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Improved Supplementary Cementitious Materials in Hybrid Fibre Reinforced Concrete

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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 stressestrain response of the concrete was examined under cyclic loading within maximum stress levels of 0.9, 0.8, and 0.75 f ' and a minimum stress level fixed at 0.1 f ', where f ' 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.

I. 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 envi- ronmental 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 light- weight 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 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 [7e10] on fiber-reinforced concrete have mainly focused on determining the flexural fatigue endurance limits for concrete using different types, volume frac- tions, and aspect ratios of fibers. Jun and Stang [11] reported that the accumulated damage level in fiber-reinforced concrete under fatigue loading was 1e2 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 fa- tigue behavior of fiber-reinforced LWC. 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 stressestrain 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. 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, SiO2, and Al2O3. 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 cm2/g, respectively, 2.23 and 3720 cm2/g, respectively, for FA, and 2.91 and 4497 cm2/g, respectively, for GGBS.

Artificially expanded clay granules having maximum sizes of 19 mm and 4 mm were used for lightweight coarse and fine ag- gregates, 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 were1.21 g/cm3 and 18.96%, respectively, and 1.65 g/cm3 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 (2.0e3.0) of natural sand.

The PVA fiber selected had a hydrophilic nature owing to the presence of eOH 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 cementi- tious 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 cemen- titious 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 andtoughness 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 of1.6 0.029 30 mm3 (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, respec- tively, values that are higher than those of PVA fibers. The AS fiber had lower modulus of elasticity than the conventional steel fiber.

II. 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 (SiO2)-to-aluminum oxide (Al2O3) 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, SiO2, and Al2O3. The basicity of GGBS calculated from the chemical composition was2.00. The specific gravity and specific surface area for OPC were 3.15 and 3466 cm2/g, respectively, 2.23 and 3720 cm2/g, respectively, for FA, and 2.91 and 4497 cm2/g, respectively, for GGBS.

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2.2 Specimens and mixture proportions

The main parameters selected for the fiber-reinforced HVS-LWC mixtures were the type and volume fraction (Vf) of the fibers. The PVA and AS fibers were added either monolithically or by hybridization. The volume fractions of the fibers were determined with reference to the commercially recommended amount needed to maintain a certain level of slump for concrete casting and economic efficiency. The conventionally recommended volume fraction (Vf r) of the AS and PVA fibers per unit weight of concrete are 0.5% and 0.07%, respectively, which results in a unit content of 36 kg/m3 for AS fiber and 0.9 kg/m3 for PVA fiber. Hence, the concrete mixtures were identified using the type and Vf of fiber added as follows: specimens A-R and A-1.5R denote concrete mixtures reinforced with monolithic AS fiber of 1.0 Vf r (0.5% corresponds to 36 kg/m3) and 1.5 Vf r (0.75% corresponds to 54 kg/m3), respectively; speci- mens P-R and P-1.5R denote concrete mixtures reinforced with monolithic PVA fiber of 1.0 Vf r (0.07% corresponds to 0.9 kg/m3) and 1.5 Vf r (0.105% corresponds to 1.35 kg/m3), respectively; specimens AP-0.5R and AP-0.75R denote concrete mixtures rein- forced with a hybrid of AS and PVA fibers at 0.5 Vf r each (incorporation of 0.25% AS fiber and 0.035% PVA fiber) and 0.75 Vf r each (incorporation of 0.375% AS fiber and 0.053% PVA fiber), respec- tively. A control fiberless mixture (N) was also prepared.

The targeted air content, initial slump, and 91-day compressive strength of the control fiberless concrete were 2.5 ± 0.5%, 200 ± 25 mm, and 30 MPa, respectively. To achieve the designed requirements, a water-to-cementitious material ratio (W=C) of 25% by weight and a fine aggregate-to-total aggregate ratio of 42% by volume were selected for all concrete mixtures. The unit water content was fixed at 155 kg/m3 for all mixtures. A polycarboxylate-based high-range water-reducing agent was added in the amount of 0.5% relative to the unit content of the cementitious materials.

The parameter selected to evaluate the fatigue performance of the prepared HVS-LWC mixtures was the constant maximum stress level (Smax), which varied as 75%, 80%, and 90% of the static uniaxial compressive strength. The constant minimum stress level (Smin) of all concrete mixtures was fixed at 10% of the static strength, regardless of the maximum stress level. During the preliminary tests, concrete specimens under Smax of 70% static strength tended to converge toward the fatigue limit

III. TEST RESULTS AND DISCUSSION

The mixing of concrete A-1.5R failed because of the segregation and ball-bearing phenomena of AS fibers during the mixing. Thus, cylinder molds for compressive testing were not produced for the A-1.5R mixture. The average values, determined from three cylin- drical specimens for each concrete mix, of compressive strength, splitting tensile strength, modulus of elasticity (Ec), and strain at the peak stress are listed in Table 4. The modulus of elasticity was calculated as the slope of the secant line joining zero stress and 40% peak stress, in accordance with ASTM C469 [14]. The control fiberless concrete mix achieved the targeted requirements. In general, the static compressive strength (f'_c) of the prepared concrete mixtures was relatively unaffected by the type and vol- ume fraction of fibers added. Meanwhile, the slump of the fresh concrete tended to decrease with increasing volume fraction and length of the fibers. The AS fiber-reinforced concrete had a higher tensile strength and modulus of elasticity than the PVA fiber- reinforced concrete.

3.1 Crack propagation and failure under cyclic loadings

Initial cracks developed at the mid-height of the specimens and then propagated toward the top and bottom loading points. With the increase in the number (N) of cycles in the cyclic loading, a few vertical macroscopic cracks developed, which generated a wide crack band zone. The rate of crack propagation and the crack band growth tended to be slower in the fiber-reinforced concrete spec- imens than in the control fiberless concrete. The addition of fiber to concrete restricts crack formation and delays crack growth along the interface between the cementitious matrix and the aggregate particles [16]. Therefore, it is commonly recognized that the un- stable growth of cracks during cyclic loading is transformed into slow and controlled growth, depending greatly upon fiber disper- sion, the elasto plastic properties of the cementitious matrix, and the effectiveness of the cementitious matrix-lightweight aggregate bond. On the other hand, the developed macrocracks tended to penetrate the lightweight aggregate particles, as shown in Fig. 2. At the failure of the concrete, pull-out of the AS fibers occurred along the macrocracks (Fig. 3)

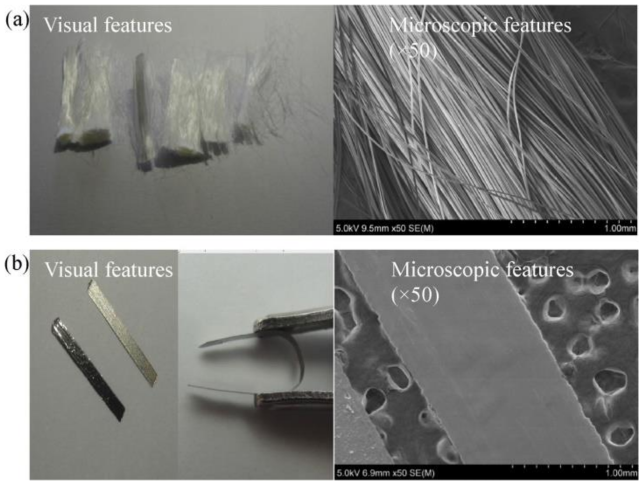

Fig.1.Photographsoffibersused.

whereas the PVA fibers ruptured before being pulled out of the cementitious matrix (Fig. 3). As a result, during cyclic loading, failure of the fiber-reinforced HVS-LWC pri- marily occurred by a combination of fracture of the aggregate and progressive pullout or rupture of fibers along the cracks. This im- plies that the contribution of fibers to the crack restriction would be weakened for LWC as compared with the case of NWC because of weakened aggregate interlocking and macrofiber bridging actions, as shown in Fig. 4. Overall, microfibers are more effective in restricting bond crack propagation along the interface between the cementitious matrix and lightweight aggregates than macrofibers such as AS fibers.

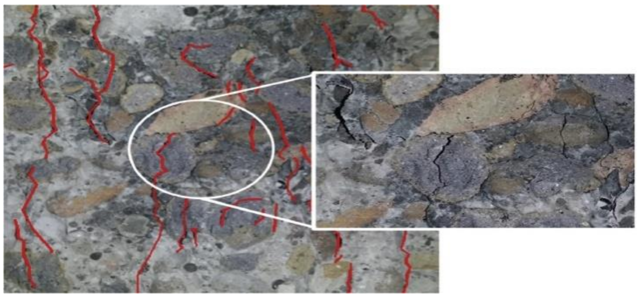

Fig.2.Typicalcrackprofilesalongfailureplaneoffibr elessLWC(specimenN).

The longitudinal cracks in the hybrid fiber-reinforced HVS-LWC propagated more slowly than those in the monolithic fiber- reinforced concrete Also, crack propagation was more rapid and resulted in more cracks with increasing N for AS fiber-reinforced concrete than for PVA fiber-reinforced concrete. The longitudinal crack propagation in aggregate particles can be more effectively controlled by longer fibers than by shorter fibers, as shown in Fig. 4.

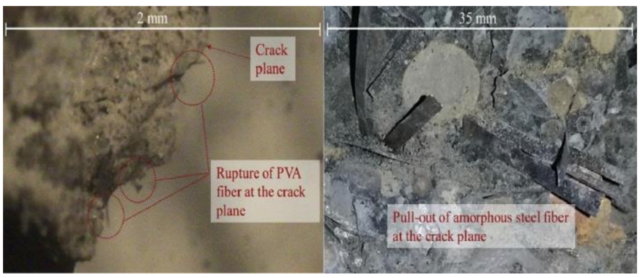

Fig.3.Typicalresistanceoffibersatthecrackplanes.

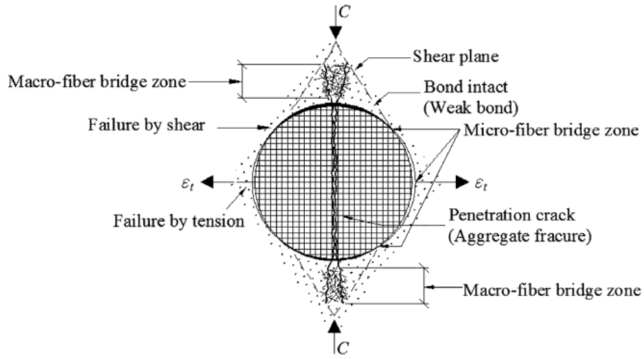

Fig.4.Localstressesandfiberbridgingzonesaroun dthelightweightaggregateparticles.

3.2 Relationship between maximum stress level and fatigue life

Fig. 5 shows a negative linear relationship between Smax and the logarithm of Nf (commonly designated as the SeN curve) measured from each HVS-LWC mixture, where Nf is the fatigue life of the concrete. The effect of the fibers on the increase in Nf can be summarized as follows: 1) The PVA fibers were more effective than the AS fibers; 2) Hybridization of both fibers was preferred tomonolithic use; and 3) These observations were more notable for higher Smax values. The increasing ratios of Nf of the fiber-containing concrete relative to that of fiberless concrete were 1.37, 2.32, and 8.53 for concrete mixtures A-R, P-R, and AP-0.5R, respectively, when Smax was 0.9, whereas those ratios were 1.39, 1.45, and 3.85, respectively, under Smax of 0.75.. In terms of restricting and slowing microcrack growth, micro-fibers are preferable to macrofibers with a larger diameter owing to the better dispersion characteristics of microfibers at the interface

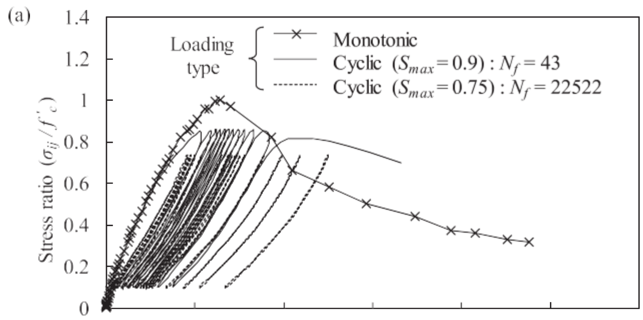

Fig.5.Fatiguestressestraincurvesofthepreparedc oncretespecimens

IV. CONCLUSIONS

To evaluate the fatigue life and fatigue damage of fiber- reinforced high-volume SCM lightweight concrete (HVS-LWC) subjected to uni-axial compression, the stressestrain response was examined under cyclic loading with constant stress ranges. The proposed conclusions given below may be somewhat tentative owing to the numerous influences on the fatigue performance of fiber-reinforced lightweight concrete. Furthermore, the available fatigue test data on fiber-reinforced LWC are very limited because the test procedure is difficult owing to long run-times and un- common mixing of such concrete. Hence, the effect of fibers on the fatigue response of HVS-LWC needs to be further examined, with a focus on additional parameters such as fiber properties and loading conditions, including load frequency and stress range. From the present elementary investigation, the following conclusions were drawn:

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