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# Strain-rate effects on the tensile behavior of strain-hardening cementitious composites

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## HIGHLIGHTS

- Sources responsible for strain-rate effects of strain hardening cementitious composites (SHCC) were discovered.
- Rate dependence in component phases, i.e. fiber, matrix, and interface, were experimentally determined.
- A dynamic micromechanics-based strain hardening model was developed for SHCC component tailoring and ingredient selection.

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## ABSTRACT

This paper investigated the strain-rate effects on the tensile properties of strain-hardening cementitious composite (SHCC) and explored the underlying micromechanical sources responsible for the rate dependence. Experimental studies were carried out to reveal rate dependence in component phases, i.e. fiber, matrix, and fiber/matrix interface. A dynamic micromechanical model relating material microstructure to SHCC tensile strain-hardening under high loading rates was developed. It was found fiber stiffness, fiber strength, matrix toughness and fiber/matrix interface chemical bond strength were loading rate sensitive and they increase with loading rates in a polyvinyl alcohol fiber-reinforced SHCC (PVA-SHCC) system. These changes in component properties result in the reduction of tensile strain capacity of PVA-SHCC as the strain-rate increases from $10^{-5}$ to $10^{-1}$ $s^{-1}$.



## 1. Introduction

Terrorist attacks and natural hazards highlight the need for assuring human safety in civil infrastructure under extreme loading such as projectile impacts and bomb blasts. While concrete has served as an eminently successful construction material for years, reinforced concrete (R/C) infrastructure can be vulnerable under severe dynamic loading [1]. Many catastrophic failures of R/C structures subjected to impact or blast loading (IBL) were associated with the brittleness of concrete material in tension as suggested by Malvar and Ross [2]. Brittle failures, such as cracking, spalling, and fragmentation, of concrete were often observed in R/C structures when subjected to IBL [3], and can lead to severe loss of structural integrity. Apart from that, high speed spalling debris ejected from the backside of the structural elements can cause serious injury to personnel behind the structural elements. There is a need to enhance concrete ductility to enhance the safety of R/C infrastructure under IBL.

Strain-hardening cementitious composites (SHCC), a new class of concrete material featuring high ductility and damage tolerance under tensile and shear loading, offers a potential solution to reducing R/C structure vulnerability under IBL. SHCC with tensile strain capacity in excess of 3% under quasi-static uniaxial tensile loading can be attained with only 2% fiber content by volume [4]. However, the success of SHCC as a ductile concrete material under IBL depends on its ability to retain tensile ductility at high strain-rates [5], which requires a systematic investigation.

Literatures on strain-rate effects of SHCC were not always consistent. For example, the authors reported the tensile strain capacity of a polyvinyl alcohol fiber-reinforced SHCC (PVA-SHCC) decreases while the tensile strength increases with increasing strain-rate from $10^{-5}$ to $10^{-1}$ $s^{-1}$ as shown in Fig. 1 [5]. Similar results were observed and reported by others [6,7]. This observation implies the brittleness of SHCC increases with loading rate which is unfavorable to the high energy absorption demand when R/SHCC structures are subjected to IBL. Maalej et al. [8], however, reported the tensile strain capacity of a hybrid steel and polyethylene fiber-reinforced SHCC shows negligible strain-rate effects when strain-rate increases from $10^{-6}$ to $10^{-1}$ $s^{-1}$. Boshoff and van Zijl [9] reported similar results with another version of SHCC. These

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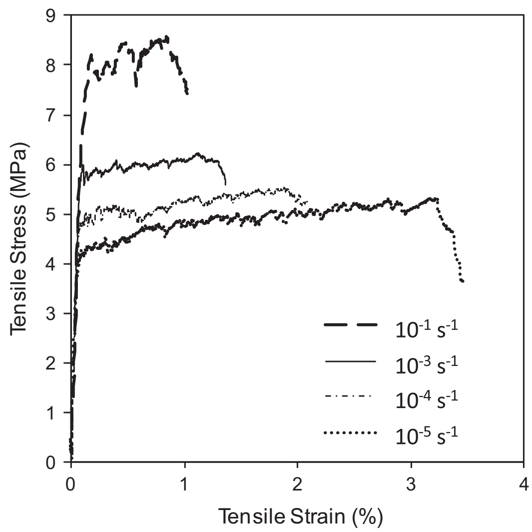


**Fig. 1.** Rate dependence of tensile stress–strain curve of PVA-SHCC (after [5]).

experimental results revealed that SHCC tensile properties may or may not exhibit rate dependence and the magnitude and the tendency of rate dependence, if it exists, will likely depend on the microstructure and material composition. For example, it has been reported that the pull-out resistance and probability of fiber rupture increased with the increase of the pull-out rate [10,11]. In addition, it was found that changes in temperature can lead to pronounced changes in the SHCC performance as well, likely due to changes in the properties of the individual components of the system [12].

These observations on the tensile strain-hardening behavior of SHCC under higher loading rates underscore a need to study the sources of strain-rate effects in SHCC. In this paper, a dynamic micromechanics-based strain-hardening model was proposed first. This analytical model linked microscopic constituent properties to macroscopic SHCC tensile strain-hardening behavior under high loading rates. Experimental studies were carried out to discover rate dependence in SHCC component phases, i.e. fiber, matrix, and fiber/matrix interface. Through the measured rate dependent constituent properties combined with the dynamic strain-hardening model, sources of strain-rate effects on the tensile behavior of SHCC were discovered.

## 2. Dynamic strain-hardening model for randomly oriented discontinuous fiber-reinforced brittle matrix composites

The theoretical foundation behind the multiple cracking phenomenon of SHCC under static loading was first explored by Aveston et al. [13] whose work was later extended by Marshall and Cox [14]. These investigations focused on brittle matrix composites reinforced with continuous and aligned fibers with relatively simple bridging laws. Emphasis was placed on the conditions for steady-state matrix cracking – extension of bridged crack length with flat crack surfaces so that the bridging elements remain intact after the passage of a crack. The fully bridged flat crack with limited width allows load transfer from the bridging fibers back into the matrix to activate additional flaw sites into new microcracks. Especially transparent in Marshall and Cox, the steady-state crack analysis employed the concept of energy balance between external work, crack tip energy absorption through matrix breakdown (matrix toughness), and crack flank energy absorption through fiber/matrix interface debonding and sliding. The steady-state flat crack model did not capture inertia effects nor did it incorporate material component rate dependence, so that its application was limited to static loading.

Under higher loading rates, inertial effect and material component (matrix and fiber bridging properties) rate dependence shall be accounted for in energy balance considerations. The dynamic energy release rate for a crack propagating at velocity $V$ was defined [15] as

$$G(\Gamma) = \lim_{\Gamma\to 0}\int_{\Gamma}\left(W + \frac{1}{2}\rho V^2 \frac{\partial u_i}{\partial x}\frac{\partial u_i}{\partial x}\right)dy - \sigma_{ij} n_j \frac{\partial u_i}{\partial x} ds \tag{1}$$

where $W$ is the strain energy density, $\rho$ is the density, $u_i$ is the displacement component, $\sigma_{ij}$ is the stress component, and $n_i$ is the unit normal vector. Eq. (1) is in general not path independent except for the special case when the crack propagates in a steady-state mode (Appendix A). For a static crack ($V = 0$), Eq.(1) reduces to the J-integral of Rice [16] which is identical to the strain energy release rate for elastic behavior. For a steady-state crack propagating against a matrix toughness of $G_{tip}$ and crack face bridging traction $\sigma_B(\delta)$ under remote steady-state tensile stress $\sigma_{ss}$ and steady-state crack opening $\delta_{ss}$, it can be shown (Appendix B) that

$$G_{tip} = \sigma_{ss}\delta_{ss} - \int_0^{\delta_{ss}} \sigma_B(\delta)d\delta \equiv G'_b \tag{2}$$

Specifically, since $G'_b$ is limited by its maximum value attained when $\sigma_{ss} = \sigma_0$ when $\delta_{ss} = \delta_0$, as shown in Fig. 2, the condition for steady-state flat crack propagation mode under dynamic condition can be stated as

$$G_{tip} < \sigma_0\delta_0 - \int_0^{\delta_{ss}} \sigma_B(\delta)d\delta \equiv C \tag{3}$$

where $C$ is the maximum complimentary energy as defined above. The crack face bridging traction $\sigma_B(\delta)$, which can be viewed as the constitutive law of fiber bridging behavior, was derived by using analytic tools of fracture mechanics, micromechanics, and probabilistic theory [17]. In particular, the energetics of tunnel crack propagation along an interface was used to quantify the debonding process and the bridging force of a fiber with given embedment length. Probabilistics was introduced to describe the randomness of fiber location and orientation with respect to a crack plane. The random orientation of fiber also necessitated the accounting of the mechanics of interaction between an inclined fiber and the matrix crack. As a result, $\sigma_B(\delta)$ was expressible as a function of ten micromechanics parameters, including fiber properties and fiber/matrix interfacial properties. An additional condition for strain-hardening was that the matrix cracking strength $\sigma_{fc}$ must not exceed the fiber peak bridging strength $\sigma_0$.

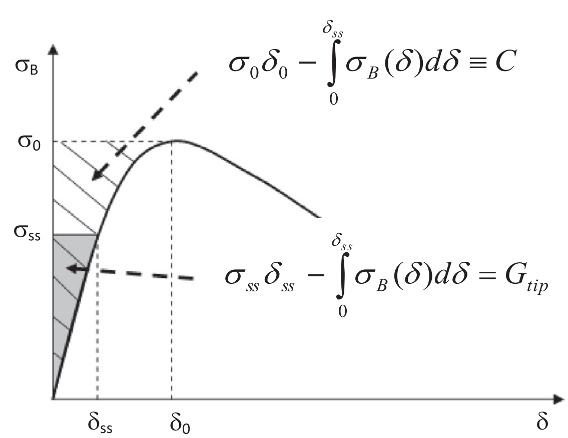


**Fig. 2.** A typical $\sigma_B(\delta)$ curve for tensile strain-hardening composite. Hatched area represents maximum complimentary energy $C$. Shaded area represents crack tip toughness $G_{tip}$.