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RESEARCH PROGRESS ON MECHANICAL MECHANISM AND CONSTITUTIVE MODEL OF CFRP STRIP ACTIVELY CONSTRAINED RECYCLED AGGREGATE EXPANSIVE CONCRETE

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Abstract

Recycled aggregate (RA) concrete has attracted much attention due to its environmental benefits, but its low mechanical properties and high brittleness limit its application in structures. Fiber-reinforced polymer (FRP) confinement is an effective means to improve its performance. Among them, the "active confinement" achieved by combining expansive concrete (EC) with CFRP strips is a promising new technology. This technology generates pre-tension stress in the CFRP strips through chemical expansion, placing the core concrete in a triaxial pre-compression state, thereby optimizing concrete performance before loading. However, the interaction between the porosity of recycled aggregate, the effectiveness of the expansive agent, and the discontinuous confinement effect of the CFRP strips is very complex, and its mechanical mechanism is not yet clear, nor is a mature constitutive model available. This paper aims to systematically review the current research status of the mechanical mechanism and constitutive model of CFRP strip-confined recycled aggregate expansive concrete. First, the multiple physical and mechanical coupling mechanisms among the expansive agent, recycled aggregate, and CFRP strips were explored. Second, the influence of key factors such as the replacement rate of recycled aggregate, the type of expansive agent, and the spacing of CFRP strips on the mechanical properties of the composite structure was reviewed. Finally, the limitations of existing constitutive models were analyzed in detail, pointing out that existing models cannot accurately describe the full stress-strain curve of this novel composite material. This paper aims to clarify the research gaps in this field and provide direction for the future development of high-precision constitutive models.

Keywords: CFRP strips, active constraint, recycled aggregate, expansive concrete, constitutive model.

ИССЛЕДОВАНИЯ МЕХАНИЗМА РАБОТЫ И КОНСТИТУТИВНОЙ МОДЕЛИ РАСШИРЯЮЩЕГОСЯ БЕТОНА НА РЕЦИКЛИРОВАННОМ ЗАПОЛНИТЕЛЕ С АКТИВНЫМ ОГРАНИЧЕНИЕМ ПОЛОСАМИ ИЗ CFRP

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Реферат

Бетон на переработанных заполнителях (RA) привлек большое внимание из-за его экологических преимуществ, но его низкие механические свойства и высокая хрупкость ограничивают его применение в конструкциях. Одним из эффективных путей применения рециклингового заполнителя является его использование совместно с напрягающим цементом в условиях активного ограничения в виде пластиковых труб с навивкой полосового армирования из CFRP. Эта технология позволяет сгенерировать предварительные напряжения в полосах из CFRP посредством физико-химического расширения, создавая в бетонном ядре в условия трехосного ограничения предварительное сжатие, тем самым оптимизируя характеристики бетона до нагружения. Однако взаимодействие между пористостью переработанного заполнителя, эффективностью расширяющегося агента и непрерывным эффектом ограничения полос CFRP очень сложно описать т. к. механизм не ясен до конца, и апробированная конституционная модель отсутствует. Настоящая статья направлена на систематический обзор текущего состояния исследований механизма и конституционной модели напрягающего бетона на переработанном заполнителе в условиях ограничения CFRP полосами. В статье подробно проанализированы существующие конститутивные модели расширения напрягающего бетона на рециклинговых заполнителях в условиях трехосного ограничения, отмечая, что существующие модели не могут точно описать полную кривую развития самонапряжения во времени для этого нового композитного материала. Целью настоящей статьи является выяснение пробелов в исследованиях в этой области и формулирования направления для будущей разработки высокоточных конститутивных моделей.

Ключевые слова: полосы из CFRP (углепластика), активное ограничение, рециклинговый заполнитель, расширяющийся бетон, конституционная модель.

1 Introduction

With the ongoing advancement of global infrastructure development and the accelerating pace of urbanisation, the construction industry's demand for concrete raw materials has grown exponentially. This has simultaneously generated vast quantities of construction and demolition waste (CDW). Addressing the dual crises of resource scarcity and environmental pollution while meeting structural performance requirements has become a pressing core issue within the civil engineering sector. Recycled Aggregate Concrete (RAC) technology achieves this by crushing and screening waste concrete to replace natural aggregates, significantly reducing carbon emissions while enabling closed-loop recycling of construction resources [1, 5]. However, the surface-adhered aged mortar and micro-fractures generated during crushing impart inherent physical and mechanical deficiencies to recycled concrete aggregate (RCA), such as elevated porosity, high water absorption, and low crushing value [7]. These inherent limitations result in recycled aggregate concrete typically exhibiting lower compressive strength, elastic modulus, and durability compared to natural aggregate concrete (NAC) of equivalent grades, thereby restricting its widespread application in high-performance structural components [7].

To enhance the mechanical properties of recycled aggregate concrete and broaden its application scope, fibre-reinforced polymer (FRP) confinement technology has been introduced into the field of recycled aggregate concrete structural reinforcement [25]. FRP materials offer advantages such as lightweight high strength, corrosion resistance, and ease of construction. They can significantly enhance the strength and ductility of the concrete core by providing lateral confinement forces. Carbon fibre reinforced polymer (CFRP), in particular, is widely adopted due to its exceptional mechanical properties. However, traditional FRP wrapping techniques primarily provide passive confinement. Under passive confinement, the restraining force of FRP relies on lateral expansion of the core concrete. This implies that the restraining effect can only be fully realised after the concrete has undergone significant axial deformation and sustained a certain degree of damage [18]. For recycled aggregate concrete, which inherently possesses low stiffness and is prone to cracking, this delayed confinement mechanism often fails to effectively suppress early crack initiation. Consequently, the stiffness enhancement of the member during the elastic stage remains limited.

To overcome the limitations of passive confinement, the concept of active confinement emerged. By introducing expansive agents (EA) to prepare expansive concrete, the interaction between the volume expansion during concrete hardening and the external FRP materials enables the establishment of chemical prestressing within the core concrete prior to loading, thereby achieving 'active confinement' [2]. This chemical prestressing not only compensates for concrete shrinkage deformation but also enhances the cracking load and initial stiffness of the member, fundamentally improving the load-bearing performance of RAC. Furthermore, considering the potential issues of poor breathability and high cost associated with full-wrap FRP, the partial confinement technique using CFRP strips offers an alternative solution that balances economy and functionality [17]. CFRP strips permit moisture and heat exchange between concrete and the external environment, benefiting the hydration of expansive agents and the long-term performance of concrete. However, this also introduces more complex non-uniform constrained stress fields and arching action issues [13].

It is noteworthy that the confinement mechanics governed by a surrounding jacket has been well established in concrete-filled steel tube (CFST) members and FRP-tube encased concrete, where equilibrium and strain-compatibility allow the core's free strains (e. g., shrinkage, thermal strain, or expansion) to be converted into interface pressure in a closed-form manner.

Such a tube-based formulation provides a rigorous baseline for explaining how expansive concrete can mobilize "active" confinement in the jacket, rather than treating confinement efficiency purely as an empirical modification.Therefore, in addition to summarizing CFRP-strip confinement and expansive concrete, this review also introduces a tube-mechanics perspective (Section 3.4) to bridge CFRP-strip active confinement with the mature CFST/continuous-tube analytical framework [5, 22, 23].

The integration of CFRP strip partial confinement technology with recycled aggregate expansive concrete establishes a novel composite structural system combining green, low-carbon, active reinforcement, and cost-effectiveness. This system involves the microporous structure of recycled aggregates, the chemical reaction kinetics of expansive agents, the non-uniform physical confinement of CFRP strips, and the complex mechanical coupling between these three elements. This paper aims to systematically review the mechanical mechanisms and constitutive model research progress concerning CFRP strip-actively constrained recycled aggregate expansive concrete. The paper will delve into the synergistic 'internal curing-expansion' mechanism between recycled aggregates and expansive agents, examine stress path effects under active confinement alongside the non-uniform characteristics of strip confinement, and critically evaluate and compare existing constitutive models. This endeavour seeks to provide robust theoretical underpinnings for the engineering design and application of such novel composite structures.

2 Material Properties and Microscopic Synergistic Mechanisms of Recycled Aggregate Expansive Concrete

2.1 Multi-interface Defect Characteristics of Recycled Aggregates and Their Potential for Internal Curing Effect

The most critical difference between recycled aggregates and natural aggregates lies in their more complex and heterogeneous interfacial structures. Recycled aggregates are typically composed of virgin natural aggregates and old cement mortar adhering to their surfaces. This "two-phase" structure inevitably leads to multiple interfacial transition zones (ITZs) within recycled aggregate concrete (RAC). These include interfaces between new and old mortar, interfaces between old mortar and virgin aggregates, and interfaces where new mortar directly contacts virgin aggregates, especially when old mortar partially peels off during the crushing process [10]. Due to the diverse interface types, poor structural continuity, and significant gradients in material properties, microstructural analysis generally indicates that the interphase zone (ITZ) of reclaimed concrete (RAC) is often more porous. Pores and microcracks are more easily enriched and interconnected in this region, a characteristic considered a significant microscopic cause of the reduced macroscopic mechanical properties of RAC. Further research data reveals the porosity characteristics of recycled aggregates at the material parameter level; their porosity is typically more than 30 % higher than that of natural aggregates, while their water absorption can reach 5 % to 10 % [21]. Therefore, in conventional concrete, recycled aggregates often introduce a stronger mixing water adsorption effect and exacerbate the interfacial weakness problem, thus adversely affecting workability and strength development.

However, in expansive concrete systems, the aforementioned high porosity and high water absorption do not necessarily imply performance degradation. On the contrary, they provide a structural basis for the system to induce an "internal curing" effect. Traditional expansive concrete often faces the risk of insufficient moisture supply in engineering applications. This is because the hydration reaction of the expansive agent continuously consumes water. If external curing is insufficient, the decrease in relative humidity inside the system will induce self-drying shrinkage, thereby weakening the compensatory role that expansion should play [11]. The porous structure of recycled aggregates allows them to quickly absorb and store a certain amount of free water in the early stages of concrete mixing. As the cement hydration and hardening process progresses, the relative humidity inside the matrix gradually decreases, forming a capillary pressure difference. This pressure difference further drives the release of water from the pores of the recycled aggregates into the surrounding paste, thus replenishing the water required for cement hydration and the reaction of the expansive agent in a more continuous manner [11]. When internal curing water is stably supplied at the microscale, its effect is not only to promote a more complete reaction of the expansive agent and increase the restricted expansion rate, but also to change the microscopic evolution path of the ITZ by improving the hydration environment of the interface zone. The C-S-H gel and hydrated aluminate generated near the interface can more effectively fill pores and bridge microcracks, making the ITZ structure more compact, thus achieving a certain degree of repair and weakening of microscopic defects in RAC [8].

2.2 Expansive Agent Reaction Kinetics and the Formation Mechanism of Chemical Prestress under Constrained Conditions

The volume increase of expansive concrete is usually achieved by incorporating calcium-based (CaO), magnesium-based (MgO), or calcium sulfoaluminate-based expansive agents. However, different expansive agents have significant differences in reaction mechanism, reaction rate, and expansion history, which directly determines the temporal characteristics of the expansion effect and its adaptability to shrinkage compensation. Calcium sulfoaluminate-based expansive agents primarily generate crystalline growth pressure within the cement paste skeleton by producing needle-like ettringite crystals (AFt), thereby driving volume expansion. This type of expansion typically occurs in the early stages of hydration and exhibits a relatively rapid development rate [4]. In contrast, MgO expansive agents generate magnesium hydroxide crystals ($Mg(OH)_2$) through hydration. Their reaction process is slower and more significantly affected by temperature, thus potentially providing a longer-lasting delayed expansion effect. This has more direct engineering significance for compensating for the later-stage shrinkage of large-volume concrete [19]. Since the expansion effect essentially originates from the generation and growth of hydration products, the system's moisture supply, temperature conditions, and pore structure all influence the reaction mechanism and final expansion contribution of the expansive agent to varying degrees, resulting in expansive concrete exhibiting a clear material-environment coupling characteristic.

When expansive concrete is within a CFRP strip-constrained system, the free expansion of the core concrete is restricted by the external FRP material. This restriction does not eliminate expansion but rather transforms it into a characterizable stress state. According to Newton's third law, the reaction of external constraints forces compressive stress σ_{pre} within the concrete, while simultaneously inducing corresponding tensile stress $\sigma_{\mathrm{frp,0}}$in the FRP strips. This state, driven by a chemical reaction and ultimately manifesting as mechanical stress, can be defined as "chemical prestressing." Previous studies have indicated that the level of chemical prestressing depends on key factors such as the type and dosage of the expansive agent, the water-cement ratio, curing conditions, and the stiffness of the external constraints [2]. When chemical prestressing is within a moderate range, the concrete more closely approximates a triaxial compressive working state, and its crack resistance and initial elastic modulus are often significantly improved. However, stronger expansion is not always more beneficial. When the expansive agent dosage is excessive or the expansion pressure exceeds the tensile strength of the concrete matrix in the unconstrained direction, new microcracks may form internally, compromising material integrity and thus negating the expected gains or even converting them into performance damage [2]. Therefore, the mix design and constraint system design of recycled aggregate expansive concrete need to simultaneously consider the regulatory effects of the water absorption and release behavior of recycled aggregate on the hydration environment, as well as the influence of the water consumption of the expansive agent during hydration and the growth of its products on the evolution of internal stress. Only by precisely matching the water supply capacity with the reaction requirements can a more stable and repeatable synergistic effect be achieved between microstructural densification and macroscopic mechanical property improvement.

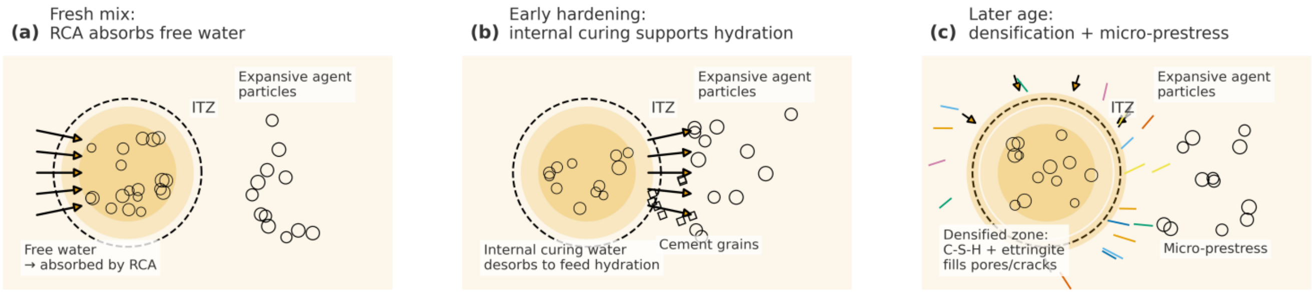

Figure 1 – Schematic diagram of the microscopic synergistic mechanism between recycled aggregate and expansion agent [2, 10, 11]

Figure 1 aims to visually present the microscopic path and structural results of the synergistic effect between recycled aggregate and expansive agent during hydration. This schematic diagram illustrates the key stages of water migration and interface evolution in a time-progressive manner. The left side of the figure corresponds to the fresh mixing stage. In the initial stage of mixing, porous recycled aggregate (RCA) adsorbs and stores a large amount of free water, and the old mortar layer attached to its surface is in a high-saturation state. The expansive agent particles are relatively uniformly dispersed in the new cement paste, providing a spatially diffusible basis for subsequent reactions. The middle part of the figure depicts the water redistribution process in the early stages of hardening. As cement hydration continues to consume external moisture, the internal humidity of the matrix gradually decreases, forming capillary tension. Under this driving force, the internal curing water stored inside the recycled aggregate undergoes desorption and migrates outward. The released water is preferentially transported to adjacent expansion agent particles and unhydrated cement particles, thereby maintaining the local water environment required for the reaction at the microscale. The right side of the figure corresponds to the structural strengthening results in the later stages of hardening. Near the interface transition zone (ITZ) between RCA and the new paste, due to continuous water replenishment, more abundant ettringite crystals and dense C-S-H gel are generated. These hydration products fill and seal the previously loose pores and microcracks, forming a identifiable "densified zone" around the interface. At the same time, the growth of expansion products is restricted by the external skeleton and constraints, inducing a prestressed state at the microscale, making the overall matrix structure more compact and possessing stronger crack resistance potential. This schematic process provides a clearer understanding of how internal curing, in conjunction with micro-expansion, affects the evolution of interfacial defects and pore structure in RAC, thereby promoting simultaneous improvement of material properties at both the micro and macro levels [10].

3 Mechanical Mechanism of CFRP Strip Active Constraint Systems

3.1 Differences in Stress Initiation Points and Path-Dependent Responses Between Active and Passive Constraint

The core prerequisite for understanding CFRP strip active constraint systems lies in clarifying the fundamental differences between ‘active constraint’ and ‘passive constraint’ in terms of constraint initiation mechanisms and stress onset points. Furthermore, it is essential to recognise how these differences influence material damage evolution and ultimate load-bearing performance through stress pathways. Traditional FRP-constrained concrete typically constitutes a passive constraint system. During the initial loading phase, the FRP jacket bears negligible effective stress. Only when the core concrete undergoes longitudinal compression under axial pressure, accompanied by lateral expansion, does the FRP develop circumferential tensile forces through passive stretching. This subsequently imposes lateral constraint pressure σ_l upon the core concrete. Within this framework, the magnitude of the confinement pressure is governed by the lateral strain ε_l, i. e., $\sigma_l = f(\varepsilon_l)$. Consequently, the establishment of confinement exhibits pronounced hysteresis. This hysteresis implies that the confinement effect is often only gradually activated after the concrete has already developed a certain degree of microcrack initiation and damage accumulation. For recycled aggregate concrete, which exhibits greater brittleness, more initial defects, and lower overall stiffness, the material is more sensitive to damage during the early loading stages. Irreversible micro-deterioration may occur before the confinement effect is fully developed, thereby inherently limiting the subsequent enhancement of strength and ductility through confinement [18].

Upon introducing expansive agents, the confinement mechanism undergoes a fundamental transformation. Concrete can generate initial lateral compressive stress $\sigma_{l,ini}$ internally through volumetric expansion before external axial working loads are applied. Concurrently, CFRP strips are prestressed due to the induced tensile strain. The presence of confining pressure alters the material's failure criteria. From the perspective of the Mohr-Coulomb failure criterion, the initial confining pressure effectively extends the elastic range of the concrete at the onset of loading and raises the crack initiation threshold. This results in earlier and more effective suppression of microcrack nucleation and propagation. More significantly, active confinement not only provides a non-zero initial confining pressure value but also fundamentally alters the stress path of the concrete: under passive confinement, confining pressure typically increases monotonically from zero as axial load increases; whereas under active confinement, confining pressure commences from a non-zero level, with its subsequent growth rate jointly governed by FRP stiffness and concrete shear-expansion characteristics. Consequently, the evolution of confining pressure exhibits distinct temporal characteristics compared to passive confinement. Extensive research indicates that concrete's mechanical response exhibits pronounced path-dependency. Even when ultimately reaching identical confining pressure levels, specimens subjected to active confinement pathways frequently demonstrate higher ultimate strengths and superior ductility [9]. This disparity does not stem from a simple comparison of ‘final confining pressure values,’ but rather relates more profoundly to whether damage is suppressed in the early stages. Active confinement imposes restrictions on microcrack evolution from the onset of loading, enabling the material to maintain higher structural integrity throughout the loading process. This provides a more stable microstructural foundation for subsequent strength development and deformation capacity.

3.2 Arch Effect of Partially Constrained Strips and Evolution of Effective Constraint Induced by Expansion

Compared to continuous FRP tubes or fully wrapped configurations, CFRP strip confinement introduces a pronounced non-uniform stress field alongside lateral restraint. This non-uniformity manifests not only in the cross-sectional direction but more markedly in discontinuous distribution characteristics along the component height. Within the strip coverage zones, concrete experiences strong confinement, whereas in the inter-strip gaps, it remains weakly confined or even unconstrained. Consequently, confinement stresses do not propagate uniformly along the height. The classical 'arching action' theory is commonly employed to explain this phenomenon. Its fundamental principle posits that confinement stress does not propagate linearly between adjacent strips but traverses the gap regions via arched stress paths, enabling transfer from one confinement ring to the next. During this process, only the concrete within the arched region forms an effective confined core and receives effective confining pressure, whereas the concrete outside the arch, closer to the free surface, is more prone to spalling or brittle failure [13]. Consequently, the load-bearing contribution of strip confinement largely depends on the adequate formation of the arch effect and the actual extent of the effective confined core under geometric and material conditions.

When the confined material transitions from ordinary concrete to expansive concrete, the mechanism of arch effect formation and confinement effectiveness exhibit heightened dynamism. This arises because expansion constitutes a volumetric deformation process, wherein the core concrete exhibits an outward expansion tendency even within the strip gaps. This tendency may manifest prior to the application of external axial loading. Should the spacing between CFRP strips be excessively large, the concrete within the gaps may crack under expansive forces, potentially leading to localised failure even before axial loading. This creates a persistent 'pre-damage' effect, prematurely diminishing the potential for strength and ductility enhancement during subsequent compression stages. Precisely because expansion introduces pre-loading deformation and internal stress evolution, the determinants of the effective confinement coefficient $\mathrm{k_e}$ are no longer confined to geometric parameters alone. Instead, they must simultaneously account for the expansion energy generated by the admixture reaction and the resulting stress redistribution process. The classical expression proposed by Mander et al. is typically written as $\mathrm{k_e} = (1 - \mathrm{s'}/2\mathrm{d_c})^2$, where $\mathrm{s'}$ denotes the net spacing between strips and $\mathrm{d_c}$ represents the core diameter [27]. This formulation essentially characterises the reduction in the effective core size through geometric relationships. However, for expansive concrete systems, direct application of this geometric coefficient often fails to reflect the actual deviations caused by expansion-induced stress increases in the interstitial zone or pre-damage effects. Consequently, $\mathrm{k_e}$ requires modification to incorporate the influence of stress redistribution induced by expansion [6]. Further research indicates that when the ratio of net strip spacing to member dimensions exceeds a certain threshold, arching effects struggle to stabilise, leading to a sudden drop in confinement efficiency. The failure mode may shift from confinement-dominated behaviour to shear failure of the interstitial concrete. This threshold is frequently reported in multiple studies to be close to 0,5 [17]. Consequently, in the strip confinement design for expansive concrete, strip spacing does not merely determine the 'strength of confinement'. It more directly influences whether the expansion phase will induce premature damage in the gap zone, thereby affecting the effectiveness and stability of the entire confinement system throughout the entire compression process.

3.3 Stress Concentration and Constraint Efficiency Modulation Induced by Cross-Section Geometric Effects

When the cross-section of a component is rectangular or square, the non-uniformity encountered by CFRP strip confinement exhibits a superposition effect, typically exhibiting significantly greater complexity than circular cross-sections. On the one hand, the strip spacing in the height direction still causes discrete distribution of confinement pressure along the height due to the arch effect. On the other hand, the corner effect in the cross-sectional direction further leads to significant in-plane non-uniformity of confinement pressure. For rectangular cross-sections, lateral confinement pressure tends to concentrate in corner regions, while confinement at the mid-sections of straight edges is relatively weaker. This occurs because FRP, as a flexible membrane material, tends to provide membrane tensile response rather than directly forming stable confining pressure in straight segments. Consequently, the mid-sections of straight edges struggle to achieve lateral compressive stress levels comparable to those at corners [14]. When the material is replaced with recycled aggregate concrete, its internal defect distribution exhibits greater randomness and heterogeneity. The non-uniform constraint stress field is more likely to trigger damage propagation at local defects and weak interfaces, manifesting as localised failure initiating and rapidly evolving into global failure. Concurrently, the high stiffness of CFRP strips provides strong confinement to localised regions but may also induce stress concentration at strip edges or locations of stress discontinuity. This generates significant shear effects within the concrete at these points, potentially triggering localised shear failure. Consequently, the overall utilisation rate and ductility contribution of the confinement system are diminished. Consequently, corner rounding of rectangular columns is widely regarded as a crucial method for enhancing confinement efficiency. Increasing the radius of curvature improves the continuity of FRP strain development and confining pressure distribution at corners, resulting in more uniform lateral confinement and enhancing the effective utilisation of CFRP material [16].

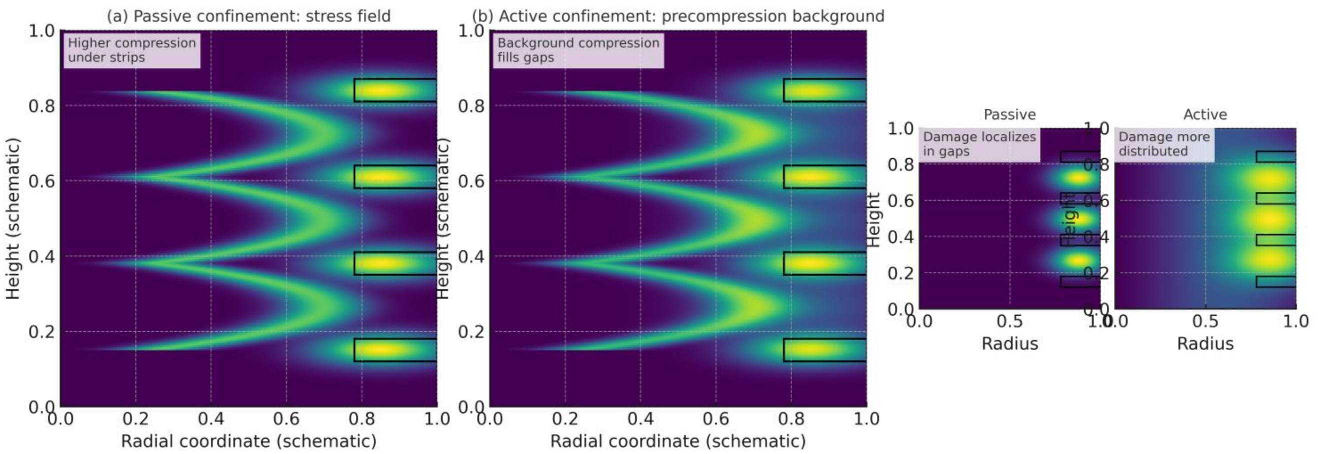

Figure 2 – Comparison of internal stress fields within CFRP-constrained concrete under active and passive constraint conditions [2, 5, 18, 24]

To elucidate the coupling relationship between active confinement and the partial confinement effect of the strips, a comparative analysis of the two states can be conducted using stress contour plots derived from finite element numerical simulations. Figure 2a corresponds to the passive confinement state, displaying the distribution of minimum principal stresses along the longitudinal section of the CFRP strip-confined concrete cylinder during the initial stage of axial loading. Where compressive stresses predominantly concentrate directly beneath the CFRP strips. Darker hues indicate higher local confining pressure levels. Distinct arched stress transfer pathways emerge between the strips: the inner arch region exhibits elevated compressive stresses forming an effective confinement core, while the outer arch area near the concrete surface shows markedly lighter colours, even exhibiting near-zero stress zones. This reflects a low-confinement blind zone where effective confining pressure is scarcely established during the early loading stage. Figure 2b corresponds to the active confinement state, illustrating the stress distribution characteristics prior to axial loading after introducing the expansive agent. Compared to Figure 2a, a background compressive stress field is observed throughout the entire cross-section, including the inter-strip void regions. While the highest compressive stress levels persist beneath the strips, stresses in the void regions are significantly elevated, and the original low-stress blind zones tend to disappear. This indicates that the initial confining pressure introduced by chemical prestressing spatially compensates for the inherent weak zones in the discontinuous confinement provided by the strips. Consequently, a continuous compressive stress field is established earlier within the component. Figure 2c further presents a comparative damage contour plot during the failure stage. The passively constrained specimen exhibits greater susceptibility to damage concentration at the strip gaps, forming distinct shear zones. Conversely, the actively constrained specimen typically displays more uniform damage distribution, with crack morphology tending towards finer and more dispersed patterns. This disparity numerically corroborates the mechanism by which active confinement mitigates stress concentration and suppresses localised failure [6].

3.4 Tube-based mechanical model and analogy with CFST members

From a mechanics viewpoint, the actively confined RAC–EC with CFRP strips can be regarded as a discontinuous approximation of a full tube surrounding the concrete core. This configuration is conceptually close to classical concrete-filled steel tube (CFST) and FRP-tube encased concrete members, in which the tube and the core concrete share compatible deformations and interact through radial interface pressure. Tube-based analytical models developed for CFST and FRP tubes therefore provide a useful reference framework for interpreting the stress transfer mechanism in the present system [5, 22, 23].

For a thin-walled circular tube with thickness ttt and mean radius rrr, made of an isotropic linear-elastic material with elastic modulus EsE_sEs and Poisson's ratio μs\mu_sμs, the hoop and axial stresses can be expressed in terms of the corresponding strains as

$$\sigma_{s,\theta}=\frac{E_s}{1-\mu_s^2}\left(\epsilon_{s,\theta}+\mu_s\epsilon_{s,z}\right),\quad \sigma_{s,z}=\frac{E_s}{1-\mu_s^2}\left(\epsilon_{s,z}+\mu_s\epsilon_{s,\theta}\right). \quad (1)$$

Assuming perfect bond at the tube–concrete interface and uniform internal pressure, radial equilibrium of a closed tube leads to the classical thin-walled relations

$$q=\frac{t}{r}\sigma_{s,\theta},\quad \sigma_{s,z}=\frac{qr}{2t}, \quad (2)$$

where q is the confining pressure acting on the concrete core. Equations (1), (2) show that the active confining pressure generated by expansion or differential deformation in the core can be directly related to the hoop and axial strains in the surrounding tube (see Figure 3).

The concrete core is simultaneously subjected to axial stress and lateral confinement. Neglecting radial stress gradients within the core and adopting an effective time-dependent modulus $E_{cm}(t)$ and Poisson's ratio μ_c, the tangential and axial concrete stresses associated with the elastic part of the strains can be written in a form analogous to generalized Hooke's law

$$\sigma_{c,\theta\theta}=\frac{E_{cm}(t)}{(1+\mu_c)(1-2\mu_c)}\left[(1-\mu_c)\epsilon_{c,\theta\theta}+\mu_c\epsilon_{c,zz}\right],$$
$$\sigma_{c,zz}=\frac{E_{cm}(t)}{(1+\mu_c)(1-2\mu_c)}\left[(1-\mu_c)\epsilon_{c,zz}+\mu_c\epsilon_{c,\theta\theta}\right], \quad (3)$$

with radial equilibrium at the interface requiring $\sigma_{c,rr}(r_i)=-q$. Together with the strain-compatibility conditions $\varepsilon_{s,\theta}=\varepsilon_{c,\theta\theta}$ and $\varepsilon_{s,z}=\varepsilon_{c,zz}$ at the interface, Equations (1)–(3) form a closed "tube model" that links the free expansive strain of RAC-EC, the tensile response of the CFRP (or steel) tube, and the resulting three-dimensional stress state in the core. In CFST members, similar formulations are widely used to quantify how temperature rise, shrinkage and creep of the concrete core generate active confinement in the steel tube; here the same approach can be used to interpret the chemical prestressing produced by expansive agents in RAC-EC.

When time-dependent effects are included, the total strains in both tube and concrete can be decomposed into instantaneous elastic parts and creep components. For the concrete core, the circumferential and axial strain increments at a generic time step t_i may be expressed as

$$\Delta\epsilon_{c,\theta\theta}^{(i)}=\Delta\epsilon_{c,\theta\theta}^{E(i)}+\sum_{j=1}^{i}\Delta\sigma_{c,\theta\theta}^{(j)}\frac{\Delta\varphi(t_i,t_j)}{E_{cm,28}}+\sum_{j=1}^{i}\Delta\sigma_{c,zz}^{(j)}\frac{\Delta\psi(t_i,t_j)}{E_{cm,28}},$$
$$\Delta\epsilon_{c,zz}^{(i)}=\Delta\epsilon_{c,zz}^{E(i)}+\sum_{j=1}^{i}\Delta\sigma_{c,zz}^{(j)}\frac{\Delta\varphi(t_i,t_j)}{E_{cm,28}}+\sum_{j=1}^{i}\Delta\sigma_{c,\theta\theta}^{(j)}\frac{\Delta\psi(t_i,t_j)}{E_{cm,28}}, \quad (4)$$

where $\Delta\varphi(t_i,t_j)$ and $\Delta\psi(t_i,t_j)$ are discrete creep functions associated with the history of tangential and axial stresses, respectively, and E_{cm} is a reference modulus at 28 days. The corresponding stress increments in the tube, $\Delta\sigma_{s,\theta}^{(i)}$ and $\Delta\sigma_{s,z}^{(i)}$, are obtained from Equation (1) using the compatible strain increments in the tube. Substituting these stress increments into Equation (2) provides the evolution of the confining pressure q(t) and thus the time-varying active confinement level in the core.

For RAC-EC members confined by CFRP strips rather than a continuous tube, the above tube model can still be used in an "equivalent-tube" sense. An effective tube thickness teq may be introduced by distributing the total strip area uniformly around the perimeter, while the non-uniformity of strip confinement is accounted for through the effective confinement coefficient ke discussed in Sections 3.2 and 4.3. In this way, the active confining pressure derived from Equations (1)–(4) can be interpreted as the mean confining pressure in the effectively confined core, and the influence of strip spacing, strip width and expansion level can be translated into modifications of teq and ke. This tube-based analytical framework provides a direct theoretical bridge between the well-established mechanics of CFST/FRP-tube systems and the more complex behaviour of CFRP-strip-actively confined RAC-EC members.

4 Axial Compression Performance, Failure Modes and Key Parameter Analysis

4.1 Failure Patterns and Their Evolutionary Mechanisms

The failure patterns exhibited by CFRP-strip-actively-constrained recycled aggregate expansive concrete under axial compression fundamentally result from the competitive and mutually reinforcing interplay of multiple mechanisms across different stages. The dominant mechanism is typically governed by the combined effects of constraint stiffness, recycled aggregate replacement rate, and expansive agent dosage. Constraint stiffness is determined not only by the number of CFRP layers but also closely relates to strip spacing, strip width, and their mode of shaping the effective constraint core. The recycled aggregate replacement rate influences crack initiation locations and propagation pathways by altering the matrix's initial defect level, interfacial weakness, and shear-expansion response; the expansive agent dosage further modifies the pre-loading initial stress state and early-loading crack initiation threshold through the magnitude and distribution of chemical prestress. Based on experimental phenomena and the temporal characteristics of failure processes, common failures can be categorised into several representative types. However, these are not mutually exclusive; they often occur sequentially or concurrently within the same specimen, differing only in their dominant features.

When confinement is strong – that is, when strip spacing is small, the number of layers is high, and the effective confinement core area is large – the specimen is more likely to exhibit a failure mode dominated by CFRP tensile rupture. This failure typically commences when tensile strain in one or several strips near the mid-column rapidly approaches its limit, accompanied by a distinct audible crack. Subsequently, due to the instantaneous loss of lateral confinement locally, the core concrete rapidly transitions to crushing failure under high axial compression, producing significant fragmentation and spalling. It is important to note that within active confinement systems, the expansion phase already induces initial tensile strain in the CFRP strips. This effectively consumes part of the strain reserve before axial loading commences. Consequently, the 'additional available fracture strain' that CFRP can provide during loading is often less than the material limit values measured in uniaxial tensile tests. Concurrently, the volume deformation and shear expansion characteristics of recycled aggregate systems are more pronounced. Under intermittent confinement conditions, the strips may exhibit greater strain inhomogeneity, causing the strain efficiency coefficient to vary across different structural parameters and material combinations [24]. This affects the actual location and sequence of reaching the limit state defined by 'reaching ϵ_f'.

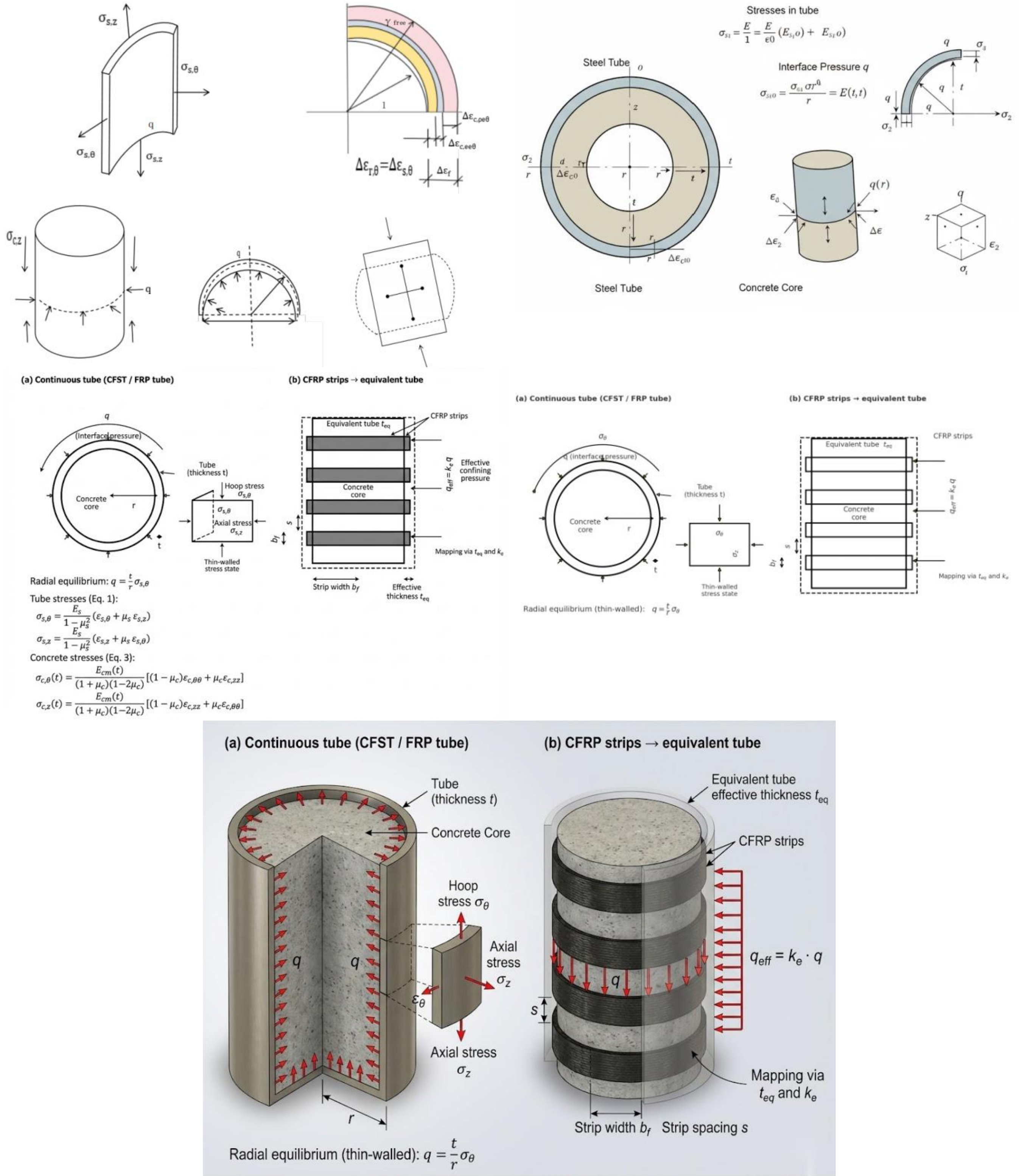

Figure 3 – Tube-based mechanical model and its analogy with CFST/FRP-tube members

When constraints are weaker – that is, when strip spacing is large and arching effects struggle to form a continuous, effective core in the height direction – failure often initiates earlier in the concrete at strip gaps. Due to insufficient confining pressure in these gap regions, the concrete is more prone to bulging outward under axial compression. The combined action of tensile strain induced by bulging and shear strain then leads to longitudinal cracks, diagonal cracks, and even local spalling. The aged mortar interface and multiple inter-tension zones (ITZ) in recycled aggregate concrete readily compromise its shear and tensile load-bearing pathways. resulting in more pronounced shear slip zones and distinct brittle behaviour. Even when CFRP strips have not reached ultimate strength or ultimate strain ϵ_f, members may prematurely lose overall load-carrying capacity due to localised core concrete instability and failure of the load-transfer chain [17]. Under such circumstances, the strips function more as ‘restricting crack propagation and delaying delamination’ rather than providing full-height confinement pressure. Consequently, their contribution to peak strength and ultimate deformation is markedly capped.

Mixed failure is more likely to occur under combinations of moderate confinement stiffness or high expansive agent dosage, often manifesting as a composite outcome of 'pre-loading state' and 'loading evolution'. Should the chemical prestress induced by expansion be substantial, CFRP strips may approach their tensile strength limit early in axial loading, thereby limiting subsequent strain development. Concurrently, excessive strip spacing or uneven local release may permit micro-precracks to form in the gap zone concrete during the free expansion phase. These may rapidly evolve into shear zones upon axial loading application. At this juncture, CFRP failure and shear crushing of concrete at the gap may occur in close temporal proximity. Macro-scopically, this manifests as FRP failure and localised concrete failure occurring almost simultaneously, resulting in a more abrupt and discrete failure process. Consequently, the residual load-bearing capacity and failure warning characteristics of the specimen become relatively weaker.

4.2 Full-Cycle Axial Stress–Strain Response

Under axial compression, the axial stress–strain curve of CFRP-strip-constrained RAC generally exhibits typical bilinear characteristics. However, its curve morphology, key inflection point locations, and late-stage evolution patterns demonstrate more pronounced differences compared to the constraint responses of conventional passive-constrained or ordinary natural aggregate concrete [2]. This divergence stems from the active confinement system introducing non-zero confining pressure and prestressing conditions from the onset of loading. This places the material under stronger triaxial compression and crack closure from the initial stage. while the strip-like partial confinement significantly influences the spatial distribution and load-dependent uniformity of confining pressure through geometric constraints. Consequently, each segment of the curve bears the combined imprint of both 'chemical prestressing' and 'arch effect confinement'.

During the initial response phase, the curve typically exhibits a steeper ascent, reflecting higher initial stiffness and a lower early damage growth rate. This primarily stems from expansion-induced chemical prestressing, which promotes closure of existing microcracks and elevates crack initiation stress levels. Consequently, RACs under macroscopic compression exhibit deformation patterns closer to those of continuous media. Simultaneously, the confining pressure background suppresses shear expansion, favouring the conversion of axial compression into volumetric compaction and skeletal co-loading. This enhances the equivalent elastic modulus during the curve's initial segment. When incorporating prestress as an initial condition, the curve's origin typically deviates from the absolute starting point, exhibiting rapid stress growth within the low-strain range. This 'origin offset' does not indicate measurement anomalies but reflects pre-existing stress reserves and crack closure effects within the system prior to loading.

As axial stress further increases, the region where the curve transitions from the initial near-linear segment to the second stage typically corresponds to the 'knee point'. This point may be regarded as the critical location where the core concrete shifts from predominantly elastic deformation to predominantly plastic damage participation. Active confinement generally significantly elevates the stress level corresponding to the knee point, delaying the onset of the pronounced damage accumulation phase. This enables the material to maintain more stable stiffness and more controllable deformation development within the service load range. This is particularly crucial for recycled aggregate concrete, as its interfacial transition zone (ITZ) defects are more readily activated at lower stress levels. Active confining pressure suppresses crack initiation, raising the threshold for micro-to-macro crack transition and promoting finer, more dispersed damage development.

Upon entering the strengthening phase, the secondary stiffness curve is primarily governed by CFRP strip stiffness and confinement efficiency. However, under strip confinement, secondary stiffness often exhibits more pronounced specimen variability. This arises because the arching effect dynamically adjusts with increasing load and shear expansion evolution, while confining pressure levels in the void zone and strip-covered zone do not increase synchronously. For RAC, owing to its stronger constitutive softening tendency, a rising strengthening segment may still form under sufficient confinement, though its slope may be slightly lower than that of natural aggregate concrete, manifesting as a slower load capacity increase. When confinement is insufficient or significant prior damage occurs in the void zone, the curve may exhibit premature softening trends, or even enter a descending branch after the peak. At this stage, the magnitude of load capacity enhancement is constrained, and the development of ultimate strain becomes more dependent on the deformation space released by local spalling and shear zone expansion.

Near the ultimate state, the influence of recycled aggregate replacement rate often presents a combined characteristic of 'decreased strength but potentially increased deformation capacity'. As the replacement ratio increases, the peak stress of the core concrete typically decreases, consistent with the fundamental principle of reduced material strength and interface quality. However, under triaxial compression and confining pressure constraints, the porous structure of RAC actually endows it with greater compaction potential. This allows it to accommodate more compaction deformation and shear-expansion-constrained deformation before overall crushing occurs, potentially increasing ultimate strain and exhibiting more pronounced ductile characteristics [20]. It should be noted that this enhanced ductility does not equate to reduced damage; rather, it manifests as 'more dispersed damage and a more gradual evolution'. Whether this translates into reliable engineering toughness ultimately depends on whether the strip spacing, number of layers, and expansion prestress collectively maintain the stability of the effectively constrained core, thereby preventing premature localised instability in the interstitial zones from dominating failure.

4.3 Key Parameter Sensitivity and Design Implications

For actively restrained RAC expansive concrete, the parameters influencing axial compression performance typically interact through three pathways: geometric constraints, chemical prestressing levels, and matrix material variations. Certain parameters exhibit high sensitivity to restraint efficiency, where slight deviations from optimal ranges may induce qualitative changes in failure modes and stress-strain responses. Regarding geometric configuration, the net spacing between strips and strip width constitute the most direct combination of parameters determining effective confinement. The net spacing exhibits particular sensitivity in influencing the effective confinement coefficient. Existing research indicates that as net spacing increases, the effective confinement coefficient follows an approximate quadratic decay pattern. This implies that increased spacing not only linearly reduces the confining pressure level but also significantly amplifies adverse effects by diminishing the effective confinement core area. When s'/d is small, the specimen's overall response more closely resembles the hardening behaviour of fully wrapped confinement, with a more pronounced curve-strengthening segment and a more significant increase in peak load-bearing capacity. When s'/d exceeds a critical threshold – commonly reported around 0,5 – the arching effect struggles to stabilise vertically. Bulging in the gap zone and expansion of shear bands begin to dominate failure, making stress–strain curves more prone to softening segments and causing load-bearing gains to plummet sharply [17]. Under such conditions, the strips primarily inhibit crack width and local spalling rather than sustainably providing adequate confining pressure. Consequently, even increasing the strip strength grade may not linearly translate to higher peak strength.

The influence of expansive agent dosage on active confinement exhibits a characteristic non-monotonic behaviour, fundamentally stemming from a significant trade-off between 'beneficial prestressing' and 'self-damage or depletion of strength reserves'. An appropriate expansion agent dosage establishes a reasonable chemical prestressing background prior to loading, enhancing initial stiffness and elevating the stress level at the knee point. This stabilises the material within the service stress range while also reducing the activation of early microcracks, thereby providing a more complete microstructural foundation for subsequent strengthening phase development. However, excessive dosage may yield adverse consequences through two pathways: firstly, during the free expansion phase, insufficient confinement may induce expansion cracks in the matrix, creating irreversible self-damage that compromises integrity at the onset of subsequent compression loading; Secondly, excessive expansion may cause CFRP strips to consume excessive strength and strain reserves prior to loading, effectively increasing the initial tensile level and reducing the subsequent available ϵ_f space. This diminishes deformation potential and load-bearing reserves at ultimate limit states [2]. Consequently, the optimal range for expansive agent dosage typically aligns with the constraint stiffness and RAC strength grade. Within this range, the establishment of chemical prestress significantly amplifies the effectiveness of strip confinement. Deviations from this range may lead to two distinct issues: 'ineffective prestress conversion' or 'reverse prestress damage'.

The replacement rate of recycled aggregates primarily influences the overall performance of the active confinement system by altering the fundamental mechanical properties, lateral deformation capacity, and time effects of the core concrete. As the replacement ratio increases, the elastic modulus of the RAC typically decreases, enhancing its tendency for lateral deformation and consequently increasing its lateral deformation coefficient. Within passive restraint systems, this characteristic may prompt FRP to enter tension earlier and become 'activated' sooner. However, in active restraint systems, confining pressure is already present prior to loading. Therefore, variations in replacement ratio more prominently manifest as the 'level of restraint required' to compensate for the loss in matrix strength and achieve the target performance level. In other words, when RAC strength diminishes and defects proliferate, insufficient constraint strength or an inadequate effective core zone may lead to failure being dominated by localised failure in the gap zone, thereby undermining the advantages of active confinement. Furthermore, the relatively high creep and pronounced long-term deformation characteristics of RAC may lead to more significant loss of chemical prestressing over time, resulting in an actual $\sigma_{l,ini}$ during loading that falls below design expectations. This time-dependent prestressing decay warrants particular consideration within design and evaluation frameworks under long-term service conditions [7]. Consequently, the replacement ratio not only determines the 'level of strength' but also alters the actual working state of the restraint system through lateral deformation and time effects. This, in turn, influences the overall shape of the stress – strain curve and the final failure mode classification.

To quantify the impact of the above parameters, we use a comprehensive data table to compare typical experimental results. Table 1 clearly shows that introducing active constraints (A) can further improve the strength compared to passive constraints (P); although the gain of strip constraints is lower than that of full constraints, the performance of active strip constraints (RAC-A-Strip) is close to or even exceeds that of ordinary full-enclosed passive constraints, proving the efficiency of this technical approach.

Table 1 – Typical influence of expansive agent dosage on active confinement effectiveness [2]

Specimen Type	Restraint Method	Expansion agent dosage (%)	Aggregate Type	Peak stress gain (%)	Maximum Strain Gain (%)	Failure Modes
RAC-Ctrl	Unrestrained	0	100 % RCA	–	–	Shear Failure
RAC-P-Full	Fully Enclosed Passive	0	100 % RCA	+120 %	+350 %	FRP Fracture
RAC-P-Strip	Strip Passive	0	100 % RCA	+65 %	+180 %	Gap Crushing
RAC-A-Full	Fully Enclosed Active	10	100 % RCA	+145 %	+320 %	FRP Fracture
RAC-A-Strip	Strip Active	10	100 % RCA	+95 %	+210 %	Mixed Mode
RAC-A-HighExp	Strip Active	20	100 % RCA	+85 %	+150 %	Pre-cracking/FRP Fracture

Note – Although the source data comes from GFRP specimens, the non-monotonic trend of strength gain regarding expansion dosage is representative and applicable to CFRP systems discussed in this review.

5 Progress and Evaluation of Constitutive Model Research

Establishing constitutive models with sufficient accuracy and transferability is a prerequisite for structural design, load-bearing capacity verification, and nonlinear finite element analysis. For CFRP strip-constrained recycled aggregate expansive concrete, both the material and constraint system exhibit characteristics such as a multi-defect matrix caused by recycled aggregates, an initial stress state introduced by expansive agents, and a non-uniform constraint stress field resulting from the strip configuration. These features render the stress-strain relationship no longer a simple response explainable by a single mechanism. Consequently, existing research typically advances along two main lines: on the one hand, targeted modifications to classical FRP-constrained concrete models to enable their application in predicting limit states for engineering design; on the other hand, a greater emphasis on constructing incremental analysis models based on physical mechanisms to generate full curves and reproduce path-dependent responses under active confinement conditions. Within this framework, a model's universality is often demonstrated by its compatibility with diverse constraint configurations, aggregate systems, and expansion levels. Its usability, meanwhile, manifests as a balance between parameter identifiability, computational stability, and engineering expressiveness.

5.1 Design-Oriented Ultimate State Models

Design-oriented models prioritise direct prediction of ultimate state indicators, typically employing peak stress f_{cc}' and ultimate strain ϵ_{cu} as core outputs. They provide engineering convenience through explicitly formulated equations that are as concise as practicable. The advantage of such models lies in their compatibility with structural verification and standardised applications, enabling rapid establishment of quantitative relationships between 'constraint strength and load-bearing capacity gains'. However, their limitations are also evident: they offer relatively limited capability to characterise stiffness evolution, inflection point locations, and softening behaviour throughout the loading process. Consequently, they are often regarded as result-oriented ultimate state estimation tools rather than complete constitutive expressions directly driving full-process numerical analysis.

5.2 Modifications to Classical Models

Among numerous ultimate limit state models, the Lam and Teng model is widely adopted due to its clear formulation and readily obtainable parameters. Its fundamental expression can be written as

$$\frac{f'_{cc}}{f'_{co}} = 1 + 3.3\frac{f_l}{f'_{co}}, \qquad \frac{\epsilon_{cu}}{\epsilon_{co}} = 1.75 + 12\frac{f_l}{f'_{co}}\left(\frac{\epsilon_{h,rup}}{\epsilon_{co}}\right)^{0.45}. \qquad (5)$$

Among these, f_{co}' and ϵ_{co} typically correspond to the peak stress and peak strain of unconstrained concrete, f_l denotes the nominal lateral confinement pressure, while $\epsilon_{h,rup}$ relates to FRP rupture. For the CFRP strip-enhanced active confinement (RAC) system, direct application of the aforementioned model often introduces systematic biases concerning confinement effectiveness and initial stress state. Consequently, researchers typically extend and modify the model across three dimensions: confinement non-uniformity, material variations within RAC, and the contribution of active confining pressure [9]. Firstly, to account for height-direction non-uniformity in confinement caused by strip spacing, the concept of effective confinement pressure should be introduced. This replaces f_l with $f_{l,eff} = k_e \cdot f_l$, where k_e is typically determined using arch effect-related formulas. When the cross-section is rectangular or corner effects are present, k_e often requires consideration alongside shape coefficients to account for non-uniformity in both height and cross-sectional directions. Secondly, recognising that the matrix strength and deformation characteristics of RAC differ from those of natural aggregate concrete, some models further incorporate reduction factors related to the replacement ratio r. These factors characterise the weakening effect of inherent defects and multiple interfacial transition zones (ITZs) on strength gain. For instance, the strength gain term may be expressed as $(1 - \alpha \cdot r)$ to reflect RAC's material properties. More significantly, under expansive concrete conditions, the confinement system already possesses an initial confining pressure $f_{l,ini}$ induced by expansion prior to external loading application. Consequently, it is essential to explicitly incorporate the active confinement contribution within the limit state expression. Some studies favour a superposition approach, decomposing the total strength gain into the sum of passive confinement gain and active prestressing gain, expressed as $f_{cc}'' = f_{co}'' + \Delta f_{passive} + \Delta f_{active}$, where Δf_{active} is treated as a term proportional to the level of chemical prestressing [3]. This approach maintains relative engineering simplicity while enabling the model to establish a more direct mapping relationship between two key mechanisms: strip non-uniform confinement and expansion-induced active confining pressure.

5.3 Incremental constitutive models for analysis

Models designed for analysis place greater emphasis on the generation and evolution mechanisms of the full stress-strain curve. Their objective is not merely to provide f_{cc}' and ϵ_{cu}, but to reconstruct the entire response process – from the elastic stage through the strengthening stage to post-peak softening or failure – via an incremental iterative procedure. Such models typically reference a family of stress–strain curves under active constraint conditions. By progressively updating confining pressure, lateral strain, and damage variables, they solve the equilibrium relationship between axial stress and constraint reaction forces at each strain increment. As strip constraints induce simultaneous spatial and temporal variations in confining pressure, incremental models offer distinct advantages in handling 'evolutionary rather than constant confining pressure'. Consequently, they are frequently employed for numerical calibration, parameter sensitivity analysis, and explaining complex constraint mechanisms.

5.4 Correction of Lateral Dilation Relationship

In analytical models, the relationship between axial strain ϵ_c and lateral strain ϵ_l is usually given by the dilation model, which is a key factor determining the evolution of confining pressure and the rate of constraint activation. For RAC, due to differences in Poisson's ratio, dilatation angle, and pore compaction behavior compared to ordinary concrete, its lateral dilation is more likely to enter nonlinear growth at lower stress levels, and the volumetric dilation point appears earlier than in natural aggregate concrete. This phenomenon suggests that RAC may activate passive constraints earlier, and also indicates that it is more prone to localized damage and premature weakening of constraint efficiency when constraints are insufficient. Including expansive concrete further complicates the problem because the system may initially possess non-zero transverse strain as an expansive strain background. This means the evolution of transverse strain no longer starts from zero, but requires the introduction of an initial strain term $\epsilon_{l,0}$ into the model to correct the superposition of the expansion path and subsequent Poisson effect [9]. From a computational perspective, the introduction of $\epsilon_{l,0}$ not only affects the starting point of the confining pressure but also alters the mapping slope in subsequent incremental iterations where "the current confining pressure is determined by the current transverse strain." Therefore, its influence on the overall curve morphology often extends throughout the entire process, not just to the initial stage.

5.5 Path-Dependent Constitutive Models

A common approach in traditional analytical models is to assume that the stress state of FRP-confined concrete passes through a series of active constraint curves under constant confining pressure, and to construct the overall response based on this. However, in actively constrained systems, this assumption faces two real-world differences: firstly, the starting point of active constraint is not at zero confining pressure; the initial confining pressure and initial transverse strain alter the damage initiation conditions; secondly, during loading, the confining pressure continuously adjusts with expansion, Poisson's effect, and shear dilatation, and strip constraints give this adjustment a distinctly non-uniform characteristic. Based on these understandings, recent research has proposed model frameworks that emphasize path dependence, clearly distinguishing the different effects of passive and active constraint paths on damage accumulation rate, yield evolution, and strength degradation behavior [9]. In terms of implementation, these models often utilize plasticity theory, introducing kinematic hardening criteria into the constitutive relation to describe the effect of expansion prestress on the position and shape of the yield surface, thus mathematically reflecting the path dependence phenomenon that "the same final confining pressure but different loading histories lead to different strengths and ductility." Compared to simply superimposing active prestress into a constant confining pressure term, path-dependent models emphasize the continuous influence of prestress on the internal state variables of the material, thus demonstrating greater mechanistic consistency in explaining the differences between early damage suppression and later strengthening.

5.6 Unified Constitutive Framework

To describe the differences between fully enclosed and strip-enclosed concrete, natural aggregate concrete and RAC, and ordinary concrete and expansive concrete within the same theoretical framework, some scholars have attempted to establish a unified constitutive framework, merging geometric nonhomogeneity and material nonhomogeneity through higher-level parameters or energy indices. The model proposed by Shayanfar et al. is representative, its core idea being to construct a unified expression based on energy balance and combined with effective constraint coefficients [16]. This framework introduces the concept of energy integral, assuming that the total energy density corresponding to the FRP reaching the fracture state can be considered approximately constant, thereby uniformly converting the height nonhomogeneity caused by strip spacing and the horizontal nonhomogeneity caused by cross-sectional shape to the same scale through energy dissipation coefficients. Because energy methods can simultaneously incorporate information from both strength and deformation dimensions, these frameworks often exhibit good universality in predicting limit states under complex constraints, and are also more convenient for comparing and calibrating different experimental databases under a unified benchmark.

5.7 Machine Learning Modeling Methods

Given the numerous parameters involved in CFRP strip active constraint RAC, and the significant nonlinear coupling relationships between variables such as strip spacing, strip width, number of layers, FRP elastic modulus, RAC replacement rate, and expansion level, traditional regression-based mechanical models often struggle to simultaneously achieve simplicity and high accuracy. In recent years, data-driven methods have gradually become an important supplement. Algorithms such as Artificial Neural Networks (ANN), Genetic Expression Programming (GEP), and Support Vector Machines (SVM) have been used to construct high-precision predictive models. Their basic strategy is to use large-scale experimental databases for training and capture implicit higher-order coupling patterns through statistical learning. Compared to explicit mechanical models, which require clearly defining the contribution of each mechanism, machine learning models excel at identifying relationships that are difficult to model directly, such as the nonlinear mapping between microstructural differences in recycled aggregates and the hydration process of the expansive agent. Therefore, in predicting key indicators such as f_{cc}' and ϵ_{cu}, well-trained ANN models often achieve higher fits, with their coefficient of determination R^2 outperforming traditional mechanical models in some studies [12]. However, from an engineering application perspective, the interpretability, extrapolation boundaries, and data quality sensitivity of these models still require further cross-database validation. Therefore, a more reasonable approach is often to use them as a supplement to mechanistic models, employing them for parameter selection, sensitivity identification, and model error correction.

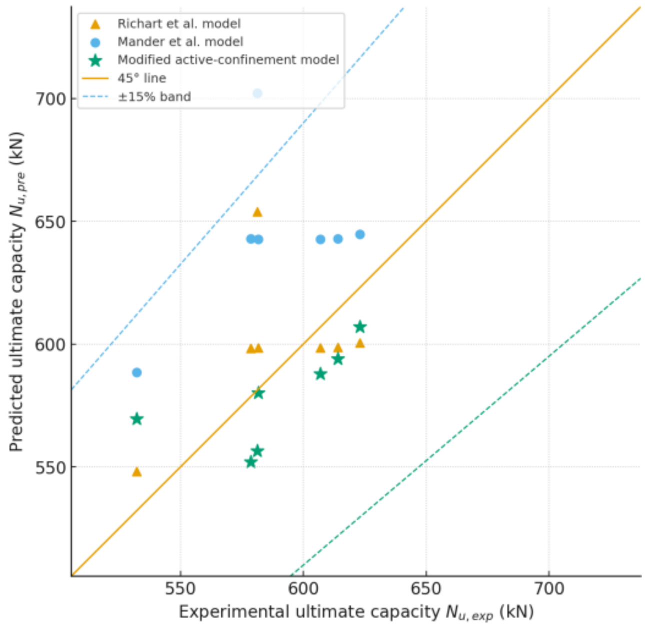

Figure 4 – Schematic illustration of the comparison between model predictions and experimental data [26, 27]

To evaluate the applicability of different models in this complex system, a scatter plot comparing model predictions and experimental measurements can be used for intuitive verification. This graph uses the experimentally measured ultimate compressive strength as the horizontal axis and the model-predicted ultimate compressive strength as the vertical axis, with a 45-degree diagonal as the baseline for "prediction equals measurement." The position and dispersion of the scatter points relative to the diagonal reflect the model's bias and stability. If the results of the uncorrected Lam & Teng model are plotted, the scatter points tend to be more concentrated below the diagonal, exhibiting a systematic underestimation trend. This is because the model does not explicitly consider the contribution of initial confining pressure caused by expansion, resulting in insufficient characterization of active constraint gains. If a Mander-type model considering RAC correction is used, the scatter point distribution may be even more discrete [25]. Although the model introduces material-level reduction to reflect the strength differences of RAC, the Mander model is initially based on the assumption of steel hoop constraint, and the constraint pressure is closer to the confining pressure expression under constant yield stress. Therefore, it is difficult to stably describe the global law when facing the variable confining pressure mechanism corresponding to FRP linear elastic constraints. In contrast, when the model explicitly introduces the effective constraint coefficient $\mathrm{k_e}$ and incorporates the active confining pressure term $\mathrm{f_{l,ini}}$, the predicted scatter points tend to be more closely distributed around the 45-degree diagonal, and the error band is more convergent. This indicates that simultaneously incorporating the geometric effect of the strip non-uniform constraint and the initial state of the expansion active constraint into the model is a key approach to improving prediction accuracy and reducing system bias.

Durability and Long-Term Performance Considerations

While CFRP strip active restraint systems can significantly improve the load-bearing capacity and deformation performance of recycled aggregate expansive concrete (RAC), from an engineering application perspective, the time effects and environmental impacts experienced by structures during their service life are often more complex. Therefore, their long-term performance and durability also need to be systematically incorporated into the evaluation and design framework. Especially under active restraint conditions, the chemical prestress and confining pressure established in the initial stage of the system do not remain permanently unchanged. The evolution of the material's volumetric deformation, the attenuation of interfacial bonding, and the cumulative effects of environmental erosion can all gradually alter the actual working state of the restraint system, thus affecting long-term safety and performance stability.

First, the coupled effects of creep and shrinkage need to be considered. Because recycled aggregates contain old mortar and have a more developed pore structure, the creep coefficient and shrinkage rate of RAC are usually significantly higher than those of natural aggregate concrete (NAC), making it more prone to additional deformation over time during long-term service. In FRP active confinement systems, concrete shrinkage, especially drying shrinkage, macroscopically offsets some of the chemical prestress established by the expansive agent, resulting in a "prestress loss" as the initial prestress level decreases over time. This loss is not merely a numerical attenuation; it also signifies a decrease in the confining pressure initiation point, a weakening of the crack closure effect, and a lowering of the threshold for entering the damage accumulation stage, thus having a cascading effect on subsequent load-bearing capacity and crack control capabilities. Simultaneously, under long-term high stress levels or repeated loading, concrete creep causes a redistribution of stress between the concrete and the CFRP strips. Tensile stress in the strips may relax or shift, and this stress redistribution alters local confinement strength and further amplifies the spatial non-uniformity of confinement efficiency. For strip systems, the concrete in the gap zone is more directly exposed to the external environment, resulting in more thorough moisture exchange and often more severe drying shrinkage. Therefore, the resulting confinement attenuation is more likely to first appear near the strip gaps, thus affecting the continued establishment of the arch effect and the long-term stability of the effective confinement core [15]. From a design perspective, this means that peak strength or ultimate strain obtained from short-term tests cannot be used as the sole basis for assessment. Instead, long-term prestress loss should be predicted and verified as a key parameter, and a reasonable safety margin should be reserved for it in material selection, strip construction, and curing and protection strategies.

Secondly, the degradation of interfacial properties under environmental erosion conditions is also a crucial factor determining the durability of the system. In complex environments such as freeze-thaw cycles, sulfate attack, chloride exposure, or alternating wet and hot conditions, the interfacial bond performance between CFRP and concrete may decline over time. Changes in bond-slip behavior directly affect the efficiency of strip constraint force transfer to concrete. Because strip structures are more prone to desquamation-sensitive zones at the ends and edges, and these areas are often accompanied by stress concentration and increased strain gradients, once interfacial properties degrade, desquamation failure is more likely to be triggered prematurely at the ends, making it difficult to maintain the confining pressure that was originally established by strip tension. For expansive concrete, environmental effects can further influence internal damage evolution by altering the stability of hydration products. For example, ettringite generated by the reaction of the expansive agent may decompose under high temperature or sulfate attack conditions, or induce delayed ettringite formation (DEF) under specific temperature and humidity conditions. This can lead to the propagation of internal microcracks and disrupt the existing constraint equilibrium, causing the confining pressure background and damage state to evolve unfavorably over time [4]. It is worth noting that CFRP materials themselves have good resistance to corrosion and chemical media. Their presence can, to some extent, act as an external coating barrier, slowing down the penetration and diffusion of corrosive media into the core concrete, thereby delaying the deterioration of internal materials. However, this protective effect does not mean that the durability requirements of the interface and end details can be ignored. Especially at critical locations such as strip edges, bonded ends, and the concrete surface of gap areas, it is necessary to reduce the impact of long-term degradation on the overall performance of the system through reasonable interface treatment, end anchoring, and surface protection measures.

Conclusion

Based on existing research, it can be concluded that introducing an expansive agent into recycled aggregate concrete and coupling it with CFRP strip confinement to form an active confinement system can establish chemical prestress before loading, making the core concrete closer to a triaxial compression state, thereby delaying microcrack development and improving elastic limit and bearing capacity [2]. Simultaneously, the high water absorption and release capacity of recycled aggregates can manifest as an internal curing effect in the expansive system; continuous water supply is beneficial for the expansion reaction and densification of the interfacial transition zone, and mitigates the adverse effects of self-drying shrinkage [11]. Strip confinement relies on the arch effect to provide effective confining pressure. If the net spacing of the strips is controlled within approximately 0.5 times the column diameter, and the active compensation brought about by expansion is utilized, the disadvantages of non-uniform strip confinement can be compensated to some extent, achieving a near-fully encapsulated mechanical effect while balancing economy and permeability.

At the model level, constitutive research is moving from empirical regression to a unified analytical framework that can simultaneously consider path dependence, damage evolution, and geometric non-uniformity. Explicitly introducing the effective constraint coefficient k_e and the active confining pressure term is often key to improving prediction accuracy. Further work needs to supplement evidence on both service life and environmental effects, focusing on clarifying the prestress loss mechanism caused by the coupling of long-term effects of CFRP creep, RAC shrinkage, and expansion, and revealing the impact of FRP-concrete interfacial bond degradation on constraint efficiency under freeze-thaw cycles, corrosion, and fire. Simultaneously, developing mesoscopic numerical models that can characterize the random aggregate distribution, non-uniform expansion nucleation, and interfacial slip in RAC, and combining these with machine learning to extract implicit patterns from large-scale databases, will contribute to achieving more accurate performance-based design [6].

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