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RESEARCH PROGRESS ON DEFORMATION CHARACTERISTICS AND CONFINEMENT EFFECT OF RECYCLED AGGREGATE EXPANSIVE CONCRETE

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Abstract

With the surge in global construction waste (CDW) production and the increasing depletion of natural sand and gravel resources, the widespread application of recycled aggregate concrete (RAC) has become a key strategy for sustainable development in the construction industry. However, the inherent multi-interface transition zone (ITZ) defects, low elastic modulus, and significant shrinkage and creep characteristics of RAC severely limit its application in high-performance structures. Introducing expansive agents (EAs) to prepare recycled aggregate expansive concrete (RAEC) and utilizing chemical prestressing to compensate for shrinkage is considered an effective approach. This paper systematically reviews the deformation characteristics of RAEC and its mechanical response under different constraint conditions. In particular, this paper focuses on the theoretical modeling of restrained expansion and creep stress relaxation, integrating a modified early-age strain development model to predict self-stress evolution. Finally, a comprehensive strategy to improve the service performance of RAEC is proposed based on carbonation modification and mix optimization.

Keywords: recycled aggregate concrete, expansion agent, deformation characteristics, constraint effect, self-stress, creep, constitutive modeling.

ИССЛЕДОВАНИЯ ДЕФОРМАЦИОННЫХ ХАРАКТЕРИСТИК И ЭФФЕКТА ОБЖАТИЯ РАСШИРЯЮЩЕГОСЯ БЕТОНА НА ОСНОВЕ РЕЦИКЛИРОВАННОГО ЗАПОЛНИТЕЛЯ

Хао Мин, В. В. Тур

Реферат

С ростом объемов производства строительных отходов и истощением природных ресурсов песка и гравия широкое применение бетона на рециклированном заполнителе становится ключевой стратегией устойчивого развития строительной отрасли. Однако присущие такому бетону дефекты многоинтерфейсной транзитной зоны, низкий модуль упругости, а также значительные деформации от усадки и ползучести серьезно ограничивают его использование в высококачественных конструкциях. Введение расширяющих добавок для получения расширяющегося бетона на рециклированном заполнителе и применение химического предварительного напряжения для компенсации усадки рассматриваются как эффективный подход. В статье систематически рассмотрены деформационные характеристики расширяющегося бетона на рециклированном заполнителе и его механический отклик при различных условиях ограничения. Особое внимание уделено теоретическому моделированию ограниченного расширения и релаксации напряжений ползучести, с интеграцией модифицированной модели развития деформаций на ранних стадиях для прогнозирования эволюции самонапряжений. В заключение предложена комплексная стратегия повышения эксплуатационных свойств расширяющегося бетона на рециклированном заполнителе, основанная на модификации карбонизацией и оптимизации состава смеси.

Ключевые слова: бетон на рециклированном заполнителе, расширяющая добавка, деформационные характеристики, эффект ограничения, самонапряжение, ползучесть, конститутивное моделирование.

1 Introduction

1.1 Research Background

In contemporary civil engineering practice and research, the goals of sustainability and high performance in material systems are being pursued simultaneously and are gradually becoming an industry consensus. Concrete, as the most widely used man-made material globally, not only involves significant energy consumption and carbon emissions during its raw material extraction, clinker production, and transportation, but also continuously consumes a large amount of natural sand and gravel resources. Meanwhile, construction and demolition waste (CDW) accounts for a considerable proportion of urban solid waste. If waste concrete can be crushed, screened, and reprocessed to prepare recycled concrete aggregate (RCA) and reused in fresh concrete production, it will generate quantifiable environmental benefits and economic value in terms of resource recycling, emission reduction, and cost control [9]. However, compared with natural aggregate (NA), RCA exhibits more prominent defects at the material level. The adhering mortar on the surface of recycled aggregate concrete (RAC) results in higher water absorption, lower density, and higher porosity. Furthermore, it often contains both an old interfacial transition zone (Old ITZ) between the old mortar and the original aggregate, and a new interfacial transition zone (New ITZ) between the old mortar and the new aggregate, creating a complex multiphase structure and multi-interface force transmission paths. This structural complexity is precisely why the overall mechanical properties of recycled aggregate concrete (RAC), especially deformation-related performance indicators, are generally weaker than those of natural aggregate concrete (NAC) [9]. Previous studies have further shown that the drying shrinkage of RAC is typically 20 % to 50 % higher than that of NAC, and the creep coefficient may also be 30 % to 60 % higher [19]. Larger volumetric deformation is more likely to trigger early cracking and reduce the overall structural integrity, thus providing pathways for chloride ion intrusion and steel corrosion, ultimately adversely affecting durability and service life [5].

1.2 Problem Description: Shrinkage and Crack Control

The risk of shrinkage-induced cracking and the resulting durability degradation are particularly prominent among the key bottlenecks in RAC engineering applications. To reduce the probability of cracking caused by high shrinkage, traditional passive crack-resistant measures, such as increasing the reinforcement ratio or installing expansion joints, can disperse deformation and restraint stress to some extent, but in practice, they often face the dual constraints of limited effectiveness and increased costs. In contrast, active crack-resistant technologies have attracted attention due to their ability to control volumetric deformation at the source. Among these, the incorporation of expansive agents (EA) into concrete is considered a strategy with engineering potential [20]. Hydration of expansive agents can induce controlled volumetric expansion. When this expansion is constrained by reinforcement or external boundaries, the system can establish a self-stress of approximately 0,2 to 2,0 MPa within the concrete to counteract the tensile stress generated during shrinkage, thereby delaying crack initiation or reducing crack propagation [10]. However, it should be noted that directly applying expansive agents to recycled aggregate concrete systems, i. e., recycled aggregate expansive concrete (RAEC), is not equivalent to a simple superposition of RAC and the expansion effect. The lower elastic modulus of RAC implies an altered efficiency in the conversion of strain $\epsilon \text{ to stress } \sigma$ at the same strain level. Simultaneously, the higher creep characteristics of RAC make the established chemical prestress more prone to relaxation and loss over time [21]. Furthermore, the porous water-absorbing nature of RAC may compete with the expanding agent for moisture during mixing and early hydration stages, thus affecting the full utilization of the expansion effect and time-history stability [23]. Therefore, strictly differentiating between "free expansion" and "restrained effective expansion," and establishing a numerical model capable of describing the coupling of shrinkage, creep, and expansion, are prerequisites for RAEC structural design.

1.3 Scope and Purpose of the Review

Based on the above background and issues, this paper aims to systematically review and comprehensively evaluate existing online academic resources, focusing on deformation characteristics and restraint effects, to provide a clearer knowledge framework for the understanding of RAEC mechanisms, model construction, and engineering design. Specifically, this paper first focuses on the physical and mechanical properties of RCA and their fundamental impact on concrete stiffness, shrinkage, and creep, thereby establishing the deformation sources at the material level. Then, it discusses the expansion and compensation mechanisms, comparing the reaction characteristics and action pathways of calcium sulfoaluminate (CSA), magnesium oxide (MgO), and composite expansion agents in the recycled matrix, with a focus on how the internal curing effect and pore structure evolution jointly shape expansion efficiency and volume stability. Based on this, it further analyzes the mechanical behavior under different restraint conditions, emphasizing the influence of system stiffness on limiting the expansion rate and the development law of self-stress, and discussing the mechanism differences in the collaborative work of restraint forms such as steel bars, steel pipes, and fibers. Finally, this paper summarizes several performance improvement technologies based on existing research, including the effects and applicable boundaries of accelerated carbonation, fiber toughening, and mix proportion optimization in improving the deformation and durability of RAEC, thus providing a comparable reference for subsequent research and engineering applications.

2 Microscopic Properties of Recycled Aggregates and Their Influence on Matrix Deformation

2.1 Multiphase Microstructure of Recycled Aggregates

Recycled aggregates are not a single, homogeneous granular material, but rather a composite material consisting of virgin natural aggregates, attached old mortar, and the interfacial transition zone (ITZ) between them. This multiphase and multi-interface microstructure causes its mechanical and deformation behavior to differ significantly from that of natural aggregates, becoming a key source of performance degradation in recycled aggregate concrete (RAC). Unlike the relatively dense surface and simpler properties of natural aggregates, RCA is often encased in a certain thickness of old mortar, and may also contain residual microcracks and pore networks. This makes its stress transmission path more complex, and local stress is more likely to concentrate at weak interfaces, resulting in macroscopically decreased strength and increased deformation.

From a material composition perspective, the content of attached mortar is one of the important indicators determining the basic properties of RCA. Existing research indicates that the content of adhering mortar typically ranges from 20 % to 55 %, and this level directly affects the water absorption, crushing index, and overall pore structure characteristics of reinforced concrete (RCA). Due to the higher porosity and more developed capillary channels of old mortar, RCA's water absorption is usually significantly higher than that of natural aggregates. This characteristic not only alters the effective water-cement ratio and workability of concrete during the fresh mixing stage but also provides more channels for moisture migration during the hardening stage, making the system more prone to moisture loss and humidity gradient evolution, thus providing more favorable evaporation and transport conditions for drying shrinkage [9]. Therefore, the content of adhering mortar is not simply a "material impurity ratio" but often indirectly shapes the long-term volume stability of RCA through pore structure and moisture migration processes.

Meanwhile, the multiplicity of the interfacial transition zone (ITZ) further enhances the heterogeneous characteristics of RCA. RAC (Range Aggregate-Insulated Concrete) typically contains various interface zones, including "aggregate-old mortar," "old mortar-new mortar," and "aggregate-new mortar" zones formed under localized spalling conditions. These interfaces, due to significant differences in composition and density, often become preferred sites for microcrack initiation and propagation. Related research indicates that failure often first occurs within the old ITZ (Insulated Zone) or old mortar, as these areas are more prone to stress concentration and exhibit lower local tensile and shear strength, leading to a decrease in overall strength. They also cause the material to enter the nonlinear deformation stage earlier under stress and exhibit greater deformation capacity [8]. From this perspective, the multiphase structure and multi-ITZ network of RAC not only explain the decline in RAC load-bearing capacity but also provide a reasonable microscopic explanation for its shrinkage, creep, and other deformation problems. To visualize the microstructural evolution of the paste matrix and the densification process over time, Figure 1 presents the scanning electron microscope (SEM) observations of the RAEC matrix at the ages of 1, 28, and 90 days.

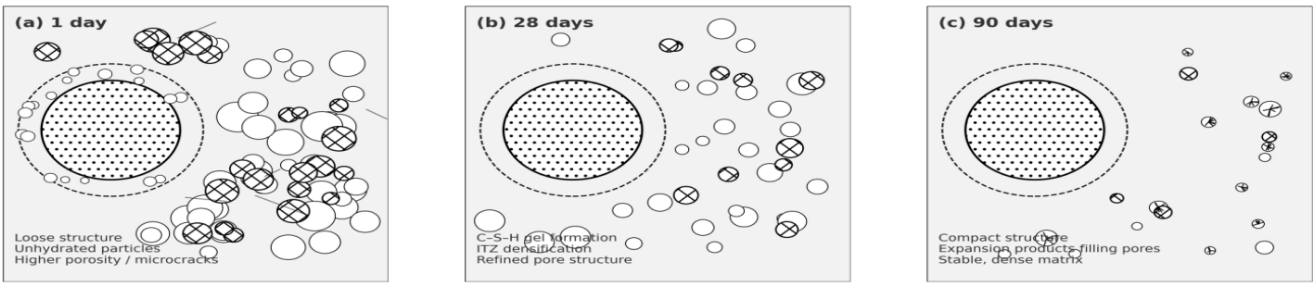

Figure 1 – Microstrctural evolution of RAEC paste matrix at diffelent ages

Source: This figure is a schematic illustration drawn by the authors, synthesized from the reported microstructural characteristics of RCA/ITZ and the internal curing-expansion mechanisms in the literature [2, 9, 10, 14]

2.2 Decrease in Elastic Modulus and Stiffness Mismatch

When discussing deformation control and volumetric stability, the elastic modulus (E_c) is one of the most fundamental parameters. It not only characterizes a material's ability to resist instantaneous deformation but also directly determines the efficiency of strain-to-stress conversion under constrained conditions. The relationship between stress and strain is typically simplified as $\sigma = E \cdot \varepsilon$ in the linear elastic stage. Therefore, when the material's E_c changes, the internal force levels corresponding to shrinkage strain, expansion strain, and strain caused by external loads will also change. This is particularly crucial for whether expansive concrete can effectively establish self-stress. Existing experimental evidence in the literature consistently indicates that incorporating recycled coarse aggregate (RCA) markedly reduces the elastic modulus of concrete. Compared with NAC, the E_c reduction of all recycled aggregate concrete can reach approximately 25 % to 45 %. This change is usually related to the lower modulus of the attached mortar, higher porosity, and more prevalent microcracks at the ITZ. When the matrix itself becomes more "soft," the distribution of load and deformation changes, making recycled concrete (RAC) more prone to exhibiting larger strain responses under compression, tension, and restraint conditions.

In the mix design and structural design of expansive concrete, this modulus reduction leads to a typical stiffness mismatch problem, with its effects being two-sided. On the positive side, when shrinkage strain levels are comparable, a lower elastic modulus generally results in a lower shrinkage-induced tensile stress, thereby reducing the driving force for early-age cracking and, to some extent, mitigating cracking risk. Conversely, during the restrained expansion stage, the development of sufficient effective prestress depends critically on whether the expansion strain can be efficiently converted into an adequate compressive stress under confinement. When E_c is low, the expansion strain required to reach the same self-stress level under the same restraint conditions will be greater. (!) If the hydration expansion capacity of the expansive agent is constrained by moisture, temperature, or dosage limits, the RAC system may struggle to achieve a prestress level comparable to the NAC system, resulting in insufficient or even failed compensation, thus diminishing its shrinkage crack control effectiveness [16]. Therefore, the low modulus of RAC is not simply a "stress reduction" effect; in an active compensation system, it simultaneously alters the conditions for achieving compensation capacity, requiring a more precise match between shrinkage risk and compensation efficiency in design.

2.3 Basic Characteristics of Shrinkage and Creep

From the empirical perspective of volumetric stability, RAC generally exhibits inferior shrinkage and creep performance compared to NAC, and this difference has direct significance in crack control and durability maintenance during the engineering service life. Regarding drying shrinkage, the presence of old mortar increases the total paste volume of the system and accelerates the moisture reduction process through a more developed pore structure and moisture migration channels; simultaneously, the lower overall stiffness of RAC weakens the restraint effect of aggregate on paste shrinkage, making shrinkage deformation more easily transformed into macroscopic volume changes. Therefore, literature typically reports that the drying shrinkage of RAC is approximately 20 % to 50 % higher than that of NAC [19], and this increase is often more pronounced with high replacement rates or high old mortar content. This trend is summarized in Table 1 and visualized in Figure 2. Greater drying shrinkage not only increases the probability of early cracking but also significantly enhances permeability after microcracks form, thus creating conditions for external corrosive media to enter. By contrast, RAEC can reduce long-term drying shrinkage substantially, with reported ranges typically falling below the NAC baseline depending on the expansion source and curing conditions (Table 1; Figure 2). Table 1 summarizes these deformation characteristics, referencing recent data sources.

Regarding creep characteristics, creep reflects the accumulation of deformation in concrete under sustained load over time. The creep coefficient of RAC is usually significantly higher than that of NAC, with related studies showing an increase of approximately 30 % to 80 % [3]. The microscopic reasons for this are closely related to its porous structure, weaker ITZ, and the stronger viscoelastic flow tendency of old mortar. Under long-term stress, cement paste is more prone to viscoelastic deformation accompanied by the slow propagation of microcracks, thus making time-related deformation more prominent. For recycled aggregate expansive concrete (RAEC), high creep has a more direct engineering consequence: the established chemical prestress is more prone to stress relaxation, resulting in more significant prestress loss. This causes the active compensation effect to decay over time and reduces resistance to long-term shrinkage [21]. Therefore, understanding the shrinkage and creep characteristics of RAC and incorporating them into compensation design is crucial not only for short-term crack control but also for maintaining stable prestress levels and reliable durability under long-term service conditions. Table 1 consolidates representative ranges reported in the literature to benchmark stiffness, shrinkage and creep gaps among NAC, RAC and RAEC. For clarity, the reported ranges of long-term drying shrinkage and elastic modulus are further visualized in Figure 2 and Figure 3, respectively.

Table 1 – Comparison of deformation characteristics of NAC, RAC and RAEC [5, 9, 10, 19]

Performance Indicators	Natural Aggregate Concrete (NAC)	Recycled aggregate concrete (RAC)	Recycled aggregate expansive concrete (RAEC)	Mechanism Notes
Modulus of elasticity	Benchmark (100 %)	55 % – 75 %	60 % – 80 %	RCA low stiffness leads to modulus reduction; expansive agents slightly enhance densification [9].
Drying shrinkage	Benchmark	120 % – 150 %	20 % – 80 % (after compensation)	RCA aged mortar exacerbates shrinkage; expansive agents compensate via chemical prestressing [5].
Coefficient of creep	Benchmark	130 % – 180 %	110 % – 140 %	Weak interfacial transition zone (ITZ) causes high creep; This factor must be considered for self-stress relaxation [19].
Compressive strength	Benchmark	75 % – 95 %	90 % – 105 %	Self-stress generated by restricted expansion constrains the core zone, enhancing apparent strength [9].
Limited expansion rate	–	Low (if EA is added)	Medium – High	Depends on system stiffness mismatch and expansion source type (MgO superior to CSA in later stages) [10].

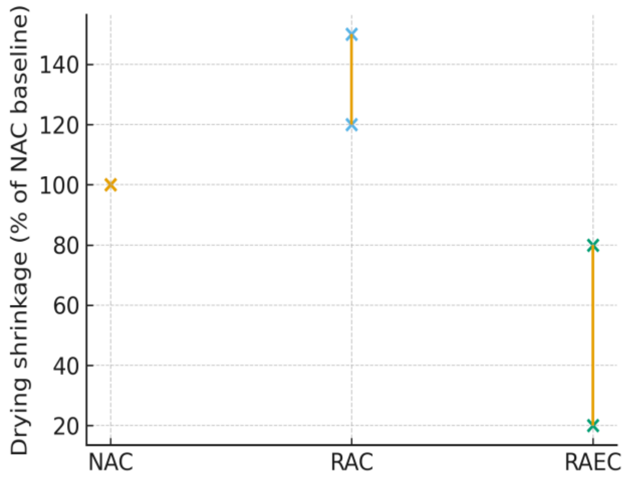

Figure 2 – Ranges of long-term drying shrinkage [5]

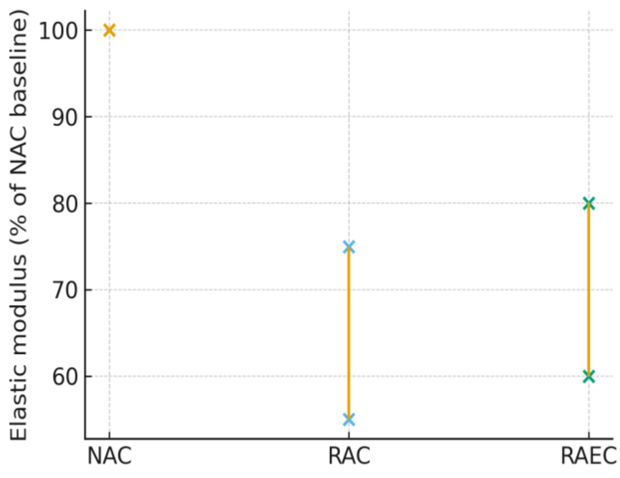

Figure 3 – Ranges of elastic modulus [9]

Data and Preprocessing

3 Expansion and Compensation Mechanism of Recycled Aggregate Expansive Concrete (RAEC)

3.1 Types of Expansion Sources and Their Hydration Mechanisms

In the RAEC system, the expansion sources used to achieve shrinkage compensation and crack control mainly include calcium sulfoaluminate (CSA), magnesium oxide (MgO), and composite systems of both. The role of different expansion agents is not merely reflected in the macroscopic result of "expansion," but more importantly, in their differences in hydration products, reaction rates, and water consumption characteristics, which determine whether an effective match can be achieved between the expansion timeline and the shrinkage process. For RAC, a matrix with more developed pores, more significant water absorption, and more pronounced creep, the selection and proportioning of expansion sources often need to simultaneously consider early compensation efficiency and later sustainability; otherwise, it is difficult to maintain stable volume coordination and crack resistance throughout the entire lifespan.

3.1.1 Calcium Sulfoaluminate (CSA) Expanding Agent

CSA-type expanding agents typically function by hydration to form ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) crystals. The basic mechanism utilizes the crystallization pressure generated by the growth of ettringite crystals within the pores and framework of cement paste to drive macroscopic volume expansion of the matrix. Because this reaction is kinetically more early-stage, the expansion contribution of CSA is often concentrated within a relatively short curing period, typically completing the main expansion process within about 14 days. Furthermore, it is quite sensitive to moisture supply and requires a relatively large amount of water. Therefore, external curing conditions, mixing moisture distribution, and aggregate water absorption behavior directly affect its effective expansion level. This characteristic of CSA is particularly prominent in RAC systems because the high water absorption of RCA may compete with CSA hydration for moisture in the early stages of mixing. Insufficient prewetting or improper control of mixing moisture can lead to local imbalances in the hydration environment, limiting ettringite formation and resulting in insufficient expansion or even compensation failure. Meanwhile, studies have also shown that when RCA undergoes saturated surface drying, the moisture stored in its pores can be released later with the humidity gradient, creating more stable local water supply conditions. This demonstrates an internal curing effect and promotes the continuous formation of ettringite and optimization of the pore structure. Therefore, the performance of CSA in RAC is not necessarily deteriorated, but rather highly dependent on moisture management strategies [23].

3.1.2 Magnesium Oxide (MgO) Expanding Agent

Unlike CSA, MgO-type expanding agents hydrate to form brucite ($Mg(OH)_2$). Its reaction rate is significantly controlled by the calcination temperature. From an engineering application perspective, the prominent characteristic of MgO expansion is its superior "time-series controllability" [14]. Lightly calcined MgO reacts relatively quickly, while heavily calcined MgO can provide a late-stage expansion effect that lasts for months or even years [2]. This timeline characteristic is highly compatible with the volumetric deformation pattern of reclaimed arc cement (RAC), as the drying shrinkage and creep of RAC often continue over a long timescale. If early expansion cannot be sustained, later shrinkage and creep may still cause a gradual attenuation of stress compensation. Therefore, the delayed expansion provided by MgO is more beneficial for covering the mid-to-late stage shrinkage process of RAC and continuously compensating for stress losses caused by drying shrinkage and creep. This advantage is usually difficult to maintain long-term when CSA is used alone [14]. Figure 4 illustrates the normalized drying shrinkage comparison, highlighting the sustained compensation effect of the MgO system.

3.1.3 CSA – MgO Composite Expansion Agent

Under the requirement of volume stability control throughout the entire age, a single expansion source often cannot simultaneously meet the early and long-term shrinkage compensation targets. Therefore, the co-doping of CSA and MgO has gradually become an important direction in RAC research and application. The basic logic of this composite system is to utilize the complementarity of the two types of expansion sources in terms of reaction rate and time history contribution, so that the expansion effect can be more evenly distributed over time, thereby forming a more reasonable synergy with the shrinkage and creep evolution of RAC. It is generally believed that CSA is more suitable for compensating for early auto-shrinkage and temperature-induced shrinkage, while MgO is more suitable for providing continuous compensation for late-stage drying shrinkage. The synergy of the two can maintain a more stable volume coordination and crack control effect at different ages. Multiple studies have further indicated that when the mass ratio of CSA to MgO is close to 2:1, concrete tends to exhibit better volume stability and crack resistance throughout its entire lifespan, while its strength and durability are also more likely to reach optimal levels [4]. For RAEC (Rapid Expansion and Internal Curing), this staged compensation strategy is even more significant because its matrix shrinkage and creep are inherently stronger and longer-lasting. Without later compensation, the favorable conditions established early on are often difficult to maintain during long-term service.

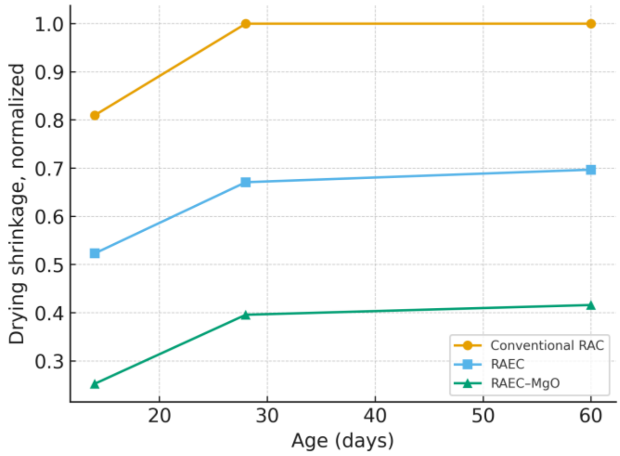

Figure 4 – Age-dependent normalized drying shrinkage of reference RAC, RAEC, and RAEC–MgO [4, 5, 23]

3.2 Effective Expansion and Internal Curing Mechanisms

In the RAEC system, RCA should not be understood as an inert filler aggregate, but rather as a porous medium with moisture storage capabilities. This internal curing effect releases stored pore water when internal relative humidity (RH) drops, providing additional moisture to the surrounding paste (as previously indicated in the microstructure evolution in Figure 1). This process maintains the high-humidity environment required for the hydration of the expansion agent, preventing hydration blockage due to localized water shortages. It also reduces the driving force of self-shrinkage by decreasing capillary tension, thus providing a dual improvement in volume stability [13]. Therefore, internal curing in RAEC is not merely "water replenishment," but a mechanism that alters the early humidity evolution path and the starting point of shrinkage stress, playing a fundamental role in the effective implementation of expansion compensation (Figure 5).

In engineering evaluation, the focus should be on "effective expansion" rather than free expansion itself. The free expansion rate only reflects the system's volume growth capacity under unconstrained conditions. However, in actual structures, expansion often occurs in parallel with shrinkage. Ultimately, what affects cracks and stress states is the net effect after deducting shrinkage, that is, the effective expansion level resulting from the combined contributions of expansion and shrinkage over time. Existing research indicates that although recycled aggregates (RACs) typically exhibit greater intrinsic shrinkage, under appropriate internal curing conditions and with the addition of suitable expansion agents, recycled aggregate expansive concrete (RAEC) can still achieve confined expansion performance comparable to or even superior to that of non-recycled aggregates (NACs). This suggests that their potential to generate effective compressive stress under constrained conditions is not necessarily lower than that of traditional systems [15]. Therefore, the key to recycled aggregate expansive concrete (RAEC) lies not in pursuing greater free expansion, but in more efficiently converting expansion into continuous compensation for shrinkage through moisture management and expansion time-history matching.

3.3 The Cumulative Effect of Shrinkage Reducing Agents (SRAs)

In addition to expansion agents, shrinkage reducing agents (SRAs) are often used to further reduce the risk of shrinkage. Their mechanism of action typically involves reducing the surface tension of the pore solution, weakening capillary pressure at the source, thereby reducing the driving force of drying shrinkage and self-shrinkage. In the RAEC system, combining SRA with an expanding agent often creates a more pronounced superposition effect. The core of this effect lies not in simply superimposing the individual gains of the two additives, but in the fact that SRA, by suppressing the shrinkage "consumption term," allows the expansion generated by the expanding agent to be more easily retained as a net effect and more fully converted into effective compressive stress. In other words, when the shrinkage driving force is weakened, the expansion effect is no longer primarily used to offset the strong shrinkage background, but is more likely to manifest as a sustainable pre-compression state, thereby improving the reliability and stability of crack control. This combined strategy, using expansion as the "supply side" and reducing shrinkage to lower the "demand side," is particularly advantageous under fully constrained or strongly constrained conditions. Related studies have shown that this strategy, under appropriate ratios and curing conditions, can significantly reduce the risk of cracking, and even enable specimens to achieve the goal of crack-free operation at the experimental scale [20].

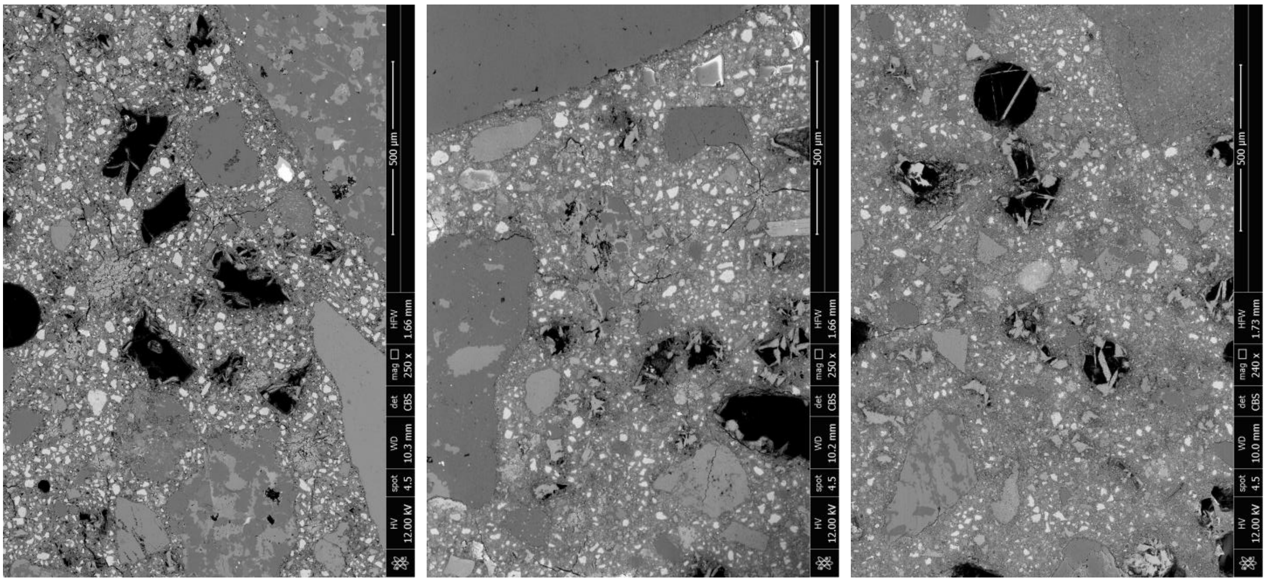

Figure 5 – Sample with SAP agent at an age of 1, 28 and 90 days allowing a qualitative assessment on the degree of hydration of the anhydrous clinker (results obtained by V. Semianiuk, EMPA)

Constraint/Restraint Effects and System Stiffness: Theory and Model

4.1 Basic Principles of Constrained Expansion

The key to expansive concrete's ability to compensate for shrinkage and inhibit cracking lies in the condition of "constraint." If the expansion process is unconstrained, the system exhibits more of a free volume growth and structural looseness, making it difficult to effectively convert expansion energy into an internal force state favorable to cracking. Only when expansion is constrained by reinforcing bars, steel pipes, or external boundaries can the deformation corresponding to expansion be transformed into a stable self-stress σ_c under constrained conditions, offsetting the tensile stress caused by shrinkage with a compressive stress background, thus achieving the goals of crack resistance and volume stability. Therefore, in theoretical analysis, constrained expansion is usually considered a problem jointly determined by deformation compatibility and mechanical equilibrium; that is, the source of expansion, the time effect of shrinkage and creep, and the reaction force provided by the constrained system must be described uniformly within the same framework.

Quantitative calculation of self-stress is usually based on the deformation compatibility equation, linking deformation components such as free expansion, shrinkage, and creep with constrained deformation and stress response. A commonly used expression can be written as

$$\epsilon_{\text{free}} - \epsilon_{\text{creep}} - \epsilon_{\text{shrinkage}} = \epsilon_{\text{restrained}} + \frac{\sigma_c}{E_c} \quad (1)$$

Here, ϵ_{free} represents the free expansion strain of the material under unrestraint conditions, ϵ_{creep} and $\epsilon_{\text{shrinkage}}$ reflect the deduction effects of creep and shrinkage on the overall deformation, respectively, while $\epsilon_{\text{restrained}}$ corresponds to the actual allowed restrained strain of the system under restrained conditions, and σ_c/E_c characterizes the strain contribution caused by self-stress in an elastic sense.

4.1.2 Preliminary analysis

As it was shown in [17] the most efficient finite element method for the case of uniaxial restraint conditions accounts for the early age expansive concrete strains by following an iterative procedure. According to this approach the restrained expansion strain $\varepsilon_{s.x}(t_{i+1/2})$ in the x-direction at the i-th time interval is expressed as follows

$$\varepsilon_{s,x}\left(t_{i+\frac{1}{2}}\right) = \sum_{j=1}^{i}\left[\left(\Delta\sigma_{e,x}\right)_j \cdot J\left(t_{i+\frac{1}{2}}, t_j'\right)\right] + \varepsilon_{q'}\left(t_{i+\frac{1}{2}}, t_{\frac{1}{2}}\right), \quad (2)$$

where $\varepsilon_{cf}(t_{i+1/2}, t_{1/2})$ = free expansion strain in the x-direction from the time interval $t_{1/2}$ to the $t_{i+1/2}$; $(\Delta\sigma_{c.x})_j$ = increment of the self-stress in the x-direction at the j-th time interval; and $J(t_{i+1/2}, t_j)$ = creep compliance function that is calculated by the formula

$$J(t_{1+\nu/2}, t_j) = \frac{1}{E_\epsilon(t_j)} + \frac{\varphi(t_{1+\nu/2}, t_j)}{E_{\epsilon 28}}, \quad (3)$$

where $E_{c.28}$ = Young's modulus of expansive concrete at the age of 28 days;

$E_c(t_j)$ = Young's modulus of expansive concrete in temperature adjusted concrete age of t_j days; and $\varphi(t_{i+1/2}, t_j)$ = creep coefficient of expansive concrete at the age of $t_{i+1/2}$ days due to the self-stress applied at the age of t_j days. Creep coefficient $\varphi(t, t_0)$ of expansive concrete at early age can be calculated according to the codes[18]

$$\varphi(t, t_0) = \varphi_0 - \beta_c(t, t_0), \quad (4)$$

where φ_0 = notional creep coefficient that depends on the relative Young's modulus $E_c(t_0)/E_{c.28}$

and is calculated according to the work[16]

$$\varphi_0 = 5{,}31\left(\frac{E_e(t_0)}{E_{e28}-1}\right)^2 + 1{,}11, \quad (5)$$

$\beta_c(t,t_0)$ = coefficient that depicts the creep at temperature adjusted concrete age t after temperature adjusted concrete age of loading t_0 and is defined as follows[18]

$$\beta_\epsilon\ (t,t_0)=\left[\frac{t-t_0}{\beta_\epsilon+(t-t_0)}\right]^{0,3}, \tag{6}$$

where $\beta_н$ is the coefficient that describes the effect of loading age on the creep development and is calculated depending on the relative Young's modulus $E_c(t)/E_{c.28}$ in accordance with the formula[16]

$$\begin{cases}\beta_\text{n}=0{,}000001, if\ 0\le E_c(t)/E_{c28}<0{,}346\\ \beta_\text{n}=40{,}5\cdot\frac{E_c(t)-0.346}{E_{c28}}+0{,}485, if\ 0{,}346\le E_c(t)/E_{c28}<1{,}0.\end{cases} \tag{7}$$

Young's modulus of expansive concrete at early age can be defined by equation[17]

$$E_c(t)=E_{c,\infty}\exp\left(s\left(1-\frac{t_\infty-a}{t-a}\right)^{0,5}\right), \tag{8}$$

where t, $t_{e.28}$ = temperature adjusted concrete age at t days and 28 days respectively; and s, a = empirical coefficients, according to the research paper [17] $s=0{,}11$, $a=0{,}2$.

The increment of strain in the x-direction at the i-th time interval is calculated according to the formula

$$\begin{gathered}(\Delta\varepsilon_{5,x})_i=\varepsilon_{5,x}(t_{i+1/2})-\varepsilon_{5,x}(t_{(i-1)+1/2})=\\=(\Delta\sigma_{x^c})_iJ(t_{i+1/2},t_i)+\sum_{j=1}^{i-1}\left[(\Delta\sigma_{x^c})_j\frac{\Delta Q(t_i,t_j)}{E_c\mathcal{D}}\right]+\varepsilon_{q'}(t_{i+1/2},t_{i/2})\end{gathered} \tag{9}$$

$$\Delta\Phi(t_i,t_j)=\Phi\left(t_{i+\frac{1}{2}},t_j\right)-\Phi\left(t_{(i-1)+\frac{1}{2}},t_j\right). \tag{10}$$

The increment of stress in the x-direction at the i-th time interval is defined by

$$(\Delta\sigma_{x.c})_i=\frac{E_c(t_i)}{1+\frac{E_c(t_i)}{E_{c.28}}\cdot\varphi(t_{i+1/2},t_i)}\left((\Delta\varepsilon_{s.x})_i-\sum_{j=1}^{i-1}\left[\frac{(\Delta\sigma_{x.c})_j}{E_{c.28}}\cdot\Delta\varphi(t_i,t_j)\right]-\varepsilon_{cf}(t_{i+1/2},t_{1/2})\right). \tag{11}$$

Although a good agreement between calculated data, which are defined according to the mentioned method, and corresponding experimental ones has been observed in the research paper[16], such a solution leads to the overestimated results with respect to elements with high energy capacity of expansive concrete especially in case of high level of restraint.

On the basis of above model the modified early age strains development model (MSDM) for the case of uniaxial restraint arrangements has been worked out in the research [17]. The distinctive idea of MSDM refers to the presence of elastic cumulative force induced by the restraint at the end of preceding time interval.

According to the MSDM for expansive concrete elements under uniaxial restraint conditions the restrained expansion strain at any i-th time interval $\varepsilon_s(t_{i+1/2})$ can be performed as an algebraic sum of free expansion strain $\varepsilon_{cf}(t_{i+1/2})$, elastic strainat i-thtime interval $\varepsilon_{el}(t_{i+1/2})$, creep strain at i-th time interval under constant self-stress applied at t_0 days $\varepsilon_{pl}(t_{i+1/2},t_0)$ and additional strain $\varepsilon_{cum}(t_{(i-1)+1/2})$ caused by the restrictive force induced by the restraint at (i-1)-th time interval

$$\varepsilon_s(t_{i+1/2})=\varepsilon_Q\left(t_{i+\frac{1}{2}}\right)+\varepsilon_{el}\left(t_{i+\frac{1}{2}}\right)+\varepsilon_{pl}\left(t_{i+\frac{1}{2}},t_0\right)+\varepsilon_{clm}\left(t_{(i-1)+\frac{1}{2}}\right). \tag{12}$$

With respect to the expansive concrete elements under biaxial restraint conditions two main problems should be pointed out.

The first one refers to the taking into consideration the development of plane stress-strain state in case of two-way orthogonal confinement in expansive concrete elements. As it is well known with reference to elastic elements, strains in one orthogonal direction are affected by ones in another orthogonal direction. The interference between longitudinal and transverse strains within the Hooke's law applicability is considered by the Poisson's ratio. It is noticeable that expansive concrete is elastic-plastic material and only part of total strain has the elastic origin (see Equation 12). Thus, concerning the expansive concrete elements under biaxial confinement, the Poisson's ratio should be applied with respect to the elastic strainat i-th time interval $\varepsilon_{el}(t_{i+1/2})$ only.

The second problem concerns the value of the Poisson's ratio with reference to the early age of expansive concrete. It should be noted that two opposite points of view in respect of the Poisson's ratio of the early age concrete have been performed in various research papers. Some researchers[20,21] consider that one is constant during the hydration and equals $\nu=0{,}2$ whereas others[7,22,23] demonstrate the evolution of the Poisson's ratio from $\nu=0{,}47$ to $\nu=0{,}2$ during the expansion period. However, it should be noted that in the paper [17] a period of time of 24 hours is considered as the early age of concrete. Taking into account that at such a short time interval the self-stressing concrete is characterized by very unstable properties and predominance of plastic deformations it is rational to accept the value of the Poisson's ratio $\nu=0{,}2$ for further calculations.

It should be pointed out that in literature the modified strains development model (MSDM) has already been implemented with respect to the expansive concrete elements with carbon textile reinforcement in the form of "simplified" MSDM24. However such "simplification" is incorrect and contradicts to the basic assumptions of the original model (MSDM).

The significance of proposed relationship lies not in providing a fixed value, but in revealing that self-stress is not solely determined by the amount of expansive agent; it is simultaneously controlled by the material's inherent stiffness, the time effect, and the limiting capacity provided by the constrained system. This naturally leads to the concept of system stiffness, because under the same expansion potential, the stronger the constraint, the smaller the constrained deformation, and the more likely the self-stress level is to increase; conversely, a weaker restraint makes it easier for expansion to be released, making it difficult to form an effective compressive stress background. Figure 6 further illustrates the typical time-history of restrained stress development under different degrees of restraint, indicating that stronger restraint generally promotes higher self-stress once expansion dominates shrinkage.

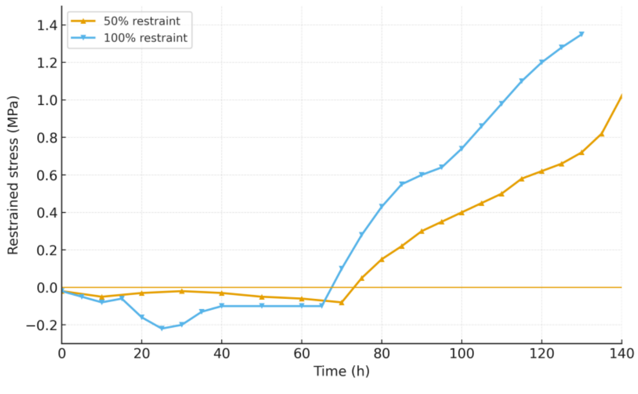

Figure 6 – Evolution of restrained stress in RAEC under different degrees of restraint [24]

4.2 System Stiffness and Stiffness Mismatch

System stiffness K describes the ability of a confined structure to resist the expansion deformation of concrete. Its physical meaning can be understood as the level of reaction force that the confined system can provide to a unit expansion deformation. For components using steel bars, steel pipes, etc., for confinement, K is related to both the elastic modulus of the confining material and its geometric configuration. For example, in a uniaxially reinforced column, the effective confinement capacity can often be considered as the result of the combined effect of the reinforcement ratio and the elastic modulus of the steel bars, and is further affected by the cross-sectional area ratio, arrangement, and boundary conditions. In RAEC studies, system stiffness is more often used to explain the difference in self-stress levels between different matrix materials under the same confinement conditions, and this difference is mainly reflected in the stiffness mismatch problem.

Since the elastic modulus of recycled aggregate concrete is usually lower than that of natural aggregate concrete, this characteristic can be summarized as $E_{rac} < E_{nac}$. When reinforcement conditions remain constant, the modulus ratio $n = E_s/E_c$ in the system increases as E_c decreases. This means that the confined body is "harder" relative to the concrete matrix, thus altering the deformation distribution mechanism between the two. If we only consider the linear relationship of $\sigma = E \cdot \epsilon$, under the same level of expansion strain, a lower E_c would theoretically result in a smaller compressive stress level achievable by the RAEC matrix, since stress is directly dependent on the modulus. However, in real components, a "softer" matrix often means that it is more prone to deformation redistribution under restrain and adapts to the restrain conditions through greater deformation. Therefore, the restrain response at the component scale is not equivalent to a linear inference from a single material point [16]. In other words, RAEC is not simply "difficult to establish self-stress," but rather, under the same restrain configuration, it is more likely to exhibit a state where lower self-stress levels and more significant deformation coexist. This makes the compensation efficiency more sensitive to the expansion strain reserve and restrain strength. Related studies indicate that to achieve a self-stress level similar to NAC in RAEC, it is often necessary to increase the amount of expansive agent to increase the available expansion strain, or to increase the reinforcement ratio and enhance the stiffness of the confinement system to improve the degree of restrain [11]. Therefore, stiffness mismatch is not simply a negative factor; it is more like a design constraint, suggesting that a more precise matching relationship must be established between expansion potential and confinement capacity to ensure that the compensation effect is truly implemented at the component scale.

4.3 Superimposed Effect of Creep and Stress Relaxation

The self-stress formed under confinement conditions in RAEC does not remain constant with age; its evolution process exhibits obvious time-varying characteristics, and creep is one of the key factors dominating this time-varying process. Self-stress is essentially equivalent to applying a continuous internal force state to concrete, thus inducing creep deformation of concrete under long-term action, and thereby causing stress redistribution and attenuation. This phenomenon is usually manifested in the form of stress relaxation. Compared to NAC, RAC exhibits higher creep levels due to its more developed pore structure, weaker ITZ, and easier microcrack propagation. Therefore, under the same initial self-stress conditions, RAEC often experiences faster self-stress relaxation. Literature reports indicate that stress relaxation in RAC can lead to approximately 40 % to 60 % prestress loss [21]. This means that even if a considerable self-stress level is established early on, without consideration for long-term relaxation, the later compensation effect may still significantly diminish, affecting durability and the sustainability of crack control.

In long-term deformation analysis, the treatment of time-related effects often requires the introduction of superposition principles. The Time-Temperature Superposition (TTS) principle is commonly used for polymer materials, but similar superposition ideas are also employed in a more general form in the field of concrete creep prediction. For example, the superposition principle combines the strain contributions from different time periods into a total strain response. For RAEC, a system with significant material heterogeneity, using overly idealized creep descriptions for ordinary concrete often fails to accurately predict the retention level of long-term self-stress. Therefore, modified creep models are needed for correction, such as introducing coefficients that consider aging effects into the effective modulus method to more reasonably reflect the viscoelastic characteristics of the material as it ages [1]. Meanwhile, the relationship between expansion, contraction, and creep in the early stages is not simply linearly additive. During rapid hydration and continuous microstructure evolution, damage accumulation and microcrack propagation alter the material's rheological path, causing RAC to exhibit more pronounced nonlinear rheological behavior. Based on this understanding, some studies have proposed introducing damage factors or correction coefficients into the model to characterize the amplification effect of microcrack evolution on creep and relaxation, thereby improving the predictive ability of early-age and long-term coupled deformation of RAEC [22].

5 Performance Enhancement Strategies: Carbonization Modification and Optimized Design

5.1 Accelerated Carbonization Treatment of Recycled Aggregates

To address the common problems of low stiffness, high water absorption, and well-developed pore structure in recycled aggregates (RCA), accelerated carbonization is widely regarded as one of the most effective and relatively engineerable aggregate modification pathways. Its core advantage lies in its ability to directly act on the old mortar and interfacial region, simultaneously improving the density of recycled aggregates through chemical reactions and pore structure reshaping, thereby enhancing the mechanical and deformation properties of RAC and RAEC from the material source. Mechanistically, the accelerated carbonization process mainly relies on the diffusion and reaction of CO_2 into the pore system of the old mortar. CO_2 reacts with $Ca(OH)_2$ and some C-S-H gel in the old mortar to form harder and denser $CaCO_2$. These calcium carbonate products can deposit and fill micropores and fine cracks, transforming the relatively loose porous structure of old mortar into a denser skeletal structure, thereby improving the density, strength, and overall integrity of recycled aggregates [12]. During this process, microscopic defects in the interfacial region are often passivated and repaired to some extent, preventing the structural shortcomings of recycled aggregates from being concentrated in the superposition effect of "high porosity and weak interfaces."

Carbonation modification typically improves deformation properties through multiple pathways and is directly coupled with the compensation mechanism of RAEC (Reinforced Expansion Coefficient). First, carbonation can restore or enhance the elastic modulus of RCA (Reinforced Compressive Acid) to a certain extent, making its overall stiffness closer to that of natural aggregates. This change is particularly crucial for constrained expansion systems because, under the same expansion strain conditions, a higher material modulus is more conducive to converting deformation into self-stress, thus making it easier for RAEC to form a higher level of effective compressive stress background under constrained conditions [6]. Secondly, carbonation reduces the porosity and water absorption of RCA, weakening the rapid migration channels of water between aggregate and paste, thus mitigating drying shrinkage caused by moisture loss and humidity gradients at the source. Simultaneously, densification of old mortar and ITZ strengthening reduce the space for long-term viscoelastic deformation, causing the creep coefficient of RAEC to tend to decrease, thereby slowing down the relaxation process of self-stress under long-term action, reducing prestress loss and improving the durability of the compensation effect [7]. The comprehensive benefits of this modification can also be seen from experimental results. For example, a research report indicates that after using carbonized fine aggregate, the compressive strength of fully recycled aggregate concrete can increase by approximately 19,8 %, the water absorption decreases by approximately 14,6 %, and there is a significant improvement in durability-related indicators [7]. These data suggest that accelerated carbonation not only improves individual performance indicators but may also provide a more stable material basis for the deformation control and crack resistance of RAEC through the combined effects of "pore structure densification, interface strengthening, and stiffness restoration."

5.2 Mix Proportioning and Curing Optimization

Beyond material-level modification, mix design and curing regime also determine whether RAEC can effectively convert its expansion potential into a usable compensation effect. Regarding the dosage of expansive agents, RAEC, due to its higher intrinsic shrinkage and creep levels, often has a stronger compensation requirement than NAC systems; therefore, the recommended dosages proposed in engineering and research are usually relatively higher. Taking CSA-type expansive agents as an example, the commonly recommended dosage range is approximately 8 % to 12 %, aiming to establish sufficient effective expansion reserves even under high shrinkage conditions. If CSA and MgO are co-admixed, a combination with a mass ratio of approximately 2:1 is often used to cover the early and late shrinkage compensation needs, achieving more balanced volumetric stability throughout the entire age [18]. It is important to emphasize that a higher expansive agent dosage is not always better. Excessive addition may lead to adverse internal damage risks under insufficient constraints or unstable moisture supply. Therefore, a reasonable dosage should be matched with the constraints, aggregate moisture content, and target compensation level.

Another key variable closely related to the dosage of the expanding agent is the water-cement ratio and curing conditions. A lower water-cement ratio generally benefits strength and reduces permeability, but it may also limit the hydration reaction and expansion development of the expanding agent, as the expansion process is more sensitive to available moisture and humidity. The RAEC system has certain unique characteristics in this regard, namely, the pore water content of RCA can provide continuous replenishment for hydration and expansion through the internal curing effect, but this replenishment capacity cannot completely replace the humidity stability brought about by external curing. Therefore, after the mix proportion is determined, maintaining a high humidity environment in the early stage through sufficient external wet curing remains a key measure to ensure expansion efficiency. Related studies usually recommend wet curing for no less than 14 days to reduce the inhibitory effect of early self-drying and insufficient moisture on the expansion reaction [23]. In engineering implementation, this also means that mix proportion optimization and curing optimization need to be considered as a whole and simultaneously. Only when the moisture supply, expansion time, and restrain conditions are matched can the compensation mechanism of RAEC function stably and achieve a more reliable comprehensive balance between strength, volume stability, and durability.

Conclusions and Outlook

A review of existing literature shows that a relatively clear consensus has been reached regarding the mechanism and engineering application of recycled aggregate expansive concrete (RAEC). Overall, although RAC inherently suffers from drawbacks such as high shrinkage, significant creep, and low elastic modulus, stable shrinkage compensation can still be achieved by appropriately introducing expansive agents, especially a composite expansive system of CSA and MgO. Under suitable constraints, considerable levels of chemical prestress can also be established. Existing studies generally indicate that RAEC can generate approximately 0,5 to 1,5 MPa of chemical prestress within a controllable engineering range, effectively offsetting the tensile stress caused by shrinkage and significantly improving crack resistance. This means that "expansion compensating for shrinkage" is not only feasible in recycled systems but also possesses a clear performance gain path. Meanwhile, the design logic of RAEC cannot simply follow the empirical framework of natural aggregate concrete (NAC). This is because the stiffness mismatch caused by low modulus alters the conversion efficiency of expansion strain into self-stress, often requiring a higher level of restricted expansion rate to achieve the same self-stress. Furthermore, a higher creep level accelerates self-stress relaxation and amplifies prestress loss, making the favorable state established early on more prone to decay during long-term service. Based on this characteristic, employing expansion sources covering the entire age range, such as MgO that can provide delayed expansion, and incorporating relaxation loss considerations into structural design are generally considered necessary conditions for improving the durability and predictability of the compensation effect.

Regarding performance enhancement technologies, the importance of aggregate modification has been repeatedly emphasized. Among these, accelerated carbonation is considered one of the most targeted key means to improve the overall performance of RAEC. The densification effect formed by the carbonation reaction can not only restore the stiffness of recycled aggregate to a certain extent but also reduce porosity and water absorption, weakening drying shrinkage caused by moisture migration at the source. It also reduces creep levels through interface strengthening and microstructure densification, thereby enabling the expansion efficiency to be more fully and stably converted into an effective self-stress background. Meanwhile, the synergistic effect of multiple restrain systems provides more structurally significant support for improving the brittleness and compensation efficiency of RAEC. Fiber-based materials such as steel fibers and basalt fibers can reduce strain concentration through crack bridging and dispersed constraints, making the expansion energy more likely to form a uniform internal restrain force distribution and suppressing the propagation of microcracks that may be induced during the expansion process. The steel tube restrain system provides continuous confining pressure at the component level and helps solve the interfacial voiding problem caused by core concrete shrinkage, thereby improving overall ductility and load-bearing stability. The above evidence collectively demonstrates that the advantages of RAEC do not stem from a single material measure, but rather rely more on the systematic matching between the expansion source time history, restrain conditions, aggregate modification, and crack control methods.

Looking to the future, RAEC research still needs to be further deepened along three main lines: long-term service mechanism, environmental durability, and engineering standardization. Firstly, regarding long-term performance, it is necessary to establish long-term constitutive and creep relaxation models that can reflect the coupling effect of RCA damage evolution and the hydration process of the expansion agent, thereby quantifying the influence boundary of stress relaxation on the self-stress retention level and structural safety, enabling design to move from short-term performance to traceable life-scale evaluation. Secondly, regarding durability, a more in-depth discussion is needed on the stability of expansion products under corrosive environments such as chloride and sulfate, especially ettringite. The long-term correlation between ettringite and the evolution of microcrack networks, changes in permeability, and the risk of steel reinforcement corrosion needs to be clarified, thereby establishing a durability evaluation path that more closely reflects actual service environments. Finally, to promote large-scale engineering applications, developing standardized design methods and mix design specifications for RAEC remains essential. In particular, the optimal type and reasonable dosage range of expansion agents corresponding to different quality grades of recycled aggregates should be clearly defined, and moisture management, curing requirements, and constraints should be incorporated into operable engineering clauses to improve the replicability and reliability of RAEC in different engineering scenarios.

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