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A database on flexural and shear strength of reinforced recycled aggregate concrete beams and comparison to Eurocode 2 predictions

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HIGHLIGHTS

- Database of experimental results on recycled aggregate concrete beams compiled.
- Database filtered by different parameters—concrete strength, anchorage, etc.
- Database analyzed to identify clear failure types—flexural or shear.
- Sub-databases formed for flexural and shear failure (with and without stirrups).
- Applicability of Eurocode 2 provisions to recycled aggregate concrete beams tested.

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ABSTRACT

A comprehensive database of recycled aggregate concrete and companion natural aggregate concrete beams' flexural and shear strength was compiled from 217 experimental results. Strict criteria were applied to determine the failure type. Sub-databases were formed with beams failing in flexure and shear with and without stirrups. On each sub-database the applicability of Eurocode 2 provisions for flexural and shear strength to recycled aggregate concrete beams was tested. The results show that flexural and shear strength of recycled aggregate concrete beams without stirrups is successfully predicted by Eurocode 2. As for beams with stirrups, further research and experimental results are necessary.

1. Introduction

The construction industry today faces urgent calls to reform. The current rate of consumption of natural resources, waste generation and greenhouse gas emissions is unsustainable. On the one hand, new concrete requires the use of natural river or crushed stone aggregates, up to 15 billion tons annually worldwide [1]. On the other hand, old concrete structures are demolished and construction and demolition (C&D) waste is generated in large quantities, around 850 million tons in the EU annually [2].

It is not surprising that alternatives are being sought out. One solution that solves both problems simultaneously is recycling of concrete waste. Through a process that usually involves multi-stage crushing, eliminating impurities and sieving, a new aggregate is produced called recycled concrete aggregate (RCA). When this new aggregate is used to make concrete, with complete or partial replacement of natural aggregate, this concrete is called recycled aggregate concrete (RAC).

Recycled concrete aggregate and recycled aggregate concrete have been studied for several decades [3]. At the material level, practically all important characteristics of RCA and RAC have been studied, from short-term and long-term mechanical properties to durability [4–8]. The main characteristic that distinguishes RCA from natural aggregate is the certain quantity of cement paste that remains attached to the aggregates after crushing. This residual cement paste is the reason for higher water absorption of RCA compared with natural aggregates, especially in the case of fine RCA [9,10]. Beside the empirical observations about the influence of higher RCA water absorption on RAC properties, there have also been deeper, fundamental studies that demonstrated how the

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moisture state and water absorption of RCA influence the evolution of cement hydration [11]. The high water absorption of fine RCA has led to them mostly being avoided when producing RAC. However, even for coarse RCA the situation isn't much better as they make up only 1% of aggregates being used in structural concrete production worldwide [12].

This doesn't mean that research into the structural application of RAC has been lacking. Beside investigations of short-term flexural and shear performance of reinforced RAC beams, which are studied in this paper, there has been significant research on various other topics such as semi-precast RAC elements [13], shaking-table and pushover analyses of complete RAC frame structures [14,15] and long-term behavior of RAC beams [16]. Important literature also exists on the ecological and economic viability of RCA production and use [17–19].

Despite all of this, coordinated efforts by national and international institutions and organizations to codify the design procedures for RAC structural members have been lacking. Code provisions for material properties of RAC have been successfully tested and proven to be applicable [20,21] but these results cannot simply be extrapolated onto structural members. With the exception of China and its Technical Code on the Application of Recycled Concrete [22], neither European nor American concrete or standardization institutes have integrated provisions for the design of RAC structural members into their respective codes [23,24], even though researchers have attempted to demonstrate design procedures of RAC members according to them [25]. Beside natural aggregate concrete (NAC), only high-strength and lightweight aggregate concretes have been dealt with in their codes. Consequently, practicing engineers are faced with uncertainties in the rare situations when they have the opportunity to design structural RAC members.

In the present paper, results on short-term flexural and shear behavior of RAC beams were gathered from available literature. Strict selection criteria were applied to determine the failure type, flexure or shear. A comprehensive database was compiled with three sub-databases: beams failing in flexure, in shear without and with stirrups. These selected results can be considered to represent well-executed experiments and clear failure types with as little shear-flexure interaction as possible. The compilation of such a database has been missing from existing literature and is critical for any design formula verification and calibration.

As a second part of this study, EN 1992-1-1:2004 (Eurocode 2 or EC2) [23] provisions for predicting flexural and shear strength were tested on RAC beams by calculating the ratio of test-to-predicted flexural and shear strengths. This ratio was called the "model factor" γ, as it represents the uncertainty and variability introduced into calculations by the model itself and by its appropriateness. This is separate from the uncertainties arising from loads and material properties, covered in design by the partial safety factors which were removed and characteristic values of material properties were replaced with mean values. This approach is, in essence, the same as that proposed by EN 1990:2002 (Eurocode – Basis of structural design) in Annex D—Design assisted by testing [26].

The accuracy and precision of EC2 provisions was assessed using qualitative and quantitative analyses. In this study, accuracy is understood as the closeness of the model factor's mean value to 1.0 and precision is determined by the value of the model factor's coefficient of variation (CoV), i.e. scatter.

2. Database formation

2.1. Selection of studies

The first step in this research was the collection of all available studies on shear and flexural strength of RAC beams. A review of existing literature yielded 16 studies [27–42] carried out in the period from 2001 to 2015 with a total of 217 experimental results. All of the studies were comparative tests of RAC and NAC beams. The replacement ratios of natural aggregate by coarse RCA, chosen for this study, were 0, 50, and 100%, i.e. NAC, RAC50, and RAC100 concretes. In studies [32,33,35] the replacement ratio of 63.5% was assigned to RAC50 and the replacement ratio of 74.3% was assigned to RAC100 concrete.

Before compiling any database, rigorous selection criteria had to be established by which results would be tested. Since the aim of the study was to test the applicability of EC2 [23] flexural and shear strength predictions on RAC beams, the selection criteria had to ensure that only well-executed experiments and unambiguous results entered the database.

Only slender beams were analyzed since the test results on non-slender RAC beams are scarce. An initial screening was performed and any beams with a shear span-to-effective depth ratio smaller than 2.4 were eliminated. This value was chosen as critical so that a comparison with other databases could be performed [43,44]. This eliminated 17 results. Since EC2 prescribes different formulas for concrete classes greater than C50/60 and since high-strength RAC is not very common, only concretes with strengths smaller than 63 MPa were considered. This eliminated another 3 results. If the beams had stirrups then the minimum transverse reinforcement ratio was checked according to the EC2 limit:

$$\rho_w \geqslant 0.08\sqrt{f_c}/f_{yw} \tag{1}$$

where

ρ_w – transverse reinforcement ratio
f_c – 28-day concrete compressive strength on a Ø150/300 mm cylinder (MPa)
f_{yw} – transverse reinforcement yield strength (MPa)

This criterion eliminated another 3 results. Finally, 194 experimental results on NAC, RAC50, and RAC100 beams were left. Data were collected on beam geometry (width, depth, and effective depth), shear span-to-effective depth ratio, longitudinal and transverse reinforcement ratios and yield strength, concrete properties (percentage of RCA, maximum aggregate size, and compressive strength), and beam shear and flexural strengths. The data were then entered into an Excel spreadsheet that can be found in Appendix A.

2.2. Anchorage and shear-flexure interaction checks

Although practically all of the studies claim to be testing either flexural or shear strength of beams, this cannot be trusted at face value. It is not uncommon for researches investigating shear strength to report a flexural failure of beams or vice versa. This means that the experimental setup and failure load for each beam have to be checked for anchorage failure and shear-flexure interaction.

To check against anchorage failure, the following condition must be satisfied:

$$\beta_{lb} = l_{b,req}/l_{b,prov} \leqslant 1 \tag{2}$$

where $l_{b,req}$ and $l_{b,prov}$ are the required and provided anchorage lengths (in mm) and β_{lb} is the anchorage criterion. The required anchorage length was calculated according to section 8.4 of EC2 as:

$$l_{b,req} = \alpha_1\alpha_2\alpha_3\alpha_4\alpha_5 l_{b,rqd} = 0.7\cdot\frac{\emptyset}{4}\cdot\frac{\sigma_s}{2.25\eta_1\eta_2 f_{ct}} = 0.7\cdot\frac{\emptyset}{9}\cdot\frac{\sigma_s}{f_{ct}} \tag{3}$$

where

α_1–α_5 – coefficients taking into account the shape of the bars, concrete cover, confinement by transverse reinforcement