Construction and Building Materials 101 (2015) 65–71

Contents lists available at ScienceDirect

Construction and Building Materials

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

Flexural load tests of full-scale recycled aggregates concrete structures

J. Pacheco [a], J. de Brito [b,*], J. Ferreira [b], D. Soares [a]

[a] CERis-ICIST, Instituto Superior Técnico – Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisbon, Portugal
[b] CERis-ICIST, Department of Civil Engineering, Architecture and Georesources, Instituto Superior Técnico – Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisbon, Portugal

HIGHLIGHTS

- Full-scale tests of eight concrete slabs made with recycled aggregates.
- Influence of the replacement ratio and of superplasticizers.
- The influence of the aggregates was smaller than that of the execution conditions.
- The use of 100% coarse recycled concrete aggregates in structural slabs is feasible.

ARTICLE INFO

Article history:
Received 16 May 2015
Received in revised form 2 September 2015
Accepted 12 October 2015

Keywords:
Recycled aggregates concrete
Sustainability
Full-scale models
Flexural loading
Finite element modelling
Superplasticizers

ABSTRACT

In order to study the behaviour of concrete structures made with coarse crushed concrete aggregates recycled from discarded elements from the precasting industry, extensive testing was performed in four full-scale structures with varying recycled aggregate (RA) ratios. This paper describes and analyses the results of vertical load tests on each slab of these double-floor structures. The Young's modulus (E) of the concrete mixes was estimated by finite element model calibration using deflection data from the tests. The response pattern of the various structures was the same and the aggregates used had a small influence on E, even smaller than the execution conditions. One of the concrete mixes included a superplasticizer (SP) and this product more than offset the loss of stiffness due to RA use. To the authors' best knowledge this is the first study ever concerning the behaviour of full-scale recycled aggregate concrete (RAC) structures subjected to vertical loading and the behaviour of slabs with significant replacement of conventional aggregates by RA.

1. Introduction and research significance

The main difference between conventional concrete and RAC is that RAC contains RA, made of natural aggregates (NA) and mortar attached to them. The presence of this mortar causes higher porosity and permeability. This results in higher water absorption, lower durability performance, lower workability and, most probably, lower mechanical performance, reflected mainly on a decrease of E [1,2]. The use of SP can offset part of these negative effects, notably in terms of compressive strength, modulus of elasticity and splitting tensile strength as referred in [3–5], mostly due to the resulting higher compactness and lower w/c ratio (for the same workability).

The structural performance of reinforced RAC is not as significantly affected by RA incorporation as the mechanical and material properties of RAC since the flexural behaviour of reinforced concrete is mostly controlled by the steel reinforcement.

Since the reduction of the environmental impact of the construction industry is a pressing subject, with different international organizations highlighting this need [6,7], experiments on full-scale RAC structures should be performed, to provide experimental data and validation as well as to increase confidence in the use of this aggregates. In this context, the authors have conducted an extensive experimental campaign that includes laboratory material and mechanical characterisation tests and material, mechanical, dynamic characterisation, vertical load and destructive load tests on full-scale structures.

Abbreviations: w/c ratio, water/cement ratio; B25, concrete with 25% incorporation of coarse RA; B100, concrete with total incorporation of coarse RA; B100SP, concrete with total incorporation of coarse RAC and 1% of superplasticizer, in cement weight; E, Young's modulus; FEM, finite element model; NA, primary/natural aggregates; ODD, oven dried density; RA, recycled aggregates; RAC, concrete with total or partial incorporation of recycled aggregates; REF, reference concrete; SP, superplasticizer.

* Corresponding author.
E-mail addresses: joaonpacheco@ist.utl.pt (J. Pacheco), jb@civil.ist.utl.pt (J. de Brito), joaof@civil.ist.utl.pt (J. Ferreira), diogoafsoares@hotmail.com (D. Soares).

http://dx.doi.org/10.1016/j.conbuildmat.2015.10.023
0950-0618/

A construction company participated in this campaign and the choices regarding the RA's sieve, production, and origin were made considering their future applicability. Also, one of the highlights of this investigation is that the structures were made in current construction environment, rather than in a laboratory environment.

These flexural load tests intended not only to study the behaviour of the four structures, but also to evaluate whether the reduction of *E* associated with the incorporation of these high-quality RA is relevant. This is a particularly important question since, as stated previously, the *E* of a given concrete is one of the mechanical properties most affected by RA incorporation. Therefore, if the influence of these RA on the elastic moduli of the concrete mixes is not significant, it is expected that their incorporation will not significantly affect the other mechanical properties of the concrete mixes.

The scope of the experimental program was to evaluate the applicability of these recycled aggregates on concrete mixes produced with common construction industry processes. Hence, these flexural load tests were particularly relevant, since they allowed a comparison between an estimated global equivalent *E* of each structure (based on the deflections of the slabs and beams) and the results of the laboratory produced specimens. These tests were also useful in the evaluation of the execution conditions of the structures.

The structural behaviour of RAC is focused on column/beam joints, columns and beams. There are few investigations concerning two dimensional RAC frame structures [8–10]. There is also a single experiment on a three dimensional ¼ scaled RAC frame [11].

In the only study of which the authors are aware regarding the behaviour of RAC slabs [10] a reduction of the load capacity for the three replacement ratios studied (5%, 10% and 15%) was observed. No mention of the deflections of the slabs is made.

2. Experimental programme

2.1. Concrete mixes' characterisation

Natural limestone coarse aggregates and river sand were used as natural aggregates to batch the concrete mixes employed in this study. The RA used in this campaign were sourced from concrete blocks used in the pre-fabrication industry as supports for long-span beams, with compressive strength well above 50 MPa. Only the incorporation of the coarse fraction of the recycled aggregates, was studied since the fine fraction tends to have a higher percentage of attached mortar, thus resulting in a larger loss of durability and mechanical properties [6].

These RA were obtained by crushing precast concrete reject elements with a jaw crusher, a cone crusher with a 40 cm opening, and another cone crusher with an opening of 20 cm.

The aggregate grading was based on practicability on-site: the crushing process that originated the RA included the sieving of the aggregates in two fractions, which were used to define the concrete mixes. This option avoided sieving the aggregates on-site and intended to replicate the common conditions of the construction industry. After sieving, the aggregates were washed to remove dust and fines.

The concrete mixes were designed using Faury's method. Compressive strength tests were made in several concrete mixes produced in laboratory conditions, in order to define the mixes. The C25/30 strength class of Eurocode 2 [12] was set as a minimum requirement for the project and the cement content was defined at 350 kg/m^3, the same as most related studies coming from our research unit [3,5]. It was found, certainly due to the high quality of these RA, that concrete strength increased with the ratio of RA. Therefore the four mixes used in this campaign were as follows: REF – reference mix without RA; B25 – mix with the maximum substitution ratio by mass (25%) of RA allowed by the Portuguese Laboratory of Civil Engineering [13] and other institutions [14], with the intent of replicating the properties of a conventional concrete; B100 – mix with full replacement of the coarse natural aggregates; and B100SP – a mix similar to the previous one but with 1% SP by cement weight. Table 1 contains the composition of each of these four mixes. The SP has a chemical basis of polycarboxylates modified in an aqueous solution with 32 ± 2% of solid content and is labelled a high-performance SP.

The water/cement ratio of each mix was defined after slump tests. The target slump was 125 ± 15 mm (4.92 ± 0.59 in), within EN 206-1's [15] S3 slump class.

The reinforcement steel used is A500, with B class of ductility.

The properties of the RA and of the concrete mixes produced in laboratory conditions can be consulted in [16]. Table 2 summarises some of the concrete properties of each mix and mentions the standards used to estimate these properties [17–19].

Table 1
Concrete mixes' composition (kg/m^3 of concrete).

Material		Concrete mix			
		REF	B25	B100	B100SP
Fine sand	0.063–1 mm	243.4	243.8	245.1	258.8
Coarse sand	0.125–4 mm	448.4	448.8	450.1	475.5
Coarse natural aggregates	4–11.2 mm	358.4	328.1	0	0
	11.2–22.4 mm	645.8	500.1	0	0
Coarse recycled aggregates	4–10 mm	0	83.3	333.3	352.0
	10–20 mm	0	171.0	683.8	722.3
CEM II A-L 42.5R cement		350	350	350	350
Tap water		185.5	194.8	206.4	159.2
Superplasticizer		0	0	0	3.5
Effective w/c ratio		0.54	0.53	0.54	0.40
Apparent w/c ratio		0.54	0.53	0.55	0.45

The water content of the superplasticizer was not taken into consideration in the definition of the w/c ratios.

In this table, the experimental results of *E* of each concrete mix estimated by dynamic characterisation tests performed on each structure are also shown [20]. These tests were made in two different series, with highly consistent results between them: one with a strong-motion seismograph and another one with accelerometers. The tests were made with the structures subjected to different excitations – vertical, horizontal (both centred and eccentric), and ambient. After estimating the natural frequencies of each modal configuration, the elastic moduli of the structures was estimated by finite element calibration, done by approximating the numerical natural frequencies to the experimental frequencies originated from the tests.

2.2. Model's characterisation

The design of the structures complied with Eurocode 2 [12] and Eurocode 8 [21]. Due to testing limitations concerning the maximum load that could be applied during horizontal destructive tests [22], some adaptations of these regulations were made, concerning the longitudinal reinforcement of the columns. Fig. 1 shows the models geometry and reinforcement layout as predicted in the design.

The reinforcement of the slabs consists of a bottom mesh of 8 mm rebars with 20 cm spacing in both directions. The foundations are large concrete blocks with adequate reinforcement and their size ensures a full base restraint of the columns. The rebars cover in the columns is 2.5 cm and in the rest of the structure 2.0 cm. A finite element model (FEM) was made for each structure, with dimensions measured on-site. The columns' cross-section size ranges between 19.4 and 21.8 cm and the slabs' thickness is shown in Table 3.

The structures were loaded with water (uniformly distributed load) which meant that hollow-brick masonry walls on the perimeter of each slab were built, as show in Fig. 2. These walls were modelled on the FEM's.

The deflections on the slabs and beams were measured with deflection transducers. The load values and deflections allowed the *E* estimation of each structure, through finite element modelling.

2.3. Test setup

The structures were produced under common construction conditions. The first structure made was the REF structure and shrinkage cracking, caused by inadequate curing and extremely hot weather during casting, occurred in this structure, as shown in Fig. 3. The curing conditions of the other structures were corrected, ensuring proper curing.

The four structures were tested at an age of about 120 days, with a 20-day margin.

Each slab was tested individually, with the following equipment: (a) displacement transducers (placed at the mid span of each beam and at the centre of the slabs); (b) a data logger, to record the displacements; (c) a hose to enable filling the floor with water; (d) four rulers.

The four rulers allow a continuous monitoring of the water height, enabling the registry of the uniformly distributed load applied on the slab at any given moment during loading and unloading. The maximum height of water was defined as 50 cm, corresponding to a uniformly distributed load of 4.9 kN/m^2. This is a typical serviceability limit-state value for a slab load considering the sum of dead and live loads. The non-elastic behaviour of the slabs was not analysed since it was fundamental to prevent potential differences in behaviour between structures caused by different cracking stages of slabs and beams during the horizontal destructive load tests.