Construction and Building Materials 48 (2013) 187–193

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

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

Deformation properties and direct shear of medium strength concrete prepared with 100% recycled coarse aggregates

Wei-lun Wang, Shi-cong Kou *, Feng Xing

Guangdong Provincial Key Laboratory of Durability for Marine Civil Engineering, Shenzhen University, China

HIGHLIGHTS

- The deformation properties and direct shear of medium strength structure RAC.
- The strengths of RAC were on the average of 85% of those NAC.
- The *E*-value of RAC was on the average of 14% lower than that of NAC.
- The deformation at peak stress of RAC larger than those corresponding NAC.

ARTICLE INFO

Article history:
Received 14 January 2013
Received in revised form 14 May 2013
Accepted 17 June 2013
Available online 27 July 2013

Keywords:
Deformation properties
Direct shear
Recycled aggregate concrete
Medium strength

ABSTRACT

The lack of a thorough understanding of the structural behavior of recycled aggregate concrete has become increasingly obvious in recent years. This paper presents the deformation properties and direct shear of medium strength structure concrete prepared with 100% recycled aggregate and Class-F fly ash (RAC) as compared to those of the corresponding natural aggregate concrete (NAC). During this study, five water–binder ratios of 0.50, 0.44, 0.40, 0.36 and 0.32 were used to prepare the concrete with target cube compressive strength ranging from 45 to 70 MPa using natural or recycled coarse aggregates. Fly ash was added of 25% by cement weight in all concrete mixtures. The results show that the 28-day cube and cylinder compressive strength, flexural and the direct shear strength of RAC were on the average of 85% of those NAC with the same mix proportions. Moreover the modulus of elasticity of RAC was on the average of 14% lower than that of NAC. Furthermore, the drying shrinkage and chloride ion penetration of RAC was on the average of 24% and 14% higher than that of NAC. The results showed that the medium strength structural concrete can be produced by using 100% recycled aggregate and Class-F fly ash.

1. Introduction

In China, the accelerating urbanization has led to a large quantity of demolitions of infrastructures in the past decade, most of which are made of concrete and masonry, even though many of them are still young. These demolitions, as well as the construction of new buildings, have led to a great deal of construction and demolition (C&D) wastes. Currently the amount of C&D wastes in China has reached 30–40% of the whole city solid wastes [1]. Among all the C&D wastes, waste concrete occupies a large percent. The use of waste materials as a source of aggregate in new construction materials has become more common in the recent decades. The depletion of the existing landfills and the scarcity of natural resources for aggregates encourage the use of construction and demolition (C&D) waste as a source of aggregates in the production of new concrete.

Over the last decades, large amount of experimental works have been carried out to investigate the material properties [2–11] and durability [12–16] of recycled aggregate concrete (RAC). Accordingly, significant progress has been gained by applying recycled aggregates into construction materials in the form of RAC members [17–20]. Compared with natural aggregates, recycled aggregates usually have greater porosity and water absorption, lower density, and lower strength than normal aggregate [21–23]. As a result, RAC structural components invariably experience inferior physical and mechanical properties compared to normal aggregate concrete (NAC), such as low mechanical performance and poor durability behavior [24–27]. For concrete made with 100% recycled aggregates, the compressive strength of RAC was reportedly decreased by 9–40% [28,29]. It is generally accepted that the lower elastic modulus of RAC is attributed to a lower modulus of elasticity of recycled aggregate, and the lower strength of RAC is mainly due

* Corresponding author. Tel.: +86 755 26958852; fax: +86 755 26535123.
E-mail address: kousc@szu.edu.cn (S.-c. Kou).

0950-0618/$ - see front matter
http://dx.doi.org/10.1016/j.conbuildmat.2013.06.065

to the weaker mortar as well as the weaker interfacial transition zone (ITZ) between the old mortar and new mortar [30].

Poon et al. [31] showed that the slump of recycled aggregate concrete was dependent on the moisture state of the recycled aggregate. When oven-dry recycled aggregate was used, a high initial slump was observed due to the high amount of water that was used to compensate the high water absorption of the recycled aggregate. Cho and Yeo [32] found that, due to the high water absorption of the recycled aggregate, a higher slump loss was observed when compared to that of natural aggregate concrete. Dhir et al. [36] showed that the compressive strength of concrete prepared with 100% coarse and 50% fine recycled aggregates was between 20% and 30% lower than that of the corresponding natural aggregate concrete. However, the reduction in strength can be minimized if the mixing procedure is modified [32,35]. Otsuki et al. [35] reported that the carbonation resistance of recycled aggregate concrete was inferior compared to that of natural aggregate concrete. Finally, the drying shrinkage and creep of recycled aggregate concrete was found to be higher than those of natural aggregate concrete [33,34].

Nevertheless, the drawbacks of using recycled aggregate could be ameliorated by employing a lower water-to-cement (w/c) ratio and using fly ash as a mineral admixture in the mix design. Kou et al. [37,38] studied the influence of using Class-F fly ash as cement replacement or as an additional cementitious material on the mechanical properties of recycled aggregate concrete. The results indicated that, when fly ash was added in the concrete mixtures, the compressive strength, tensile splitting strength, flexural strength and elastic modulus of concrete specimens were all higher than those of concrete without fly ash addition. Furthermore, the mechanical properties of concrete continued to gain strength with age at all fly ash addition levels. The drying shrinkage of the adhesive reduced when fly ash was employed as 0–25% sand replacements.

Many of the building codes such as the ACI code [39] relate the modulus of elasticity of the concrete to the specified compressive strength f'_c and assume that the peak stress occurs at a strain of 0.002. RAC has been shown to be weaker than a similar concrete made of natural aggregate [40–46], and could hence be softer in that the strain at peak stress could be larger than the typically assumed value of 0.002. Hence the modulus of elasticity and the strain at peak stress of locally produced RAC need to be investigated to obtain the necessary confidence required for structural use.

The shear strength of concrete depends significantly on the ability of the coarse aggregate to resist the shearing stresses. Angelakos et al. [47] reported that in normal strength concrete, the shear crack propagates in the hardened cement matrix, and around the relatively stronger coarse aggregate. In higher strength concrete where the matrix is relatively stronger, the shear crack passes through the matrix as well as the aggregate, forming a smoother crack surface. In RAC, the recycled aggregate from field-demolished concrete for example can be relatively weaker than a typical natural aggregate, and hence can yield reduced shear strength. Han et al. [48] studied the shear behavior of beams made with RAC. They concluded that using the current ACI code equations, the shear strength of RAC can be overestimated.

2. Research significance

Due to the wide variation in the properties of the available resources, properties using local materials need to be investigated in order to gain the required confidence in the performance of the new material. In China, waste concrete from demolished sites constitute the larger resource for recycled coarse aggregates and hence need to be studied. Although there are many studies related to the effect of recycled aggregate (RA) on the mechanical properties of non-structural concrete, the effect of RA on the deformation properties of structural concrete produced with 100% RA was still limited. The lack of a thorough understanding of the structural behavior of recycled aggregate concrete has become increasingly obvious in recent years. The main aim of this paper is to investigate the possibilities of using the RA replacement NA in structural concrete with the 28-day compressive strength ranging from 45 to 70 MPa by studying the effect of RA on the deformation properties, direct shear and durability of concrete produced from 100% RA.

3. Experimental details

3.1. Materials

ASTM Type I Portland cement and ASTM Class-F low-calcium fly ash were used in the concrete mixtures. The physical properties of cement and fly ash are given in Table 1.

Natural and recycled aggregates were used as the coarse aggregate in the concrete mixtures. In this study, crushed granite was used as the natural coarse aggregate and recycled aggregate sourced from a recycling facility in Shenzhen was used. The RA contained more than 96.3% crushed recycled rubbles. The nominal sizes of the natural and recycled coarse aggregates were 20 and 10 mm and their particle size distributions conformed to the requirements of BS 882 (1985). The physical and mechanical properties of the coarse aggregate are shown in Table 2. The porosity of the aggregates was determined using mercury intrusion porosimetry (MIP). River sand was used as the fine aggregate in the concrete mixtures. As expected, the absorption is significantly larger and specific gravity is lower in the recycled aggregates. The measured water absorption of 3.52% and 4.26% for 20 mm and 10 mm RA, respectively is higher than that of NA because of the presence of cement paste on the surface of the RA.

3.2. Concrete mixes

Five different mix proportions commonly used by Pan mixer in Shenzhen for concrete with target cube strength between 45 and 70 MPa were used. Table 3 gives the details of the mix proportions. The water–binder ratio ranged from 0.32 for 70 MPa concrete to 0.50 for 45 MPa concrete, which is named C70, C60, C55, C50 and C45, respectively.

The five NAC mixes and five RAC mixes were cast using the natural aggregates and recycled aggregates, respectively, giving a total of 10 mixes. The amount of super-plasticizers (ADVA-109) added to the mixes was adjusted to obtain a slump of about 100–120 mm. The aggregates were in SD conditions at the start of the mixing operation. Seventeen 100 mm cubes, nineteen 100 × 200 mm in diameter cylinders, seventeen 150 × 150 × 500 mm beams and three 70 × 70 × 285 mm prism were cast in steel moulds from each mix for the compressive strength, the elastic modulus, chloride ion penetration, the shear strength and drying shrinkage tests, respectively. In addition, five 100 × 100 × 500 mm beams were cast to measure the flexural strength.

3.3. Testing

3.3.1. Compressive strength and modulus of elasticity

The development of the compressive strength was monitored in accordance with BSEN 12390-3:2001 [49] by testing the 100-mm cubes at the age of 1, 4, 7, 28 and 90 days. The load was applied at a rate of 200 kN/min. The compressive strength was calculated by dividing the maximum compressive load by the cross sectional area of the cube specimen on which the load was applied.

The modulus of elasticity tests were conducted in accordance with ASTM C469 [50]. Five 100 mm × 200 mm cylinders were tested for the modulus of elasticity at 28 days using a 3000 kN Denison testing machine. The strain was measured over a 60 mm central gage length using two strain gages attached on opposite sides around the perimeter of the specimen. At 28 days, all specimens tested for modulus were subjected to identical initial loadings regardless of the compressive strength. This initial cycle of loading and unloading was repeated at least twice before the

Table 1
Physical properties of cement and fly ash.

Properties	Materials	
	Cement	Fly ash
Density (g/cm^3)	3150	2310
Specific surface area (cm^2/g)	3520	3960