RILEM Technical Letters (2026) 11: 66-73
https://doi.org/10.21809/rilemtechlett.2026.235

Opening letter of RILEM TC MTZ: Influence of recycled aggregates on multi-interfacial transition zones in recycled concrete

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This article presents an opening scientific statement of RILEM TC MTZ.

Received: 15 January 2026 / Accepted: 22 May 2026 / Published online: 12 June 2026

Abstract

Recycled aggregate concrete (RAC) has emerged as a practical route toward low-carbon construction, offering clear environmental advantages by reducing both natural resource consumption and waste generation. The incorporation of recycled aggregates in concrete results in the coexistence of multiple interfacial transition zones (MITZ), which have significant influence on the mechanical performance, durability and functional properties of RAC. However, the formation and performance evolution of MITZ and its influence on performance of RAC remain insufficiently understood. To achieve a better understanding of ITZs in RAC , this Technical Committee (TC) will focus on (1) investigating the formation mechanisms and damage evolution of MITZ, (2) characterizing the anisotropic and heterogeneous characteristics of MITZ across different scales, (3) exploring the key variables on ITZ performance, (4) quantifying the influence of MITZ on the macro properties of RAC, (5) developing innovative technologies to strengthen MITZ, and (6) establishing quantitative models for MITZ evolution.

Keywords: Recycled aggregate concrete, Multi-interfacial transition zones, Multi-scale characterization, Properties and regulation.

1 Introduction

Concrete serves as the backbone of modern infrastructure worldwide and is commonly regarded as a heterogeneous composite material composed of aggregates, cement paste, and the interfacial transition zones. Among these constituents, the interfacial transition zone (ITZ), located between aggregate and the surrounding paste, is generally characterized by higher porosity and a lower elastic modulus than the bulk mortar. As a result, the ITZ plays a critical role in governing the mechanical performance and durability of concrete. Its relatively porous and heterogeneous microstructure can facilitate crack initiation and aggressive ion ingress, thereby compromising long-term durability [1, 2].

Today, in the context of global warming, resource conservation, and sustainable construction, performance expectations for concrete are evolving. Recycled aggregate concrete (RAC) is increasingly recognized as a resource-efficient construction material because it can reduce the demand for natural aggregates and facilitate the recycling of construction and demolition waste [3]. Recycled aggregates introduce three distinct ITZs (Figure 1): ITZ1 between old aggregate and new mortar, ITZ2 between old aggregate and old mortar, and ITZ3 between old mortar and new mortar. Variations in the age and spatial distribution of parent concretes, together with micro-cracks induced during crushing and the presence of residual old mortar and old ITZs, make RAC microstructure far more intricate than that of natural-aggregate concrete (NAC). In such systems, ITZ regulate global behaviour even more critically than in NAC.

From Figure 2, it can be observed that the number of publications on RAC has been steadily increasing over the past two decades, accompanied by a gradual rise in papers specifically addressing the interfacial transition zone (ITZ) within RAC systems. Moreover, the proportion of ITZ-related studies relative to the total publications on RAC has shown a

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*Corresponding author: Jianzhuang Xiao, E-mail: jzx@tongji.edu.cn consistent upward trend, indicating that the ITZ has attracted growing attention and is becoming an increasingly significant research focus in the field of RAC. The bibliometric data were retrieved from the Web of Science Core Collection for the period 2003–2024. For RAC-related publications, the search term was “recycled aggregate concrete”. For ITZ-related publications within RAC systems, the search query was (“ITZ” OR “interfacial transition zone”) AND “recycled aggregate concrete”. Moreover, VOSviewer was used to conduct the keyword co-occurrence analysis and to visualize the evolution of research focus, as shown in Figure 3. Keyword clusters show a growing focus on the ITZ and its influence on strength and durability in RAC. This rising attention reflects its role in governing material performance. The study on multiple ITZs is emerging as an active direction in RAC research.

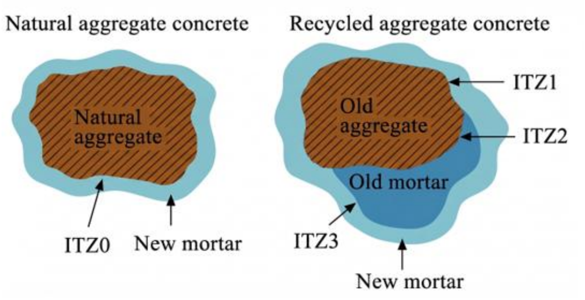

Figure 1. Schematic illustration of interfacial transition zones (ITZs) in natural aggregate concrete and recycled aggregate concrete.

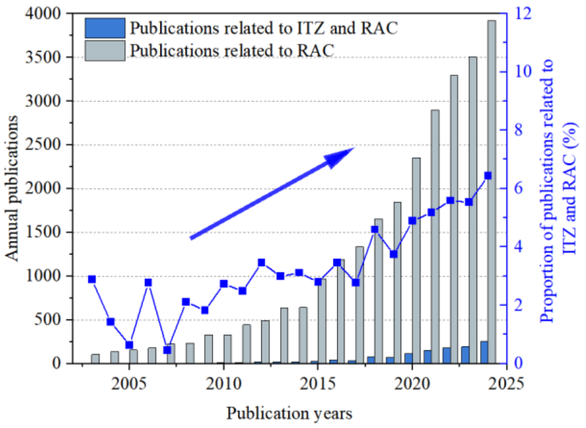

Figure 2. Annual publication trends for RAC and ITZ research from 2003 to 2024, based on Web of Science data.

MITZ in RAC exhibit dual effects. They can weaken mechanical strength, durability, and elastic modulus, while increasing deformation under load [4–6]. However, it can also enhance its functional properties such as thermal insulation [7], fire resistance [8], and sound absorption [9, 10] and damping capacity through interfacial slip and energy dissipation [11–13]. This dual nature is detrimental to some properties yet beneficial to others—requires systematic understanding for effective material design.

To precisely control the properties of recycled aggregate concrete, in-depth research on the formation mechanism, damage evolution, and performance regulation of the multi-interface transition zone (MITZ) is essential.

2 Current status and research challenges of the ITZ

2.1 Formation mechanisms of the ITZ

Since the introduction of water-cement ratio theory by Duff Abrams in 1918 [14], concrete had long been perceived as a two-phase composite material composed of coarse aggregates embedded within a continuous mortar matrix. Researchers did not recognize the distinct interfacial transition zone (ITZ) until Farran [15] in 1956 used a colored resin impregnation technique to observe a thin transition layer surrounding the aggregates. This region which is situated between the aggregate surface and the surrounding paste, exhibits chemical and microstructural characteristics that differ from those of the bulk mortar.

The differences between the ITZ and the bulk paste are due to the variations in chemical composition and microstructural characteristics. The ITZ has hydration products that are similar to those in the bulk mortar, like calcium hydroxide (CH), ettringite (AFt), calcium silicate hydrate (C–S–H) gel, and leftover unhydrated cement. However, the amounts of these phases vary significantly. Previous research consistently indicates that the ITZ possesses elevated levels of CH and AFt, a higher local water–cement ratio, and an increased Ca/Si ratio compared to the surrounding paste [16, 17]. The concentration of CH and AFt generally rises toward the aggregate surface, with the amount of AFt potentially being several times greater than in the bulk matrix [18]. Additionally, CH crystals within the ITZ tend to be larger and more plate-like, growing preferentially perpendicular to the aggregate surface [19].

The ITZ generally exhibits higher porosity and more microcracks than the surrounding mortar phase [20]. For example, Branch et al. [21] found that porosity of ITZ can be roughly three to four times that of the bulk mortar matrix. This higher porosity arises from several concurrent mechanisms [20]. The wall effect is considered the dominant contributor [22]. Together, these mechanisms form a porous and heterogeneous ITZ adjacent to the aggregate surface. The wall and flocculation effects reduce local particle packing density, while local bleeding increases the effective water-to-cement ratio. These conditions favor the accumulation of AFt and oriented CH crystals, and local shrinkage may further generate microcracks within the ITZ.

The formation and development mechanisms of these interfacial zones in recycled aggregate concrete are not yet fully understood and require further systematic investigation. In natural aggregate concrete (NAC), there is only one type of ITZ, namely the ITZ between aggregate and the surrounding mortar. In contrast, recycled-aggregate concrete (RAC) features three distinct types of ITZs: (1) natural aggregate–old mortar (ITZ1), which can suffer microstructural damage during the parent concrete's service life and further deterioration during crushing; (2) natural aggregate–new mortar (ITZ2), formed when recycled aggregate is embedded

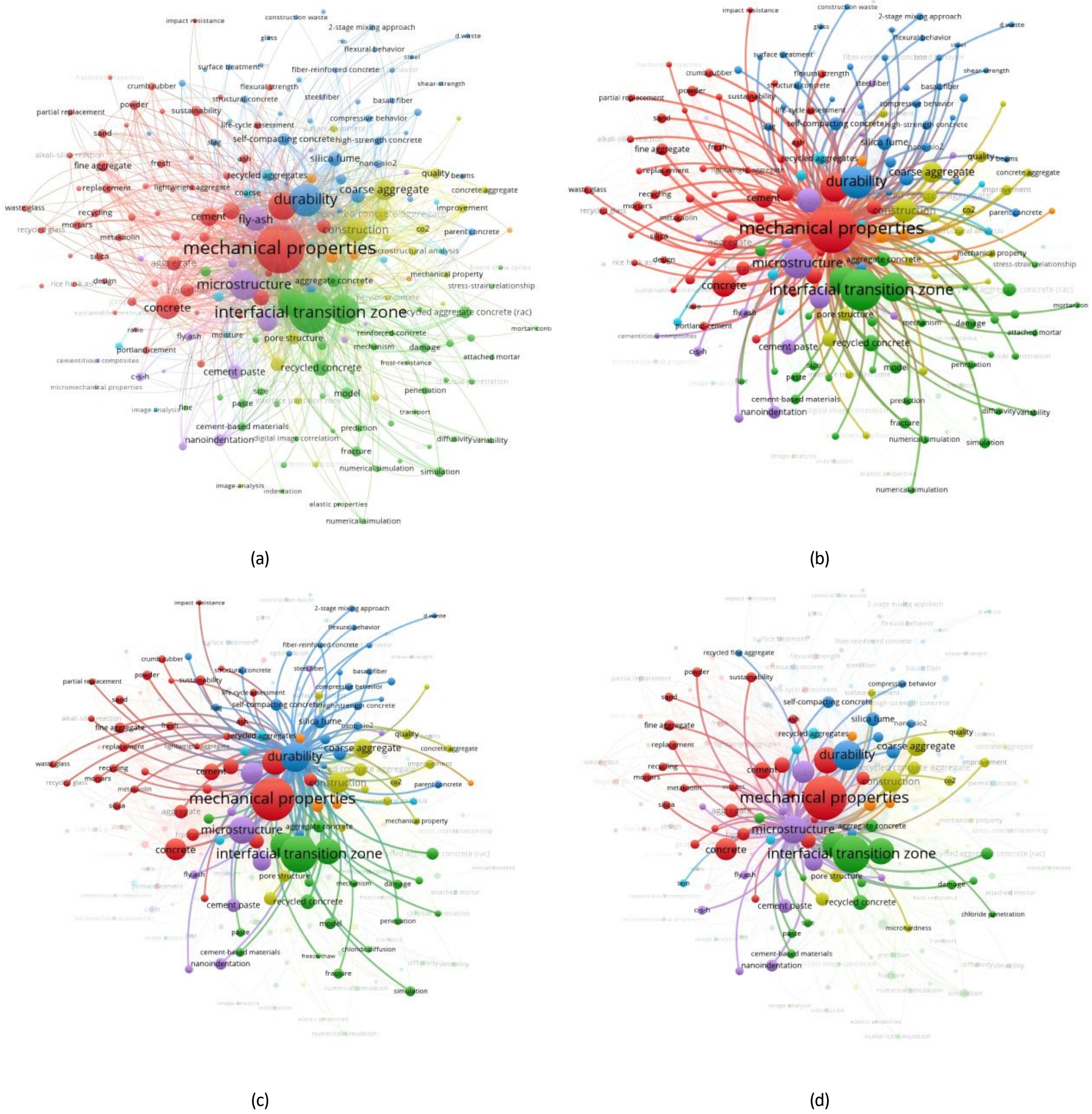

Figure 3. Literature visualization of MITZ based on Web of Science (2003-2024). The input keywords are 'ITZ' or 'interfacial transition zone' and 'recycled aggregate concrete'. (a) Overall keyword network; (b) mechanical-properties cluster; (c) durability-related cluster; and (d) microstructure-related cluster.

in fresh paste; and (3) old mortar–new mortar (ITZ3), representing the interface between newly cast mortar and adhered old mortar, fundamentally different from the aggregate–mortar interface in natural concrete. The formation and development mechanisms of these interfacial zones, especially the old–new mortar interface, are not yet fully understood and require further systematic investigation.

2.2 Multi-scale experimental techniques for characterizing MITZ

The characterization of MITZ in recycled aggregate concrete should first distinguish the specific interfacial object being examined. In RAC, MITZ can generally be classified into ITZ1, ITZ2, and ITZ3, corresponding to the old aggregate–new mortar interface, the old aggregate–old mortar interface, and the old mortar–new mortar interface, respectively. These interfaces represent different interfacial regions in RAC and can be comparatively evaluated using multi-scale experimental techniques.

At the macroscopic scale, tensile, shear, and fracture-based techniques are mainly used to evaluate interfacial mechanical performance, including tensile bond strength, shear resistance, fracture energy, and fracture toughness. These methods provide a useful basis for comparing the mechanical behaviour of ITZ1, ITZ2, and ITZ3. (Figure 4). These methods quantify key mechanical parameters—including tensile bond strength, shear resistance, fracture energy, and fracture toughness—which reflect the apparent mechanical performance of the targeted ITZ. Because concrete exhibits inherently low tensile capacity and typically fails through debonding at the aggregate–mortar interface, the tensile response of the MITZ is strongly linked to the overall performance of the material. Current tensile test methods primarily include direct tensile loading [23], which evaluates the interfacial bond strength by applying a load perpendicular to the MITZ surface, and splitting tensile tests [24], commonly used to examine interfacial debonding behaviour. As a heterogeneous composite, the shear resistance of concrete is also closely associated with MITZ behaviour. The response of the MITZ under shear loading reflects Mode-II fracture behaviour. Two common approaches are used to assess interfacial shear performance: direct shear tests [25] and push-out tests [26]. Cracks in concrete typically initiate and propagate along the aggregate–mortar interface, making fracture testing essential for evaluating the interfacial fracture behaviour of the MITZ. The three-point bending test is widely used for this purpose [27], enabling the determination of fracture energy and fracture toughness associated with interfacial cracking. This test effectively captures the resistance of the MITZ to crack initiation and stable crack growth.

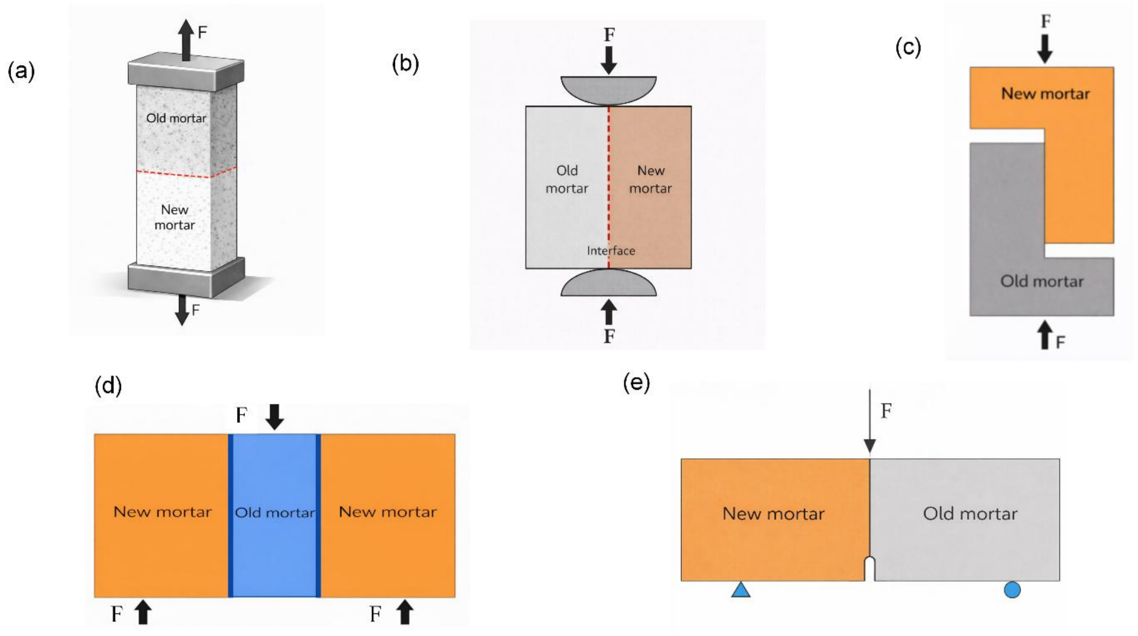

Figure 4. Macroscopic mechanical testing techniques for characterising the interfacial transition zone (ITZ). (a) direct tensile test (b) splitting tensile test (c) direct shear test (d) push-out test (e) three-point bending test.

At the micro- and nano-scales, experimental techniques provide localized information on the mechanical, microstructural, and chemical characteristics of MITZ. Nano-indentation provides spatially resolved measurements of elastic modulus and hardness, enabling the construction of modulus maps across the ITZs. Nano-scratch testing can be effectively applied to investigate interfacial mechanical behaviour, fracture mechanisms, and frictional properties at the microscale, providing valuable insight into the local resistance to sliding, debonding, and surface damage within the ITZ. Microstructural techniques—including scanning electron microscopy (SEM), backscattered electron (BSE) imaging, and energy-dispersive spectroscopy (EDS) —are commonly employed to characterize morphology, porosity, microcracks, hydration products, and elemental distributions across different ITZs [23, 31]. BSE imaging is particularly effective for distinguishing phases based on atomic number contrast, allowing quantitative analysis of porosity and the width of the MITZ. SEM provides high-resolution imaging of microcracks, voids, and the spatial arrangement of hydration products, while EDS enables the determination of elemental distributions such as Ca/Si ratios, which are critical for evaluating local variations in hydration and chemical gradients within the ITZ.

Although these multi-scale experimental methods provide valuable insights into interfacial behaviour, accurately characterizing the constitutive mechanical response and anisotropic characteristics of MITZ remains challenging. Here, anisotropy refers to the direction-dependent microstructural arrangement and mechanical response within a local interfacial region along three orthogonal directions, such as the interface-normal direction and two mutually perpendicular interface-parallel directions. Microscopic experimental methods effectively assess the heterogeneity of ITZs, yet they often necessitate specific specimen preparation, which can cause discrepancies between experimental data and concrete's actual behavior. Furthermore, current microscale loading techniques are limited. To advance this field, future microscale experiments could benefit from designing custom specimen shapes and specialized loading devices to enable more diverse tests, including tensile, shear, fracture, and fatigue loading at the microscale.

2.3 Numerical modelling approaches for MITZ

Numerical simulation is crucial for investigating the mechanical behavior and formation mechanisms of MITZ, effectively linking experimental observations with theoretical insights. Various numerical methods have been devised to characterize MITZ geometry, material properties, and mechanical responses, depending on the modeling scale.

At the mesoscale, the simplest approach ignores MITZ thickness and assumes a perfect bond between aggregates and the surrounding mortar. While these models fail to capture interfacial debonding or post-peak softening behavior, they are still valuable for large-scale simulations, such as impact or explosion analyses, where computational efficiency is crucial [28–30]. A more advanced method involves inserting zero-thickness cohesive elements at aggregate–mortar interfaces to explicitly model interfacial debonding, frictional sliding, and fracture [31–34]. Alternatively, finite-thickness solid elements can represent the MITZ, often with an assumed thickness larger than the actual value to facilitate meshing [35, 36]. Some studies use a constant MITZ thickness around all aggregates, while others adjust it based on aggregate size to better reflect realistic heterogeneity [37]. Besides the finite element method (FEM), other numerical approaches, such as the discrete element method (DEM) [38] and the rigid body spring model (RBSM) [39], have been used to simulate the mechanical behavior and damage evolution of the ITZ.

Assigning precise material properties to MITZ is a significant challenge. MITZ is characterized by pronounced heterogeneity, anisotropy, and randomness, but most existing models do not adequately capture these attributes due to the difficulty of directly measuring local properties. As a result, many numerical studies employ simplified constitutive relationships by empirically reducing the strength, stiffness, or fracture energy of the mortar matrix instead of utilizing experimentally obtained MITZ data. These homogenized assumptions ignore the spatial variability of hydration degree, porosity, and microcracking within the ITZ, resulting in discrepancies between simulated and experimental outcomes.

Recent advancements in microscale particle-based modeling have facilitated a more accurate physical depiction of MITZ formation and evolution. Researchers have developed reaction–diffusion–crystallization frameworks to effectively capture the intertwined chemical and physical processes that govern MITZ formation, thereby establishing a direct connection between material composition and interfacial morphology. These physics-based microscale models effectively bridge the gap between hydration chemistry and structural mechanics, enabling the prediction of ITZ properties from fundamental material parameters [40].

Existing experimental techniques are still unable to directly measure key attributes of the ITZ—such as its heterogeneity, anisotropy, and stochastic variability. Consequently, experimentally validated constitutive models that are truly representative of MITZs have not yet been established. As a result, most numerical simulations continue to rely on simplified constitutive laws obtained by empirically reducing the properties of the mortar matrix. Developing constitutive relationships that reflect the genuine mechanical characteristics of the MITZ therefore remains an important direction for future research. In addition, multi-scale methods, including molecular dynamics simulations, are needed to link formation mechanisms with macroscale behavior.

2.4 Strategies for engineering properties of MITZ

Existing studies on MITZ engineering have primarily focused on mitigating the weakening effects of interfacial regions by increasing interfacial strength, reducing porosity, and improving bonding performance. In NAC, ITZ engineering generally concerns the natural aggregate–mortar interface. In RAC, however, MITZ engineering involves more complex interfacial objects, including the old aggregate–new mortar interface, the old aggregate–old mortar interface, and the old mortar–new mortar interface. Therefore, engineering strategies for RAC may target the recycled aggregate itself, the adhered old mortar, the newly cast mortar, or their mutual bonding.

Recent studies indicate that the surface texture of coarse aggregates plays a crucial role in the interfacial mechanical performance of concrete. Specifically, crushed rock aggregates with rough and angular surfaces enhance mechanical interlocking and bonding at the ITZ, resulting in greater strength and toughness. In contrast, natural pebble aggregates with smoother surfaces create weaker interfaces and reduced bonding strength. Consequently, modifying aggregate surface roughness provides an effective strategy for regulating ITZ properties and enhancing the interfacial performance of RAC [41]. Pre-treatment methods for recycled aggregates (RAs), such as particle reshaping, thermal treatment, microwave processing, and acid soaking, can remove adhered old mortar and reduce microcracks in concrete [42].

Additionally, carbonation [43, 44], pozzolanic slurry coatings such as fly ash and silica fume [45–47], and nanomaterial coatings such as nanosilica [48–50] can be applied to recycled aggregates to improve the properties of ITZ. These treatments facilitate the formation of dense $CaCO_3$ or secondary C–S–H phases on the aggregate surface, thereby enhancing interfacial bonding and improving the mechanical and durability properties of recycled concrete. Bio-mineralization has also been explored as a biological treatment method for recycled aggregates to improve the ITZ through a nano–micro multi-scale mineralization process. In the denitrification-mediated biomineralization process, bacteria induce the in-situ precipitation of $CaCO_3$ on the surface and within the pores of recycled aggregates. These $CaCO_3$ crystals fill microcracks, refine the pore structure, and create a compact mineralized layer (approximately 5–10 µm) at the aggregate–paste interface. This layer offers physical densification and sealing, mechanical interlocking with C–S–H gels, and chemical bridging between $CaCO_3$ and hydration products, collectively leading to a more cohesive and crack-resistant ITZ structure [51].

Certainly, ITZ can also be enhanced from the mortar side by adjusting the properties of the cementitious matrix. This can be achieved by altering the water-to-cement ratio or incorporating supplementary cementitious materials (SCMs) like silica fume [52] and metakaolin [53]. Silica fume mainly improves the ITZ through its ultrafine filler effect and pozzolanic reaction, which refine the pore structure and promote secondary C–S–H formation. Metakaolin, as a reactive aluminosilicate SCM, consumes $Ca(OH)_2$ and promotes the formation of C–S–H and C–A–S–H gels, thereby densifying the cementitious matrix and improving bonding performance at the ITZ.

Existing strategies offer limited quantitative control and focus primarily on mitigating weakening effects while neglecting potential strengthening benefits. They rely on empirical trial and error rather than mechanism-based optimization. Comprehensive, quantitative regulation methods addressing MITZ's dual nature are needed for sustainable, performance-driven concrete design.

3 Objectives and expected outcomes

The primary aim of RILEM TC MTZ is to develop a thorough scientific and engineering framework to understand, quantify, and engineer the MITZ in RAC. The specific objectives will be presented below. Through international collaboration and cross-disciplinary integration, the TC aims to transform qualitative observations of MITZ’s behaviour into quantitative, multiscale, and predictive knowledge that can guide the design of high-performance, low-carbon recycled aggregate concrete.

3.1 Specific objectives

- **Mechanisms of formation and damage evolution**

Investigate the time-dependent formation mechanisms of MITZ from physical and chemical perspectives. The physical mechanisms include the evolution of the wall effect, particle packing, micro-bleeding, and water absorption/release of recycled aggregates with curing age, while the chemical mechanisms include hydration gradients and chemical interactions, particularly at the old mortar–new mortar interface, which may involve mineral recrystallisation and the formation of new phases over time. Reveal the time-dependent damage evolution of MITZ from mechanical and durability perspectives. Mechanical damage includes interfacial cracking, debonding, crack propagation, and degradation of interfacial strength and stiffness under loading, whereas durability-related damage involves ion ingress, transport-property deterioration, secondary ettringite formation, ASR-related products, and other reaction products affecting long-term durability during service exposure.

- **Characterization of anisotropy and heterogeneity**

Investigate and quantitatively characterize the spatial heterogeneity and anisotropic behavior of multiple interfacial transition zones (MITZs) with respect to their microstructural and mechanical features.

- **Development of advanced experimental-numerical frameworks**

Develop and integrate advanced experimental techniques to achieve refined multiscale characterisation of MITZ properties—from nano- and micro-scales to meso- and macro-levels. In parallel, dedicated numerical simulation methods will be established at each scale to accurately reproduce the interfacial formation mechanisms, mechanical behaviour, transport characteristics, etc., of MITZ within their respective domains.

- **Establishment of cross-scale correlation and integration models**

Establish quantitative, MITZ-centred cross-scale correlations by employing numerical simulation and neural-network approaches. The framework will quantify how parent concrete properties and recycled aggregate characteristics affect the formation, microstructure, and mechanical properties of MITZ, and further link MITZ properties to the macroscopic mechanical, durability and functional performance of RAC.

- **Evaluation of material and environmental influences**

Explore the effects of aggregate particle size (fine recycled aggregate, coarse recycled aggregate, large-size coarse recycled aggregate for hydraulic engineering, etc.), aggregate type (recycled concrete aggregate, recycled brick aggregate, etc.), curing age, admixtures, environmental conditions, and other key variables on ITZ performance in RAC.

- **Technologies for strengthening and regulation**

Propose targeted strategies—including nano-modification, surface treatment, and optimized mix design—to enhance MITZ and balance its inherent dual-effect nature of weakening and strengthening.

3.2 Expected outcomes

RILEM TC MTZ is expected to produce a set of concrete scientific, technical, and educational outputs that will enhance global understanding and engineering practice for recycled aggregate concrete.

- **Comprehensive RIELM technical report (State-of-the-art report)**

A consolidated account of current knowledge and new findings produced within the TC, summarizing experimental data, modeling advances, and cross-scale insights into MITZ formation, damage evolution, and performance control. This report will serve as an authoritative reference for future research and standardization efforts.

- **Standardized multiscale characterization protocols**

Harmonized experimental procedures developed via interlaboratory round robin studies, leading to RILEM Recommendations or Standard Test Methods.

- **Validated models and open data platform**

Benchmark datasets and validated physics-driven and data-driven models will be developed to reproduce MITZ formation, behaviour, and transport. A unified digital platform linking molecular to macro scales will enable data sharing, model validation, and performance prediction across the RILEM community.

- **Guidelines for performance optimization and material design**

Development of practical recommendations for mix design, MITZ modification, and processing routes to enhance the characteristics of MITZ and achieve balanced mechanical, durability and functional performance in recycled aggregate concrete.

- **Educational, dissemination, and outreach activities**

Preparation of tutorials, manuals, and training materials for researchers and engineers on MITZ characterisation and modelling. TC members will organise workshops and conference sessions and publish joint papers in high-impact journals. A RILEM Symposium on ITZ-related topics will be held near the end of the TC's term to consolidate outcomes and define future research directions.

Acknowledgement

The authors gratefully acknowledge the insightful discussions and constructive suggestions shared by colleagues, especially the members of RILEM TC MTZ, which greatly contributed to the development of this Opening Letter.

Authorship statement (CRediT)

Jianzhuang Xiao: Conceptualization; Project administration; Writing – Review & Editing. **Miao Yu:** Writing – Original Draft; Writing – Review & Editing; Visualization. **Belén González-Fonteboa:** Writing – Review & Editing. **Long Li:** Writing – Review & Editing. **Amardeep Singh:** Writing – Original Draft; Writing – Review & Editing.

Competing interests

The authors declare no competing interests.

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