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High Performance Fiber Reinforced Cement Composites

Bétons de fibres à haute performance

Hohe Festigkeit Faserverstärkter Betone

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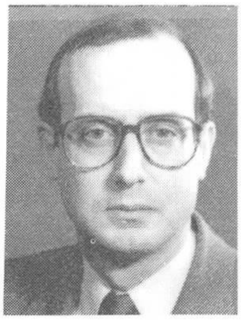

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SUMMARY
A brief synthesis of the behavior and mechanics of fiber reinforced cement based composites in tension, compression, and flexure is presented with particular emphasis on their stress-strain, stress-elongation, or load-deflection relationships. The latest advances in the field are cited and optimum strength and toughness properties achievable using current technology are pointed out.

RÉSUMÉ
Un sommaire synthétique du comportement en tension, compression, et flexion des bétons armés de fibres est présenté. Leurs courbes typiques de contrainte-déformation sont décrites. Les limites mécaniques optimales pouvant être atteintes en l'état actuel de leur développement sont mentionnées.

ZUSAMMENFASSUNG
Eine Zusammenfassung über das mechanische Verhalten faserverstärkter Betone wird gegeben. Dabei wird vor allem das Spannungs-Dehnungsverhalten beschrieben. Die neuesten Erkenntnisse werden aufgeführt, und das Vorgehen für Erhalt optimaler Festigkeit und Fähigkeit unter Ausnützung des heutigen Technologiestandes wird erläutert.

1. DEFINITIONS

The definition of a cementitious composite is that of a portland cement based matrix reinforced with fibers. The term high strength implies here strengths of up to 140 MPa (20 ksi) in compression. The term high performance refers here to the combination of strength and toughness-ductility as imparted by the addition of fibers. Concrete generally refers to concrete, mortar, or paste. Conventional FRC (Fiber Reinforced Concrete) implies premixing of discontinuous fibers with a fresh cement based matrix in proportion of less than about 3% by volume. SIFCON (Slurry Infiltrated Fiber Concrete) is a composite obtained by infiltrating with a rich cement based slurry a tridimensional network of fibers preplaced in a mold. The slurry is primarily composed of a fluid cement paste to with several additives are added such as superplasticizers, fly ash, microsilica, or polymers. SIFCON composites generally contain high volume fractions of fibers (8% to 20%) which could not be otherwise achieved by premixing the fibers with the matrix.

2. TENSION

2.1 Load-Elongation Response

Cement based matrices are known to fail in tension in a rather brittle manner and to show extremely small tensile strains at failure. The addition of fibers to such matrices, whether in continuous of discontinuous form, may lead to a composite with properties substantially improved in comparison to the properties of the unreinforced matrix. Several tensile properties of interest may be studied in details, among which the modulus of elasticity, the stress at cracking, the maximum postcracking stress, the post-peak portion of the stress strain response which symbolizes ductility, and the toughness of the composite. Although it is not within the scope of this paper to address the case of cement composites with continuous fibers or meshes like ferrocement, such composites should not be overlooked as they provide a useful basis for comparing some limiting mechanical properties.

The tensile load-elongation response of a high performance fiber reinforced cement composite such as SIFCON can be divided in the most general case into three parts (Fig.1). For all practical purposes the first part can be considered linear up to first cracking in the matrix (cracking stress), and is very similar to the load elongation response of the unreinforced matrix. Cracking is a drastic event identified by a significant change in the slope of the load-elongation curve. If the maximum post-cracking stress is larger than the cracking stress, then a second stage of behavior can be identified as the multiple cracking stage, and corresponds to the portion of the load elongation curve that joins the cracking stress point to the maximum post-cracking stress point (peak point of the curve). Several cracks develop along this portion of the curve and up to the maximum stress, defined as the strength of the composite. Beyond the peak point a third stage of behavior exists characterized by failure and/or pull-out of the fibers about a single critical crack. The corresponding descending branch of the load elongation curve can be steep or of moderate slope depending on the fiber reinforcing parameters and whether a brittle or a ductile failure occurs. Along stages I and II (Fig.1) the

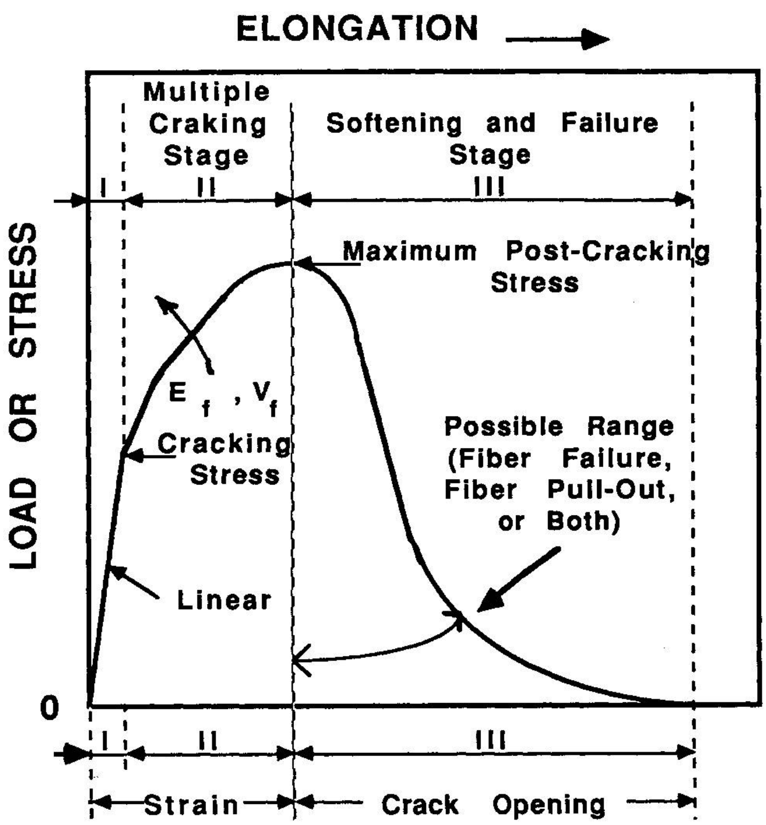

Figure 1. Typical Load Elongation Response in Tension of a High Performance FRC Composite Such as SIFCON.

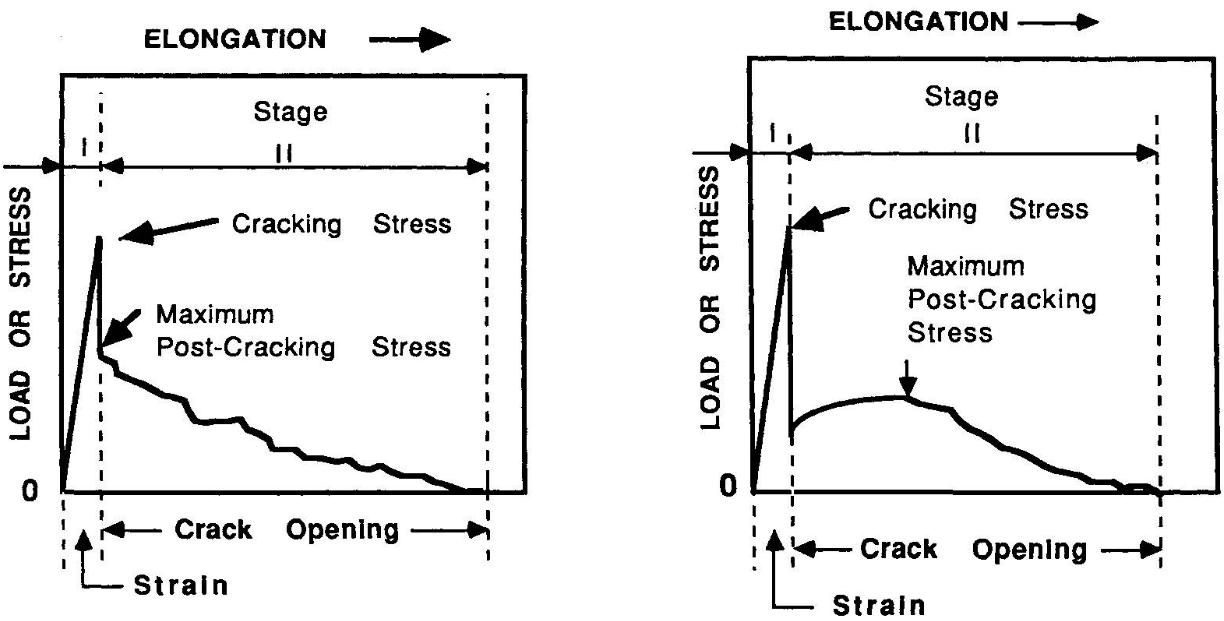

Figure 2. Typical Load Elongation Response in Tension of Fiber Reinforced Concrete: a) Using Premixed Steel Fibers, and b) Using Premixed Polypropylene Fibers.

elongation of the composite (assumed measured along a defined gage length) can be transformed into an equivalent strain. However along stage III, the elongation corresponds primarily to the opening of a single critical crack and cannot be translated into strain since crack opening is independent of the gage length.

It should be noted that multiple cracking (stage II) occurs only if the maximum post-cracking stress is larger than the cracking stress. Otherwise the second portion of the curve vanishes and the load elongation response is reduced to two main parts (stages I and III) as illustrated in Figs.2a and 2b. The typical curves of Fig.2 are characteristic of the tensile response of conventional fiber reinforced concrete with a relatively small volume fraction of fibers. The curve of Fig.2a is due to high modulus fibers such as steel fibers, while that fo Fig.2b is due to low modulus fibers such as polypropylene fibers. A typical comparison of load elongation curves of a steel fiber reinforced mortar specimen and a SIFCON specimen is shown in Fig.3.

2.2 Strength Prediction

To predict the main characteristics of the stress-elongation curve of fiber reinforced cement composites in tension, several analytical approaches can be used such as the mechanics of composite materials, fracture mechanics, damage mechanics, and empirical approches. Following are some predictions equations developed by the writer and based on the mechanics of the composite.

The tensile stress in the composite at cracking of the matrix can be predicted from the following equation [1]:

$$\sigma_{cc} = \sigma_{mu}(1 - V_f) + \alpha_1 \alpha_2 \bar{\tau} V_f L/d \qquad (1)$$

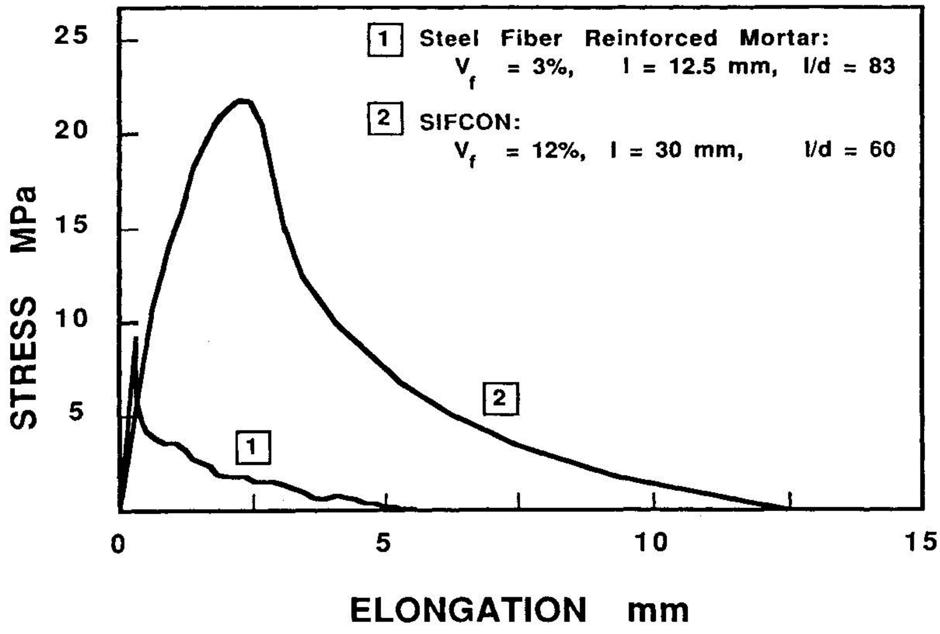

Fig.3 Typical Stress-Elongation Curves of Conventional Fiber Reinforced Mortar and SIFCON.

In which σ_{mu} is the tensile strength of the matrix, V_f is the volume fraction of fibers, L and d are respectively the length and diameter of the fiber, $\bar{\tau}$ is the average bond strength at the fiber matrix interface, α_1 is a bond coefficient representing the fraction of bond mobilized at matrix cracking, and α_2 is the efficiency factor of fiber orientation in the uncracked state of the composite.

The strain at cracking can be obtained from the stress at cracking and the modulus of elasticity of the composite assuming linear behavior. The elastic modulus of the composite can be estimated as a first approximation from the law of mixtures, that is:

$$E_c = E_m V_m + E_f V_f \quad (2)$$

in which E is used for modulus, V for volume fraction, and the subscripts c, m, and f represent the composite, the matrix and the fiber respectively.

The maximum postcracking stress can be estimated from the following equation [1] which assumes that: 1) a crack exists across the section of the test sample, the crack is normal to the tensile stress field, and 3) the contribution of the cracked matrix to the tensile strength of the composite is negligible:

$$\sigma_{pc} = \lambda_1 \lambda_2 \lambda_3 \bar{\tau} V_f L/d \quad (3)$$

in which λ_1 is the expected pull-out length ratio, λ_2 is the efficiency factor of orientation in the cracked state, and λ_3 is a group reduction factor associated with number of fibers pulling out from the same area.

No information is known to this writer on the quantitative prediction of the multiple cracking portion (stage II of Fig.1) of the stress-strain curve in tension. For conventional steel fiber reinforced concrete with low fiber contents in which stage II vanishes, the strain at maximum post-cracking stress can be taken equal to the strain at first cracking.

In order for multiple cracking to occur, the maximum post-cracking stress must be larger than the cracking stress. Using Eqs. 1 and 3 leads to the following general condition:

$$V_f\left[1 + \frac{\bar{\tau}}{\sigma_{mu}} \frac{L}{d} (\lambda_1 \lambda_2 \lambda_3 - \alpha_1 \alpha_2)\right] > 1 \quad (4)$$

Equation 4 can be used to derive a critical volume fraction for a given fiber, or a critical combination of fiber properties to achieve multiple cracking.

Little information exists on modeling the descending branch of the stress-elongation curve (stage III of Figs. 1-2), also called stress-displacement curve, stress crack opening curve, or stress softening curve. However, for steel fiber reinforced concrete in which fiber pull-out occurs through a single critical crack, two prediction equations were proposed in Refs. 2 and 3 and are suggested for use when needed. This information, combined with the use of Eqs. 1 to 4 should allow for the prediction of the entire load elongation curve of fiber reinforced concrete in tension.

3. COMPRESSION AND BENDING

Because of manuscript length constraint, sections regarding these properties have been severed from this shortened version of the paper. However, a copy of the full length paper can be obtained from the author upon request and availability. Additional information can also be found in Refs. 4 to 8.

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