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Compressive behaviour of recycled aggregate concrete under impact loading

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ABSTRACT

The compressive behaviour of recycled aggregate concrete (RAC) with different recycled coarse aggregate (RCA) replacement percentages was experimentally investigated under quasi-static to high strain rate loading. Quasi-static tests at a strain rate of 10^{-5}/s were first carried out using a stiff-framed servo-hydraulic machine. Impacting tests at strain rates ranging from 10^1/s to 10^2/s were then performed using a 74 mm-diameter Split Hopkinson Pressure Bar (SHPB) facility. The strain rate effects on the failure pattern, compressive strength, initial elastic modulus and peak strain were studied. The results showed that the compressive strength and initial elastic modulus increased with increasing strain rate while the peak strain did not display clear strain rate dependence. At high strain rates the compressive strength decreased with increasing RCA replacement percentage, whereas the dynamic increase factor (DIF) showed a reverse tendency. Furthermore, the dynamic compressive strength of wet RAC was lower than that of naturally dried RAC.

1. Introduction

With the rapid development of the construction industry which requires an excessive consumption of natural resources and may result in the deterioration of the natural environment, the conflicts between the desire to achieve sustainable development of the construction industry and the shortage of resources will become more and more serious, especially in developing countries like China. At the same time, a large amount of concrete waste is produced from both the construction of new buildings and demolition of old buildings every year. Moreover, natural disasters such as the 2008 Wenchuan earthquake, 2010 Yushu earthquake and 2011 Yunnan earthquake have resulted in a huge amount of waste concrete in China [1]. Today, the possibility of recycling construction waste, in particular concrete, has become a major issue around the world. The use of recycled aggregate concrete (RAC) is considered to be an effective measure to develop green ecological concrete and achieve sustainable development in the construction industry. As a result, RAC has attracted increasing interest in both academia and industry. A number of studies have been conducted on RAC especially in relation to understanding the mechanical properties of RAC. Previous investigations have shown that the mechanical properties of RAC such as strength and elastic modulus are inferior to those of natural aggregate concrete (NAC) with the same water-to-cement ratio [2–4]. Most studies indicated that the strength of RAC decreases with increasing recycled coarse aggregate (RCA) replacement percentage [5,6]. However, there are exceptions especially when the grade and quality of RCA are particularly good, e.g. Manzi et al. [7]. So far, almost all the attention paid to RAC has been its quasi-static behaviour. But in practice, a variety of civilian and military infrastructures are likely to face extremely high strain rate loadings induced by such events as earthquakes, explosions and accidental impacts. Therefore, it is essential to understand the dynamic behaviour of RAC under high strain rates regarding its application in infrastructures subject to extreme loading.

Since the pioneer work by Abrams [8] in 1917, a large number of studies on the dynamic properties of NAC have been conducted in terms of compressive strength, tensile strength, flexural strength, elastic modulus, peak strain (strain at the peak stress), Poisson's ratio and so on. It is concluded that the compressive strength of concrete increases with increasing strain rate [9–11]. Although the elastic modulus of concrete is less sensitive to strain rate than strength, it still increases with increasing strain rate [12,13]. However, there is no consensus on the magnitude of the increase as the strain rate increases. Moreover, there are no clear conclusions on the rate sensitivity of peak strain. Bischoff and Perry [14] carried out a review of the dynamic compressive behaviour of concrete at high strain rates and showed that the strain rate sensitivity of concrete may be influenced by many factors including concrete grade, aggregate quality, curing and moisture conditions, age

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and so on. However, there are few studies reporting the mechanical behaviour of RAC under high strain rate loadings. Chakradhara Rao et al. [15] compared the impact behaviour of RAC beams with different RCA replacement percentages and showed that the accelerations, maximum displacement and strains at the middle of RAC beams were larger than those of normal concrete beams at a given impact energy, and the impact resistance of RAC beams decreased with increasing RCA replacement percentage. Lu et al. [16] preliminarily studied the impact behaviour of RAC based on the split Hopkinson pressure bar test, and demonstrated that the impact behaviour of RAC including dynamic compressive strength, critical compressive strain and specific energy absorption increased with increasing strain rate. These early studies have proven that the dynamic properties of RAC are different from our common knowledge of concrete prepared with natural aggregates. Therefore, it is necessary to conduct further research to understand the compressive behaviour of RAC under high strain rates.

2. Research significance

The objective of this study was to enhance the understanding of the dynamic properties of RAC at high strain rates ranging from 10^1/s to 10^2/s. The effects of strain rates on the failure pattern, stress–strain curve, initial elastic modulus, compressive strength (peak stress) and peak strain of RAC specimens with different RCA replacement percentages were investigated using a 74 mm-diameter Split Hopkinson Pressure Bar (SHPB) facility. The effect of moisture on the compressive behaviour of RAC under high strain rates was also studied by comparing the results of RAC specimens under wet and naturally dried conditions.

3. Experimental program

3.1. Materials

Ordinary Portland cement of 42.5 Grade was used in this investigation. The water was potable water. The fine aggregate was river sand. The selected coarse aggregates were natural coarse aggregates (NCA) from a local aggregate production plant and RCA derived from waste concrete which were obtained from a local RCA manufacturing plant in Shanghai, China. The physical properties of the NCA and the RCA are given in Table 1.

In this paper, RCA replacement percentage is defined as the ratio of the mass of RCA to the total mass of coarse aggregates used in the concrete. Five RCA replacement percentages, i.e., 0%, 30%, 50%, 70% and 100%, were used in the tests; the corresponding specimens in natural dried condition were named NAC, RAC30, RAC50, RAC70 and RAC100, and NAC and RAC100 specimens in wet condition were named NAC (wet) and RAC100 (wet) respectively. Due to the high water absorption of RCA, it was necessary to increase the total quantity of added water to assure the same effective water–cement ratio. This part of the water is called additional water, which was calculated from the measured effective water absorption (the water absorption from natural state to saturated surface dry) of the aggregates. The measured effective water absorption of the RCA in the test was about 4%. The mix proportions of concretes are listed in Table 2.

Table 1
Physical properties of NCA and RCA.

Type	Coarse aggregate grading (mm)	Bulk density (kg/m^3)	Apparent density (kg/m^3)	Crushing index (%)
NCA	5–12.5	1395	2634	5.0
RCA	5–12.5	1290	2620	12.4

Table 2
Mix proportions of concretes.

Specimen	w/c	Cement (kg/m^3)	Sand (kg/m^3)	NCA (kg/m^3)	RCA (kg/m^3)	Mixing water (kg/m^3)	Additional water (kg/m^3)
NAC	0.45	467	582	1082	0	210	0
RAC30	0.45	467	574	746	320	210	12.8
RAC50	0.45	467	568	528	528	210	21.12
RAC70	0.45	467	562	313.5	731.5	210	29.26
RAC100	0.45	467	554	0	1029	210	41.46

3.2. Specimens

The specimens were first cast in polyvinylchloride (PVC) pipelines with the dimensions Φ75 mm × 320 mm. The diameters of specimens were about 70 mm. They were demoulded one day after casting and were cured in an environmentally-controlled room under 20 degrees centigrade and 95% relative humidity for 28 days. The specimens were cut with their two ends ground smooth and parallel to produce 70 mm-diameter and 35 mm-long cylindrical specimens for the SHPB test, and 70 mm-diameter and 140 mm-long cylindrical specimens for the quasi-static tests. In each case, five specimens were prepared for the SHPB tests and the quasi-static tests. After that, the specimens were kept under indoor conditions until testing. Two days before testing, some RAC100 and NAC specimens were submerged in water in an indoor environment to study the moisture effect on the compressive behaviour of RAC at high strain rates.

3.3. Quasi-static tests

The prepared specimens with the dimensions Φ70 mm × 140 mm were loaded under quasi-static uniaxial compression at a strain rate of 10^{-5}/s using a stiff-framed servo-hydraulic testing machine. The cylinder specimens had the same diameter as those used in the SHPB tests but with a length/diameter (L/D) ratio of 2.0. Wang et al. [17] have suggested that this kind of specimen size would be suitable for determining the quasi-static strength to calculate the dynamic increase factor (DIF) based on the stress state and failure pattern. In order to reduce the frictional constraints, two Teflon sheets with a thickness of 0.2 mm were used at the top and bottom surfaces of the specimens [18].

3.4. Split Hopkinson Pressure Bar (SHPB) tests

Impact tests under strain rates ranging from 10^1/s to 10^2/s were conducted using a 74 mm-diameter conic variable cross-sectional SHPB as shown in Fig. 1. The SHPB apparatus consists of four basic parts: a striker bar (37 mm in diameter, 400 mm in length); a conic variable cross-sectional incident bar (the striking end is 37 mm in diameter, the other end is 74 mm in diameter, 3060 mm in length), a transmitter bar (74 mm in diameter, 1800 mm in length) and the testing specimen. The material used for fabricating these bars was high-strength alloy steel (E_s = 210GPa, ρ = 7850 kg/m^3, f_y = 400 MPa). The specimens were sandwiched between the incident and the transmitted bars. Vaseline was applied uniformly to the two bar/specimen contact surfaces to reduce friction. The striker bar, propelled by a pressurized gas, impacts against the incident bar with a known velocity, which generates a stress pulse in the incident bar. Then, the stress pulse of the incident bar impinges on the specimen. Because of the impedance mismatch between the specimen and the incident bar, part of the stress pulse is reflected from the specimen as a tensile pulse, and part of the pulse is transmitted through the specimen as a compressive pulse into the transmitted bar. The incident, reflected and transmitted pulses were recorded by the strain gauges on the incident and the transmitter bars. The distance of the strain gauge on the incident bar from the incident bar/specimen interface was 1282 mm.