

Bending Behavior Analysis of Recycled Aggregate Reinforced Concrete Beams According to CBA 93 and Eurocode2 Regulations

Bellakehal Hizia¹, Latar Radia², and Kharat Sondes²

¹ University of Amar Thelidji Laghouat, Civil Engineering Department, Laghouat, Algeria.

² Master's student, University of Laghouat, Algeria.

Abstract. Construction waste has been widely used in the civil engineering field in recent decades. This alternative serves to preserve natural resources in terms of aggregates and to reduce public landfill surfaces. However, its use until today has been limited to pavements, sidewalks, decorative elements, embankments, etc. The use of recycled concrete aggregates in the structure elements (beams and columns) is still under development, particularly concerning the development of standards and regulations that encourage and facilitate the usage of recycled concrete. This paper presents the adaptation of Eurocode and CBA 93 rules to predict the bending behavior of reinforced concrete beams in which natural aggregates of concrete are partially substituted by recycled concrete aggregates. The aggregate substitution rates varied from 0% to 100%. Theoretical results showed that the substitution rate does not affect the theoretically predicted values.

1 Introduction

In Algeria, several structures were demolished after natural disasters such as earthquakes and floods, or the aging and deterioration of public buildings, bridges, and industrial facilities. An estimate in 2016 was made by the National Center for Study and Integrated Research in Building (CNERIB) on the inert waste of four states in the center region of Algeria (Algiers, Blida, Boumerdas, and Tipaza); it estimates between 300 thousand and 500 thousand t/year, 40% of which is concrete never recycled [1-2]. On the other hand, the depletion of available natural sources of aggregates and the stricter laws relating to protecting the environment are all factors that favor the recycling of construction waste. The majority of these demolished materials are made of concrete. This kind of waste constitutes a big part of solid waste in the world [3].

The need to improve the use of recycled concrete aggregates (RCA) in the construction field requires studying the capacity of concrete with recycled aggregates to ensure good adhesion with reinforcement. In recent years, several studies have been carried out on reinforced concrete beams made from recycled aggregates to examine their flexural behavior [4-9].

Based on the literature review, the bending behavior of RAC beams is still to be studied, particularly in the development of standards and regulations that encourage and facilitate the usage of recycled concrete. This paper aims to theoretically investigate the flexural behavior of reinforced concrete beams with a reinforcement ratio of 0.67%. The concrete matrix includes RCA with different

percentages (0%, 15%, 30%, 50%, and 100%). Deflections are predicted by the Eurocode 2 standard [10] and Algerian regulation CBA 93[11]. The obtained results are compared with experimental results obtained from the literature [12].

2 Evaluation of deflection

The deformations due to bending are obtained by a double integration of the curvatures. The difficulty of the calculation lies in taking cracking into account because it modifies the rigidity of the sections. Furthermore, depending on the desired objective, delayed deformations must be taken into account. In common cases, we use the classic relations of the resistance of materials by introducing fictitious inertia and the instantaneous or deferred modulus of elasticity of the concrete.

Elements that are not expected to be loaded beyond the loading level, which would cause, in any section, the tensile strength of the concrete to be exceeded, should be considered uncracked. For elements predicted to be cracked but not completely cracked, they should be considered to be behaving in an intermediate manner between the uncracked state and the fully cracked state:

- If $M_{ser} < M_{cr}$: the section is not cracked, the whole section contributes to the resistance.
- If $M_{ser} \geq M_{cr}$: the section is cracked, and only the compressive concrete contributes to the resistance.

M_{ser} and M_{cr} : Are, respectively, the serviceability moment corresponding to the characteristic

combination, and the cracking moment. For the case of a beam subjected to the four-point bending test and having a dead weight q , the moment M_{ser} is given by:

$$M_{ser} = \frac{qL^2}{4} + \frac{P}{2}a \quad (1)$$

2.1 Evaluation of deflection according to CBA 93 regulation

In the case of simply supported or continuous beams and strips of slabs, continuous or not, oriented in the direction of the short span, the expression for the deflection is given by equation (2). The deflections due to instantaneous loads are calculated by the instantaneous elastic modulus and moment of inertia (E_i and I_{fi}). However, deflections due to long-term loads are calculated by the deferred elastic modulus and moment of inertia (E_v and I_{fv}).

$$f = ML^2 / (10 EI) \quad (2)$$

$$\text{With } E_i = 11000 f_{c28}^{\frac{1}{3}} \text{ and } E_v = 3700 f_{c28}^{\frac{1}{3}} \quad (3)$$

$$I_{fi} = 1.1 I_0 / (1 + \mu \lambda_i) \text{ and } I_{fv} = I_0 / (1 + \mu \lambda_v) \quad (4)$$

$$\lambda_i = \frac{0.05 f_{t28}}{\left[\rho \left(2 + 3 \frac{b_0}{b} \right) \right]} \text{ and } \lambda_v = 0.02 f_{t28} / \left[\rho \left(2 + 3 \frac{b_0}{b} \right) \right] \quad (5)$$

$$\mu = 1 - \frac{1.75 f_{t28}}{(4 \rho \sigma_{st} + f_{t28})} \quad (6)$$

I_0 : Moment of inertia of the homogeneous total section ($I_0 = b_0 h^3 / 12$)

ρ : Reinforcement rate ($\rho = A_s / b_0 d$)

σ_{st} : Stress in the tensioned reinforcements at a given load level.

f_{c28} and f_{tj} : Compressive and tensile strength of concrete at 28 days, respectively.

The value of μ is given by the result of equation (6) if it is positive, and zero otherwise.

For uncracked sections, $f = f_i$, for cracked sections $f = f_v$.

$$\text{Where } M_{cr} = \frac{I_{fi}}{d_G} f_{ct28} \quad (7)$$

d_G : is the neutral axis of the uncracked section.

2.2 Evaluation of deflection according to the Eurocode 2 standard

If the element works mainly in bending, the following expression, appropriately, predicts its behavior:

$$f = \zeta \cdot f_{II} + (1 - \zeta) f_I \quad (8)$$

f : is the calculated average deflection.

f_I, f_{II} : are the deflections calculated, respectively, in the uncracked state and in the cracked state, obtained by:

$$f_i = \frac{M_{ser} L^2}{10 E I_i} \quad (9)$$

ζ : is a distribution coefficient (which takes into account the participation of the tensioned concrete in the

section). $\zeta = 0$ for non-cracked sections, otherwise is given by the following expression:

$$\zeta = 1 - \beta \left(\frac{M_{cr}}{M_{ser}} \right) \quad (10)$$

β : coefficient taking into account the influence of loading duration or loading repetition on the average deformations: $\beta = 1.0$ in the case of a single loading of short duration; $\beta = 0.5$ in the case of prolonged loading or a large number of loading cycles.

The elastic modulus of the uncracked section and that of the cracked section are given, respectively, by equations 11 and 12:

$$E_{cm} = 22 \left(\frac{f_{cm}}{10} \right)^{0.3} \quad (11)$$

$$E_{c,eff} = \frac{E_{cm}}{1 + \varphi_{ef}} \quad (12)$$

$$\text{Where } f_{cm} = f_{c28} + 8 \quad (13)$$

And φ_{ef} is the creep coefficient for the considered load and the time interval.

For all stresses calculated at a distance y from the neutral axis (see figure 1), we will therefore need to determine, for the two cases of the uncracked homogenized section and the cracked section, the position of the neutral axis (d_{GI}, d_{GII}), and the moment of inertia (I_I, I_{II}).

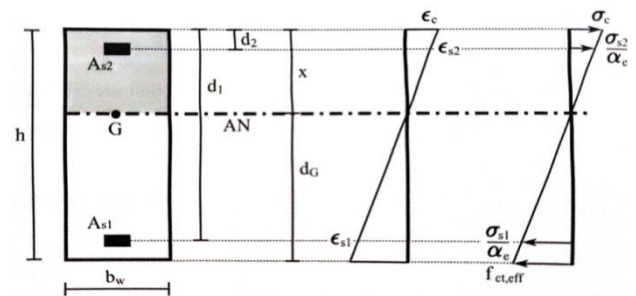


Fig. 1. Beam section at serviceability limit states.

3 Experiment

3.1 Materials

The used cement was ordinary Portland cement CEM-42.5. The natural aggregates are crushed limestone gravel 3/8 and 8/15, and natural river sand. The recycled concrete aggregates (RCA) were obtained from waste laboratory concrete samples, where the original concrete properties were unknown.

3.2 Concrete mixture

Seven reinforced concrete beams were designed and tested under four-point bending tests until failure, five with RCA and two control beams (T1.0S0G and T2.0S0G) containing only natural aggregates (NA). Table 1 reports the substitution rats of recycled aggregates, the compressive strength, and the tensile

strength obtained by the flexural tensile test of the seven mixtures.

Table 1. Substitution rats of recycled aggregates and the mechanical properties of concretes.

Beams	Volume Substitution rate of RCA (%)		f_{c28} [MPa]	f_{t28} [MPa]
	Sand	Gravel		
BT1S0G0	0	0	32.14	4.69
BT2S0G0	0	0	36.41	4.72
BS0G100	0	100	29.33	3.88
BS100G0	100	0	26.73	3.65
BS0G50	0	50	30.79	3.71
BS30G50	30	50	29.75	2.52
BS15G30	15	30	30.95	3.80

BS%G% indicates concrete with a percentage of recycled sand of (S%) and a percentage of recycled gravel of (G%)

3.3 Beam design

All beams were designed to fail in flexure. The beam dimensions are 10x15x140cm. Each beam was reinforced longitudinally with 02 HA8 bars in the tension zone, 02 HA8 bars in the compressive zone, and stirrups of Ø6mm spaced by 10cm as transverse reinforcement. The mechanical properties of reinforcement are the manufacturer's specified values. Figure 2 and Table 2 present the beam geometry and reinforcement properties.

Table 2. Mechanical properties of reinforcement.

Designation	Fe E 235	HA Fe E 40 A
Yield stress [MPa]	235	400
Tensile strength [MPa]	410	480
Ultimate strains [%]	22	14

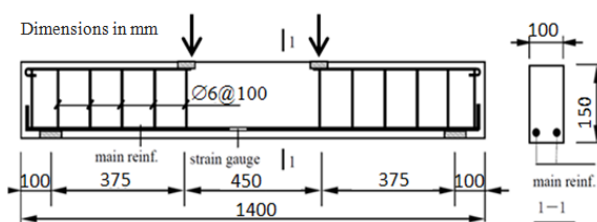


Fig. 2. Beams geometry and reinforcement details.

4 Comparison of theoretical and experimental results

Figure 3 presents the deflection variation at mid-span as a function of the mechanical load obtained from the four-point bending test for all the tested beams. The figure illustrates a comparison between the deflection values measured experimentally and those obtained theoretically using Eurocode 2 (EC2) and the CBA93 regulation, as well as the classical equations of material

resistance. Figure 4 presents the load-deflection curves obtained experimentally for all the tested beams.

It can be seen that the bending behavior of reinforced aggregate concrete (RAC) beams is similar to that of control beams of ordinary concrete. Also, we observe that the bending stiffness is slightly decreased compared to that of the control beam (Figure 4).

All the beams show that the agreement between the theoretical and experimental results in terms of deflection is very high at the elastic stage, i.e., before cracking of concrete. Beyond this point, the agreement between the results obtained by the EC2 model is less good. This can be referred to as the moment of inertia estimation of the cracked section (I_v) of each model. The CBA assumes that I_v depends on the applied load variation, unlike the EC2, which assumes that I_v is independent of the applied load, but it depends on the neutral axis of the cracked section, which is different from the neutral axis of the initial uncracked section. We can conclude that the Eurocode overestimates the flexural stiffness of beams, consequently, it underestimates the deflection prediction after concrete cracking, whether the type of aggregate, is recycled or not.

Indeed, at the final stage, generally, the beams yielded under a constant load. However, theoretical models show an unlimited linear increase in the deflection. This is because the theoretical models (EC2 and CBA93) and the equations of the material's resistance are based on the theory of elasticity laws, and they are not intended to predict the deflection at the ultimate limit state.

Regarding the effect of the recycled aggregate substitution rates on the deflection prediction, it can be observed that this effect is quite negligible given that the chosen rates did not significantly affect the concrete compressive strength (f_{c28}). Figure 4 shows, within the range of the experimentally obtained values of f_{c28} , that the variation of deflections is negligible when f_{c28} changes, particularly at service loads. Consequently, the requirements of Eurocode 2 and CBA93 remain applicable for flexural elements containing specific rates of RCA, in particular, for service loads.

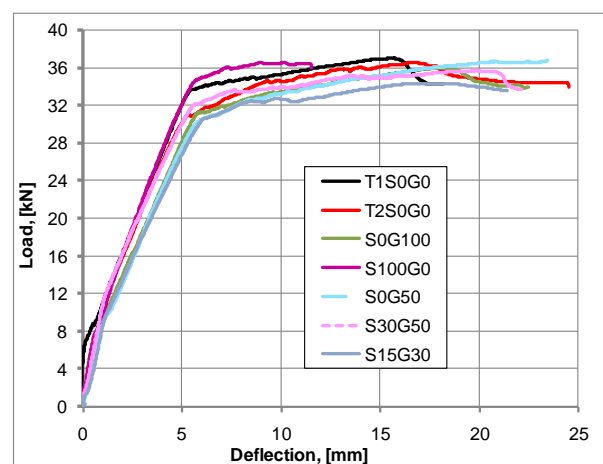


Fig.4. Experiment Load – Deflection curves at the mid-span [12].

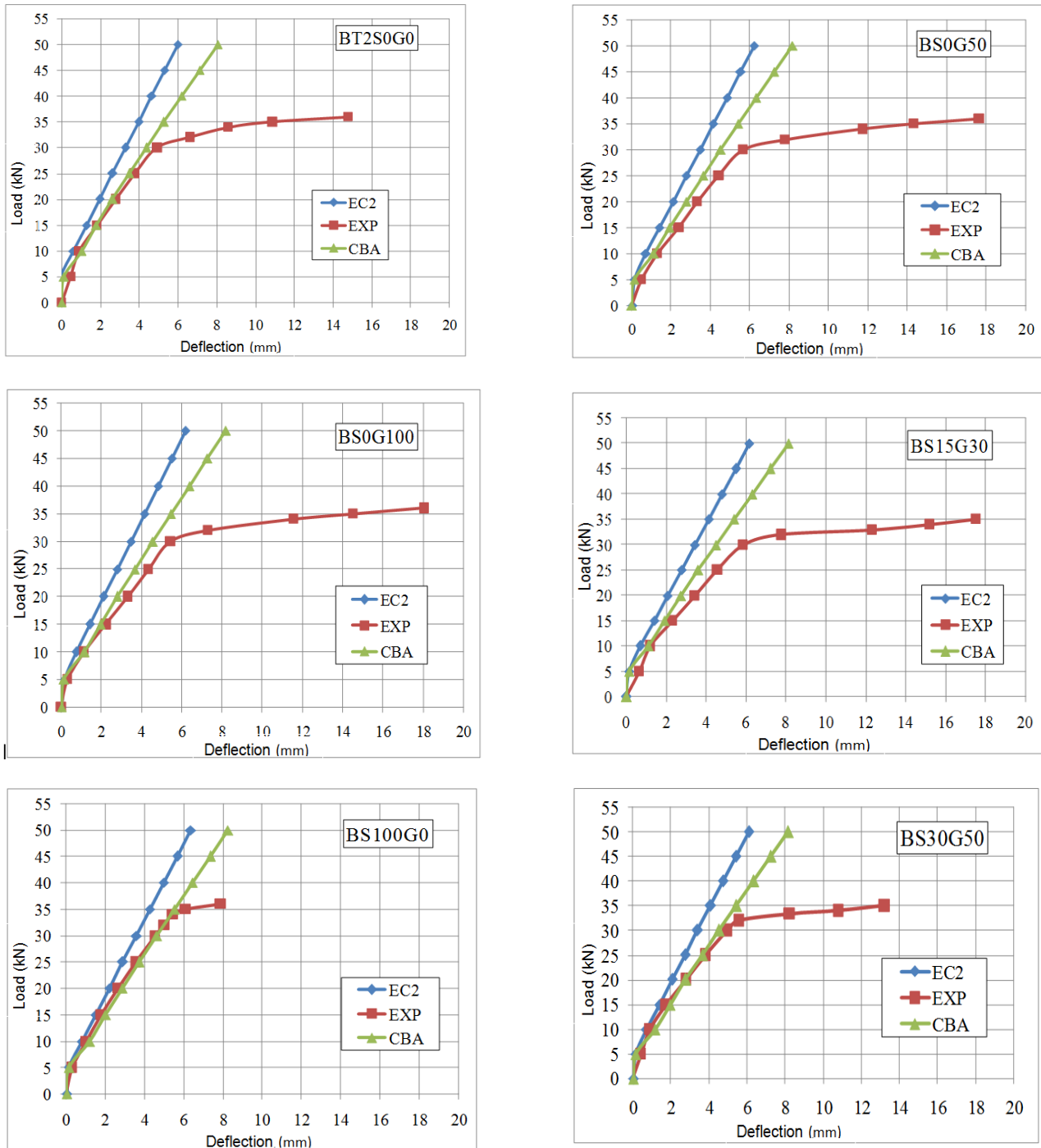


Fig. 3. Load – deflection curves at mid-span..

5 Conclusions

The objective of this study is to theoretically analyze the flexural behavior of reinforced concrete beams containing recycled concrete aggregates, following the requirements of Eurocode 2 and CBA93 regulations. This analysis is supported by a comparison of the obtained results with experimental results found in the literature. The impact of this study is to assess the applicability of these regulations' requirements for the design of beams containing recycled aggregates.

Within the limits of this research in terms of the used materials, the main conclusions that can be drawn from this study are as follows:

- The flexural behavior of recycled aggregate concrete beams is similar to that of natural aggregate concrete beams. The recycled aggregates didn't significantly affect the ultimate strength, the flexural stiffness, or the yielding point of the beams.
- The behavior of recycled aggregate concrete beams at the failure stage is similar to that of conventional reinforced concrete beams.

- Generally, it can be concluded that the substitution rates of natural aggregates (gravel and sand) by recycled aggregates of 15 to 50% will not affect the bending behavior of beams made from recycled aggregates.
- Before concrete cracking, the models proposed by EC2 and CBA93 to predict the deflection at the mid-span of the beams are in good agreement with the experimental results, independent of the RCA substitution rates.
- After concrete cracking, the model proposed by CBA93 to predict the deflection agrees rather well with the experimental results than the EC2 model. This is referred to as the effective moment of inertia estimation of the cracked section of each model.
- Independently of the aggregate type (natural or recycled), EC2 underestimates the deflections after concrete cracking.

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