FRACTURE TOUGHNESS MODEL FOR POLY(VINYL ALCOHOL) FIBER REINFORCED HIGH-PERFORMANCE CEMENTITIOUS MATERIAL

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ABSTRACT: This study focuses on the development of a lightweight high-performance cementitious composite material which is reinforced with Poly(vinyl alcohol) (PVA) fiber and contains Poly(vinyl butyral) (PVB) as the sole aggregate. A model based on fiber bridging mechanics and the rule of mixtures is developed to characterize fracture toughness. Comparisons are made with a lightweight concrete having equal density, and a normal-weight concrete. In general, the fracture toughness increases linearly with increasing fiber volume fraction. A good correlation is obtained for each of the three materials tested when experimental results are compared to those predicted by the model.

Keywords: high-performance, PVB, PVA fiber, fracture toughness

1. INTRODUCTION

1.1 PVB- Cementitious Composite

Prior research has shown that by employing Poly(vinyl butyral) (PVB) as a total replacement for aggregate and using PVA fiber as reinforcement, cementitious composite materials display strong interactions at the molecular level; resulting in improved ductility, impact resistance, and fracture toughness with increasing fiber volume fraction [1].

Poly(vinyl butyral) (PVB) is a member of the class of poly(vinyl acetal) resins commercially prepared by a well-known reaction between aldehydes and alcohols [2]. The resulting polymer is a terpolymer of varying amounts of PVB, polyvinyl alcohol (PVA), and polyvinyl acetate. The presence of hydroxyl groups in the polymer molecule furnishes a reactive site for chemical combination with thermosetting resins. Furthermore, the presence of acetate and relatively non polar rings provides a mixed hydrophilic hydrophobic character and a good mechanical property and the ability to interact with the C-S-H matrix.

PVA fiber, contains hydroxyl groups that bond well with the cementitious matrix. The formation of the resulting microstructure has been attributed to the effect that PVA has on the nucleation of CH and C-S-H at the fiber surface and on the presence of polymer around fibers placed in sand used as fine aggregate [3]. PVA fiber also has other very attractive characteristics, such as high strength, high modulus, and low gravity [4].

The presence of the hydroxyl groups in both PVB and PVA fiber provides electrostatic attractive and hydrogen bonding interactions on the molecular scale. These interactions enable remarkable changes in the surface bond strength, not only between the aggregate and the matrix, but also between the fiber reinforcement and the matrix and its aggregates. Additionally, the ether oxygen functional group acts as a weak base and can interact with lewis acids and electropositive materials such as CSH or magnesium.

1.2 Development of Fracture Toughness Model

The resistance to fracture of a material is known as its fracture toughness. The latter can be considered as a stress-based estimation derived from a function of the applied force and a specimen's geometry. Linear elastic fracture mechanics (LEFM) may be employed but this method is valid only as long as nonlinear material deformation is confined to a small region surrounding the crack tip.

There are other methods that can be used to estimate the fracture toughness, such as crack-tip-opening displacement (CTOD) and the J-integral formulation [5]. These methods are used to assess the elastic-plastic behavior of materials such as metals and alloys by considering crack-tip plasticity.

But, because there is almost no plasticity developed in a brittle material such as concrete, a stress-based estimation of fracture toughness is developed herein. The formulation is based on a well known concept called the "rule of mixtures" [6]. Although, many models have been developed based on this concept to calculate the tensile stress of fiber reinforced composites [7-9] little attention has been paid to models involving fracture toughness.

2. THEORETICAL BACKGROUND

2.1 Ultimate Tensile Strength by Fibers

Li, V.C. et al. [10, 11] showed that the ultimate tensile strength of a fiber reinforced composite is a function of the fiber, the interface between the fiber and the matrix, and the matrix characteristics. The following equation was derived based on a micromechanical model involving the bridging mechanism of randomly oriented short straight fibers:

$$\sigma_t = \frac{1}{2} V_f g \tau \left(\frac{L_f}{d_f} \right) \tag{1}$$

where V_f, L_f, and d_f are the fiber volume fraction, length of fiber, and the diameter of the fiber, respectively. τ is the fiber/matrix frictional bond strength; and, g is a set of interface parameters developed for different fiber types as follows:

$$g = \frac{2}{\left(4 + f^2\right)} \left(1 + e^{f\pi/2}\right) \tag{2}$$

In Eq. 2, f is a snubbing coefficient that must be determined experimentally for a given fiber/matrix system.

The fiber volume fraction can be calculated from the following equation:

$$V_f = \frac{\rho_m W_f}{\rho_f W_m + \rho_m W_f} \tag{3}$$

where W_f is the weight of fibers; W_m is the weight of the matrix; ρ_f is the density of the fibers; and ρ_m is the density of the matrix.

Optimization of the interfacial bond strength can only be achieved when the fiber has a length large enough to provide resistance to fiber pull-out and a sufficiently high fiber modulus of rupture to avoid fiber fracture [12]. If the fiber length used in the mix design is less than a critical length, fiber pull-out will occur. If the fiber length is longer than the critical fiber length, then fiber rupture will be the primary mode of failure.

2.2 Rule of Mixtures

At low strains, where the fibers and the matrix behave elastically, the composite modulus, E, is determined by a modulus balance which weights the fiber modulus, E_f, and matrix modulus, E_m, by their corresponding volume fractions V_f and V_m, respectively. Mathematically,

$$E = E_f V_f + E_m V_m \tag{4}$$

Eq. 4 is the well known rule-of-mixtures (ROM) for the tensile modulus of a composite material and is applicable when the reinforcing fibers are both continuous and well aligned with stress applied along the direction of the fibers [13]. Equation 4 may be reformulated to reflect the fact that the matrix and fiber develop the same strain, ε, as follows:

$$\sigma = \sigma_f V_f + \sigma_m V_m \qquad (5)$$

Keeping in mind that:

$$V_m = 1 - V_f \qquad (6)$$

Eq. (5) becomes:

$$\sigma = \sigma_f V_f + \sigma_m \left(1 - V_f\right) \qquad (7)$$

2.3 Matrix Fracture Toughness

The matrix fracture toughness of plain concrete can be calculated using ASTM E 399 [14], Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{1c} of Metallic Materials, as follows:

$$K_m = \frac{PS}{BW^{1.5}} f\left(\frac{a}{W}\right) \qquad (8)$$

where, P is the load applied to a single edge notch bending (SENB) specimen; S is the distance between the supports; B is the specimen width; W is the specimen thickness; a is the notch length; and, $f(a/W)$ is a shape function calculated as follows:

$$f\left(\frac{a}{W}\right) = \frac{3\frac{S}{W}\sqrt{\frac{a}{W}}}{2\left(1+2\frac{a}{W}\right)\left(1-\frac{a}{W}\right)^{1.5}} \qquad (9)$$
$$\left\{1.99 - \frac{a}{W}\left(1-\frac{a}{W}\right)\left[2.15 - 3.93\left(\frac{a}{W}\right) + 2.7\left(\frac{a}{W}\right)^2\right]\right\}$$

The shape function is developed based on a finite element analysis; solutions of this type are typically fit to a polynomial expression [5].

3. FRACTURE TOUGHNESS MODEL

In prior work done on PVB/PVA materials, observations made in failed specimens revealed that many of the fibers remained intact; indicating that they pulled away from the matrix [1]. Thus, it can be construed that failure occurs as a result of fiber pull-out, where the fiber length used in the mix design is less than the critical fiber length.

Specifically, at the beginning of the loading process the matrix and fiber work together to resist the tensile stress. In this case, the stress is transferred from the matrix to the fiber via the fiber/matrix interface. But when loads are increased to the point at which the matrix begins to crack, the stress is transferred to the fibers alone. Since the fibers have a higher tensile strength than the friction bond strength at the interface, they pull out of the matrix and failure occurs.

The tensile stress of the composite at mid-span in the SENB is given by Eq. 7 where the term $(\sigma_f V_f)$ represents the contribution made by the fibers. Assuming that pull-out dominates failure, this contribution may be described by Eq. 1. Making the appropriate substitution:

$$\sigma = \frac{1}{2} V_f g \tau \left(\frac{L_f}{d_f}\right) + \sigma_m \left(1 - V_f\right) \qquad (10)$$

In Eq. 10, σ is the tensile stress of the composite which can be calculated according to beam theory as:

$$\sigma = \frac{M \cdot c}{I} \qquad (11)$$

where c is the distance from the neutral axis to the extreme tensile fiber. Referring to the test and parameters described in conjunction with Eq. 8,

$$c = \frac{W - a}{2} \tag{12}$$

Consequently, Eq. 11 can be written as:

$$\sigma = \frac{M \cdot c}{I} = \frac{M \cdot \frac{W - a}{2}}{I} = \frac{PS(W - a)}{8I} \tag{13}$$

where P is the force at mid-span, S is the length of the free span, W is the height of the beam, and I is the centroidal moment of inertia parallel to the axis about which the moment is applied. The maximum tensile stress that the matrix can sustain is equal to:

$$\sigma_m = \frac{P_0 S(W - a)}{8I} \tag{14}$$

where P_0 is the failure load of a specimen placed without fiber.

Substituting Eqs. 13 and 14 into Eq. 10 yields:

$$\frac{PS(W - a)}{8I} = \frac{P_0 S(W - a)}{8I}\left(1 - V_f\right) + \frac{1}{2} V_f g \tau \left(\frac{L_f}{d_f}\right) \tag{15}$$

Thus, P can be expressed as,

$$P = \frac{8I}{(W - a)S}\left[\frac{P_0 S(W - a)}{8I}\left(1 - V_f\right) + \frac{1}{2} V_f g \tau \left(\frac{L_f}{d_f}\right)\right] \tag{16}$$

where the centroidal moment of inertia is calculated as follows:

$$I = \frac{1}{12} B(W - a)^3 \tag{17}$$

Substituting Eqs. 16 and 17 into Eq. 8 leads to the following expression for the fracture toughness:

$$K_{Ic} = \frac{2(W - a)^2}{3SW^{0.5}}\left[\frac{3P_0 S}{2B(W - a)^2}\left(1 - V_f\right) + \frac{1}{2} V_f g \tau \left(\frac{L_f}{d_f}\right)\right] f(a/W) \tag{18}$$

where $f(a/W)$ is the shape function expressed in Eq. 9.

4. EXPERIMENTAL TESTING

4.1 Fracture Toughness

Fracture toughness tests were performed on single edge notch bending (SENB) specimens accordance with ASTM E399 [14]. As illustrated to the left in Fig. 1, the test specimens measured 23×46×203 mm (0.9x1.8x8.0 in.). They had a notch height to beam height (a/W) ratio equal to 0.5 and a free span to beam height ratio of 4.0.

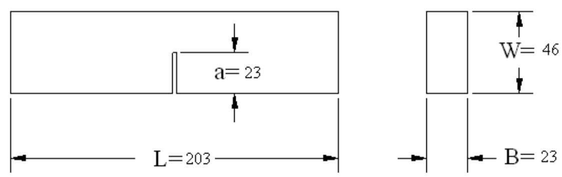

Fig. 1 Dimensions for SENB specimens (mm).

Referring to the photograph shown in Fig. 2, specimens were tested in three-point bending, at a loading rate of 33 MPa-m$^{0.5}$/min (30 ksi-in$^{0.5}$ /min).

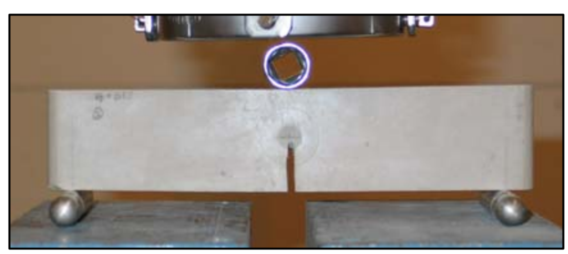

Fig. 2 Specimens were tested in three-point bending.

Fracture toughness values for the three materials tested, with and without fiber, are listed in Fig. 3. The points represent average values for three different specimens.

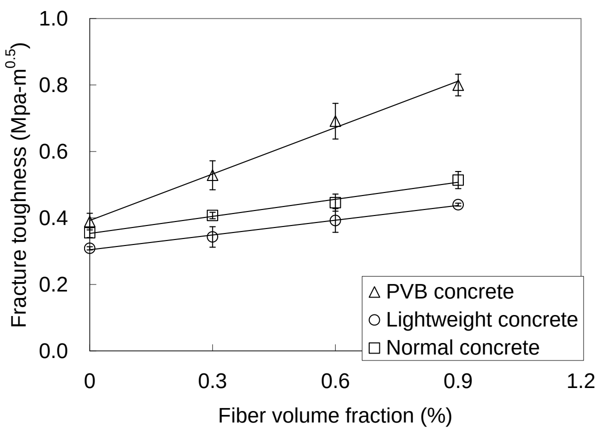

Fig. 3 Fracture toughness with fiber volume fraction.

In general, the increase in fracture toughness is linear with increasing fiber volume fraction. It is evident for mixes without fiber that the fracture toughness of lightweight concrete and normal weight concrete is slightly lower than that of the PVB composite material. Note that the improvement of fracture toughness with the addition of PVA fiber is significantly greater when compared with the other two groups at the same fiber volume fraction.

Specifically, the fracture toughness of the PVB composite was 0.389, 0.528, 0.691 and 0.800 MPa-m$^{0.5}$ (0.354, 0.481, 0.629 and 0.728 ksi-in$^{0.5}$) for fiber volume fractions of 0, 0.3, 0.6, and 0.9%, respectively, resulting in improvements ranging from 37% to 108%. This trend indicates that the PVB composite has higher interfacial bond strength as compared to the other two materials.

4.2 Flexural Stress and Interfacial Bond Strength

In order to calculate the fracture toughness from Eq. 18, it is necessary to obtain the interfacial bond strength, τ. The latter is defined as the friction between the fiber and the matrix and this is affected by many factors.

Although, the ultimate tensile strength is not measured directly herein, it can be estimated by the modulus of rupture *R*. Moreover, it is assumed that the tensile strength and the modulus of rupture of fiber reinforced concrete are very similar to those of plain concrete, since the volume fractions are relatively low (<2%) [15].

As discussed in Sect. 3, the tensile stress at the extreme fiber in the mid span can be expressed as the summation of the tensile stress of the matrix and the fiber. Hence, the interfacial bond strength can be obtained from Eq. 10, provided that a flexural test is done to obtain the flexural stress, σ_m.

To that end, and as illustrated in Fig.4, the flexural stress was measured by placing test specimens in third point bending. The specimens, which measured 70×25×210 mm (2.75x1x8.25 in.), were loaded at a rate of 667 N/min (150 lb/min), corresponding to a stress increase at the bottom surface (tensile side of the beam) of 2.1 MPa/min (308 psi/min).

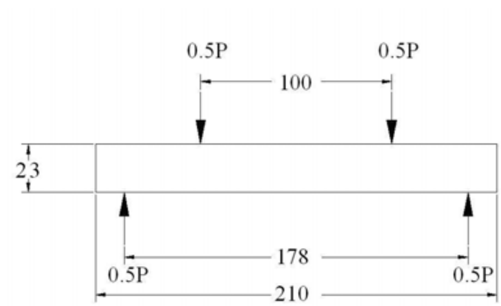

Fig 4. Experimental set up for third point bending (mm).

Figure 5 shows the flexural stress for the three materials tested, with and without fiber. In general, this quantity increases with volume fiber fraction. The increase is more significant in the PVB composite, as compared to lightweight and regular concrete.

Table 1 shows the shear bond strength for the three materials tested, with and without fiber. It is evident that the PVB mix has a higher interfacial bond strength than that of lightweight and normal concrete.

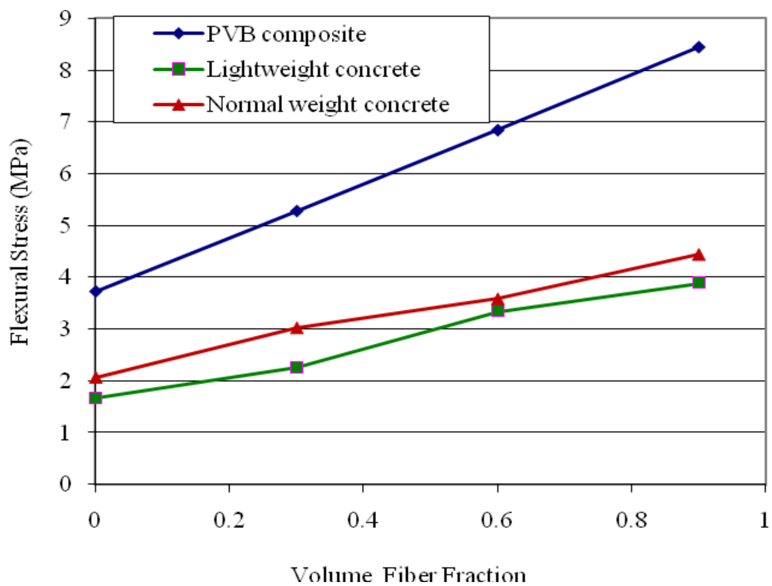

Fig. 5. Flexural stress vs. volume fiber fraction.

Table 1. Interfacial bond strength.

	Flexural stress σ (MPa)				g*	L_f/d_f	τ (MPa)
	V_f=0%	V_f=0.3%	V_f=0.6%	V_f=0.9%			
PVB composite	3.73	5.28	6.84	8.44	1.5	200	3.46
Lightweight concrete	1.67	2.26	3.35	3.89	1.5	200	1.61
Normal weight concrete	2.06	3.02	3.58	4.44	1.5	200	1.86

* According to Li.[16]

5. EXPERIMENTAL VS. ANALYTICAL RESULTS

Table 2 shows the results of the fracture toughness data calculated from Eq. 18 expressed as a function of the fiber volume fraction.

Table 3 lists the theoretical results obtained from these expressions along with the average values obtained from the tests. Figure 6 includes data taken from all specimens (3) of each type, clearly illustrating that the results from the model compare well with the test data.

Table 2. Theoretical fracture toughness.

	P_0 (N)	g*	L_f/d_f	τ (MPa)	K_{Ic} (MPa-m$^{0.5}$)
PVB composite	178.4	1.5	200	2.82	0.39+48.8V_f
Lightweight concrete	141.6	1.5	200	1.31	0.31+22.6 V_f
Normal weight concrete	163.1	1.5	200	1.52	0.36+26.1 V_f

* According to Li.[16]

Table 3. Comparison of fracture toughness.

	Source	Fracture toughness (MPa-m$^{0.5}$)			
		V_f=0%	V_f=0.3%	V_f=0.6%	V_f=0.9%
PVB concrete	Calculation	0.389	0.535	0.682	0.828
	Test	0.389	0.528	0.691	0.800
Lightweight concrete	Calculation	0.309	0.377	0.445	0.512
	Test	0.309	0.343	0.392	0.440
Normal weight concrete	Calculation	0.356	0.434	0.513	0.591
	Test	0.355	0.407	0.446	0.514

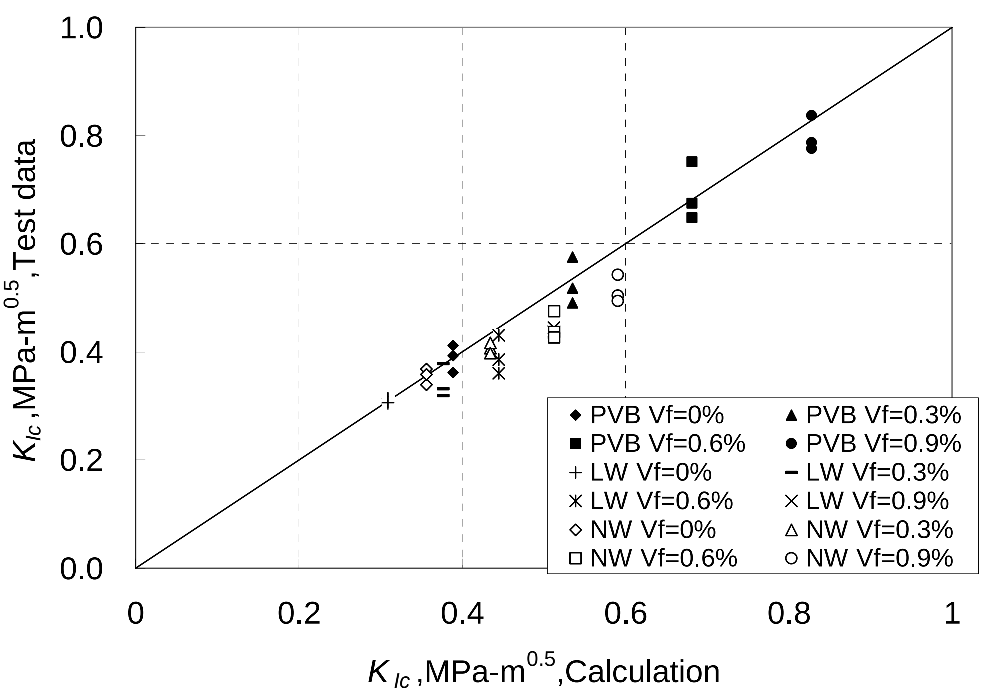

Fig. 6. Comparison of fracture toughness.

6. CONCLUSIONS

Poly(vinyl butyral) (PVB) and PVA fibers were used as fine aggregate and reinforcement, respectively, to develop a novel cementitious composite material. Fracture toughness was tested and a fracture model developed. Lightweight concrete of the same density, and normal weight concrete were cast and tested for comparison purposes.

The following conclusions can be drawn:

1. A PVB cementitious composite, placed without fiber, has higher flexural strength and fracture toughness than lightweight and normal weight concrete. This implies that PVB, when used as an aggregate, bonds very well with the cement matrix. This is attributed to the fact that PVB contains hydroxyl groups which have the potential to form hydrogen bonds between molecules. Additional effects on the cement matrix itself may occur through available ether group interactions which may alter the cement matrix structure or nucleation reaction.
2. With the addition of the same volume fraction of PVA, the flexural strength and fracture toughness of PVB is better than those associated with lightweight and normal concretes. This implies that the PVB composite has a higher bond at the fiber/matrix interface.
3. The increase in fracture toughness was found to be linear with increasing fiber volume fraction.
4. The fracture toughness model developed in this study showed a good correlation with the fracture toughness tests. However, more experimental data must be collected to further verify the model.
5. PVB/PVA fiber cementitious composites have almost twice the fracture toughness of regular fibered cement mortars despite having almost half the density.

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