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Influence of recycled coarse aggregate replacement percentage on fatigue performance of recycled aggregate concrete

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HIGHLIGHTS

- Compressive fatigue performance of concrete with different percentage RCA was studied.
- Fatigue life, residual strength and stiffness decreased differently with RCA percentage rising.
- Degradation models of residual strength and stiffness were obtained.
- RCA replacement percentage effect on decline ratios of strength and stiffness was analyzed.
- RCA replacement percentage effect on damage evolution was analyzed.

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ABSTRACT

The fatigue residual strength or stiffness of concrete refers to its strength or stiffness after a certain extent of fatigue loading. They decrease with loading cycles, a distinct feature of the fatigue process. To investigate the influence of recycled coarse aggregate (RCA) content on the fatigue performance of recycled aggregate concrete (RAC), an experiment about compressive fatigue residual strength on RAC with different replacement percentages was conducted. The results show that fatigue life, residual strength, and residual stiffness all decrease with an increase in RCA replacement percentage, with the smallest effect on stiffness. The residual strength and stiffness degradation curves of RAC were obtained by regression analysis and the replacement percentage effect on degradation laws was discussed. Furthermore, fatigue damage evolution was analyzed by defining the damage variable based on residual strength.

1. Introduction

Recently, demand for structural materials and disposal of construction waste have been increasing in line with construction development. Concrete, as the most common structural material, is moving towards more environmentally friendly forms in the interest of global environmental protection and resource conservation. The use of recycled aggregate concrete (RAC), through either partial or total substitution of natural aggregates with recycled aggregates, is a popular approaches that reduces natural resources consumption by reusing concrete waste. The means has attracted substantial attention in civil engineering, and extensive research has been carried out worldwide.

Most scholarship related to RAC has been focused on the rheological properties of fresh concrete and the mechanical properties of hardened concrete under static loads as well as durability [1–10]. RAC generally exhibits a decline in physical and mechanical properties compared with natural aggregate concrete (NAC), such as slump, strength and elastic modulus. Limited research has been conducted on the fatigue performance of RAC. Xiao et al. [11] investigated the fatigue strain, fatigue modulus and damage evolution of RAC with 100% RCA under uniaxial compression loading, and found no obvious differences in compressive fatigue behavior between RAC and NAC. However, the fatigue life of RAC under the same stress level was lower than that of NAC under cyclic bending loading, contrary to the compression case. Yang et al. [12] discovered the residual fatigue strain of steel-fiber- reinforced recycled concrete develops more slowly than that of steel-fiber-reinforced pebble concrete under the same stress conditions; they also proposed a residual fatigue strain equation and fatigue damage evolution equation. Thomas et al. [13,14] studied the strain, stiffness, and fatigue limit of NAC and RAC with partial and total coarse aggregate replacement under different water-cement ratios. Three

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different stages were observed on strain-cycle curves, and RAC presented a greater stiffness loss than NAC. The fatigue limit also decreased as the degree of RCA substitution increased. Breccolotti et al. [15] analyzed monotonic complete stress-strain curves and the cyclic compressive behavior of concrete with RCA percentages of 0%, 50%, and 100%. No significant differences in fatigue life were observed by increasing the RCA content from 50% to 100%; fatigue strain development resembled the three-stage trend described in the literature on NAC. Arora and Singh [16] compared the flexural fatigue performance of concrete beams made with 100% RCA to those with 100% natural coarse aggregate (NCA). The fatigue life distributions of RAC and NAC can be modeled by the two-parameter Weibull distribution, but variability of RAC has been found to be higher than that of NAC. The two-million-cycle endurance limit for RAC was 50%, slightly lower than that of NAC. The aforementioned studies concentrate mostly on fatigue strain, fatigue life, fatigue strength, and strain-based fatigue damage, whereas residual strength and residual stiffness after a number of loading cycles are seldom studied due to time-consuming and labor-taking. In this paper, a uniaxial compressive fatigue experiment was conducted on NAC and RAC with different replacement percentages. Residual strength and residual stiffness were obtained, and the influence of replacement percentage on the degradation of each is analyzed to provide insight into potential RAC applications under fatigue loading.

2. Experimental program

2.1. Materials and mix proportions

Ordinary Portland cement (P.O. 42.5) and natural sand were used as a binder and fine aggregate respectively. RCA was crushed from concrete waste specimens (C30-grade) in the laboratory using a jaw crusher. NCA with comparable grading was crushed stones from local market. Fig. 1 shows the RCA and NCA used in this study, and their basic properties are given in Table 1. Five batches of concrete with RCA replacement percentages of 0%, 30%, 50%, 70% and 100% were produced. Mix proportions are listed in Table 2. The mix proportion of NAC was designed according to China standard JGJ 55-2011 [17]; that of RAC was designed based on NAC and the additional water that brought RCA from an air-dried condition to a saturated-surface-dried condition.

2.2. Specimens and testing

20 cube specimens measuring 100 mm $\times$ 100 mm$\times$100 mm for each concrete mix proportion were demolded after 24 h of casting and then naturally cured in the laboratory atmosphere of about T = 25 °C and RH = 60% for 28 days. After curing, the cubes for each mix proportion were employed in a series of static or fatigue tests in uniaxial compression in fives as follows: (1) the first group was statically loaded to obtain the initial compression strength and initial secant modulus; (2) the second group was cyclically loaded to obtain the fatigue life N_f, the number of fatigue loading cycles to failure; (3) the third and fourth groups, were first loaded under cyclic uniaxial compression loads and then unloaded to be tested under static compression loads to obtain the residual strength and secant modulus at 25–30% and 55–60% of the mean fatigue life. As noted in [18,19], the secant modulus is defined as the slope of the secant intersecting the origin and the 50% peak stress on the ascending branch.

For fatigue tests, load was applied in a constant amplitude sinusoidal wave under force control. An upper limit of 2×10^6 cycles was chosen, and the maximum and minimum stress levels $\left(S_{max} = \frac{\sigma_{max}}{f_c},\ S_{min} = \frac{\sigma_{min}}{f_c}\right)$ of 0.75 and 0.1 were selected, respectively. Cyclic loading frequency was 1 Hz as it in the range of 1–30 Hz has insignificant effect on the fatigue behavior of concrete if the maximum stress level is kept less than about 75% of the static strength [20]. All static and fatigue tests were performed automatically using a RMT-150C rock mechanics testing system where the loading parameters can be pre-established and results such as load, deformation, stress, strain and secant modulus are automatically recorded and computed. The test setup is shown in Fig. 2.

3. Experimental phenomena and results

Cracks developed progressively in concrete cubes with different RCA replacement percentages as the number of loading cycles N increased (see Fig. 3). The phenomena indicates that the fatigue failure processes of NAC and RAC are similar to the corresponding failure processes under static loads, displaying distinct stages of crack emergence, propagation, and unstable interconnection.

Tables 3 and 4 summarize the mean values and the standard deviations of the fatigue tests on fatigue life, initial strength with secant modulus, and residual strength with secant modulus, respectively. A few specimens with RCA replacement percentages above 30% failed before the cycle ratio N/N_f reached 0.55–0.60, which were eliminated in the results.

4. Influence analysis of RCA replacement percentage

4.1. Influence on fatigue life, compression strength and secant modulus

To better analyze the influence of RCA replacement on fatigue life, compression strength and secant modulus, results in Table 3 were normalized to relative values using the foundings of concrete with RCA replacement percentage of 0% (i.e. NAC). Relative values vs. RCA replacement percentages are presented in Fig. 4.

(a) RCA

(b) NCA

Fig. 1. Coarse aggregates.