачественных бетонов (ВКБ) в морской среде в условиях циклического замораживания и оттаивания в решающей степени определяется состоянием контактной зоны (ITZ) между цементным камнем и заполнителем. В данной теоретической статье анализируется роль контактной зоны как преимущественного пути проникновения хлоридов и очага образования микротрещин. Авторы обосновывают, что синергетическая деградация, при которой морозная деструкция ускоряет перенос ионов и наоборот, происходит преимущественно через эту межфазную область. В работе сформирована концепция повышения долговечности за счет направленного проектирования уплотненной контактной зоны путем оптимизации гранулометрии (упаковки частиц) и применения ультрадисперсных минеральных добавок. Сделан вывод о том, что переход к явному моделированию и проектированию микроструктуры контактной зоны необходим для прогнозирования и продления срока службы морских гидротехнических сооружений в условиях холодного климата.

Ключевые слова: высококачественный бетон (ВКБ), контактная зона (ITZ), долговечность, морская среда, циклы замораживания и оттаивания, проникание хлоридов, микроструктура, минеральные добавки, синергетическая деградация, моделирование срока службы.

Introduction. The durability of marine and coastal infrastructure in cold climates represents a significant challenge for modern civil engineering. These structures are subjected to a synergistic degradation process involving penetrating chloride ions, sulfate attack, and the physical stresses of freeze-thaw (F-T) cycles. While High-Performance Concrete (HPC), characterized by its low water-to-binder ratio and resultant low permeability, is the material of choice for such demanding applications, its long-term integrity is not guaranteed [9, p. 562]. A critical, yet often overlooked, determinant of its durability is the Interfacial Transition Zone (ITZ) – a thin region of cement paste surrounding aggregate particles. Historically identified as the «weak link» in conventional concrete due to its higher porosity and oriented crystal structure, the ITZ's role in HPC requires re-evaluation. This article posits that even in HPC, the ITZ remains a preferential pathway for deleterious agents and a nucleus for damage initiation under combined marine and F-T exposure [5, p. 3517–3519]. The aim of this theoretical analysis is to synthesize existing research and propose a conceptual model elucidating how the microstructure of the ITZ governs the degradation kinetics of HPC in these aggressive conditions.

Main body. The formation and characteristics of the ITZ in conventional concrete are well-understood, primarily resulting from the «wall effect» of the aggregate surface, which leads to a local increase in water-to-cement ratio and the subsequent formation of a porous, micro-cracked interface rich in oriented calcium hydroxide (CH) crystals [6, p. 199–200]. However, in High-Performance Concrete, this paradigm is fundamentally altered. The use of low water-to-binder ratios and high-range water-reducing admixtures minimizes water film thickness and particle segregation, thereby producing a denser and more homogeneous ITZ with a significantly reduced width. Furthermore, the incorporation of supplementary cementitious materials (SCMs) such as silica fume and metakaolin induces a profound microstructural transformation [8, p. 106275]. These ultra-fine particles act both physically, by packing the interstitial spaces between cement grains near the aggregate, and chemically, through pozzolanic reactions that consume the weak CH crystals to form additional strengthening calcium-silicate-hydrate (C-S-H) gel. Consequently, the ITZ in well-designed HPC evolves from a weak boundary into a densified, less permeable region that more closely resembles the properties of the bulk cement paste, though it may still retain a distinct, albeit improved, microstructure [7, p. 453].

The degradation of HPC in a combined marine and F-T environment can be conceptualized as a multi-stage process initiated and propagated at the ITZ. The first stage involves the preferential transport of aggressive ions, where the ITZ, despite its improvement in HPC, still acts as the primary conduit for the ingress of chloride and sulfate ions from seawater. The interconnected pore network within the ITZ facilitates faster diffusion and capillary suction compared to the denser bulk paste. The second stage is the synergistic initiation of damage, where two key mechanisms interact. During freeze-thaw cycles, the cryo-suction of water into the ITZ's capillaries generates hydraulic pressures upon freezing, leading to the nucleation of microcracks specifically within this vulnerable zone [1, p. 167]. Concurrently, chlorides migrating along the ITZ rapidly reach the steel reinforcement, depassivating the surface and initiating corrosion. This leads to a critical positive feedback loop: the microcracking from F-T cycling increases the permeability of the ITZ, which in turn accelerates the ingress of chlorides and sulfates [11, p. 329]. The resulting corrosion products, which have a larger volume than the original steel, exert expansive stresses, while sulfate crystallization within the newly formed cracks further propagates them [3, p. 107753]. This synergy relentlessly degrades the ITZ, transforming it from a mere transport pathway into a zone of active deterioration, ultimately compromising the composite integrity of the concrete and leading to surface scaling, spalling, and a loss of structural serviceability.

Discussion. The preceding analysis underscores that the long-term performance of high-performance concrete in aggressive environments is not solely a function of the bulk matrix but is critically governed by the quality of the Interfacial Transition Zone. Consequently, mix design must evolve from a focus on general composition to the targeted engineering of this interfacial region. The foundational principle for optimizing the ITZ lies in mitigating its inherent weaknesses – high initial porosity and chemical vulnerability [4]. This can be achieved through a multi-scale approach that first addresses particle packing. By optimizing the granular skeleton, including the selection of well-graded fine and coarse aggregates, the phenomenon of water accumulation at the aggregate surface – the primary cause of a porous ITZ – is minimized. This physical densification is then profoundly enhanced by the strategic incorporation of ultra-fine supplementary cementitious materials [10, p. 123472]. Materials such as silica fume and metakaolin act synergistically; their fine particles physically occupy nano-scale pores within the ITZ, while their pozzolanic reactivity consumes the portlandite crystals, which are both soluble and poorly structured, replacing them with durable calcium-silicate-hydrate gel [2, p. 142405]. This chemical transformation effectively eliminates the weak phase and homogenizes the microstructure between the aggregate and the bulk paste. Furthermore, the rheology of the fresh concrete must be carefully controlled through superplasticizers to ensure a cohesive mix that prevents particle segregation and bleeding, which can re-create a weak boundary layer.

From a predictive modeling perspective, these microstructural improvements necessitate a refinement of existing service-life models. Traditional chloride diffusion models that treat concrete as a homogeneous medium may significantly overestimate durability. A more accurate approach would require multi-phase models that explicitly represent the ITZ as a distinct, albeit densified, phase with its own transport properties, acknowledging that its enhancement shifts the rate-limiting step of degradation from the ITZ itself to the bulk paste [12, p. 111348]. Future research should therefore pivot towards advanced micro-mechanical and chemo-physical modeling, validated by nano-indentation and high-resolution microscopy, to quantitatively link specific ITZ properties to macroscopic durability factors, ultimately enabling the rational design of next-generation concrete with predictable performance in the harshest environments.

Conclusion. In conclusion, this theoretical analysis has established that the Interfacial Transition Zone remains a critical and deterministic factor for the durability of High-Performance Concrete exposed to the synergistic degradation of marine environments and freeze-thaw cycles. While the low-permeability matrix of HPC provides a robust first line of defense, the ITZ persists as the preferential pathway for the ingress of deleterious ions and the nucleus for micro-crack initiation. The proposed conceptual model illustrates a vicious cycle of degradation where freeze-thaw action and chloride penetration mutually reinforce each other, with the ITZ serving as the primary locus for this damaging synergy. Consequently, the strategic densification of the ITZ through the use of ultra-fine supplementary cementitious materials and optimized mix designs is not merely a supplementary improvement but a fundamental prerequisite for disrupting this cycle and achieving long-term durability. By effectively transforming the ITZ from a weak boundary into a strengthened, less permeable interface, its role as the Achilles' heel of the composite can be mitigated. Therefore, a paradigm shift towards the explicit microstructural engineering of the ITZ, supported by advanced multi-phase modeling, is essential for the development of concrete infrastructures with predictable and enhanced service lifespans in the most demanding climatic conditions.

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