Construction and Building Materials 176 (2018) 593–607

Contents lists available at ScienceDirect

Construction and Building Materials

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

Long-term flexural performance of reinforced concrete beams with recycled coarse aggregates

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HIGHLIGHTS

- Long-term flexural performance of structural recycled concrete (RC) was analysed.
- Deflections and strains over time have been obtained and analysed.
- Recycled concrete shows higher long-term deformability than conventional concrete.
- A corrector factor has been proposed to predict long-term deflections of RC.

ARTICLE INFO

Article history:
Received 14 February 2017
Received in revised form 21 February 2018
Accepted 7 May 2018

Keywords:
Recycled aggregate concrete
Flexural performance
Long-term deflection
Long-term strain
Sustained load

ABSTRACT

The aim of this study is to investigate the behaviour of recycled aggregate concrete subjected to sustained loading. For the tests, eight reinforced concrete beams were manufactured with recycled coarse aggregate, using water-to-cement ratios of 0.50 and 0.65, and four replacement percentages: 0%, 20%, 50%, and 100%. First, the basic concrete properties, mechanical strength and modulus of elasticity, were determined after 28 d, and at the ageing load. The beam specimens were then loaded at 42 d, using a four-point bending test. Bending moments and deformations were obtained during the loading process, when cracking and serviceability conditions were reached, as well as the long-term deformations of recycled concrete beams up to 1000 d.

Based on these results, it can be reported that long-term deformations are greater for recycled aggregate concrete than for conventional concrete, regarding both strain and deflection. Furthermore, a direct relationship was found between these deformations and the replacement percentage used. Lastly, code-based expressions were used to calculate the long-term deflections of RC beams subjected to sustained loading, which included the recycled coarse aggregate content and corrections previously proposed to predict the mechanical properties, creep, and shrinkage of recycled aggregate concrete.

1. Introduction

The use of recycled aggregate for structural concrete has been widely recognised as a means of reducing the issues associated with concrete waste. In order to promote environmentally friendly practices and procedures in the construction field, numerous attempts have been made to provide useful guidelines, and to encourage the use of more sustainable concrete structures, which include recycled aggregate from concrete demolition debris. In this regard, broad experimental programmes have been conducted by numerous researchers to assess recycled concrete behaviour with different replacement percentages.

It is generally accepted that the use of recycled aggregate influences basic concrete properties, such as density, mechanical strength, and modulus of elasticity [1–19], as well as long-term properties, such as creep and shrinkage strain [20–25]. However, the study of the structural performance of recycled concrete is not yet widespread, and although numerous researchers have studied structural recycled concrete, only a limited number of the studies actually included full-scale structural tests. The bulk of these structural studies focused on bond behaviour [26–29], or short-term RC beam behaviour [30–39].

In order to contribute to a better understanding of, and greater confidence in, the use of recycled concrete, recent studies [40,41] have analysed Eurocode predictions to design structural recycled

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https://doi.org/10.1016/j.conbuildmat.2018.05.069
0950-0618/

Nomenclature

t	concrete age (days, d)
t_o	loading age (days, d)
$t - t_o$	time under sustained load (days, d)
σ	compressive stress (MPa)
σ/f_c	stress level (%)
f_c	compressive strength by cylinder specimens of 15 × 30 cm at 28 d
$f_{c,42}$	cylinder compressive strength at 42 days, (specimens of 15 × 30 cm)
E_c	modulus of elasticity at 28 d
$E_{c,42}$	modulus of elasticity at 42 d
$\varepsilon_{sh\ (42,\ 1042)}$	shrinkage strain at 1000 d after loading
$\varphi_{(42,\ 1042)}$	creep coefficient at 1000 d after loading
M	bending moment at beam's midspan (kN·m)
M_{cr}	cracking moment at beam's midspan (kN·m)
M_Q	acting moment at beam's midspan (kN·m)
δ_{cr}	cracking deflection at beam's midspan (mm)
δ_o	immediate deflection at beam's midspan at 42 d (mm)
$\delta\ (t - t_0 = 1000$ days)	total deflection at beam's midspan at 1000 d after loading (mm)
$\delta_{dif}\ (t - t_0 = 1000$ days)	long-term deflection at beam's midspan at 1000 d after loading (mm)
δ_{sh}	shrinkage deflection at beam's midspan (mm)
δ_φ	creep deflection at beam's midspan (mm)
k_{sh}	shrinkage induced curvature
ε_0	elastic strain of concrete at t_0
$\varepsilon\ (t - t_0 = 1000$ days)	total concrete strain at beam's midspan at 1000 d after loading
$\varepsilon_{dif}\ (t - t_0 = 1000$ days)	long-term concrete strain at beam's midspan at 1000 d after loading

concrete, based on the results of other researchers. One such study [40] carries out a parametric analysis of structural concrete, while incorporating recycled aggregates according to Eurocode 2. Therefore, we propose an equivalent functional unit that enables us to predict structural behaviour, by considering the different mechanical and durability performances of recycled concrete. Another study [41] assesses the accuracy and precision of Eurocode 2, when calculating the flexural strength of structural recycled concrete members using a database. However, these studies are focussed on the short-term behaviour of recycled concrete beams, including flexural strength and analysis at failure, and do not provide experimental results.

Regarding the long-term structural behaviour of recycled concrete, experimental results available for establishing good agreement on its full load-deformation response are scarce.

2. Research significance and objectives

Few researchers have conducted experimental studies on RC beam flexural behaviour when subjected to sustained loads [42,43].

Knaack and Kurama [42] report that an increase in recycled aggregate content results in a reduction in initial stiffness, and an increase in deflections. They conclude that code-based procedures, according to the Eurocode and the American Concrete Institute (ACI), used with conventional concrete can also be applied to predict recycled concrete flexural behaviour. Furthermore, they suggest that additional studies should be conducted to further investigate the use of recycled aggregates in reinforced concrete, e.g. long-term creep and shrinkage deformations, age effects and strength gain of concrete, prediction of concrete properties, and service-load and ultimate-load behaviour.

Other studies on the long-term deflections of recycled concrete [43] reported that recycled concrete beams exhibit a similar crack pattern to conventional ones. In terms of deflections, the long-term to instant deflection ratios of recycled concrete beams are lower than those of conventional beams. However, both recycled and conventional concrete beams satisfy the maximum permissible deflections according to the ACI code provisions. The long-term deflections can also be calculated according to the modified ACI approach, providing acceptable agreement with the experimental results. Lastly, because of the reduction of interfacial bonding strength between the mortar and recycled coarse aggregate, differences in the neutral axis depth of the beam have been detected with 100% recycled aggregate.

These studies [42,43] deal with time-dependent deformations up to 140 d and 380 d after loading, respectively. However, the results obtained indicated that the time-dependent deformations had not yet stabilised, and concrete deformations tended to increase over time. Therefore, further analysis of this issue is required, in order to determine the long-term behaviour of recycled concrete after one year.

Based on a literature review, it can be concluded that further research is required to evaluate the effect of recycled coarse aggregate content on the long-term performance of structural concrete. Therefore, this work deals with the analysis of the flexural performance of recycled concrete subjected to sustained load over time (after one year), in order to provide trustworthy guidelines for it to be designed with the same structural reliability as conventional concrete.

3. Experimental program

This study is part of an extended research project to further analyse the flexural performance of structural recycled concrete. Physical and mechanical properties, bond behaviour, shrinkage, and creep have already been evaluated in previous studies [28,44–46]. In terms of flexural behaviour, short- and long-term analyses have been conducted. For this test, two series of eight reinforced concrete beams were manufactured with different recycled aggregate replacement percentages. One of these series was loaded up to failure at 28 d in order to analyse the short-term behaviour of RC beams. The other eight twin RC beams were subjected to sustained load for 1000 d, in order to evaluate the long-term performance of recycled aggregate concrete.

This study focusses on this last analysis. The long-term behaviour of RC beams manufactured with recycled aggregate tested in flexure, and basic concrete characterisation, both in fresh and hardened states, was also covered.

3.1. Materials and concretes used

CEM I–52.5N/SR cement, according to EN 197-1, and a superplasticiser, SIKAMENT 500 HE, as a water reducing admixture, were used. Three different coarse aggregate size fractions were used, including two natural aggregates from crushed limestone, and one recycled aggregate obtained from the demolition of concrete structures, primarily comprising aggregate with adhered mortar. In the case of the fine aggregate, only natural sand was used, which was also obtained from crushed limestone. Table 1 summarises the