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Structural, material, mechanical and durability properties and behaviour of recycled aggregates concrete

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ABSTRACT

Sustainability is a pressing concern of the 21st century. Social development in most countries is raising awareness of the needs of future generations and legislation to protect the present and future quality of life. These needs are compelling various sectors, including construction, to find sustainable solutions. This paper investigates the feasibility of incorporating high-quality recycled concrete aggregates in new concrete, providing a recycling option for precast rejects. The massification of recycled aggregate incorporation would decrease the environmental impacts of the concrete industry, for instance due to reduced landfill disposals, less quarry mining and shortened transport distances. The study presented in this paper concerns the material, mechanical, durability and short-term structural behaviour of concrete specimens and structures made with recycled aggregates sourced from high-quality concrete elements. This paper intends to provide a holistic view of the study, from the procurement and crushing process that generated the aggregates to the conclusions of the different experiments performed. The results of this experimental campaign are benchmarked with other investigations and the importance of the quality of the RA is evaluated. This paper concerns the first full-scale experiments made on recycled aggregates concrete structures. Also, some of the tests performed were the first of their type made on recycled aggregates concrete.

1. Introduction

World development has resulted in massive amounts of waste and a significant toll on the environment. Construction and demolition activities are one of the most relevant contributors to the environmental damage of present days and, with increasing construction activities in developing countries, it is expected that this contribution further increases.

The expected annual worldwide production of natural aggregates (NA) in 2015 was 48.3 billion tonnes [1]. The use of recycled aggregates (RA) could reduce this production, and at the same time reduce landfill disposals. Research in this area has progressed, since Hansen's [2] first state of-the-art on the subject. Presently, the studies are not only focused on the material properties of concrete, but also on the durability and rheological behaviour, as well as on the structural performance of concrete elements.

Standards that regulate RA incorporation [3] have been made with data from outdated experiments, made when the knowledge on recycled aggregate concrete (RAC) was not as developed as it is today, and present procedures like water compensation (to offset the water absorption of RA) during mixing were not common. The limitations these standards impose are too restrictive and do not reflect present knowledge. Also, the construction agents are cautious about using this material since RAC is often seen as having high scatter of properties and unpredictable behaviour.

To address this over-cautious attitude, this experimental campaign was made following standard procedures of a construction company and four structures were made by construction workers, in order to evaluate whether the change from a laboratory environment, where most RAC studies have been conducted, to an actual construction environment produced significant changes in the results. The three most common sources of RA are concrete, masonry and mixed (concrete and masonry) construction and demolition wastes. In this experiment RA sourced from concrete precast rejects from the company (Opway) that sponsored the experiment was studied. The objective of the experiment was to determine whether precast rejects produced by Opway, or other

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construction companies, could be used in new concrete mixes. Only the effects of incorporating the coarse fraction of the recycled aggregates (RCA) were studied.

2. Experimental programme

2.1. Programme planning

The experimental research studied most relevant short-term properties of RAC, as well as the durability and rheological behaviour of this material. The objective was to analyse commonly studied concrete properties, in order to benchmark the results of this experiment with other investigations, and to make innovative experiments that would increase the state-of-the-art of RAC and open new experimental prospects. The experimental campaign was divided in two branches: the test of standard concrete specimens produced in laboratory conditions [4] and on-site experimental testing on four full-scale structures [5–8]. The specimens produced in laboratory conditions were tested for the material, mechanical and durability properties shown in Table 1.

The on-site properties of the concrete structures were also tested. Table 2 concerns the tests and standards used.

The absence of experimental testing on the response of RAC structures, cutting short of isolated concrete elements, justified an ambitious RAC structural behaviour assessment campaign: dynamic characterization, vertical load tests and destructive horizontal load tests were made. The dynamic properties of RAC have not been studied up to date, whilst vertical load tests so far have been limited to beams [9,10] [11–13], slabs with low RA incorporation ratio (15%) [14] or the punching behaviour of slabs [15]. The experiments concerning horizontal loads affecting RAC structures have been focused on columns [16–19], column-beam joints ([16,17,20] or two-dimensional frames [14,20–22]. Wang and Xiao [23] studied the behaviour of a 1:4 3D RAC structure. To the authors' best knowledge to date no nonlinear static analysis had been performed on RAC structures.

The full-scale nature of the experiments is particularly relevant, since scale effects on RAC have not been studied and the response of RAC structures to horizontal loads has only been tested in scaled specimens, which can overestimate the ductility [24]. Another relevant aspect of this experiment was the decision to use common construction industry processes: the aggregate grading was chosen following the practice of the construction company that supported this project, the recycled aggregates were obtained by crushing in a typical crushing plant, and the concrete structures were made by actual construction workers in an actual construction environment. This choice intended to offset suspicion over artificially good RAC properties due to the better execution conditions of laboratory environments.

Table 1
Tests on laboratory specimens.

Concrete tests	Standard	Concrete tests	Standard
Slump	EN 12350 – 2 (2009)	Abrasion resistance	DIN 52108 (2010)]
Fresh-state density	EN 12350 – 6 (2009)	Shrinkage	LNEC E 398 (1993)
Compressive strength	EN 12390 – 3 (2011)	Water absorption by immersion	LNEC E 394 (1993)
Splitting tensile strength	NP EN 12390 – 6 (2009)	Water absorption by capillarity	LNEC E 393 (1993)
Young's modulus	LNEC E 397 (1993)	Ultrasonic pulse velocity (UPV)	EN 12504 – 4 (2004)
Carbonation resistance	LNEC E 391 (1993)	Chloride penetration resistance	LNEC E 463 (2004)

Table 2
On-site material characterization tests.

Concrete test	Standards	Elements tested
Compressive strength	EN 12504 – 1 (2004)	On-site produced standard specimens
	EN 12390 – 3 (2011)	Concrete cores taken from the structures
Ultrasonic pulse velocity (UPV)	EN 12504 – 4 (2004)	Structural elements (beams, columns and slabs)
Surface hardness (rebound number)	EN 12504 – 2 (2002)	Structural elements (beams, columns and slabs)

2.2. Crushing process and properties of the aggregates

The first step of the experimental campaign was the production of the RA. Some factors had to be considered in this choice: (a) the objective was to recycle precast rejects resulting from activities of Opway; (b) these rejects had to generate enough RCA for the whole experiment (estimated at 40 m^3); (c) a RA grading that minimized waste was targeted; (d) to reduce costs and crushing time, elements with as reduced reinforcement steel ratios as possible were foreseen; (e) only the coarse fraction of the RA was used.

An initial survey of precast rejects stored in production facilities owned by Opway was made. None of these elements was rejected because of poor material properties. Fig. 1 shows some of the potential candidates for recycling.

After the inspection of several elements, four candidates for RCA production were shortlisted: (a) spare standard concrete specimens; (b) inverted π-beams used in bridge construction; (c) hollow core slabs; (d) supports of long-span beams with the same concrete composition as the beams they supported. The standard concrete specimens were discarded because different concrete compositions were mixed and a homogenous source of RA was desired. The π-beams were slender, with a significant amount of reinforcement which made crushing overly difficult. The hollow core slabs were the preferred solution, due to low reinforcement ratio. However, a crushing and sieving trial promptly proved that they were unsuitable for RCA production. The RA produced with this solution had a totally unsuitable grading, with over 60% of fines and the production of 1 m^3 of concrete would require the crushing of about 10 m^3 of hollow core slabs. This source material was discarded. The supports of long-span beams (bottom right of Fig. 1) were chosen, despite having significant reinforcement steel. The presence of this reinforcement complicated the crushing process since a first step of demolition and reinforcement removal had to be made. Nevertheless, elements from the precast industry have significant reinforcement and this was already expected. The use of these elements instead of the inverted π-beams had the practical advantage of avoiding slender elements. These concrete elements had a compressive strength above 50 MPa. The elements were crushed in a quarry, using the common processes used to obtain NA. The last stage of the crushing process included sieving and washing. The fine fractions of the aggregates were removed.

The crushing process was tertiary with a jaw crusher and two hammer mill crushers, ensuring a good shape index, reduced roughness and suitable grading. All of these factors address some of the common problems associated with RA incorporation [25]. The jaw crusher had a 60 mm opening, while the hammer mills had openings of 40 mm and 20 mm. Fig. 2 shows the three crushers. The material was sieved into three fractions: 0–4 mm, 4–10 mm and 10–20 mm. The smaller fraction was not used in this