55
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STEPGRAD
СТЕПГРАД

Žarko Petrović, University of Nis, zarko.petrovic@gaf.ni.ac.rs
Bojan Milosevic, University of Kragujevac, milosevic.b@mfkv.kg.ac.rs
Marija Spasojević Šurdilović, University of Nis, marija.spasojevic.surdilovic@gaf.ni.ac.rs
Andrija Zorić, University of Nis, andrija.zoric@gaf.ni.ac.rs
Dragana Turnić, University of Nis, dragana.turnic@gaf.ni.ac.rs

LOAD–DEFLECTION BEHAVIOR OF CONTINUOUS SCC BEAMS WITH RECYCLED COARSE AGGREGATES

Abstract:

This study examines the load–deflection response of continuous self-compacting concrete (SCC) beams incorporating recycled coarse aggregates. Nine two-span beams with reinforcement ratios of 0.65–0.94% were experimentally tested using 50% and 100% aggregate replacement. Recycled aggregate beams showed slightly reduced stiffness and increased post-cracking deflections, while ultimate load capacities remained comparable, particularly for 50% replacement. The influence of recycled aggregates was more pronounced at lower reinforcement ratios. Experimental ultimate loads exceeded EC2 and ACI 318 predictions, indicating effective moment redistribution and ductile behavior. The results confirm the structural applicability of high-quality recycled aggregates in continuous SCC beams.

Keywords: recycled aggregate concrete (RAC), self-compacting concrete (SCC), continuous beams, load–deflection behavior

ПОНАШАЊЕ КОНТИНУАЛНИХ SCC ГРЕДА СА РЕЦИКЛИРАНИМ АГРЕГАТОМ

Сажетак:

Ова студија истражује понашање оптерећења и деформације континуираних армиранобетонских греда направљених од самозбијајућег бетона са додатком крупног рециклираног агрегата. Девет континуираних греда је експериментално тестирано у два распона са процентима арматуре у распону од 0,65% до 0,94%, са процентима замјене агрегата од 50% и 100%. Греде са рециклираним агрегатом показале су благо смањену крутост и повећане деформације након пуцања, док су оптерећења при лому остала упоредива, посебно у случају замјене агрегата од 50%. Ефекат рециклираног агрегата био је израженији при нижим процентима арматуре. Експериментално оптерећење при лому превазилази предвиђања EC2 и ACI 318, што указује на ефикасну прерасподјелу момената и дуктилно понашање. Резултати потврђују структурну примјену висококвалитетног рециклираног агрегата у континуираним самозбијајућим бетонским гредама.

Кључне ријечи: рециклирани агрегати, самоуграђујући бетон, континуалне греде, понашање оптерећење-деформација

1. INTRODUCTION

The increasing demand for sustainable construction materials has led to the growing interest in recycled aggregate concrete (RAC) as a viable alternative to conventional natural aggregate concrete (NAC). Recycled aggregates, obtained from crushed concrete elements, offer environmental benefits by reducing construction and demolition waste, while also conserving natural resources [1], [2], [3].

The experimental program reported in Petrović et al. [4] forms the basis of this study on continuous SCC beams with recycled aggregates.

Self-compacting concrete (SCC) has emerged as a widely adopted construction material due to its excellent flowability, ability to fill formwork under its own weight, and enhanced surface finish without the need for vibration [5], [6]. Integrating recycled aggregates into SCC presents both opportunities and challenges: while RAC can partially replace natural coarse aggregate without severely compromising mechanical performance, its lower density, higher water absorption, and residual cement paste content may affect concrete stiffness and strength [1], [2], [7], [8], [9].

Recent studies have demonstrated that careful selection of high-quality recycled aggregates can mitigate these adverse effects. Kou and Poon [1] and Grdić et al. [7] reported that SCC containing up to 50% recycled coarse aggregate achieved comparable compressive and tensile properties to conventional SCC. Similarly, Silva et al. [2] highlighted the importance of aggregate quality and mix design adjustments for maintaining consistent performance.

In addition to material properties, the structural behavior of reinforced concrete members incorporating recycled aggregates has received increasing attention in recent years. Experimental investigations have shown that RAC beams generally exhibit similar failure mechanisms to conventional reinforced concrete beams, although reductions in stiffness and cracking load are commonly reported due to the lower elastic modulus and tensile strength of recycled aggregate concrete. Previous studies have also indicated increased deflections and wider crack patterns in RAC beams, particularly at higher replacement levels of recycled aggregates [10], [12]. Nevertheless, several experimental programs have demonstrated that adequate flexural capacity and ductile failure modes can still be achieved when appropriate reinforcement ratios and mix designs are adopted [10], [11], [13]. Long-term investigations further indicated that recycled aggregates may influence deformation behavior and crack development, although the overall structural performance remains comparable to that of conventional concrete members under flexural loading [14], [15], [16].

This study aims to experimentally investigate the influence of RAC content on the load–deflection response of continuous SCC beams with varying reinforcement ratios, providing insights into their structural applicability and practical design considerations. Moreover, limited experimental evidence is available regarding the combined influence of recycled aggregate content and reinforcement ratio on moment redistribution capacity in statically indeterminate SCC members. Addressing this gap contributes to a more reliable assessment of structural applicability of RAC in continuous beam systems.

2. MATERIALS AND EXPERIMENTAL PROGRAM

2.1. CONCRETE MIXTURES

Three types of self-compacting concrete (SCC) were prepared:

- NAC – conventional SCC with natural aggregates
- RAC50 – SCC with 50% coarse aggregate replaced by recycled aggregate
- RAC100 – SCC with 100% coarse aggregate replaced by recycled aggregate

The recycled aggregates were sourced from high-quality precast concrete elements, ensuring low variability and adequate mechanical performance [1], [2], [7], [12]. Mix proportions were adjusted to account for the higher water absorption of recycled aggregates, maintaining uniform workability across all mixtures.

Fresh-state performance of the investigated mixtures was evaluated by means of the slump flow test and the determination of the T500 flow time, following the recommendations provided by EFNARC [6] and EN 206-9:2010 [17]. The recorded slump flow diameters were close to 600 mm for all mixtures, which indicates a consistent deformability of the fresh concrete independent of the type of aggregate incorporated in the mix. The corresponding T500 values were approximately 5 s, suggesting a satisfactory flow rate and an adequate viscosity of the mixtures during spreading. Based on the classification system defined in EFNARC [6] and EN 206-9:2010 [17], these values place all tested mixtures within slump flow class SF1 and viscosity class VF1. Such results demonstrate that the mixtures satisfied the workability requirements typically associated with self-compacting concrete. In addition, the similar fresh-state parameters observed among the mixtures suggest that the presence of recycled aggregates did not significantly alter the rheological behavior of the concrete in comparison with conventional mixtures.

2.2. STRUCTURAL SPECIMENS

The experimental program comprised nine reinforced concrete (RC) continuous beams with rectangular cross-sections (150 × 200 mm, b × h) and a total length of 3400 mm, designed as two-span members with 1600 mm clear spans.

For each concrete type (NAC, RAC50, and RAC100), three longitudinal reinforcement ratios were adopted (ρ = 0.65%, 0.86%, and 0.94%).

- Beams with a reinforcement ratio of 0.65% (–065) were reinforced with 2Ø10 tension bars.
- Beams with 0.86% reinforcement (–086) contained 2Ø10 + 1Ø8 tension bars.
- Beams with 0.94% reinforcement (–094) were reinforced with 2Ø12 tension bars.

Accordingly, the specimens were designated as NAC-065, NAC-086, NAC-094, RAC50-065, RAC50-086, RAC50-094, RAC100-065, RAC100-086, and RAC100-094.

2.3. TEST SETUP AND INSTRUMENTATION

Beams were tested under two-point loading at mid-span of each span, applied through 100 mm wide steel plates with a 30 mm diameter steel roller to ensure uniform load distribution (Figure 1). Support conditions simulated fixed and movable ends.

Figure 1. Test setup of the continuous beam (photograph by author).

Load application was displacement-controlled, increasing at 0.02 mm/s (1.2 mm/min) until failure or no further load increase. Mid-span deflections were measured using LVDTs beneath the load application points. Tensile and compressive strains in concrete and steel were also monitored, though strain results are not discussed in this study.

Load data were recorded via an electronic dynamometer (U2A, HBM, Darmstadt, Germany) and processed through MGCplus and SPIDER8 acquisition systems using CATMAN software. Crack monitoring was performed visually, but crack width data are excluded from the current analysis.

3. RESULTS AND DISCUSSION

3.1. MECHANICAL PROPERTIES OF NAC AND RAC IN RELATION TO ANALYTICAL MODELS

The mechanical performance of the self-compacting concrete (SCC) mixtures incorporating recycled coarse aggregates was evaluated by comparing experimental results with analytical relationships commonly adopted in design standards and previous research. The investigated models describe correlations between compressive strength, tensile strength, and the secant modulus of elasticity. Experimental results for NAC, RAC50, and RAC100 mixtures were plotted against reference curves (Figures 2 and 3).

Figure 2 presents the relationship between splitting tensile strength and compressive strength. The experimental data for all mixtures fall within the prediction ranges of established analytical models [18], [19], [20], [21], [22]. Although RAC50 and RAC100 exhibit slightly lower tensile strengths compared to NAC at equivalent compressive strengths, the differences remain moderate. The results confirm that the incorporation of high-quality recycled aggregates does not significantly alter the fundamental strength relationship governing crack initiation and flexural behavior.

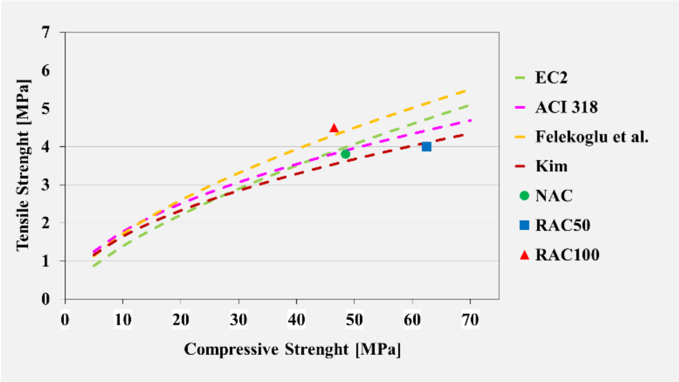

Figure 2. Tensile strength versus compressive strength of NAC and RAC mixtures compared with EC2, ACI, and literature models (drawing by author).

Figure 3 illustrates the correlation between secant modulus of elasticity and compressive strength. The measured modulus values for all mixtures show good agreement with widely used predictive expressions [14], [15], [16], [17], [18] with the closest fit observed for NAC. As expected, RAC50 and RAC100 demonstrate a slight reduction in stiffness due to the lower density and higher porosity associated with recycled aggregates. However, the deviations remain within predictable and design-acceptable limits.

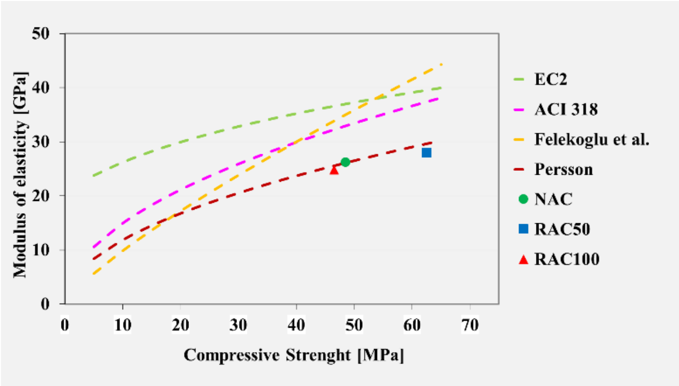

Figure 3. Elastic modulus versus compressive strength of NAC and RAC mixtures compared with EC2, ACI, and literature models (drawing by author).

Overall, the alignment of experimental data with analytical models confirms that SCC containing recycled coarse aggregates-particularly at 50% replacement-retains mechanical characteristics consistent with conventional design assumptions. This provides a reliable material basis for interpreting the structural load–deflection behavior discussed in the following sections.

In addition, the observed agreement between experimental and analytical relationships indicates that existing code-based material models remain applicable to SCC incorporating recycled aggregates, without the need for modification factors within the investigated replacement range. This consistency is particularly relevant for the interpretation of cracking loads, stiffness degradation, and moment redistribution in continuous beams, as these structural phenomena are directly influenced by tensile strength and elastic modulus values.

3.2. EXPERIMENTAL LOAD–DEFLECTION RESPONSE

The load–deflection behavior of the continuous beams was analyzed at mid-span sections I and III for all reinforcement ratios. Beams cast with RAC50 exhibited ultimate load capacities comparable to NAC, while RAC100 beams showed slightly lower ultimate loads, especially at higher reinforcement ratios.

All beams demonstrated a three-stage load–deflection response:

- Elastic stage – linear behavior prior to cracking
- Post-cracking stage – nonlinear response up to yielding of tensile reinforcement
- Post-yield stage – large deflections leading to failure

The initial deflections before cracking were similar across all concrete types. After cracking, beams with recycled aggregates exhibited slightly larger deflections than NAC beams, indicating a minor reduction in stiffness due to the recycled aggregate content (Figure 4-6).

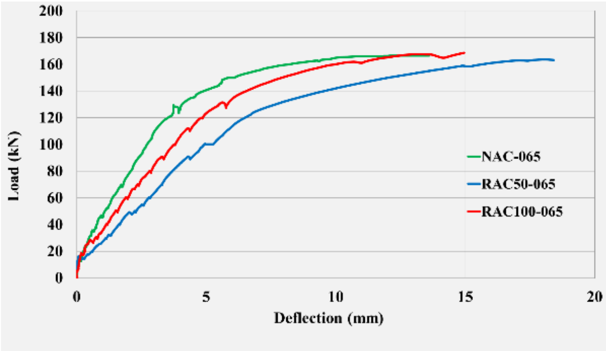

Figure 4. Load–deflection response for beams with reinforcement ratio ρ = 0.65% (drawing by author).

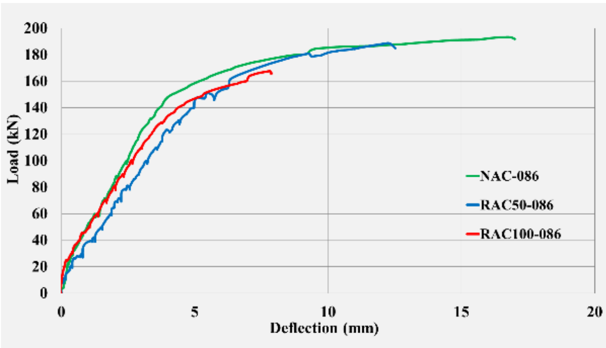

Figure 5. Load–deflection response for beams with reinforcement ratio ρ = 0.86% (drawing by author).

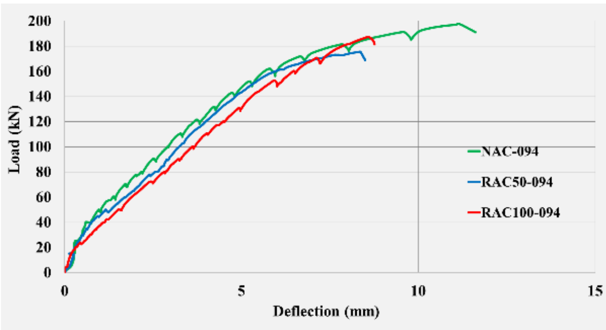

Figure 6. Load–deflection response for beams with reinforcement ratio ρ = 0.94% (drawing by author).

3.3. DUCTILITY AND SERVICEABILITY

Ductility indices (μ) were calculated as the ratio of displacement at maximum load to displacement at steel yielding (Figure 7). These values indicate satisfactory post-yield deformation and confirming the tension-controlled behavior of the continuous beams.

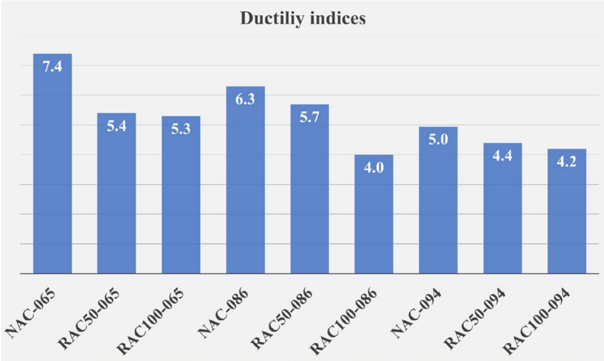

Figure 7. Displacement-based ductility indices (μ) for tested continuous beams (drawing by author).

Serviceability was assessed at 50% of the ultimate load (~$0.5F_u$). All beams satisfied code-based mid-span deflection limits according to EC2 ($\delta/L \leq 1/250$) [18] and ACI 318 ($\delta/L \leq 1/360$) [19] (Figure 8). Some RAC beams exhibited slightly higher deflections under service loads, but the differences remained within acceptable limits.

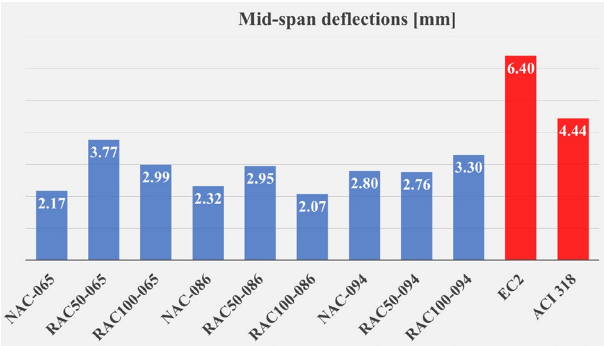

Figure 8. Mid-span deflections under service load (~$0.5F_u$) (drawing by author).

3.4. COMPARISON WITH CODE PREDICTIONS

Ultimate moments for each span were estimated according to EC2 and ACI 318 provisions and are shown in Table 1.

Table 1. Ultimate bending moments calculated according to EC2 and ACI 318 provisions [4].

Beam ID	M_u (EC2) [kNm]	M_u (ACI 318) [kNm]
NAC-065	15.15	15.11
NAC-086	19.52	19.67
NAC-094	21.57	21.38
RAC50-065	15.15	15.11
RAC50-086	19.62	19.67
RAC50-094	21.73	21.38
RAC100-065	15.15	15.11
RAC100-086	19.68	19.67
RAC100-094	21.60	21.38

The ultimate loads were calculated using the standard relation:

$$F_u/2 = 6M_u/L \quad (1)$$

where F_u denotes the ultimate load, and M_u represents the ultimate bending moment capacity of the cross-section. A comparison between calculated and experimental ultimate loads is presented in Figure 9.

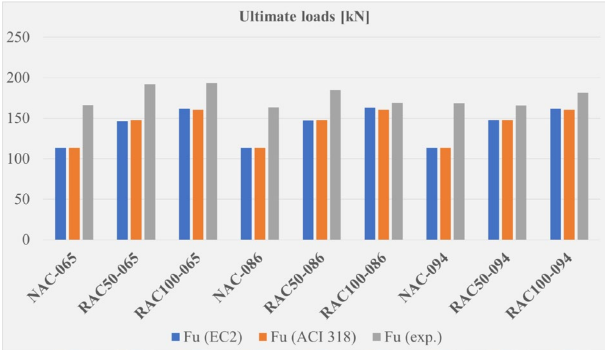

Figure 9. Comparison of analytically and experimentally obtained ultimate loads (drawing by author).

The experimental ultimate loads exceeded the code-based predictions, indicating the occurrence of moment redistribution and the development of plastic hinges within the continuous system.

3.5. EFFECT OF CONCRETE TYPE AND REINFORCEMENT RATIO

- At lower reinforcement ratios (ρ = 0.65%), differences in ultimate load and deflection among NAC, RAC50, and RAC100 were most pronounced.
- At higher reinforcement ratios (ρ = 0.86–0.94%), steel dominated the structural response, and the differences due to concrete type became less significant.
- Overall, partial replacement of natural aggregates with high-quality recycled aggregates (RAC50) did not compromise structural performance and maintained comparable stiffness, ultimate load, and ductility.

These observations confirm that recycled aggregate concrete (RAC) can be effectively used in continuous SCC beams, particularly when high-quality aggregates and appropriate reinforcement ratios are employed.

4. CONCLUSION

Based on the experimental investigation of continuous self-compacting concrete (SCC) beams incorporating natural (NAC) and recycled aggregates (RAC), the following conclusions can be drawn:

- Load–deflection behavior of beams with partial (RAC50) or full (RAC100) replacement of natural aggregates remained comparable to beams with NAC, particularly at lower replacement levels. RAC beams exhibited slightly higher deflections due to reduced stiffness, but ultimate load capacities were only marginally affected.
- The reinforcement ratio strongly influenced structural response. At lower reinforcement ratios, differences in stiffness and ultimate load among NAC, RAC50, and RAC100 were more pronounced. At higher reinforcement ratios, steel dominated the flexural behavior, mitigating the effect of recycled aggregates.
- Ductility indices of RAC beams confirmed adequate post-yield deformation and redistribution capacity, consistent with continuous beam behavior.
- Serviceability under 50% of ultimate load (~0.5Fu) was satisfied for all beams, with mid-span deflections well within EC2 and ACI 318 code limits.
- Code-based predictions for ultimate moments (EC2, ACI 318) were conservative, with experimental ultimate loads often exceeding the calculated values due to moment redistribution in continuous beams.
- Overall, high-quality recycled aggregates can be successfully used in SCC continuous beams without compromising structural performance, provided appropriate reinforcement ratios are applied. Partial replacement (RAC50) offers an optimal balance between sustainability and mechanical performance.

The results further demonstrate that conventional design approaches based on EC2 and ACI 318 assumptions remain applicable to SCC beams with recycled aggregates, as no abnormal stiffness degradation or brittle behavior was observed. These findings support the broader implementation of recycled aggregates in structural SCC elements, contributing to sustainable construction practices without requiring substantial modifications to current design procedures.

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