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Shear behaviour of recycled aggregate concrete beams with and without shear reinforcement

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ABSTRACT

An experimental study of the shear behaviour of recycled aggregate concrete (RAC) beams with and without shear reinforcement is presented. Nine full-scale simply supported beams were loaded in four-point bending tests until failure. Three different replacement ratios of coarse natural with coarse recycled concrete aggregate (0%, 50% and 100%), and three different shear reinforcement ratios (0%, 0.14% and 0.19%) were the main parameters. All natural aggregate concretes (NAC) and recycled aggregate concretes (RAC) were designed and experimentally verified to have similar compressive strength and workability. It was found that the shear behaviour and the shear strength of the beams with 50% and 100% of recycled concrete aggregate were very similar to that of the corresponding natural aggregate concrete beams. The applicability of different code provisions for shear strength predictions of the RAC beams with and without shear reinforcement was tested by comparison with test results obtained on 85 beams, 58 RAC and 27 corresponding NAC beams. The shear strength of RAC50 and RAC100 beams with and without shear reinforcement was conservatively predicted by the analyzed codes with similar reliability as for the corresponding NAC beams shear strength. At this state-of-knowledge, the application of the analyzed codes' provisions for NAC beams shear strength can be recommended both for the RAC50 and the RAC100 beams.

1. Introduction

Recycled aggregates produced from demolished concrete, commonly by crushing, screening and removing contaminants by magnetic separation, water cleaning or air-sifting are known as recycled concrete aggregates (RCA). Recycling generally represents a way to convert a waste product into a resource. It has the potential to reduce the amount of waste disposed of in landfills, preserve natural resources, and provide energy and cost savings while limiting environmental disturbance. Consequently, recycling of demolished concrete and the use of RCA in new structures may have key importance in achieving sustainable construction.

RCA is commonly used in lower quality product applications such as back-fills and road sub-base and base, where they compare favourably to natural aggregates (NA) in many local markets today [1]. However, only a small amount of RCA is used today for higher quality product applications such as structural concrete. Although in many countries standards allow the utilization of RCA in structural concrete [2], actual application remains limited to less than 1% of the amount of aggregates used in structural concrete [3]. On the other hand, the potential of demolished concrete recycling to decrease the environmental burdens of concrete can be fully utilized only if RCA replaces NA in structural concrete, since this is by far the largest application of aggregates. Such a concrete in which NA is replaced with RCA (partially or completely) is called recycled aggregate concrete (RAC).

Several experimental studies on the shear behaviour and shear strength of RAC beams have been performed [4–14]. In all of them, full-scale beams in four-point bending tests were loaded until failure, where the following parameters were varied: replacement percentage of NA with RCA, concrete compressive strength, cross-section size, longitudinal and shear reinforcement ratio and shear span-to-depth ratio. The effect of shear reinforcement on shear strength [4–6,8] was less investigated, i.e. there are more test data on the shear strength of RAC beams without shear reinforcement [7,11–14].

From the reported research a few important conclusions are drawn. In the case of RAC beams without shear reinforcement, cracking load, crack patterns, load-deflection behaviour and type of failure are very similar to those of the corresponding natural aggregate concrete (NAC) beams, regardless of the replacement ratio. Premature cracking and lower initial stiffness was observed

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by some researchers but generally without effect on the shear strength [5,13]. However, non-negligible decrease in failure load of 11% and 16% in RAC beams with 50% and 100% coarse RCA compared with NAC beams was also reported [6]. Shear strength of RAC beams is slightly lower than the shear strength of the corresponding NAC beams, strength decrease being larger with larger replacement ratios. The largest strength reduction (for shear span-to-depth ratios higher than 2) was reported in [12] for a 100% replacement ratio and it was about 25% compared with the corresponding NAC beam. When the equivalent mortar volume mix proportioning method (EMV) is used [15], the shear strength of RAC beams with 63.5% and 74.3% replacement ratios is higher than the shear strength of corresponding NAC beams [7].

Comparisons to code predictions in the published research were usually performed only for own experimental results. RAC shear strength was mainly conservatively predicted by different codes, regardless of the replacement ratio. Some researchers concluded that codes for NAC are applicable [5,11,13] while according to others the ratio of test-to-code predicted capacity is higher for corresponding NAC beams than for RAC beams with a 100% replacement percentage [12,14] and therefore the applicability is questionable.

Regarding the RAC beams with shear reinforcement, no significant difference between the shear behaviour and shear strength of RAC and corresponding NAC beams with shear reinforcement was reported. The code predictions are much less consistent and more conservative than in the case of shear strength without shear reinforcement, both for RAC and NAC beams. However, the test database is relatively small [4,6,8]. Furthermore, the application of existing empirical relations for calculating the concrete contribution to the shear resistance of conventional reinforced NAC to RAC beams is questionable because of different findings regarding the aggregate interlock contribution [6,9,10].

Although a lot of research on the mechanical, time-dependent and durability related properties of RAC has been performed in the course of the past few decades [16–18], a comprehensive research on the structural behaviour of RAC is still lacking. This is especially important for the types of structural behaviour that are mainly governed by the properties of concrete, such as shear strength, punching shear strength and short and long-term deformational behaviour of structural elements. Therefore, a comprehensive test database is needed for gaining confidence in the applicability of this material for structural use, as it was done in the past for conventional concrete – NAC with a cement binder.

This paper presents the results of the experimental study on the shear behaviour of RAC beams, obtained in full-scale, four-point bending tests up to failure on nine simply supported beams. Three different replacement ratios of coarse NA with coarse RCA (0%, 50% and 100%), and three different shear reinforcement ratios (0%, 0.14% and 0.19%) were the main parameters in this study. All NAC and RAC mixtures were designed and experimentally verified to have similar compressive strength and workability.

2. Objective

The objective of the presented work was twofold. One aim was to widen the existing experimental database on the shear strength, crack pattern and stress distribution of RAC beams with large replacement ratios of coarse NA with coarse RCA (50% and 100%) with and without shear reinforcement. A detailed explanation of RAC beams' shear behaviour together with reported test data will contribute to the definition of parameters for finite elements analysis (FEA) of RAC beams and increase the reliability of FEA models.

The other aim was to determine whether code equations for NAC are applicable for the prediction of shear strength of RAC beams, based on the comparison with different codes and including test data currently available in literature. Furthermore, understanding of shear mechanisms in RAC beams could be used as a certain contribution to the performance based design of RAC beams according to standard provisions for NAC beams [19].

3. Materials and methods

3.1. Component materials

The origin of RCA used in this study was twofold: (1) from a demolished 40 year-old reinforced concrete frame structure and (2) from laboratory waste concrete samples. In both cases, the properties of the original concrete were unknown, similar to the industrial practice where RCA is usually obtained from a mix of concrete waste from different sources and of unknown quality. After the processing of concrete waste in a mobile recycling plant, the obtained coarse aggregate was sieved into three sizes: 4/8 mm, 8/16 mm and 16/31.5 mm. The fine fraction (0/4 mm) was natural sand in all mixtures, while "Morava" river gravel was used as coarse NA in NAC mixtures. The physical and mechanical properties of all types of aggregates used in the presented research are given in Table 1. All tests were conducted according to the national standards and CEN provisions [20–25]. Regarding the most important RCA properties, saturated surface dry bulk density varied from 2400 kg/m^3 to 2480 kg/m^3, while water absorption after 24 h varied from 3.8% to 4.6%, depending on the particle size. This means that the RCA can't satisfy requirements for the best class (class H), according to Japan's standard JIS A 5021 [26] nor the requirements for the best class of RCA according to the classification proposed in [27]. On the other hand, the values of water absorption were above the recommended lower boundary of RCA for structural use [28–31]. Hence, it can be considered as a representative for the class of RCA that could be usually used for structural elements made of RAC. Results of sieving for all aggregate types and sizes are presented on Fig. 1. Obviously, they fulfil standard requirements for natural aggregate except in the case of fine grains in the 8/16 mm fraction of RCA, which exceeds the limit for a few percentages. However, it was taken into account during the design of the aggregate mix which also had to fulfil standard requirements [32].

A blended cement with mixed additions of slag and limestone (up to 20%), CEM II 42.5R, was used in all concrete mixtures.

3.2. Concrete mixtures and properties

In order to investigate the shear performance of reinforced RAC beams three types of concrete mixtures were designed – NAC (fine and coarse NA), RAC50 (50% by mass of coarse NA replaced by RCA) and RAC100 (100% by mass of coarse NA replaced by RCA). There were two design targets – 28 day compressive strength equal to 40 MPa on 150 mm cubic samples and workability (slump) of 8 ± 2 mm, measured 30 min after mixing, for all types of concrete.

This period of 30 min was adopted as the usual period from the moment of concrete production prior to concrete casting in place. During that period water is available to be absorbed by RCA and that would certainly change the concrete properties including workability. In order to avoid the negative effect of high water absorption of RCA on the workability of concrete an additional quantity of water, added water, was carefully determined in accordance with predetermined water absorption of RCA after 30 min, Table 1. The quantity of cement (mc) and 'free' water (mv), for a target design strength were derived from the previously determined relationship between the 28 day compressive strength and water-to-cement ratio (w/c) for both NAC and RAC [33]. For that