Engineering Structures 156 (2018) 32–45

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

# Flexural performance of reinforced concrete beams made with recycled concrete coarse aggregate

Sindy Seara-Paz[a], Belén González-Fonteboa[b,*], Fernando Martínez-Abella[b], Javier Eiras-López[b]

[a] Department of Construction Technology, University of A Coruña, E.U. Arquitectura Técnica, Campus Zapateira s/n, 15071 La Coruña, Spain
[b] Department of Construction Technology, University of A Coruña, E.T.S.I. Caminos, Canales, Puertos, Campus Elviña s/n, 15071 La Coruña, Spain

ARTICLE INFO

*Keywords:*
Recycled concrete
Flexural performance
Deflection
Serviceability
Cracking

ABSTRACT

This work deals with the flexural performance of recycled concrete subjected to increasing loads up to failure. For this purpose, eight reinforced concrete beams were made with recycled coarse aggregates using two different water to cement ratios (0.50 and 0.65) and four replacement percentages (0%, 20%, 50% and 100%). Firstly, the basic concrete properties were determined (mechanical strengths and modulus of elasticity) and then, beam specimens were loaded up to failure using a four-point bending test at 28 days. As a result, bending moments, deflections, strains and curvatures were obtained at different load levels (cracking, service, yielding and ultimate state conditions), and also, the crack pattern.

On the basis of these results, it can be noted that service, yielding and ultimate state of recycled concrete exhibits, in general, a similar trend to that of conventional concrete. However, the cracking behaviour shows differences between recycled and conventional concrete. Finally, code-based expressions were used to calculate bending moments and deflections under flexural load, taking into account the different content of recycled coarse aggregate.

## 1. Introduction

In order to promote the sustainability of concrete, efforts have been made to address some of the environmental problems associated with concrete waste. In line with this, numerous researches have been conducted to analyse the structural performance of recycled concrete [1–13]. However, its use in real building and civil engineering applications requires more full scale studies, to assess the load-deformation response of recycled concrete that leads to good agreement on structural design.

Regarding flexural performance of structural recycled concrete, different investigations have been carried out [4,8,9,12]. However, the number of studies on concretes with high replacement percentages is scarce and additionally, some contradicting conclusions have been detected. While some authors [1,9,10,13] have found that recycled concrete beams show higher deflections, and cracking moments lower or similar to those of the conventional, others [6,8] have reported no significant difference between recycled and conventional concrete in terms of flexural performance.

On the basis of the literature review, it can be seen that the code-based procedures for conventional concrete can also be applied to recycled concrete predictions for flexural behaviour [2,6,9], although some differences have been detected. In line with this, the increase in recycled coarse aggregate results in the reduction of concrete stiffness [9], which is consistent with the increased beam deflections of recycled concrete. Most authors [2,8–10] point out similar yielding and ultimate behaviour, but some [7] have found little differences in cracking behaviour, in terms of crack spacing and pattern.

In general, it can be said that recycled concretes are able to fulfill strength and serviceability requirements similarly to conventional reinforced concrete. However, in order to encourage its use as structural concrete, it is important to be able to design reinforced concrete members made with recycled coarse aggregate, using existing design methods [6]. Accordingly, recent publications [2,9] have indicated that more full-scale research should be done to stablish a good agreement on its flexural performance and increase the results database for structural recycled concrete. This would lead to concrete properties, service-load and ultimate–load behaviour being predicted with the same approximation degree as conventional concrete.

Furthermore, with the aim of carrying out an accurate structural design, some concrete parameters have to be considered such as, tension stiffening, strength capacity or cracking behaviour. Tension stiffening is known as the concrete contribution after cracking and has significant importance in structural design. This parameter is required

* Corresponding author.
*E-mail addresses:* gumersinda.spaz@udc.es (S. Seara-Paz), bfonteboa@udc.es (B. González-Fonteboa), fmartinez@udc.es (F. Martínez-Abella), jeiras@udc.es (J. Eiras-López).

https://doi.org/10.1016/j.engstruct.2017.11.015
Received 8 November 2016; Received in revised form 19 September 2017; Accepted 8 November 2017
0141-0296/

to accurately design concrete structures as customary serviceability conditions occur after cracking. The strength capacity after cracking can be obtained based on the height of the compression zone of cracked concrete, which depends on the concrete deformability and reinforcement ratio. Regarding cracking behaviour, most authors have pointed out that recycled concretes show, in general, worse behaviour than conventional ones [1,9,10,13]. This will probably result in lower stiffness and therefore, lower concrete contribution after cracking when recycled coarse aggregate is used in structural members. The increased shrinkage strain of recycled concrete is related to its higher concrete deformation and lower tensile splitting strength, which result in a premature cracking and lower stiffness [14,15]. In line with this, it is expected that greater shrinkage of recycled concrete [16–21] leads to different flexural performance of recycled concrete structures.

Another important concrete feature in the design of structural concrete is the concrete-steel bond behaviour. Crack spacing and crack width depend on the interaction between concrete and steel rebars, which is also directly related to concrete stiffness after cracking. Although the lower bond strength of recycled concretes leads to the prevision of lower stiffness, this property has not been further analysed for different replacement percentages of recycled coarse aggregate. Additionally, stiffness after cracking largely depends on the compression height, which can be experimentally determined using a strain diagram of the cross section. Therefore, a sectional analysis is required to fully understand the structural behaviour of recycled concretes, especially its serviceability.

After reviewing available literature, it can be detected that there is no agreement on the effect of these features when their joint influence is analysed on a full-scale concrete structure made with recycled coarse aggregates. Hence, the aim of this work is to provide useful guidelines for a full structural serviceability and ultimate stage design, involving different replacement percentages of recycled coarse aggregates and the effect of concrete properties.

## 2. Objectives and methodology

The main goal of this work is to analyse the flexural performance of recycled concrete, in order to design structural concrete using recycled coarse aggregates with a similar degree of approximation as conventional concrete.

For said purpose, simply-supported reinforced concrete beams were tested using a full scale load test up to failure with displacement control. All beam specimens were gradually loaded up to collapse using a four-point bending and loading procedure. In order to analyse the flexural performance of recycled concrete beams under short term load, the moments and deflections were determined, and studied at cracking, service, yielding and ultimate state. The cracking pattern was also evaluated.

The methodology chosen to analyse the results was developed in two stages. In the fist stage, the objective is to know how much the main flexural parameters (cracking moment, yielding moment, deflections, cracking…) are affected by the incorporation of recycled aggregate. Therefore, all concretes were made with the same dosage but for the coarse aggregate, which was replaced with recycled concrete coarse aggregate (by volume) at different percentages. With the different concretes the beams were made and their flexural behaviour compared after being tested up to failure.

In the second stage the objective is to analyse if it is necessary or not to adapt the flexural code proposals (adjusted for conventional concretes) to take into account the recycled aggregates used. This analysis has been made using the ratios "experimental parameter/calculated parameter". If the ratios obtained with conventional and recycled beams are similar, code expression can be used and provide a similar approximation degree regardless the type of the concrete (recycled or conventional). If the ratios are different code expression need to be corrected.

This methodology lead to the assessment of, not only the flexural behaviour of structural concrete made with recycled coarse aggregate, but also the suitability of current code expressions to design this concrete.

Abbreviations

| | |
|---|---|
| $f_c$ | Compressive strength at 28 days (MPa) |
| $f_{ct}$ | Tensile splitting strength at 28 days (MPa) |
| $E_c$ | Modulus of elasticity at 28 days (MPa) |
| $\delta_{cr}$ | Cracking deflection at midspan beam (mm) |
| $\delta_{yiel}$ | Yielding deflection at midspan beam (mm) |
| $\delta_{ult}$ | Ultimate deflection at midspan beam (mm) |
| $\delta_{ser}$ | Service deflection at midspan beam (mm) |
| M | bending moment (kN m) |
| $M_{cr}$ | Cracking moment at midspan beam (kN m) |
| $M_{yiel}$ | Yielding moment at midspan beam (kN m) |
| $M_{ult}$ | Ultimate moment at midspan beam (kN m) |
| $M_{ser}$ | Service moment at midspan beam (kN m) |
| $M_{L/350}$ | Moment related to the maximum deflection admitted by Structural Code at midspan beam (kN m) |
| $W_{ck}$ | Crack width (mm) |
| $S_{r,max}$ | Maximum crack spacing (mm) |
| $\varepsilon_{sm}–\varepsilon_{cm}$ | Average of steel and concrete strains at tensile stress (με) |
| x | Depth of the compression zone (mm) |
| c | Concrete cover (mm) |
| $\phi$ | Bar diameter (mm) |

## 3. Experimental program

This investigation is part of a long research project, whose main objective was to carry out a full study of structural recycled concrete. Physical and mechanical properties, bond behaviour, shrinkage and creep have already been evaluated in previous works [7,11,22]. This research focuses on the flexural performance of reinforced concrete beams made with recycled coarse aggregate. For said purpose, reinforced beams were made from each designed concrete and loaded up to failure, to obtain deflections and strains at different load levels (pre-cracking, cracking, service, yielding and ultimate state conditions). This experimental program also encompassed basic concrete characterization, both in fresh and hardened state.

### 3.1. Materials and concrete mixtures

CEM I–52.5N/SR cement according to EN 197-1 and a superplasticizer as a water reducing admixture SIKAMENT 500 HE were used.

Three different size fractions of coarse aggregate were used, two conventional aggregates from crushed limestone and one recycled aggregate from the demolition of concrete structures mainly consisting of aggregate with adhered mortar. Regarding fine aggregate, only natural sand was used, also from crushed limestone. Table 1 summarizes the basic properties of these aggregates and Fig. 1 shows their grading

**Table 1**
Basic properties of the aggregates used [7,11,22].

| | | 0–4N | 8–20N | 4–12N | 4–16R |
|---|---|---|---|---|---|
| Density (EN 1097-6) | $kg/m^3$ | 2669.4 | 2655.9 | 2610.4 | 2566.0 |
| Density in oven-dry conditions (EN 1097-6) | $kg/m^3$ | 2520.3 | 2565.2 | 2468.8 | 2254.0 |
| Water absorption (EN 1097-6) | % | 2.2 | 1.3 | 2.2 | 5.4 |
| Los Angeles Abrasion (EN 1097-2) | % | – | 23.1 | – | 34.3 |
| Fineness module (EN 933-1) | | 3.7 | 7.4 | 6.2 | 7.2 |
| Fines percentage (EN 933-1) | % | 11.5 | 0.4 | 1.5 | 0.3 |
| Moisture content (EN 933-1) | % | 0.1 | 0.1 | 0.1 | 2.9 |