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ASSESSMENT OF EXPANSIVE CONCRETE WITH RECYCLED AGGREGATES PROPERTIES UNDER FREE AND RESTRAINT CONDITIONS

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This review synthesizes serviceability evidence for expansive concrete with recycled aggregates (RAC) under free and restrained conditions in building applications. Uniaxial compression is interpreted in the standard cylinder convention ($\phi 100 \times 200$ or $\phi 150 \times 300$; $h/d = 2:1$), with chord modulus referenced to an explicit ASTM C469 stress window; ASTM C157 informs free length change, and ASTM C1581 provides a relative restrained-cracking indicator. Across digitizable datasets, RAC shows a lower elastic modulus and slightly larger peak strain than NAC at a given strength. With expansive systems, free deformation capacity increases, whereas restraint moderates' deformation and raises apparent stiffness. We supply a traceable source register and typical ranges for screening, and recommend a minimal verification suite (strength, chord modulus, free length change, one restrained method) with equivalent restraint stiffness and key environmental assumptions reported.

Keywords: recycled aggregate concrete, serviceability, chord modulus, stress–strain, free length change, restrained testing.

ОЦЕНКА СВОЙСТВ РАСШИРЯЮЩЕГОСЯ БЕТОНА НА ВТОРИЧНЫХ ЗАПОЛНИТЕЛЯХ В УСЛОВИЯХ СВОБОДНОГО И СТЕСНЕННОГО РАСШИРЕНИЯ

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В данном обзоре обобщены данные по эксплуатационной пригодности расширяющегося бетона на вторичных заполнителях (RAC) в условиях свободного и стесненного расширения применительно к строительным конструкциям. Одноосное сжатие интерпретируется в соответствии со стандартными параметрами цилиндрических образцов ($\phi 100 \times 200$ или $\phi 150 \times 300$ мм; $h/d = 2:1$), при этом текущий модуль упругости соотносится с конкретным диапазоном напряжений по стандарту ASTM C469; свободное изменение линейных размеров оценивается по ASTM C157, а относительный показатель трещиностойкости в стесненных условиях – по ASTM C1581.

Анализ оцифрованных наборов данных показывает, что при заданной прочности бетон на вторичных заполнителях (RAC) обладает более низким модулем упругости и несколько большими пиковыми деформациями по сравнению с бетоном на природных заполнителях (NAC). В расширяющихся системах способность к свободным деформациям возрастает, в то время как наличие стеснения сдерживает деформации и повышает видимую жесткость. В работе приводится реестр проверяемых источников и типичные диапазоны значений для предварительного отбора. Рекомендуются минимальный набор про-

верочных испытаний (прочность, секущий модуль упругости, свободное изменение длины, один метод оценки стеснения) с обязательным указанием эквивалентной жесткости стеснения и ключевых условий окружающей среды.

Ключевые слова: вторичный бетон (RAC), эксплуатационная пригодность, секущий модуль упругости, диаграмма деформирования, свободное расширение, испытания при стеснении деформаций.

Introduction

Recycled aggregate concrete (RAC) is increasingly specified in buildings to cut embodied impacts; however, due to adhered mortar and a modified interfacial transition zone, RAC typically exhibits a lower elastic modulus and a shifted compressive stress–strain response relative to normal aggregate concrete (NAC), with direct consequences for deflection and crack-width control in serviceability design [1; 2]. Expansive or shrinkage-compensating systems are adopted to mitigate early-age cracking, yet their effectiveness depends on mixture proportioning, agent reactivity, and curing temperature, and should be substantiated against recognized guidance before use in structural elements [3].

This review is serviceability-oriented and compares expansive concretes with recycled aggregates under free and restrained conditions. For comparability, uniaxial compression results are discussed in the standard cylinder convention ($\phi 100 \times 200$ mm or $\phi 150 \times 300$ mm; height-to-diameter 2:1), and the chord modulus is referenced using the stress window defined in ASTM C469. Free length change is characterized by ASTM C157, and restrained cracking behavior is summarized using the restrained-ring procedure ASTM C1581 as a relative indicator of cracking susceptibility (noting the standard’s explicit caveat that it is not intended for expansive materials) [4–6], and the discussion is organized to keep the reporting convention explicit (standard cylinder, stated stress window) so that results remain comparable across sources [1].

Materials and Methods

Scope and search strategy: The review targets studies reporting compressive strength–deformation information for normal-aggregate concrete (NAC) and recycled-aggregate concrete (RAC), together with tests that characterise free length change and restrained cracking for concretes incorporating expansive (shrinkage-compensating) systems in building applications. For like-for-like discussion, uniaxial compression results are read in the standard cylinder convention ($\phi 100 \times 200$ mm or $\phi 150 \times 300$ mm; height-to-diameter = 2:1); chord modulus follows the stress-window definition in ASTM C469, free length change follows ASTM C157, and restrained cracking is summarised via the ASTM C1581 ring procedure as a relative indicator of cracking susceptibility (noting the standard’s caveat that it is not intended for expansive materials) [7–9]. Where guidance specific to shrinkage-compensating concrete is relevant to reporting and verification, ACI PRC-223-21 is referenced for terminology and practice alignment [10].

Inclusion and exclusion criteria: Studies were included when they provided at least one of the following for building-grade mixes: (1) a digitizable uniaxial stress–strain relationship under free and/or restrained conditions; (2) chord modulus with an explicit or inferable ASTM C469 stress window; (3) peak or ultimate strain (e.g., at 85% post-peak); (4) free length change at a defined age per ASTM C157; or (5) a restrained measurement representative of stiff boundaries (e.g., ring-test age at cracking per ASTM C1581, or reinforcement-provided restraint). Flexural-only studies, records lacking essential mixture information, and duplicates were excluded.

Data fields and definitions: Extracted items comprised compressive strength f_c^i ; E with the C469 measurement window noted; ϵ_{peak} and (where defined) ultimate strain (e.g., 85% post-peak); free length change at stated ages (C157); restrained indicators (e.g., ring age-at-cracking or induced tensile-stress metrics per C1581); specimen geometry (normalised to the cylinder convention); and a concise restraint description.

Restraint categorisation and stiffness descriptor: Restraint was classified as free (no external restraint) or restrained, the latter including ring assemblies, stiff sleeves/forms, or reinforcement-provided axial restraint. Where information permitted, boundary restraint was expressed using an equivalent axial restraint stiffness

$$k_r = \sum \left(\frac{E_r A_r}{L_r} \right)$$

reported per unit height for cross-setup comparison; for ring tests, the inner-ring geometry and steel modulus were listed as the effective circumferential restraint. Consistent with agency practice, ring-test metrics were interpreted as relative cracking susceptibility rather than absolute crack prediction [9; 11].

Synthesis approach: Eligible sources were catalogued in a condensed register indicating: (1) curve availability (free, restrained, or both), (2) the presence of paired free/restrained data for the same mixture and curing history, and (3) whether expansive systems were used. Indicators were harmonised to the cylinder convention and ASTM C469/C157/C1581 definitions and then summarised by category and restraint condition as typical ranges; no statistical pooling or model fitting was undertaken.

Quality control: For modulus, only measurements with an explicit or inferable C469 window were retained; when authors used a different window, it was recorded and cross-mix comparisons were avoided. For deformation, consistent peak/ultimate definitions were applied where possible. Curing temperature and moisture histories and specimen size/shape were recorded when available to flag comparability [7].

Limitations and verification pathway: Heterogeneity in mixture design, curing regimes, restraint implementations, and reporting conventions remains substantial, especially for RAC with expansive agents. Accordingly, compiled ranges are intended for screening and like-for-like discussion. Prior to adoption in project design, a minimal verification suite is recommended: compressive strength and chord modulus per ASTM C469, free length change per ASTM C157, and one restrained method (e.g., ASTM C1581 or reinforcement-provided restraint representative of the element), with the restraint reported using k_r and the measurement window explicitly stated. Where constitutive curves are required for analysis, baseline shapes may be taken from Popovics (1973) or fib Model Code 2010 and then refined using mix-specific indicators summarised in this review [12; 13]. For RAC-specific stiffness and strain-capacity trends that inform these refinements, see the evidence syntheses by Silva et al. (2016) and Xiao et al. (2005) [1; 2].

Results

1.1 Literature dataset for strength–strain in free and restrained conditions

To appraise strength–deformation under free and restrained boundaries, we assembled a concise register of publicly available studies covering uniaxial compression on NAC and RAC, together with free-length change and restrained-cracking tests for concretes incorporating expansive systems intended for building applications [3–5].

How restrained samples were tested. In addition to uniaxial compression on standard cylinders, “restrained” evidence in the literature largely comes from the restrained-ring test (ASTM C1581), where a steel inner ring provides circumferential stiffness and the age at cracking and induced tensile stress are used as relative indicators of cracking susceptibility; agencies routinely use this as a comparative screen while recognising the standard’s caveat that it is not intended for expansive materials in an absolute sense [11]. Studies also report reinforcement-provided axial restraint (e.g., prisms with ≈1% longitudinal steel) or rigid sleeves/collars, which we describe using an equivalent axial restraint stiffness $k_r = \sum(E_i A_i / L_i)$ when data permit so that boundary conditions remain comparable across set-ups [14].

Full stress–strain curves for RAC that enable baseline comparisons to NAC are widely available (multiple strength grades and RCA contents), and they consistently show lower elastic modulus at a given f'_c and slightly larger peak strain; we rely on these datasets and reviews for the “free” baseline in this paper [15]. See Table 1 for the literature register used in strength–deformation and restraint appraisal.

Table 1. – Literature sources used for strength–deformation and restraint appraisal

Material system (with reference)	RCA (%)	Expansive system	Restraint implementation	Curve available	Key indicators
NAC & RAC, digitizable full curves	0–100	No	Uniaxial compression (standard cylinder)	Yes	f'_c , E, full stress–strain
RAC evidence synthesis ($E-f'_c$)	Multiple	No	Uniaxial compression	Many	$E-f'_c$ trends, ϵ_{peak} ranges
Restrained ring (relative cracking)	–	Often Yes	ASTM C1581 ring	–	Age at cracking; induced tensile stress
Free vs restrained benchmarking practice	–	Possibly	C157 + C1581 pairing	–	Free shrinkage vs restrained response
Guidance for shrinkage-compensating concrete	–	Yes	Free & restrained (practice guidance)	–	Mix/test guidance; reporting items
Baseline constitutive shapes for comparison	–	–	Uniaxial compression (model)	–	Popovics/fib curve parameters

Compared with NAC, RAC exhibits a systematically lower modulus at a given strength level and a modestly larger peak strain under free compression; when restraint is introduced (ring or reinforcement-provided), deformation growth is curbed and the post-peak response appears less severe, an effect that scales with boundary stiffness, hence the practical value of pairing free and restrained checks for dosage selection and serviceability verification.

1.2 Pooled indicators relevant to building serviceability

To provide starting values for design screening, we compiled typical ranges by category and restraint condition from the sources in Table 1. These values are for scoping only and should be calibrated to the target mixture and thermal history using a minimal verification suite (compressive strength & chord modulus per ASTM C469, free length change per ASTM C157, and one restrained method such as ASTM C1581 or a reinforcement-provided restraint).

Table 2. – Typical indicator ranges for serviceability screening

Category	Representative condition	f'_c (MPa)	E (GPa)	ϵ_{peak} ($\times 10^{-3}$)	Free length change at 28 d ($\mu\epsilon$)	Notes restrained appraisal
NAC baseline	Uniaxial compression (free)	30–50	30–35	1.8–2.2	–	Baseline for comparison
RAC w/o expansive system	Uniaxial compression (free)	28–45	22–30	2.0–2.8	–	Lower (E) than NAC at similar f'_c
Expansive concrete with RAC (free)	Free deformation / uniaxial	28–45	20–30 (dosage/reactivity dependent)	2.4–3.2	100–400	Increased deformation capacity; monitor modulus
Expansive concrete with RAC (restrained)	Ring or rigid boundary	Similar	Apparent stiffness higher	2.0–2.6	–	Restraint moderates deformation; use ring age-at-cracking as relative metric

Paired free and restrained measurements for the same mixture and curing history are rare but decisive for choosing expansive-system dosage and verifying serviceability performance in building elements; adopting a consistent cylinder convention and an explicit chord-modulus window (C469) keeps reported values comparable across studies.

Conclusions

Serviceability checks for expansive concrete with recycled aggregates should start from RAC's baseline: at a given strength it has a lower elastic modulus and a slightly larger peak strain than NAC. When using expansive systems, report both free (length change) and restrained results for the same mix and curing history, as restraint in building elements shifts apparent stiffness, peak strain, and cracking propensity. Keep comparisons like-for-like by using the standard cylinder convention and stating the chord-modulus stress window; interpret ring tests as relative indicators. For modelling, adopt a baseline compressive curve (e.g., Popovics/fib) and adjust with RAC-specific stiffness/strain observations. Before adoption, confirm with a minimal suite: compressive strength and chord modulus (window stated), free length change, and one restrained method representative of the target boundary; report the equivalent restraint stiffness K_r and key environmental assumptions.

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