Journal of Cleaner Production 191 (2018) 283–296

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Static and impact behaviour of recycled aggregate concrete under daily temperature variations

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ARTICLE INFO

Article history:
Received 30 January 2018
Received in revised form
26 March 2018
Accepted 26 April 2018
Available online 26 April 2018

Keywords:
RAC
Static and SHPB tests
Strain rate
Modified CEB model

ABSTRACT

Concrete continuously suffers from impact loading and variations in daily temperature. In this study, tests on static compressive, static flexural, and impact compressive concrete specimens with different replacement percentages of recycled coarse aggregate (RCA), additional water, and cyclic temperatures were carried out to investigate the mechanical behaviour of recycled aggregate concrete (RAC). The static tests were conducted using a universal mechanical testing machine, and the impact tests were then applied using a 100-mm diameter split Hopkinson pressure bar facility. The failure mode, compressive strength, flexural strength, brittleness coefficient, strain-strain curve, and dynamic increase factor (DIF) were analysed and discussed. The results showed that (1) the influence of the replacement percentage of RCA and additional water on the static behaviour of RAC mainly depend on the effective water-to-cement ratio, RCA strength, and bond strength between the mortar and RCA, (2) the strain rate has a significant effect on the impact performance of RAC, and (3) the cyclic temperature significantly weakens the material properties of RAC. Finally, based on an empirical formula given by Comite Euro-International du Beton (CEB), a modified CEB model was proposed to accurately estimate the relationship between the strain rate and DIF of RAC.

1. Introduction

Recently, significant attention has been paid to recycled aggregate concrete (RAC), an innovative and environmentally friendly concrete produced using recycled coarse aggregate (RCA) collected from concrete debris (Li, 2008; Fathifazl et al., 2011; Butler et al., 2013). Hence, many researchers have made progress in their understanding of the mechanical behaviour of RAC (He et al., 2017; Huang et al., 2012, 2016). It has been indicated that the use of RCA at high percentages in concrete will worsen the material property of RAC (Zhang and Ingham, 2010; Tabsh and Abdelfatah, 2009). To improve the performance of RAC, researchers have attempted to add an additive agent, such as natural pozzolan (Omrane et al., 2017) or nanoparticles (Li et al., 2016b). In general, improvements regarding the mechanical behaviour of RAC have been abundant, and RAC is deemed a future material that can be used toward sustainable development (Kisku et al., 2017).

Thus far, a number of researches have focused on the static behaviour of RAC. In practice, however, a variety of civilian and military infrastructures are likely to be subjected to extremely high strain rate loadings, such as explosions or accidental impacts. Hence, a comprehensive understanding of the impact response of concrete is of great importance. A series of studies on the impact performance of RAC has been carried out. Li et al. (2016b) investigated the effects of nanoparticles on the impact behaviour of RAC through split Hopkinson pressure bar (SHPB) tests, and found that nano-SiO_2 is more effective at improving the impact compressive strength of RAC when compared with nano-$CaCO_3$. Lu et al. (2014) indicated that, owing to the short duration of the impact loading, the strain rate (the derivative of strain over time) of the material is significantly higher than that under quasi-static loading conditions. According to their experimental results, they found that the impact property of RAC exhibits a strong strain rate dependency, and increases approximately linearly with an increase in the strain rate. Xiao et al. (2015) used the dynamic increase factor (DIF), which is defined as the ratio of impact compressive strength to its

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https://doi.org/10.1016/j.jclepro.2018.04.237

corresponding static compressive strength, to assess the effects of the strain rate on concrete. They verified that, at high strain rates, the compressive strength decreases with an increase in the replacement percentage of RCA, whereas the DIF shows a reverse tendency. Li et al. (2016a) found that waste-rubber-modified RAC has an enhanced strain rate effect and a good impact resistance compared with RAC.

The temperature also significantly influences the mechanical behaviour of concrete. The long-term exposure of concrete to daily air temperature conditions could lead to inherent changes, for instance, a loss of strength and durability, or a reduction in service life. The amount of damage depends on the maximum temperature, minimum temperature, range of daily temperature variations, and exposure time. Comprehensive and systematic researches on the mechanical behaviour of RAC at elevated temperatures have been carried out, but remain in an early stage. Xiao and Zhang (2007) analysed the fire-induced damage and residual strength of RAC, and indicated that, when the replacement percentage of RCA is larger than 50%, its residual strength after exposure to elevated temperatures is larger than that of natural aggregate concrete (NAC). An experimental study carried out by Yang et al. (2016) showed that, as the temperature elevates, the residual shear strength and shear modulus decline rapidly, whereas the peak strain increases linearly. It is worth noting that the aforementioned researches did not consider the influence of daily air temperature conditions. Sadati and Khayat (2016) casted a 300-m long pavement section using RAC to monitor the early age and long-term deformation of different pavement sections and evaluate the in-situ properties of RAC under variations in daily temperature. However, more systematic studies on the mechanical behaviour of RAC under such variations in daily temperature are required.

This paper aims at investigating the static and impact behaviours of RAC under daily temperature variations. Static and impact tests on static compressive, static flexural, and impact compressive concrete specimens were conducted. During the tests, the cyclic temperature was applied to simulate the daily air temperature conditions during the summer. Moreover, the parameters of the replacement percentage of RCA and additional water were considered. The test results were analysed and discussed. Finally, according to the empirical formula given by Comite Euro-International du Beton (CEB), a modified CEB model, which is an effective tool for accurately estimating the relationship between the strain rate and DIF of RAC, was developed. The application of RCA has a number of advantages, including the preservation of natural resources, the effective utilization of concrete debris, sustainable social and economic development, and energy saving. The achievements of this paper have important theoretical and practical meaning, and will be of great help toward the development of RAC.

2. Experimental program

2.1. Raw materials

Ordinary Portland cement with a grade of 42.5 MPa (GB 175, 2007), density of 3150 kg/m^3, sulphur trioxide content of 3.18%, magnesium oxide content of 1.42%, dipotassium oxide content of 0.59%, disodium oxide content of 0.46%, loss on ignition of 2.46%, and cement fineness modulus of 2.7 was used in this investigation. The water applied was ordinary tap water. The fine aggregate was river sand with continuous gradation and a particle size of <5 mm, an apparent density of 2580 kg/m^3, and a fineness modulus of 2.6. The natural coarse aggregate (NCA) used was granite with a continuous gradation and particle size of 5–10 mm. Meanwhile, RCA with a continuous gradation and particle size of 5–10 mm was also selected. The physical properties of NCA and RCA are shown in Table 1. In addition, a polycarboxylic high-performance water reducer was adopted.

Table 1
Physical properties of NCA and RCA.

Type	Bulk density (kg/m^3)	Apparent density (kg/m^3)	Crushing index (%)	Water absorption (%)
NCA	1515	2690	5.25	1.9
RCA	1265	2322	13.6	3.77

2.2. Mix proportions and parameters

The mix proportion design of the concrete was based on the “Specification for mix proportion design of ordinary concrete (JGJ 55, 2011)”. Meanwhile, a water-to-cement ratio of 0.44 (defined as the basic water-to-cement ratio in this paper) and 375 kg/m^3 of cement were adopted for the concrete specimens. The basic mix proportion was designed for NAC, as listed in Table 2. The water, cement, sand, and water reducer of RAC were equal to that of NAC in terms of quantity.

For concrete specimens without exposure to cyclic temperature, two parameters were varied in the mix proportion of RAC. The first parameter was the replacement percentage of RCA. The replacement percentage of RCA was calculated according to the total weight of the coarse aggregate content (Kwan et al., 2012). Five replacement percentages of RCA, i.e., 0%, 25%, 50%, 75%, and 100%, were used in the mix proportion. The other parameter was the additional water applied. Owing to the high water absorption of RCA (Zhao et al., 2017), additional water is usually required in RAC. The full amount of additional water $W_{A,f}$ was defined as the water absorbed by RCA during a limited period and can be calculated using Eq. (1). In Eq. (1), m_D represents the mass of RCA under dry conditions, and S_A represents the water absorption. To investigate the influence of additional water on the mechanical behaviour of RAC, the effective water-to-cement ratio μ_e, total water-to-cement ratio μ_t, and basic water-to-cement ratio μ_0 were proposed, as expressed in Eqs. (2)–(5). In Eqs. (2)–(5), W, W_A, and W_0 represent the total water, additional water, and basic water, respectively, and C represents the cement. Three additional waters of 0%$W_{A,f}$, 50% $W_{A,f}$, and 100%$W_{A,f}$ were added to the mix proportion. The mix proportion and water-to-cement ratio of RAC without exposure to the cyclic temperature are listed in Tables 2 and 3. Concise symbols were assigned to these mix proportions for an explicit understanding. Here, A, B, and C represent 0%$W_{A,f}$, 50%$W_{A,f}$, and 100%$W_{A,f}$ for RAC, respectively, and 25, 50, 75, and 100 represent the replacement percentage of RCA.

$$W_{A,f} = m_D \times S_A \tag{1}$$

$$W = W_A + W_0 \tag{2}$$

$$\mu_e = \frac{W - W_{A,f}}{C} \tag{3}$$

$$\mu_t = \frac{W}{C} \tag{4}$$

$$\mu_0 = \frac{W_0}{C} \tag{5}$$

For concrete specimens with exposure to a cyclic temperature, the additional water was 0%$W_{A,f}$. Three replacement percentages of