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Compressive fatigue performance of fiber-reinforced lightweight concrete with high-volume supplementary cementitious materials

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ABSTRACT

As a part of the fundamental investigation to evaluate the compressive fatigue damage of fiber-reinforced lightweight concrete using high-volume supplementary cementitious materials (SCMs), the stress–strain response of the concrete was examined under cyclic loading within maximum stress levels of 0.9, 0.8, and 0.75 f_c' and a minimum stress level fixed at 0.1 f_c', where f_c' is the concrete compressive strength. To produce a high-volume SCM binder, 20% fly ash and 50% ground granulated blast-furnace slag were used as a partial replacement for cement. Amorphous steel (AS) and polyvinyl acetate (PVA) fibers were added individually or in combination considering their conventionally recommended volume fractions. The fatigue tests were carried out by controlling the load between two limits with a sinusoidal variation at a frequency of 1 Hz. Test results showed that PVA fiber was preferable to AS fiber in enhancing the fatigue life of HVS-LWC, whereas the fatigue damage of the PVA fiber concrete was lower than that of the AS fiber concrete. This trend was more notable under a higher maximum stress level. To improve the fatigue life and fatigue damage of concrete, hybridization of both fibers rather than monolithic use is recommended.

1. Introduction

With increasing interest in the development of sustainable concrete technology, large volumetric reuse of by-products such as fly ash (FA) and ground granulated blast-furnace slag (GGBS) has been practically applied in the concrete industry as a high-volume replacement for ordinary Portland cement (OPC). Furthermore, incinerator bottom ash and FA are high-reuse value materials for producing lightweight aggregates [1,2]. This high-volume recycling of by-products significantly contributes to the reduction of environmental loads, including CO_2 emissions, energy consumption, and depletion of natural resources in the concrete industry [3]. The pozzolanic activity of FA and GGBS is also effective for forming a denser matrix, which results in higher strength in terms of long-term aging and better durability of the concrete [4]. The lightweight aggregate concrete saves energy in buildings because of the enhanced thermal insulation capacity through the lower thermal conductivity of lightweight aggregates. For these reasons, gradual growth is expected in the large volumetric reuse of by-products in concrete as supplementary cementitious materials (SCMs) and/or alternatives to natural aggregates.

There are several structural advantages to using lightweight concrete (LWC) as a structural element. The use of LWC allows for the fabrication of smaller and lighter-weight structural members, which reduces the dead load and improves the seismic resistance capacity of structures. Furthermore, smaller and lighter elements of precast concrete members are preferred because of easier towing, greater buoyancy, and less expensive handling and transporting systems. As a result, the application of LWC to floating structures has gradually attracted great attention [5]. On the other hand, such floating structures are subject to fatigue by wave loading. It is commonly pointed out [6] that the fatigue resistance of LWC is somewhat lower than that of normal-weight concrete (NWC) because of lower aggregate strength and poorer cohesion between pastes and aggregate particles. Furthermore, the lower tensile strength and crack resistance of LWC lead to deterioration of the fatigue life of a concrete member. Hence, enhancing the fatigue strength of LWC is essential for the durable and stable design of

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structures subjected to endless loop loads such as wave and traffic loads.

The most important improvements attained by the addition of fibers to concrete are an increase in toughness, ductility, tensile strength, and crack restriction. Owing to improved ductility and a decrease in the unstable crack propagation of fiber concrete, its dynamic properties, including fatigue response, can be enhanced. Hence, it is expected that the addition of fiber would be one of the best alternatives for enhancing the crack resistance and fatigue life of LWC. Most of the fatigue studies [7–10] on fiber-reinforced concrete have mainly focused on determining the flexural fatigue endurance limits for concrete using different types, volume fractions, and aspect ratios of fibers. Jun and Stang [11] reported that the accumulated damage level in fiber-reinforced concrete under fatigue loading was 1–2 orders of magnitude higher than the level recorded in static testing of the same material. Cachim et al. [12] conducted fatigue tests on steel fiber-reinforced concrete in compression and concluded that the superior fatigue life of fiber-reinforced concrete as compared to plain concrete depends on the initial imperfections such as microcracks or voids. Thus, the presence of fibers, especially larger fibers, may be an additional cause of imperfections, creating bridges between the aggregates and increasing initial residual stress. Moreover, some fibers remain glued, creating a large fiber ball that accelerates the imperfection and bridge-formation problem. Paskova and Meyer [13] showed that the fatigue life of concrete reinforced with 0.75% steel fiber is smaller than that of concrete with 0.25% steel fiber. Overall, special attention should be taken when the type, aspect ratio, and content of fiber are selected in order to ensure the targeted fatigue life of concrete. However, an understanding on the fatigue performance of fiber-reinforced concrete is very limited and still controversial, especially for LWC. Additionally, reliable test data are needed to for the development of accurate models capable of predicting the fatigue behavior of fiber-reinforced LWC.

The objective of the present study is to examine the feasibility of enhancing the fatigue performance of high volume supplementary cementitious material (HVS)-LWC in compression by using different fibers. To produce a high-volume SCM binder, 20% FA and 50% GGBS were used as a partial replacement for OPC. Amorphous steel (AS) fibers and polyvinyl acetate (PVA) fibers were added individually or in combination in order to improve the crack and tensile resistance of concrete. Based on the measured compressive stress–strain curves at each loading cycle, the effect of the added fibers on the deformation capacity of HVS-LWC under fatigue loading was evaluated by comparing the fatigue and residual strain values and the fatigue damage responses of concrete specimens. The fatigue life of fiber-reinforced HVS-LWC was also examined under different maximum stress levels.

2. Experimental program

2.1. Materials

The prepared cementitious materials were OPC conforming to ASTM Type I, FA belonging to Class F of ASTM C618, and GGBS conforming to ASTM C989 [14]. The FA had low calcium oxide (CaO) and a silicon oxide (SiO_2)-to-aluminum oxide (Al_2O_3) ratio by mass of 1.91, as given in Table 1. The loss of ignition (LOI) and 28-day activity coefficient of FA were 0.29% and 89%, respectively. The main chemical composition of GGBS was CaO, SiO_2, and Al_2O_3. The basicity of GGBS calculated from the chemical composition was 2.00. The specific gravity and specific surface area for OPC were 3.15 and 3466 cm^2/g, respectively, 2.23 and 3720 cm^2/g, respectively, for FA, and 2.91 and 4497 cm^2/g, respectively, for GGBS.

Artificially expanded clay granules having maximum sizes of 19 mm and 4 mm were used for lightweight coarse and fine aggregates, respectively. The lightweight aggregate particles were spherical, having a closed surface with a slightly rough texture. The core of the particle had a uniformly fine and porous structure, which led to a high water absorption capacity and low strength. The apparent density and water absorption for coarse particles were 1.21 g/cm^3 and 18.96%, respectively, and 1.65 g/cm^3 and 13.68%, respectively, for fine particles. The apparent density was thus lower in the 19 mm coarse aggregates than in the 4 mm fine aggregates, whereas the water absorption was higher in the coarse aggregates than in the fine aggregates, as given in Table 2. The fineness modulus of the lightweight fine aggregates was slightly higher than the common value (2.0–3.0) of natural sand.

The PVA fiber selected had a hydrophilic nature owing to the presence of –OH groups, which led to better dispersion within fresh concrete and improved interfacial bond strength with the cementitious matrix as compared with other synthetic polymers. It is commonly known [15] that PVA fibers provide a positive effect on the crack resistance and tensile strength of concrete or cementitious composites through their good interfacial bond with the cement matrix, high tensile strength, and good affinity with fresh concrete. In contrast, the low lateral stiffness of PVA fibers may lead to premature fiber rupture before being pulled out of the cementitious matrix. A graphical illustration of the monofilament PVA fibers used is shown in Fig. 1(a). The nominal length and diameter of the PVA fiber were 6 mm and 0.015 mm, respectively, producing an aspect ratio of 400, as given in Table 3. The nominal tensile strength and modulus of elasticity of the PVA fiber used were 1269 MPa and 27640 MPa, respectively.

AS fiber is a new material that has superior strength and toughness and enhanced corrosion resistance against acidic and aqueous environments as compared with conventional steel fibers. Unlike crystalline metal, amorphous metal forms random and irregular arrays of atoms [16]. Thus, amorphous metal has a densely filled structure, showing liquid characteristics and high flexibility in the solid state, as shown in Fig 1(b). The AS fiber used in this study was in the shape of a very thin sheet with dimensions of $1.6 \times 0.029 \times 30$ mm^3 (width × thickness × length), producing an aspect ratio of 18.75. The AS fiber had a smooth surface and no anchorage device at either end. The tensile strength and modulus of elasticity of the AS fiber were 1700 MPa and 140000 MPa, respectively, values that are higher than those of PVA fibers. The AS fiber had lower modulus of elasticity than the conventional steel fiber.

2.2. Specimens and mixture proportions

The main parameters selected for the fiber-reinforced HVS-LWC

Table 1
Chemical composition of the cementitious materials (% by mass).

Materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	TiO_2	SO_3	LOI
OPC	22.1	5.0	3.0	64.8	1.6	0.54	0.35	0.30	2.0	0.31
FA	53.3	27.9	7.8	6.79	1.11	0.84	0.55	–	0.82	0.29
GGBS	31.55	13.79	0.53	44.38	5.2	0.4	0.18	0.98	2.79	0.2