Effect of Perlite Addition on Fracture Properties of Discontinuous Fiber-reinforced Cementitious Composites Manufactured by Extrusion Molding

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ABSTRACT: We investigated the effect of perlite addition on poly vinyl alcohol (PVA) reinforced cementitious composites manufactured by extrusion molding. The PVA fiber composites of Perlite/C=10% and W/C=80% produced pseudo strain-hardening behavior with multiple cracking, and their ultimate tensile strain of this PVA fiber composite reached 2.2%. It was demonstrated that multiple cracks in the composite became invisible on naked eyes, possibly due to the matrix microstructure modified by the addition of perlite.

Keywords: Extrusion molding, Perlite, Poly vinyl alcohol fiber, Multiple cracking

1 INTRODUCTION

Extrusion molding is one of the important industrial production methods of discontinuous fiber reinforced cementitious composites (Shah & Shao, 1994, Shao et al. 1995, Stang & Li 1999). Extruded structural components have currently been used as exterior walls and decorative parts of residences. If extruded structural components are toughened, they would find wider applications, for example, in seismic resistant parts and permanent formworks.

One of the most effective ways for improving the ductility of cementitious composites is the use of multiple cracking phenomenon induced by fiber reinforcement. The multiple cracking phenomenon produces pseudo strain-hardening behavior characterized by a sustained and increasing load capacity after first matrix crack (Aveston & Kelly 1973).

In the process of extrusion molding, discontinuous fiber reinforced composites are typically prepared by an extruder from a mixture containing the ordinary Portland cement, fine silica powder, discontinuous fibers and molding aid agents. The mixture is mechanically compressed during the extrusion process, and thus the extruded composite tends to has higher matrix toughness. However, the higher matrix toughness tends to result in a smaller strain capacity of the discontinuous fiber reinforced composite. It has been shown that lower matrix toughness and higher interfacial friction bond strength are beneficial for toughening of fiber reinforced cementitious composites by multiple cracking with small fiber volume fractions (Wu & Li 1994).

In this paper, we investigated the effect of perlite addition on poly vinyl alcohol (PVA) discontinuous fiber reinforced cementitious composites manufactured by extrusion molding. The objective of the perlite addition is to modify and control the matrix toughness and microstructure. Perlite is one of the artificial light weight aggregates with lower fracture strength and may be expected to serve as extremely small defects in the matrix. We prepared PVA fiber extruded composites with different fiber and water contents to examine the effect of the matrix toughness on the fracture properties of the extruded fiber composites. Direct tension tests were carried out to determine the fracture properties such as ultimate tensile strength and strain of the PVA fiber extruded composites.

2 EXPERIMENTAL PROCEDURE

2.1 *Materials*

The mix proportion used to form a matrix is as follows; ordinary Portland cement: fine silica powder: methyl cellulose: pulp: mineral fiber = 1.00:0.60:0.02:0.01:0.05. The Perlite/C and W/C ratios of the matrix are shown in Table 1. All the mix proportions shown in the table are by weight of the ingredients. Density of the perlite used in this study is 0.2-0.3g/cm^3 and the largest size of the perlite particle is 0.6mm. The objective of incorporating pulp is to maintain the extruded shape. The pulp was used as Laubholz Bleached Kraft Pulp with the diameter of approximately 25 μm and the length of approximately 0.5mm. The purpose of mineral fiber and methyl cellulose addition is to enhance the slip property of the raw materials mixture. The mineral fiber was used as magnesium silicate hydrate with the diameter of approximately 2 μm and the length of approximately 0.4mm. PVA discontinuous fibers with constant fiber volume fraction (3 volume %) were employed in this study. The fiber dimensions and properties are shown in Table 2.

2.2 *Specimen Preparation*

Firstly, the raw materials were mixed for three minutes without water by an Eirich mixer. Water was then added into the mixture and mixed for two minutes. Next, the mixture is kneaded for three minutes by a kneader with two blades. The kneaded mixture was used to prepare the extruded fiber composites. The extrusion molding was conducted using a ram extruder as shown in Figure 1.

Table 1. Matrix mix proportion (percentage by weight with respect to ordinary portland cement)

	1	2	3	4	5	6	7	8
Perlite	0	5	10	20	0	5	10	20
Water	60	60	60	60	80	80	80	80

Table 2. PVA fiber dimensions and properties

Diameter	Length	Tensile strength	Young's modulus	density
mm	mm	MPa	GPa	g / cm^3
0.0379	6	1650	43.7	1.3

Figure 1. Procedure of extrusion.

The extruded samples had the cross section of 80mm × 15mm. The extruded specimens were cut into a length of 250mm perpendicular to the extrusion direction. The specimens of the extruded composites were steam-cured for five hours at 70˚C. All the specimens were machined into a rectangular coupon of size 230mm × 40mm× 15mm.

2.3 *Testing Procedure*

The tensile behavior of extruded composites was determined by conducting uniaxial tension tests as shown in Figure 2. The coupon specimens were tested under displacement control in a 50kN material testing system. The displacement rate used was

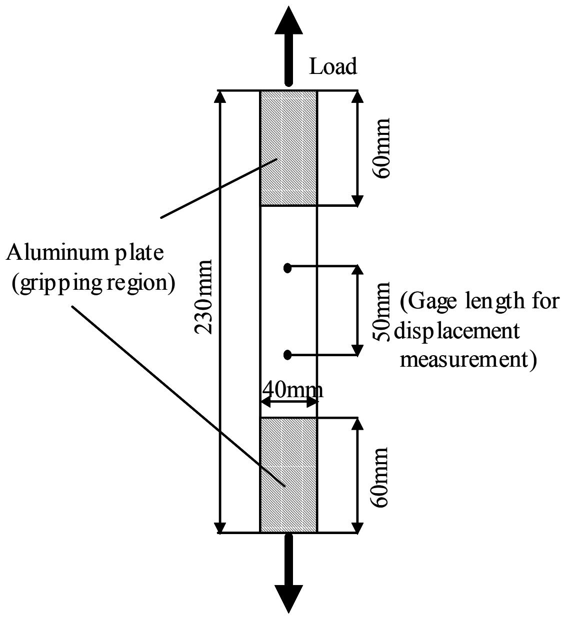

Figure 2. Specimen configuration of tension test.

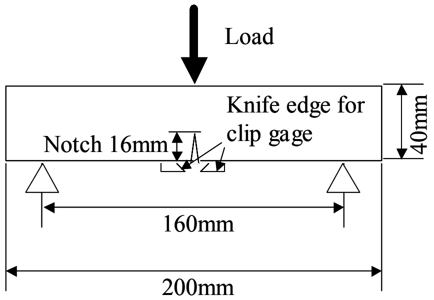

Figure 3. Specimen configuration of fracture toughness test.

0.5mm/min. For gripping purpose, aluminum plates were glued by epoxy resin onto the ends of the tension specimens. A linear variable differential transducer was used to measure the displacement between two points on the specimen at a gage length of 50mm.

3 point bending tests were conducted to determine the fracture toughness of the matrix K_m and Young's modulus of matrix E_m, following ANSI/ASTM E 399 (Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials). The dimensions of the 3-point bending specimens are shown in Figure 3. A pre-notch was introduced by a diamond wheel saw, and the tip of the pre-notch was sharpened with a silicon carbide blade. The notch tip radius was approximately 0.15 mm. The specimens were loaded until a fast fracture took place. The crack opening displacement was monitored by a displacement transducer (clip gage) in addition to the applied load. Three specimens were tested for the each mix proportion and the results were averaged. The experimental data presented in the following sections are averaged data.

3 RESULTS AND DISCUUSION

3.1 *Matrix toughness*

Figure 4 shows the effects of Perlite/C and W/C on the extruded matrix toughness. The matrix toughness decreases with increasing Perlite/C from 0 to 20%, probably reflecting the introduction of small defects due to perlite addition. As expected, the matrix toughness also decreases when the higher W/C ratio was used in the matrix.

In principle, the objective of incorporating perlite into extruded cementitious materials is to produce a light-weight product. On the other hand, the breakage of perlite was observed on the fracture surface of the fracture toughness specimens by scanning electron microscope (SEM) observations. The perlite used in this study has an extremely porous microstructure and then low fracture strength. Thus, incorporating perlite into the matrix seems to result in the increase of initial defect population as well as the decreased weight.

3.2 *Fracture properties of PVA fiber composites*

Figure 5 shows tensile stress versus strain curves of the PVA fiber reinforced composites for perlite/C=0, 5, 10 % and W/C=80%. It is seen that the PVA fiber composites of Perlite/C=0% and

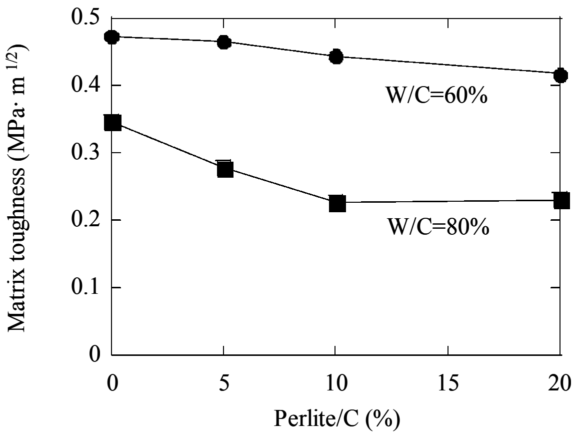

Figure 4. Matrix toughness.

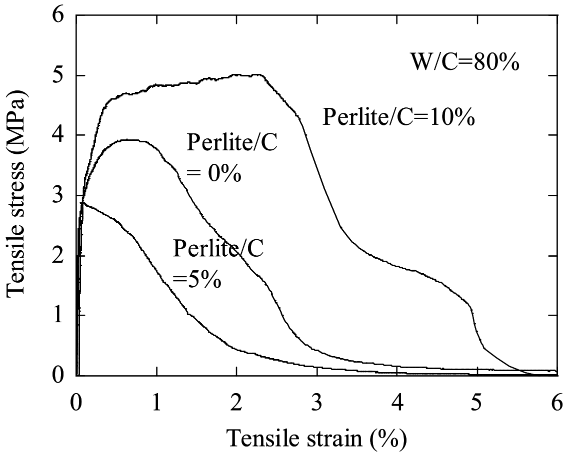

Figure 5. Tensile stress vs. strain curves of PVA fiber composites.

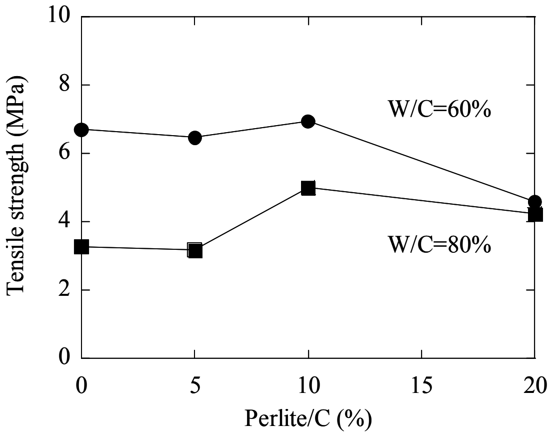

Figure 6. Tensile strength of PVA fiber composites.

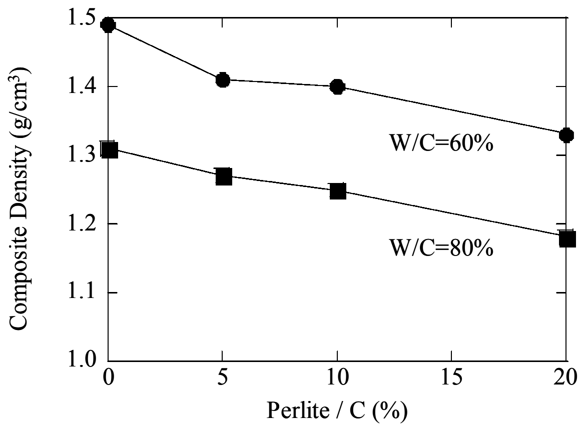

Figure 8. Density of PVA fiber composites.

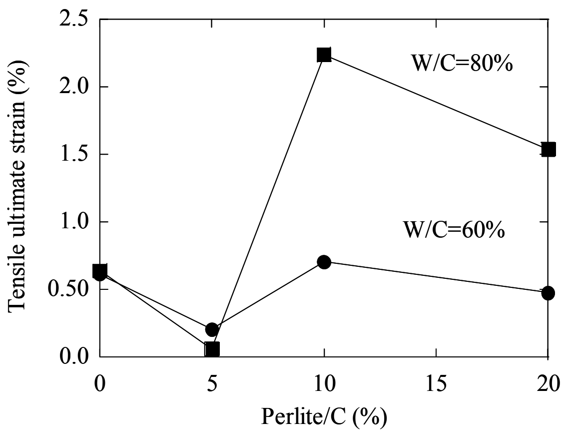

Figure 7. Tensile ultimate strain of PVA fiber composites.

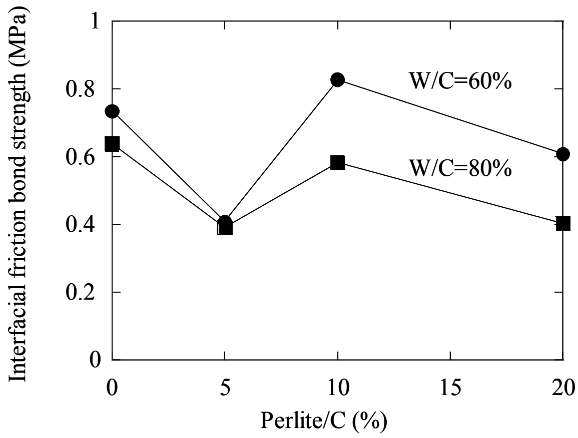

Figure 9. Interfacial friction bond strength.

W/C=80% show pseudo strain-hardening behavior induced by multiple cracking. In contrast, the fracture behavior for Perlite/C=5% is characterized by the formation and propagation of a single crack, even though the composite shows a gradual stress decrease after the peak stress due to the fiber bridging action. The PVA fiber composites of Perlite/C=0, 10%, 20% and W/C=60, 80% have also shown pseudo strain-hardening behavior. For all the PVA fiber composites, complete fiber pull-out was observed.

Figure 6 and 7 show the tensile strength and ultimate tensile strain of the PVA fiber composites, respectively. In the case of W/C=80%, the tensile strength increases for the Perlite/C ratios greater than 10%, whereas the tensile strength is kept approximately constant up to 10% and decreases slightly at 20% for W/C=60%. By the addition of perlite, the ultimate tensile strain of the PVA fiber composites are improved or maintained with respect to the matrix only, except for Perlite/C=5%. The strain capacity decreases significantly in the case of Perlite/C=5% for both the W/C ratios. It is seen that the strain capacity of the PVA fiber composites can be significantly enhanced with the Perlite/C ratios greater than 10% and W/C ratio of 80%.

Figure 8 shows the density of the PVA fiber composites prepared in this study. It is noted that the density of the PVA fiber composites which give highest strain capacity is less than 1.25g/cm^3. The comparison between Figures 6 through 8 suggests that the addition of perlite into the matrix is useful in the improvement of the fracture properties as well as for weight-saving of the PVA fiber composites.

In principle, the interfacial friction bond strength should be determined by conducting a single fiber pull out test (Li & Chan 1994, Kanda & Li 1998, Easley et al. 1999). In this study, an estimate of the interfacial friction bond strength τ was obtained from the uniaxial tension tests indirectly. As detailed in the reference (Takashima et al. 2003), an estimate of the interfacial friction bond strength can be obtained from measurements of fracture energy based on micromechanics models for aligned fiber composites.

Figure 9 indicates the interfacial friction bond strength of the PVA fiber composites, as estimated by the above-mentioned indirect method. As expected, the lower W/C ratio yields higher interfacial strength. It is shown that the Perlite/C ratio of 5% gives the lowest interfacial friction bond strength for both the W/C ratios of 60% and 80%. While the lower interfacial strength for Perlite/C=5% may explain the decreased strain capacity of the PVA fiber composite, the reason for the decreased interfacial strength at the specific Perlite/C ratio is unclear at present and should be studied in detail. It can be noted that the Perlite/C ratios greater than 10% are effective in order to increase or maintain the interfacial strength with respective to the one without perlite addition (Perlite/C=0%).

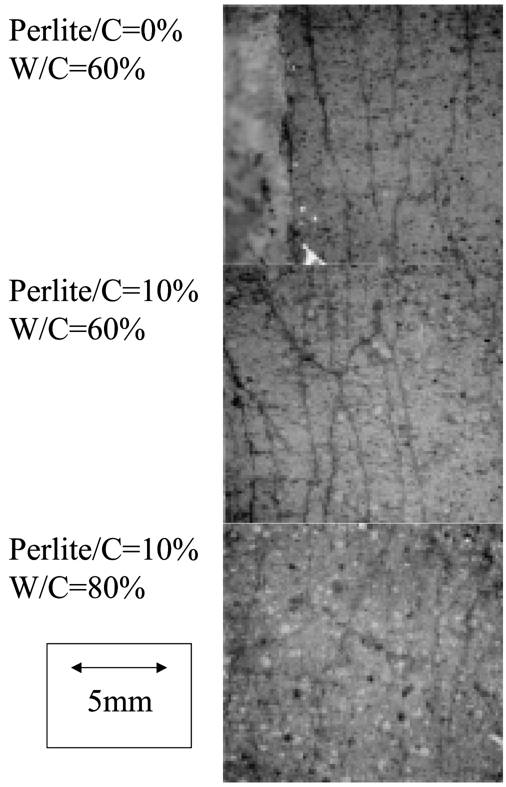

Figure 10. Multiple cracking.

Even though the W/C ratio of 80% gives the lower interfacial strength, the water content provides the higher ultimate tensile strain compared with that for 60%. In general, lower matrix toughness is beneficial for inducing multiple cracking and for increasing strain capacity of the fiber composite. Thus, the higher strain capacity obtained for W/C=80% suggests that the toughening effect due to the reduction of the matrix toughness overrides the effect of the interfacial strength decrease for the PVA fiber composites prepared in this study. The highest strain capacity for W/C=80% and Perlite/C=10% may be due to the fact that the interfacial strength reduction is suppressed under the processing condition.

3.3 *Invisible multiple cracking*

As shown above, the ultimate tensile strain provides a maximum value and reaches 2.2% in the PVA fiber composites with Perlite/C=10% and W/C=80%, most likely due to multiple cracking. However, it was demonstrated that no multiple cracks was observed by visual inspection on the specimen surface of the PVA fiber composite.

In order to facilitate the observation of induced multiple cracks, the PVA fiber composite specimens were impregnated with epoxy resin and observed under an optical microscope.

Figure 10 shows microscopic observations of the specimen surface of the selected PVA fiber composites. In the PVA fiber composite of W/C=60 % with Perlite/C=0% and 10%, the sub-parallel multiple cracks can be readily observed. However, it is difficult to observe the cracking behavior in the PVA composite with Perlite/C=10% and W/C =80 % by optical microscopy. It is interesting to note that the processing condition, which provides the highest strain capacity, produces pseudo strain-hardening behavior with invisible multiple cracking. Thus, the addition of perlite appears to be useful not only to enhance the strain capacity of the composite, but also to suppress the visibility of multiple cracking. Although the perlite addition is expected to alter the optical microstructure of the matrix, the cause for the invisibility is unknown at present.

Takashima et al. (2003) have already reported that theoretically the critical fiber volume fraction for multiple cracking can be obtained from eq. (1).

$$V_f \geq V_{f,crit} = \frac{6d_f^2 E_f}{\tau^2 L_f^3 (1+\eta)} J_{tip} \qquad (1)$$

where, d_f, = fiber diameter, L_f = fiber length, τ = an interfacial friction bond strength. The elastic modulus of matrix and fiber are E_m, E_f, respectively and the volume fraction matrix and fiber are V_m, V_f, respectively. $\eta \equiv (V_f\ E_f\ /\ V_m\ E_m)$. η is the parameter given by $V_f\,E_f\,/\,V_m\,E_m$.

The crack tip toughness J_{tip} in eq. (2) may be approximated as:

$$J_{tip} \approx \frac{K_m^2}{E_m} \qquad (2)$$

The fiber parameters used for the computation of critical fiber volume fractions are shown in Table 2. The data shown in Figures 4 and 9 are used for the matrix toughness, and interfacial friction bond strength, respectively. In the computation of critical

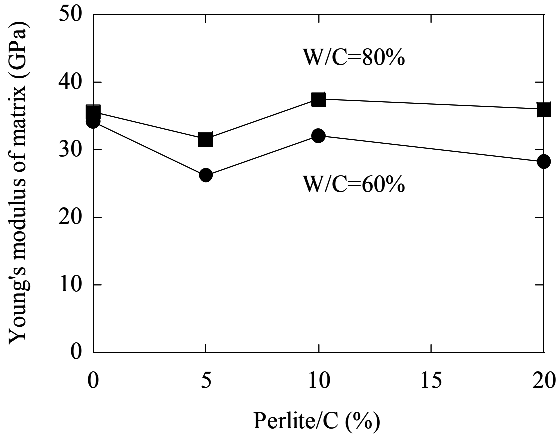

Figure 11. Young’s modulus of matrix.

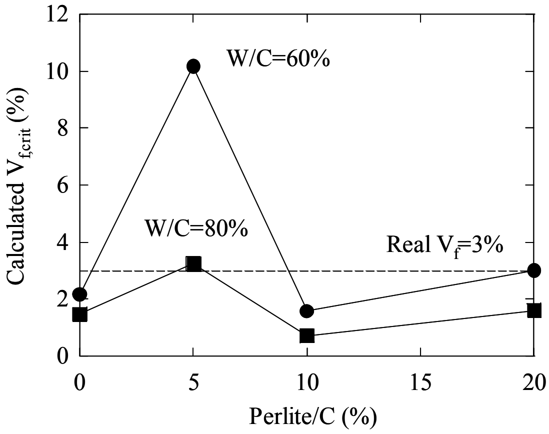

Figure 12. Verification of the critical fiber volume fraction for multiple cracking.

fiber volume fraction, the influence of perlite addition is lumped into the matrix toughness. The Young’s modulus of matrix was evaluated from the experimental results of the fracture toughness tests conducted on three point bending specimens of the matrix only. The initial slope of load versus crack opening displacement and the existing compliance data for the specimen geometry was used to determine the matrix Young’s modulus as a function of the W/C and Perlite /C ratios. The computed results are shown in Figure 11.

Figure 12 summarizes the critical fiber volume fraction for multiple cracking, calculated using eqs. (1) and (2). In this study, we prepared the PVA fiber composites with fiber volume fraction of 3%. It is shown that the critical fiber volume fraction predicted by the micromechanics model reasonably agrees with the experimental results. The micromechanics model has been verified for PVA fiber composites without perlite addition in our previous study. Therefore, the agreement of the micromechanics prediction with the experimental observation for the Perlite/C=10% and W/C=80% may support the occurrence of invisible multiple cracking in the PVA fiber composite.

3.4 *Comparison with tensile properties of extruded composite*

The density of our extruded composites has been measured to be 1.18-1.49g/cm^3. There are a limited number of papers which describe both fracture

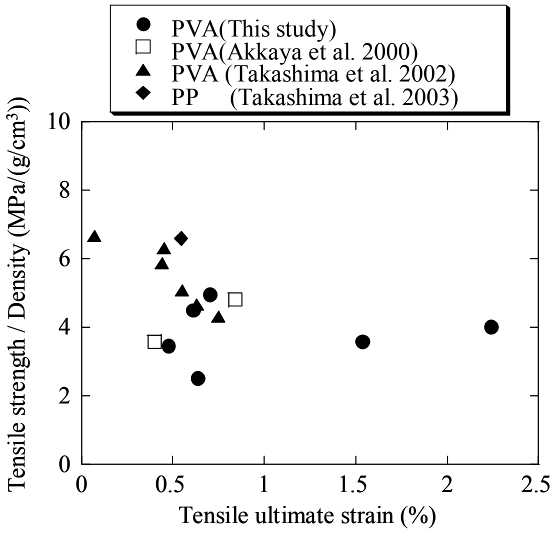

Figure 13. Comparison of tensile properties of extruded composites.

properties of fiber reinforced extruded composites and composites density. Akkaya et al. (2000) reported fracture properties of their PVA fiber composites using different lengths of fibers. Their composite density is 1.89-2.05g/cm^3. Figure 13 shows a comparison with the ultimate tensile strength and strain of the PVA fiber reinforced extruded composites among Akkaya's data and our data in this study and we have already reported (Takashima et al. 2002 and Takashima et al. 2003). The ultimate tensile strength of the extruded composites is divided by the composite density in order to reveal the effect of density. Akkaya's data for the PVA fiber composite is as follows: fiber diameter = 0.014mm, fiber length = 6mm and 2mm, fiber tensile strength = 1900MPa, Young's modulus = 41GPa and fiber volume fraction=3%. It is noted that the PVA fiber composites prepared in this study provides significantly higher strain capacity than that of Akkaya's and our previous composites, although the specific tensile strength of the present composites gives comparable or lower values relative to the previous data. Thus, it appears that the addition of perlite is useful in particular to enhance the strain capacity of the fiber composites.

4 CONCLUSIONS

In this study, we investigated the effects of perlite addition on the fracture properties of PVA fiber reinforced cementitious composites by extrusion molding. The matrix toughness was controlled by changing W/C and Perlite/C ratios. Direct tension tests of the PVA fiber composites showed that the addition of perlite is effective to improve particularly the composite strain capacity. The improvement was shown to be caused by the reduced matrix toughness due to the perlite addition. The maximum ultimate strain reached 2.2% in the PVA composite with W/C=80% and Perlite/C=10%.

Furthermore, it was demonstrated that the above processing condition suppressed the visibility of the multiple cracks induced in the PVA fiber composite, in spite of the enhanced strain capacity. The present preliminary study suggests the usefulness of adjusting the perlite content in producing lightweight fiber composites as well as in enhancing the composite fracture properties.

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