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Flexural fatigue behavior of ultra-lightweight cement composite and high strength lightweight aggregate concrete

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HIGHLIGHTS

- Study the fatigue behavior of ultra lightweight cement composite (ULCC) and lightweight aggregate concrete (LWAC).
- ULCC shows higher fatigue life than plain high strength LWAC, both of having similar strength.
- Probabilistic analysis of the fatigue data modeled by Weibull distribution.
- Weibull distribution parameters and fatigue equations for different failure probabilities were obtained.
- This would be useful for the rational fatigue design of ULCC and LWAC structures.

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ABSTRACT

This paper investigated the fatigue performance of ultra-lightweight cement composite (ULCC) and lightweight aggregate concrete (LWAC) subjected to flexural load. The ULCC having mean density of 1450 kg/m^3 contained cenosphere as micro aggregates and 0.9% volume of polyvinyl alcohol (PVA) fibers. The average 28-days cylinder compressive strengths of the ULCC and LWAC were 62 MPa and 63 MPa, respectively. 108 specimens were tested to measure the flexural fatigue strength under third-point loading. All the specimens were sized as 100 × 76 × 406 mm with an effective span of 300 mm. Using the experimental results, S-N curves were plotted and regression analysis was conducted to propose the equations (called Wöhler equations) for predicting the flexural fatigue strength of ULCC and LWAC. Also, the probabilistic distributions of fatigue life of ULCC and LWAC at a given stress level were modeled using the two-parameter Weibull distribution. The distribution parameters were obtained using three different methods. Design fatigue lives were obtained at different stress levels for ULCC and LWAC corresponding to different failure probabilities. The S-N relationship incorporating the failure probability is found more conservative than that found by Wöhler fatigue equation. The flexural fatigue performance of ULCC is better than that of LWAC, both of having similar strength.

1. Introduction

The use of lightweight cement composites for civil, offshore and marine structures has long been recognized as a durable method of construction [1–3]. Lightweight concrete has been used in civil construction for over 2000 years with widespread use in the past 100 years. Some of the ancient structures from the Roman Empire that still survive today have elements that were constructed with lightweight concrete [4]. Those structures in the Mediterranean region used lightweight concrete made from natural volcanic materials [5]. From 20th century, lightweight concrete is produced using manufactured lightweight aggregate (LWA) such as expanded shale, expanded clay or foam slag [6]. In recent years, lightweight aggregates such pumice, perlite, cenospheres, polyurethane foam, diatomite earth, expanded glass, aerogel, and high-impact polystyrene are used to produce low thermal conductive structural lightweight concrete [7].

In the late 20th century, high strength lightweight aggregate concrete was successfully developed with strength ranging from 57 to 102 MPa and density ranging from 1595 to 1880 kg/m^3 [8]. According to a state-of-the-art review on development of high strength lightweight concrete [9], the compressive strength of lightweight aggregate concrete (LWAC) typically decreases with the decrease of density, and it is a big challenge to produce LWAC with density below 1500 kg/m^3 and compressive strength above

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50 MPa. However, LWAC with low-density ranging from 1440 to 1840 kg/m^3 can achieve high strength levels (35–70 MPa) by incorporating various pozzolans (silica fume, fly ash, metakaolin, volcanic ashes, calcined clays and shales) combined with mid- to high-range water reducing admixtures or both [10].

Recently developed Ultra Lightweight Cement Composite (ULCC) [11,12] was a type of novel composite, which could be categorized as low density ($\leq$1450 kg/m^3) with high compressive strength ($\geq$60 MPa) cementitious composite. Originally, this cementitious material was developed to use in sandwich composite structures for offshore and marine applications [13]. To achieve low density, cenospheres were used as a filler material in the ULCC mix. The cenospheres are lightweight, inert, and hollow microspheres recycled from ash pond in coal-burning thermal power plants. The hollow interior of the cenospheres are covered by thin shells made of aluminosilicate that are thermally stable. They are being used in many applications due to their superior physical and chemical properties [14].

The mechanical properties of ULCC was documented by Chia et al. [11] and Wang et al. [7]. Structures with ULCC (e.g. reinforced slabs, steel-concrete-steel sandwich panels and double skinned steel tubes) were tested for both static and impact load [7,12,15,16]. However, the long-term effect such as fatigue performance of this newly developed cementitious composite is not known yet. The resistance of a material to repeated loading is obviously an important factor in the design of concrete structures, like bridges, building floors, offshore structures and composite decks, subjected to such type of load. Knowledge of the relationship between the number of cycles to the failure and applied stress is essential. Most of the previous research studies on flexural fatigue were carried out on normal weight concrete. Such type of research on lightweight concrete is very limited in the literature [17,18]. The main conclusion from these studies is that the fatigue life varies with the type of concrete.

In this study, the flexural fatigue performance of the ULCC at different stress levels was determined experimentally. The relationship between the number of cycles to failure and applied stress level (i.e. S-N curve) was established. The material coefficient of fatigue equation was determined, so that it could be used to predict the endurance limit of the ULCC for flexural load. The fatigue performance of the ULCC was compared with high strength light weight aggregate concrete (LWAC) and normal weight concrete (NWC) having similar compressive and flexural strengths. Another aim of this paper was to implement the probabilistic analysis concepts to describe the fatigue characteristics of ULCC and LWAC. The two-parameter Weibull distribution was examined to describe the fatigue behavior of ULCC and LWAC. Application of the failure probability in the S-N relationship was also discussed in this paper.

2. Fatigue of concrete and cement composites

Concrete or cement composites, when subjected to repeated load, may develop extensive cracks that eventually lead to failure after a sufficient number of load repetitions. The fatigue fracture process in concrete can generally be divided into three phases. In the first phase, flaws (cracks) initiate in weak regions within the concrete. The second phase is the crack propagation phase, where the initial flaws or cracks grow slowly and progressively to a critical size termed as micro cracking. In the last phase, a sufficient number of continuous and unstable cracks have developed eventually leading to failure [19]. The fatigue strength of cementitious material can be defined as a fraction of static strength that can be supported by the material repeatedly for a given number of load cycles. The general factors that influence the fatigue strength of cementitious materials are loading range (or stress ratio), loading rate, matrix composition, mechanical properties, boundary conditions and environmental conditions [20].

A number of experimental investigations have been carried out on the fatigue behavior of normal weight concrete, lightweight concrete and other cement based composites since the early 20th century. Various prediction models were proposed to evaluate the fatigue performance of concrete from these studies. Some researchers [21–23] adopted a relationship between stress level S, which is the ratio of maximum fatigue stress, $f_{\max}$ to the flexural strength, f_r, and the number of loading cycles, N that causes failure. The established relationship is known as the Wöhler fatigue equation [23,24], and is given by:

$$S = \frac{f_{\max}}{f_r} = a + b\log_{10}(N) \tag{1}$$

where a and b are experimental coefficients. Oh [24] obtained the values of coefficients a and b in Eq. (1) for plain concrete using the fatigue test data.

Another form of the fatigue equation used by other researchers [18,23–25] is a modification of the Wöhler equation that incorporates a fatigue stress ratio R into the Wöhler equation. The fatigue stress ratio R is the ratio of minimum fatigue stress f_{min} to the maximum fatigue stress f_{max}, and is included to simulate the loading conditions in actual structures where the minimum value of the repeated stress may not be zero. The modified Wöhler equation takes the following form:

$$S = \frac{f_{\max}}{f_r} = 1 - \beta(1 - R)\log_{10}(N) \tag{2}$$

where β is an experimental material coefficient and it can be obtained from the S-N curve. This equation is only suitable when $R = f_{\min}/f_{\max} \geq 0$ (i.e. no stress reversal). Aas-Jakobsen [26] obtained the value of β as 0.0640 in Eq. (2) for compression fatigue of concrete. Tepfers and Kutti [18], however, recommended the value of β as 0.0685 for both NWC and LWAC under compression. Oh [24] tested Eq. (2) for flexural fatigue of plain concrete and obtained the value of β as 0.0690. In case of steel fiber reinforced concrete, the average values of β for 0.5%, 1.0% and 1.5% steel fiber content are 0.0536, 0.0425 and 0.0615, respectively [27].

3. Experimental investigation

3.1. Materials and mix proportions

Flexural fatigue behavior of the ULCC with 0.9% PVA fiber was evaluated in this study in comparison to that of a high strength lightweight aggregate concrete (LWAC) with comparable compressive and flexural strength. The ULCC contained microspheres (cenosphere), ordinary Portland cement, undensified silica fume, chemical admixtures and polyvinyl alcohol (PVA) fibers. The average length and diameter of the fibers were 6 mm and 27 μm, respectively. The tensile strength, elastic modulus, percentage of elongation and specific gravity of the fiber were 1600 MPa, 39 GPa, 7% and 1.30, respectively. It was used to reduce brittleness and improve tensile capacity of plain ULCC. The cenospheres used as lightweight filler material and they had low particle density typically ranging from 600 to 900 kg/m^3 due to their hollow structural form as mentioned earlier. Most of the particles had sizes ranging from 10 to 300 μm with maximum size of ~600 μm. Water to binder ratio kept low by using superplasticizer (AVDA® 181) to achieve good workability. Meanwhile, the mixtures also contained shrinkage-reducing admixture (Eclipse® Floor) in order to reduce shrinkage strains and air contents. The mix proportion of the ULCC is given in Table 1.