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Towards a unified interface mechanics of concrete

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Despite two centuries of engineering success, concrete still lacks a unified scientific theory. The failure of concrete is often traced to the interfacial transition zone (ITZ), a region that governs the mechanical behaviour of concrete yet whose own properties remain incompletely understood. We identify three fundamental dependencies, namely orientation, time, and scale, that should be resolved to establish an interface mechanics in concrete.

In the two centuries since the invention of Portland cement, concrete has become a cornerstone of modern civilization. With an annual production of 30 billion tonnes, it is the second most consumed substance on Earth after water.[1] Despite this ubiquity, our fundamental understanding of concrete remains far from complete. It is time to re-think this ancient yet still youthful man-made material.

Although we build towering skyscrapers and kilometre-span bridges, we still cannot pinpoint the exact microstructural origin and triggering mechanism of failure within a simple 10-centimeter concrete cube. The origin of failure is often hidden within the interfacial transition zone (ITZ), a region merely tens of micrometres thick between the aggregate and the mortar. As the weakest link in concrete, the ITZ plays a key role in damage initiation and propagation. While other material characteristics and environmental conditions also contribute to concrete failure, the ITZ is widely recognized as the primary site of damage initiation.[2] However, the physical and chemical characteristics of the ITZ remain poorly understood.

A FRAGMENTED KNOWLEDGE BASE

Concrete research is marked by a critical imbalance, as technological applications have outpaced fundamental scientific understanding. New material systems, from recycled concrete to ultra-high-performance and engineered cementitious composites, have emerged almost in response to specific engineering demands and have been rapidly deployed in practice. The development of recycled concrete, for instance, was driven by the urgent need to manage construction and demolition waste.[2] The dominant paradigm has long been engineering-first, prioritizing immediate application over deeper mechanistic insight.

While this engineering-first approach has been highly effective in addressing short-term engineering challenges, the paradigm has left the knowledge system of concrete highly fragmented. Variants of concrete are often treated as distinct materials, each with its own mix designs, standards, and even academic communities. Consequently, the universal fundamental principles that could transcend these material categories remain largely unidentified. In essence, concrete research is rooted in engineering practice, while concrete science as a unified and independent body of knowledge is still taking shape.

Establishing a unified theory is therefore essential to achieving predictive control over concrete properties. Such a theory would be a performance-control theory for all concretes. Its core would be the control of mechanical properties, with additional attention to durability and functional properties. It is unified because, unlike past approaches that developed separate control theories for different concrete types such as natural aggregate concrete and recycled aggregate concrete, it relies on common features of concrete materials. Hence, it transcends individual concrete types and is theoretically applicable to all of them. The ITZ, as a ubiquitous weak link in all concrete variants, offers a natural scientific fulcrum for such a theory. Its consistent characteristics across material types and its dominant influence on macroscopic behaviour imply that a theoretical framework centred on the ITZ can provide a fundamentally coherent, cross-cutting foundation.

INTERFACE MECHANICS IS THE CORNERSTONE

Concrete is a heterogeneous, three-phase composite consisting of an aggregate phase, a mortar matrix, and the intervening ITZ. The ITZ bridges two constituents with vastly different mechanical properties, and its microstructure governs macroscopic performance. It is not only the weakest link in terms of mechanical performance but also the primary site of durability degradation. In many cases, it further serves as a critical determinant of functional properties such as acoustic and thermal performance.[2]

Among concrete's many attributes, mechanical performance remains the primary foundation of concrete science. Without adequate strength and toughness, all other functions become irrelevant. Consequently, we identify interface mechanics as the pivotal domain for breakthroughs in a unified theory of concrete. This is a deliberate strategic choice. Although the thickness of an individual ITZ is only several tens of micrometres, ITZs can collectively account for 20% to 40% of the total mortar volume.[2] Therefore, the ITZ represents a pervasive and influential microstructural unit within concrete, providing important leverage to regulate and optimize concrete performance.

Despite decades of investigation, the intrinsic characteristics of the ITZ are still incompletely understood, and a persistent gap remains in our understanding of its mechanical behaviour. The fundamental obstacle is rooted in its structural nature. The ITZ forms a thin, spatially distributed layer that irregularly encapsulates aggregates within the mortar matrix, leaving only a small and difficult-to-access region for analysis.[3] Consequently, these spatial and geometric constraints impede the direct application of conventional characterization techniques, which are typically optimized for the bulk mortar phase, to the study of the ITZ.

Current consensus provides only a preliminary framework of the ITZ, and its formation and evolution remain unclear. While it comprises the same fundamental phases as the mortar, including calcium silicate hydrate (C-S-H), calcium hydroxide (CH), and unhydrated cement particles, these constituents follow a distinct compositional gradient. Specifically, the ITZ is characterized by an enrichment of highly oriented calcium hydroxide, a depletion of C-S-H, and a porosity that can be several times higher than that of the mortar phase. These characteristics arise from a combination of factors, most notably the wall effect.[2,4] The physical presence of the aggregate surface imposes steric constraints that hinder the close packing of large cement particles. This results in the formation of a localized water-rich region and an effectively elevated water-to-cement ratio near the aggregate surface, ultimately yielding a more porous and weaker microstructure.

However, several recent multi-scale studies have begun to elucidate the long-standing black box of the ITZ. Gao *et al.*[5] revealed a coupling mechanism among the wall effect, ionic transport, and aggregate characteristics, demonstrating that ITZ formation is a synergistic result of

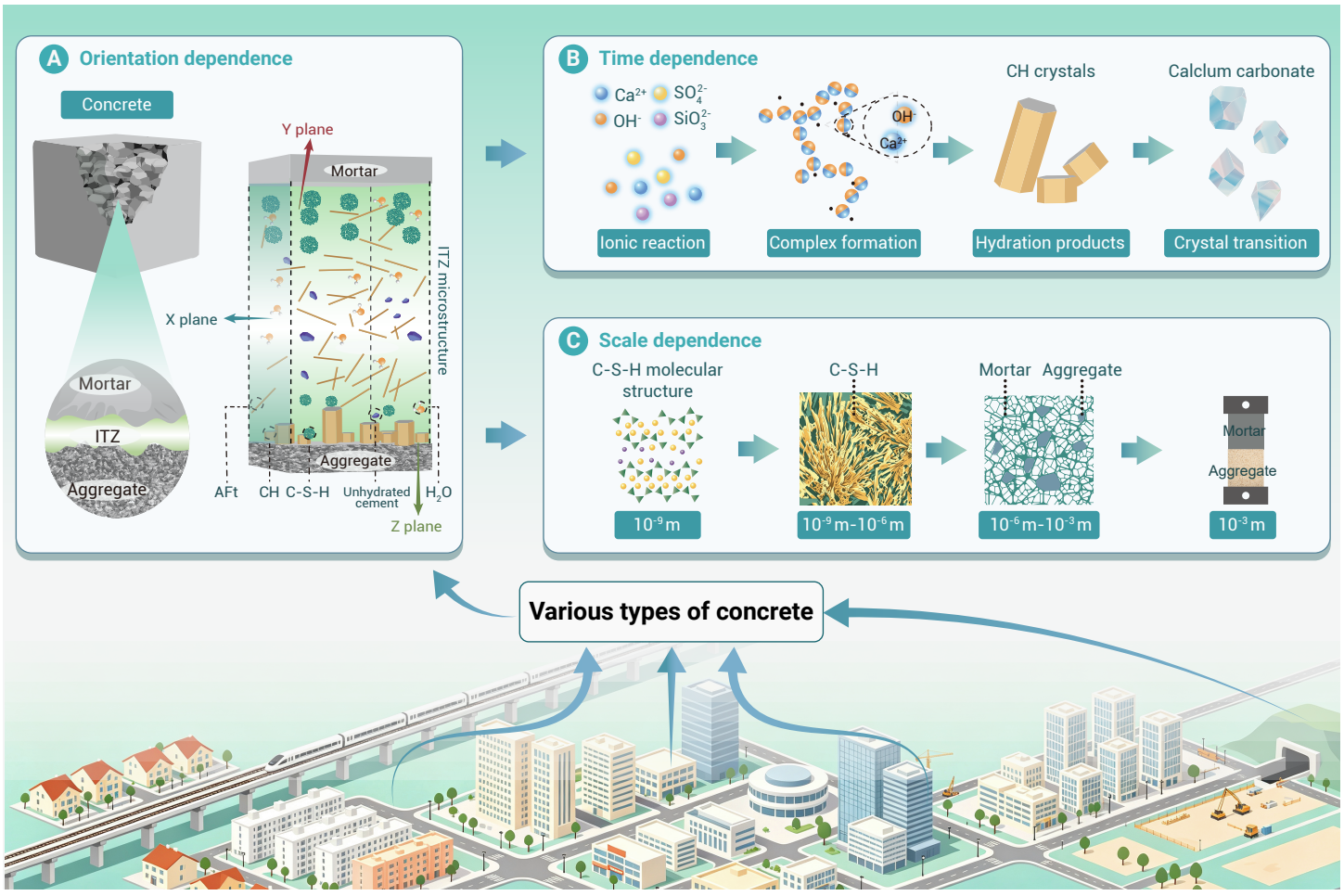


Figure 1. Theoretical framework of interface mechanics in concrete.

multiple factors rather than a single mechanism. Liu *et al.*[6] tracked the temporal evolution of mechanical properties of the ITZ, revealing a significant time-dependent increase in both scratch hardness and fracture toughness, confirming that this region is dynamic rather than static. Gan *et al.*[7] reported a striking scale effect, showing that the interfacial flexural strength at the micrometre scale can exceed macroscopic measurements by an order of magnitude. Reflecting this growing momentum, the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) has recently established a new technical committee, chaired by Jianzhuang Xiao, dedicated to multiple ITZs, aiming to reassess their critical role in recycled concrete (https://www.rilem.net/news/new-technical-committees-696). While seemingly disparate, these breakthroughs collectively converge on a fundamental realization: the ITZ cannot be adequately described with any single-scale framework. Instead, they expose a critical need for a multi-scale framework that accounts for spatial orientation, temporal evolution and scale dependency.

THREE ESSENTIAL DEPENDENCIES

Bridging the three dependencies of the ITZ, namely orientation, time, and scale, is not an incremental improvement. It is a basic prerequisite for establishing a rigorous and systematic interface mechanics of concrete. Figure 1 presents the relationships among these three dependencies, which are clearly coupled. Orientation dependence is arguably the most fundamental challenge. It is central to the mechanical properties of the ITZ. Time and scale dependencies are largely built upon orientation dependence. In other words, time and scale dependencies mainly describe how orientation dependence varies over time and across scales.

Orientation dependence

The compositional gradient of the ITZ, oriented perpendicular to the aggregate surface,[3] implies that its mechanical response may be inherently orientation dependent. However, due to the challenges in specimen preparation and the resolution limits of conventional characterization techniques, the ITZ has historically been idealized as an isotropic material in mechanical models. Although this simplification reduces theoretical complexity, it obscures the inherent mechanical anisotropy of the ITZ. By conceptualizing the ITZ as a rectangular prism, we can define three critical load-bearing plane orientations: the X- and Y-planes, perpendicular to the aggregate surface, and the Z-plane, parallel to the aggregate surface. While the former planes have been extensively studied, the latter remains a hidden dimension, shielded by the surrounding aggregates and mortar, rendering it largely inaccessible to standard analytical probes. Consequently, our understanding of the Z-plane remains limited and fragmented; in terms of fundamental mechanical properties, it represents an unresolved frontier in interfacial science.

These analyses suggest that our current understanding of the interface relies on unidimensional data, inevitably leaving its true mechanical behaviour under-characterized. A primary challenge in probing orientation dependence lies in developing methods capable of acquiring data simultaneously from the X-, Y-, and Z-planes. One potential strategy involves regularizing aggregate geometry[3] to enable non-destructive separation from the mortar phase, an approach that presents significant technical challenges. More fundamentally, a critical fundamental scientific question remains: even if Z-plane data were accessible, would the governing physical laws mirror those of the X- and Y-planes? If they diverge, the decades-old assumption of mechanical isotropy would be rejected. In this light, the ITZ would no longer be viewed as a homogeneous weakened layer, but rather as a critical, structural complex region defined by intrinsic anisotropy. Such a distinction would transcend mere model refinement, fundamentally reshaping our understanding of concrete mechanics and the strategies for engineering material performance.

Temporal dependence

The phase characteristics and properties of the ITZ are inherently dynamic, undergoing continuous evolution throughout the material's lifecycle. During early formation and evolution, the microstructure undergoes rapid reconfiguration driven by vigorous hydration kinetics.[8] Over its service life, the ITZ experiences gradual transformations mediated by mechanical loading, freeze-thaw cycles, and the ingress of aggressive media, such as the carbonation of calcium hydroxide into calcium carbonate. As demonstrated by Liu *et al.*,[6] such evolution over timescales of days to months is sufficient to fundamentally alter mechanical properties. Elucidating this time-dependency requires capturing the full temporal trajectory of the interface, a task that likely necessitates in-situ characterization techniques capable of real-time microstructural monitoring without compromising the structural integrity of the ITZ, such as synchrotron-based X-ray methods.[9]

Notably, temporal and orientation dependencies are inextricably coupled; the evolution of orientation dependence over time may provide the definitive mechanistic insight into the long-term behaviour of the ITZ. This synergy raises fundamental questions: do the X and Y planes evolve along identical temporal trajectories, or are they governed by divergent time-dependent laws? Such questions remain largely unexplored in the literature, yet their resolution is essential. The answers may dictate the fundamental architecture of the next generation of life-prediction models for cementitious materials.

Scale dependence

While multi-scale research methodologies are well established for metallic and ceramic systems, and some progress has been made in correlating the macroscopic and microscopic behaviours of bulk concrete,[10] a pervasive gap remains: dedicated multi-scale investigations of the ITZ remain extremely limited. This lack of data constitutes a primary barrier to understanding the intrinsic mechanical nature of the ITZ. The characteristics and properties of the ITZ differ markedly across spatial dimensions: at the macroscopic scale ($> 10^{-3}$ m), the ITZ is often simplified as a zero-thickness geometric surface; at the mesoscopic scale (10^{-6}—10^{-3} m), it is modelled as a finite region defined by uniform or gradient properties; at the microscopic scale (10^{-9}—10^{-6} m), it appears as a heterogeneous, three-dimensional multiple-phase assembly; and at the molecular scale ($< 10^{-9}$ m), it consists of fundamental units such as C-S-H and calcium hydroxide, governed by intermolecular interactions. This multi-scale nature leads to a well-recognized phenomenon in which mechanical properties of the ITZ measured across these scales can diverge by multiple orders of magnitude.[7]

The core task in characterizing the scale-dependent nature of the ITZ lies in establishing robust, quantitative relationships across its multi-scale behaviours. Traditionally, cross-scale constitutive models are derived from physicochemical mechanisms, a strategy that has proven fruitful in idealized systems. However, when applied to the stochastic and highly heterogeneous ITZ, such mechanistic derivation often becomes intractable due to an expansive parameter space. Data-driven paradigms, including big data and artificial intelligence, offer a promising alternative by bypassing mechanistic complexity to directly reveal statistical mappings between microstructural features and macroscopic properties across scales. Developing multi-scale experimental and simulation techniques for the ITZ is therefore essential. Yet, a fundamental question persists: do these data-driven approaches advance fundamental understanding, or do they primarily reveal correlations whose mechanistic origins remain to be deciphered?

THE MOMENT OF PARADIGM SHIFT

The ultimate objective of interface mechanics theory is to develop a unified mathematical framework. By integrating fundamental insights into orientation, time, and scale dependencies, such a framework would provide a universal theoretical architecture for predicting and tailoring the mechanical properties of diverse cementitious systems. Such a theoretical prototype would manifest as a multidimensional constitutive relationship, one that moves beyond traditional simplifications towards a mathematically rigorous treatment and representation of the interface's inherent complexity.

Realizing this vision requires deep interdisciplinary integration. Materials scientists should continue to probe the fundamental origins and intrinsic characteristics of the interface while pioneering advanced characterization methods. In parallel, artificial intelligence specialists can leverage machine-learning architectures to extract latent structure-property correlations from massive multiscale datasets and establish cross-scale statistical models. Ultimately, engineering mechanics researchers must synthesize these insights into robust theoretical frameworks that capture the multifaceted behaviour of interfaces, translating microscale mechanisms into predictable macroscale performance.

As these challenges are addressed, concrete research will enter a new scientific epoch. Cementitious materials may transcend their legacy as products of empirical formulation and become materials designed according to scientific principles. Within a unified framework, properties will become predictable and controllable, enabling a new generation of cementitious materials designed from first principles.

From the Roman Pantheon to modern sea-crossing bridges, the history of concrete is a testament to human engineering. Yet in a fundamental sense, we remain empiricists, and the ITZ stands as a critical gateway to concrete science.

Now is the time to converge across disciplines and decisively open that door.

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AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.