Fiber Reinforcement for Concrete

Keywords: carbon; evaluation; **fiber reinforced concretes;** glass fibers; metal fibers; **patents;** polypropylene fibers; **reviews;** strength.

A selective chronological review of the earliest patents on fiber reinforcement for concrete is included in this article. The underlying idea for each patent is explained and the objectives are evaluated. The most desirable fiber characteristics are pointed out and currently available fibers described.

by Antoine E. Naaman

The concept of using fibers to improve the behavior of building materials is old and intuitive. Examples include adding straw fibers to sun-dried mud bricks (adobe) and asbestos fibers to pottery, thus creating a composite with a better performance.

Such performance could be translated in the case of adobe by a better resistance to cracking and a better resistance to fragmentation after cracking induced by repetitive changes in temperature and humidity. It is no surprise that when portland cement concrete started evolving as a building material, attempts were made to add fibers to it to improve its behavior.

The patent of Joseph Lambot in 1847 suggested the addition to concrete of continuous fibers in the form of wires or wire meshes to create a new building material. This led to the development of ferrocement and reinforced concrete as known today.

However, the use of continuous reinforcement requires careful placement and higher labor technical skills, hence higher cost. It also leads to an anisotropic building material with which the average layman was not very comfortable.

The idea of using strong discontinuous fibers as reinforcement for concrete seems to have been both a seduction and a challenge to many civil engineers. Adding the reinforcement to the mixer in the form of fibers, simply like adding aggregates or admixtures, to create a homogeneous, isotropic, moldable structural material is a dream that started more than a century ago, is still in the making today, and is not far from being attained.

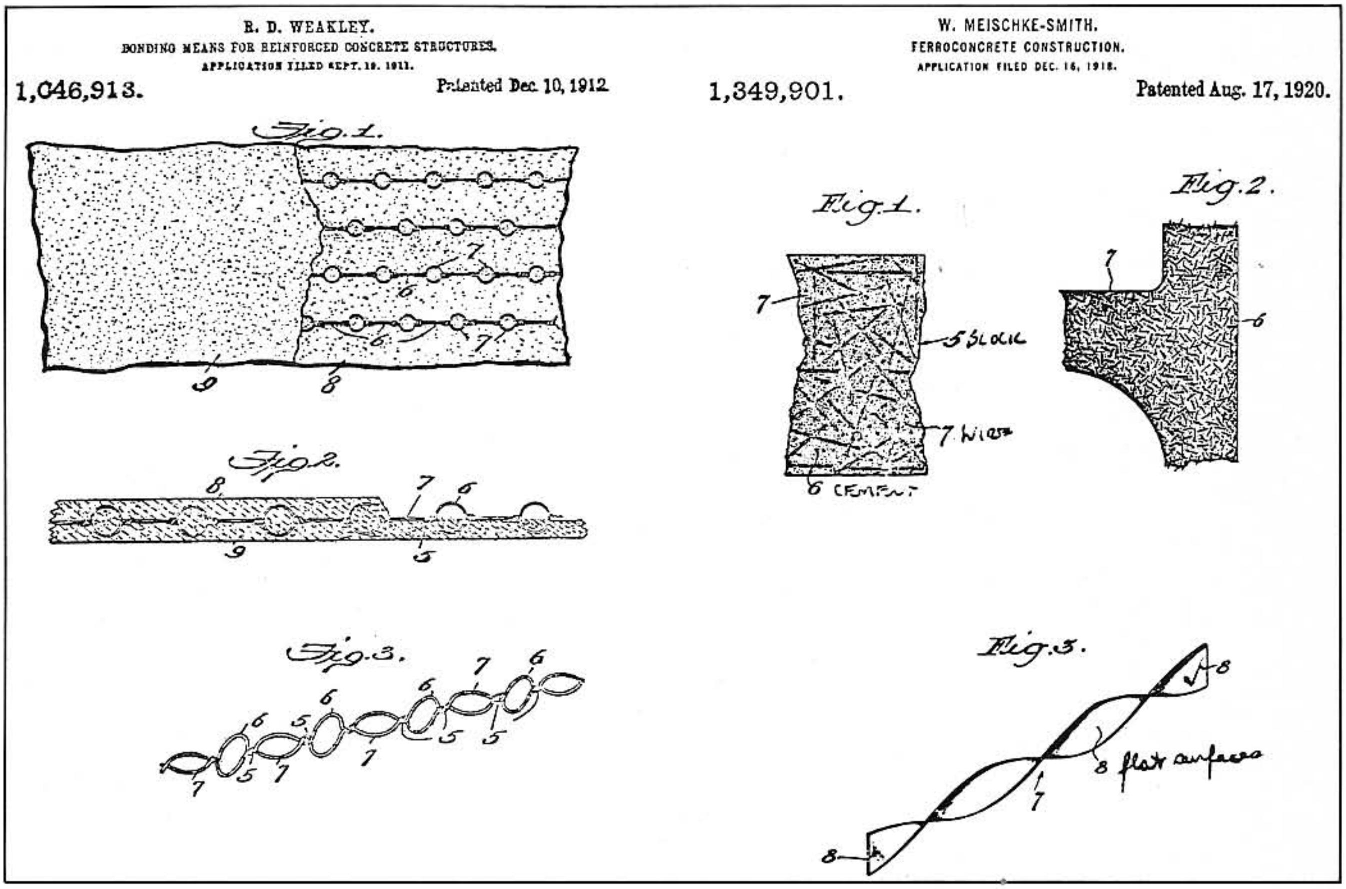

Fig. 1a — Some early patents on fibers for concrete. Left is the Weakley patent; right is that taken out by Meischke-Smith.

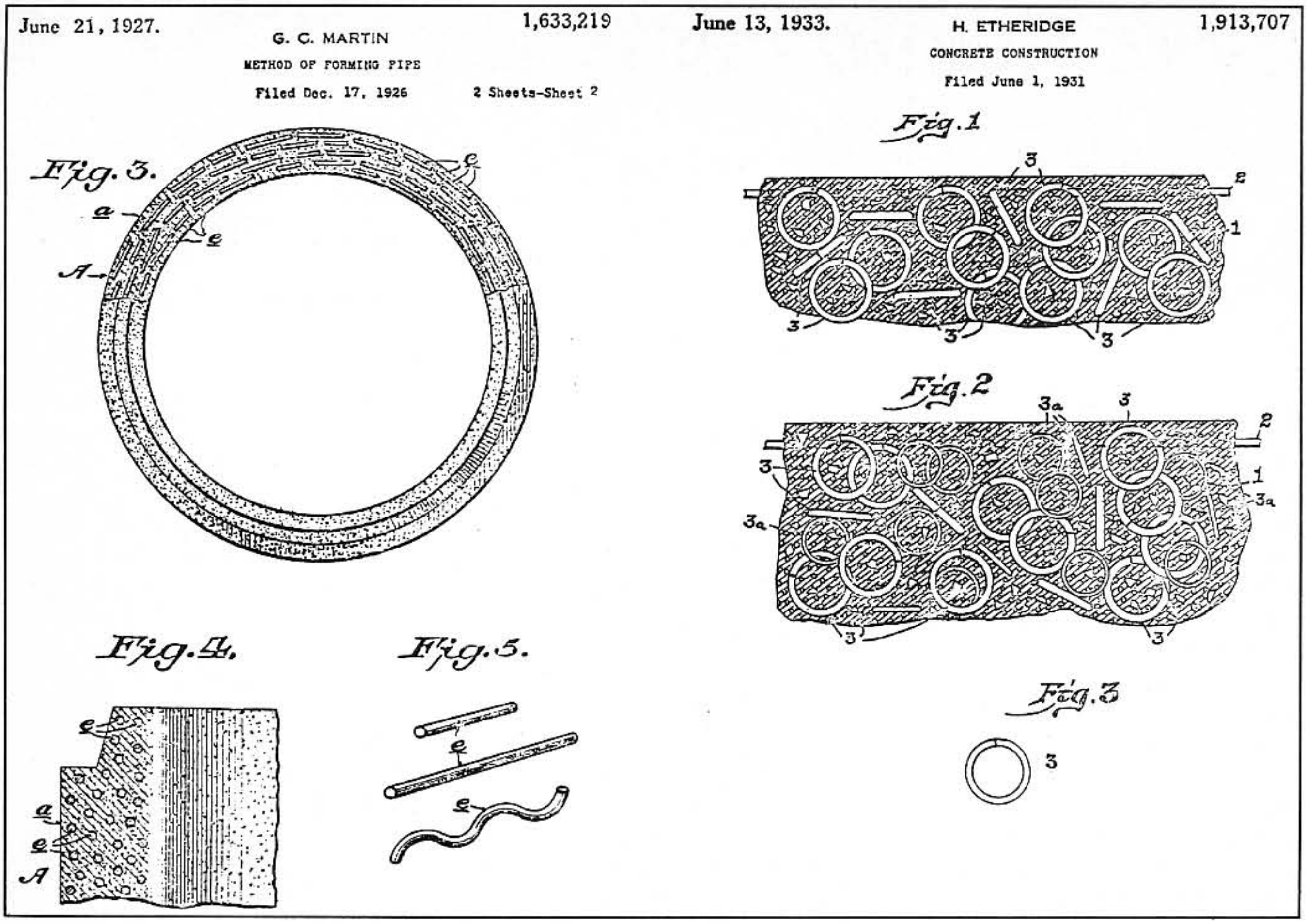

Fig. 1b — More early patents on fiber for concrete. Left is the Martin patent; right is Etheridge's 1933 filing.

Fibers for concrete

Two main time periods seem to characterize the pace of development of fiber reinforcement for concrete. The first period, prior to the 1960s, corresponds to a slow pioneering phase with almost no applications, while the second period, since the early 1960s, corresponds to a phase of more rapid modern developments parallelled by increasing applications.

Numerous patents on fiber reinforced concrete have been granted. They generally address one or a combination of the following: the fiber, the fiber reinforced concrete mix, the production process, and the application. A selective number is reviewed next, to illustrate the underlying idea behind each patent and the evolution of new ideas with time.

Pioneering developments

The first patent (1874) on fiber reinforced concrete seems to be due to A. Berard from California who suggested the use of granular waste iron in a concrete mix to create an artificial stone.

A French patent dated 1918 by H. Alfsen describes a process to improve the tensile strength of concrete by uniformly mixing small longitudinal bodies (fibers) of iron, wood or other materials. It also suggests that the surface of these fiber elements must be rough or roughened and, if possible, their ends bent in order to provide better adherance to the concrete.

R. Weakly (Missouri) obtained a patent in 1912 for using a steel wire strip made out of two wires and containing loops to secure a durable bond with concrete (Fig. 1). In 1920, A. Kleinlogel from Germany filed a patent for mixing a relatively large volume of iron particles with concrete in order to produce a mass capable of being chilled, turned, sawed, and filed similarly to an iron mass.

Shortly thereafter in 1927 two patents were granted in California to G. Martin and W. Meischke-Smith. Martin's patent (Fig. 1) describes the use of plain or crimped pieces of steel wires mixed with concrete to strengthen concrete pipes. Meischke-Smith's patent (Fig. 1) describes the use of flat twisted pieces of wires as fiber reinforcement for concrete mixtures.

The idea of improving the shape of the fiber to increase its contributions was pushed one step further by Etheridge (New Jersey, 1933) who proposed adding "annuli" fibers (Fig. 1) of different sizes and diameters to improve the crack resistance and fatigue of concrete for use in railway ties. He wrote: "The object that I have in view is the prevention of local cracks and fractures and I accomplish such object by mixing with the plastic concrete a mass of metal annuli in sufficient quantity to effect coupling of what I may term the 'stitching' together of the adjacent masses of concrete . . ."

Many patents were granted in different countries in the following years. That of G. Constantinesco (England 1943, United States 1954) deserves a special mention as the fiber reinforcing parameters he recommended are quite similar to those of steel fiber reinforced concrete of today. The patent (Fig. 2) describes the use of coiled or helical type steel fibers in order to increase the crack resistance and energy absorption of concrete masses. Suggested applications included army tanks, air raid shelters, machinery foundations, and the like.

Modern developments

The modern developments of fiber reinforcement for concrete started in the early 1960s. A multitude of fibers and fiber materials were introduced and are being continuously introduced in the market as new applications are identified. These include:

—Steel fibers (straight, crimped, twisted, deformed with hooked or paddled ends).

—Glass fibers.

—Carbon fibers.

—Natural organic and mineral fibers (wood, sisal, jute, bamboo, coconut, asbestos, rockwool).

—Polypropylene fibers (plain, twisted, fibrillated, with buttoned ends).

—Many other synthetic fibers like kevlar, nylon, and polyester.

Examples of currently used steel fibers are shown in Fig. 3 as taken from the report of ACI Committee 544.* A tridimensional steel fiber made with four wires forming a frame like two successive footballs was patented in 1974 (Fig. 4). It was shown to provide higher composite strength through an efficient anchorage, and higher toughness through extensive elongation and crushing of the matrix inside the balls. However, it is not commercially available.

Fig. 5 shows typical examples of glass, carbon, and polypropylene fibers. Tridimensional fiber mats (Fig. 6) to be impregnated by a concrete matrix have also been used, at least in research, to produce uniform, homogeneous fiber distribution, and reduce mixing difficulties associated with large fiber contents. The procedure is also used in slurry infiltrated fiber reinforced concrete, SIFCON.

These developments are invariably preceded and accompanied by a better understanding of the mechanics of fiber reinforcement (mechanics of composite materials, fracture mechanics, damage mechanics). Such studies point toward a better understanding and identification of desirable fiber characteristics for any particular application.

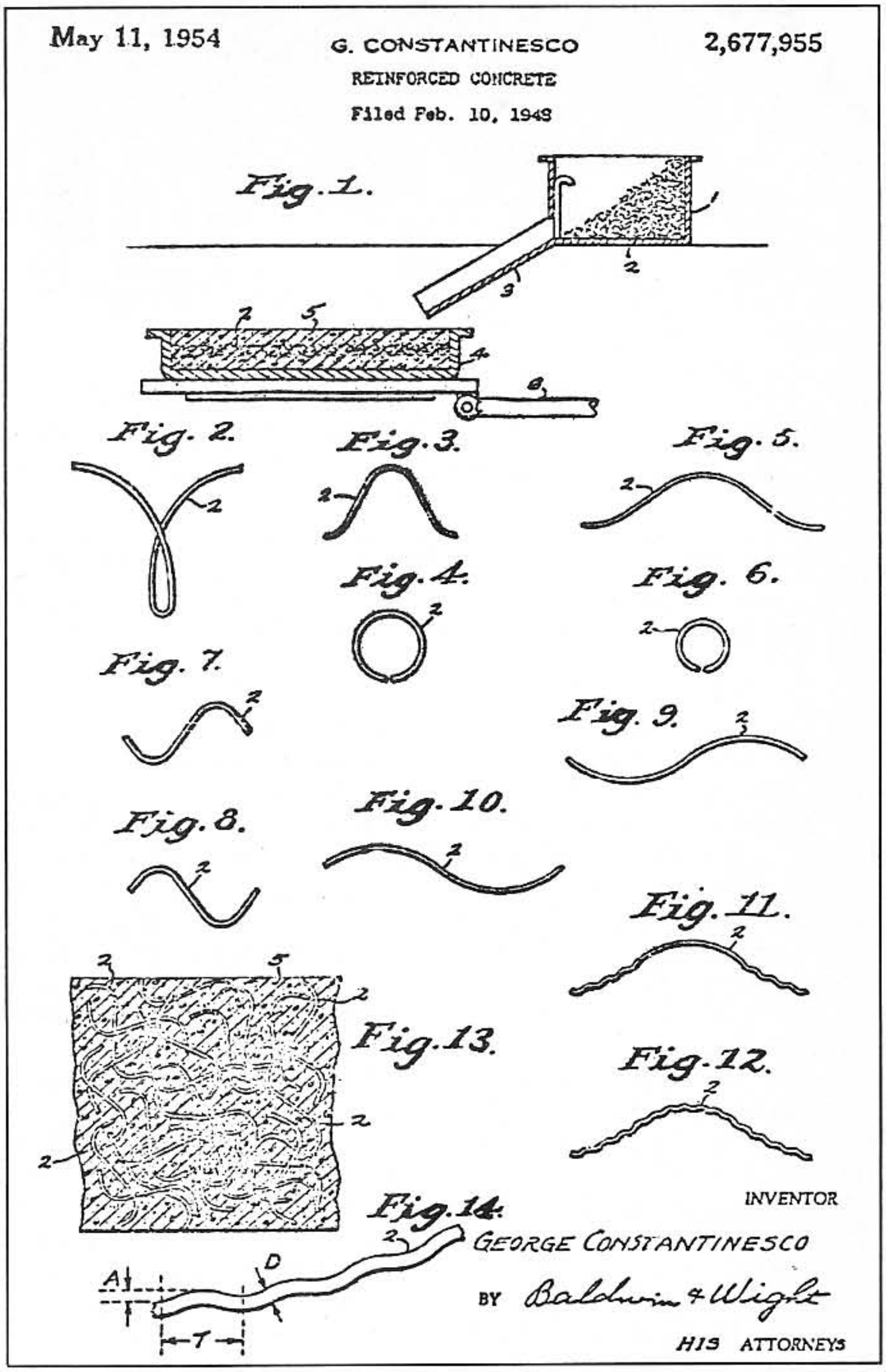

Fig. 2 — Constantinesco's patent.

Desirable fiber characteristics

The most desirable fiber characteristics are those that will induce, with the highest possible efficiency, substantial increases in the composite's strength and tough-

*ACI Committee 544, "State-of-the-Art Report on Fiber Reinforced Concrete," (ACI 544.1R-82), American Concrete Institute, Detroit, 1982, 16 pp.

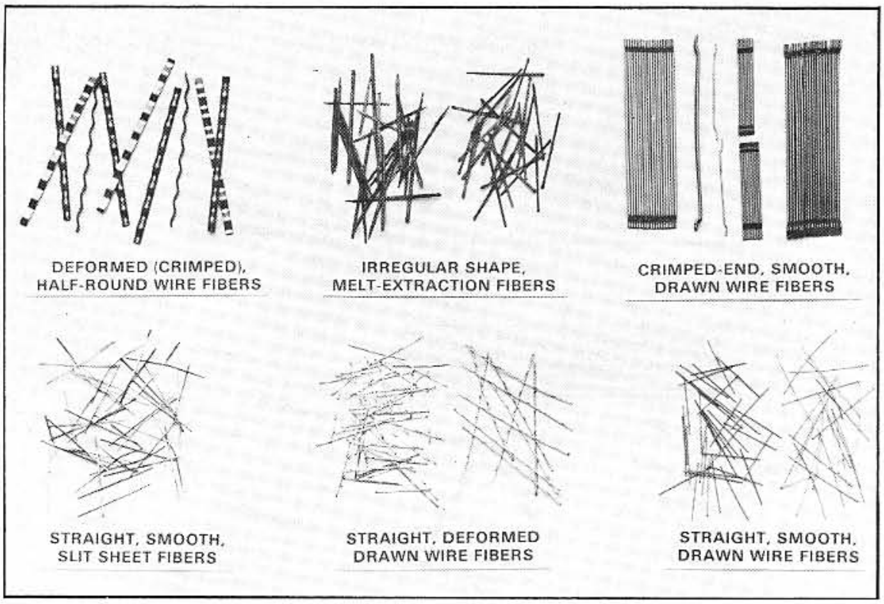

Fig. 3 — Typical commercially available steel fibers. (From ACI 544.1R-82)

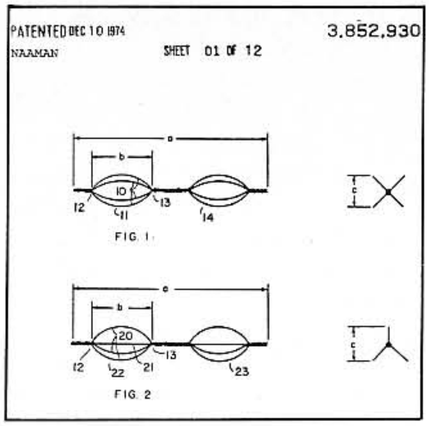

Fig. 4 — Tridimensional steel fibers.

ness (or energy absorbing capability) in the short and the long term. These characteristics include:

1. Geometrical characteristics: length, diameter, aspect ratio, shape, surface deformation, bond or anchorage property.

2. Physico-chemical characteristics: surface roughness, density, chemical stability, non-reactivity, fire resistance.

3. Mechanical characteristics: strength, stiffness (elastic modulus), ductility, elongation to failure.

It is generally agreed that the stiffer the fiber, the better it is. This does not mean that low modulus fibers such as polypropylene fibers, which have an elastic modulus 30 times less than steel fibers, are not acceptable.

In sheet-like applications where the composite's deflection is large in comparison to its thickness, polypropylene fibers were shown not only to substantially improve strength but also to induce enormous toughness through extensive multiple cracking and deformation.

These described characteristics are mostly technical. From an application viewpoint, the cost of the fiber and its density or specific gravity are very important. This is because the cost is generally per unit weight of fibers while the fiber content in the composite is evaluated on a volume basis.

Thus, to provide the same volume percent of fibers in the composite, the weight of steel fibers will be about 8 times that of polypropylene fibers and 3 times that of glass fibers. Hence, for equal cost per unit weight and equal performance, the lower density fiber provides a lower cost composite. Note, however, that it is unlikely to achieve equal performance with the same volume percent of fibers of different materials.

From past to future

An analysis of the ideas underlying the earliest patents on fiber reinforced concrete indicates that fibers were meant primarily to improve the strength of the composite. As the compressive strength of concrete does not increase much with fiber addition and as the flex-

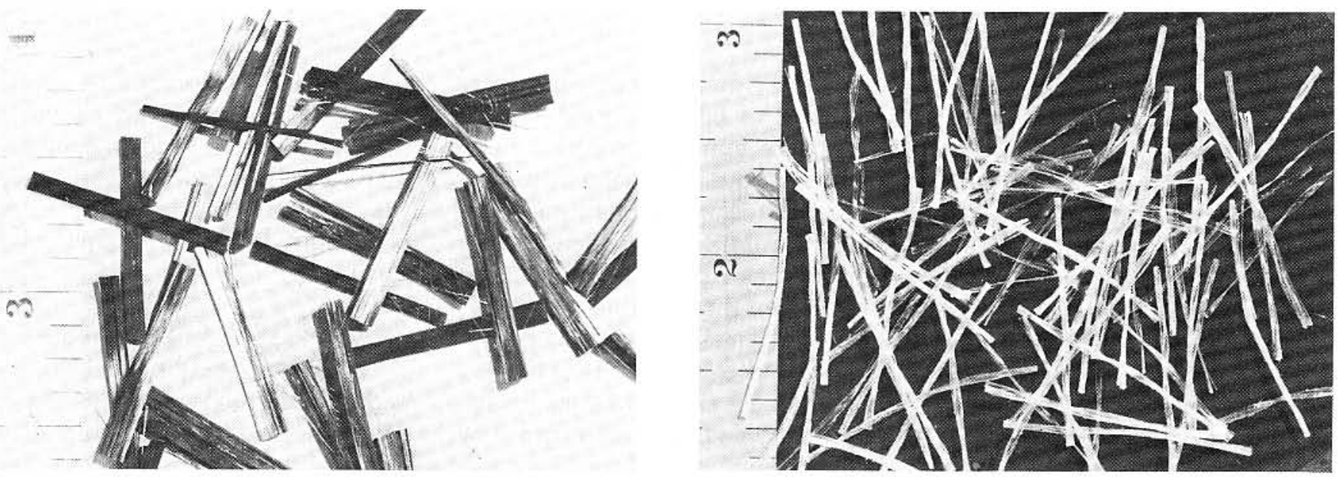

Fig. 5a — Examples of non-metallic fibers. Left photo is of carbon fibers; twisted polypropylene fibers are shown at right.

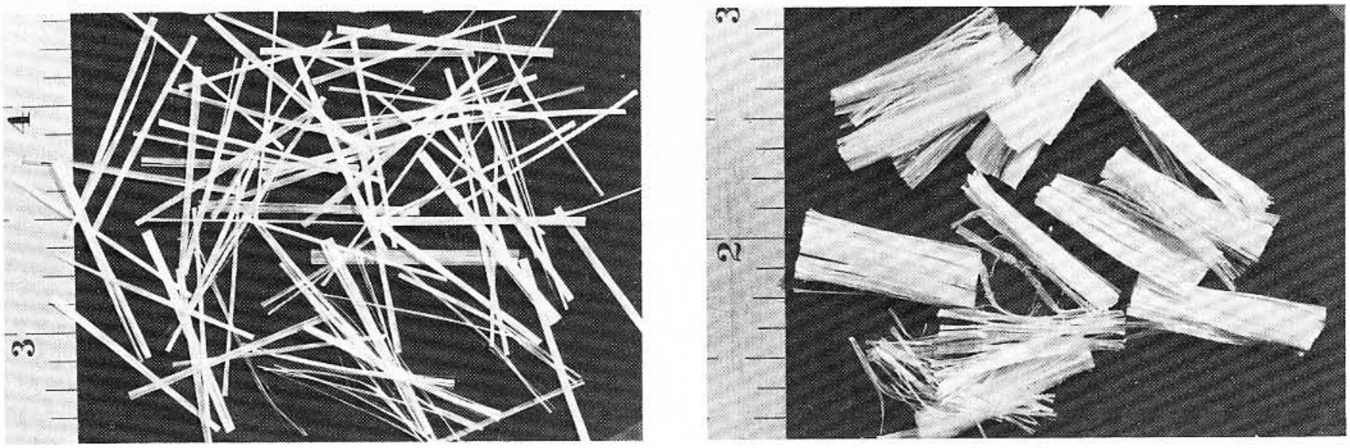

Fig. 5b — More examples of non-metallic fibers. Glass fibers are shown at left; fibrillated polypropylene at right.

ural or tensile strengths increase only for the proper combination of fiber reinforcing parameters, the benefits of fiber reinforcement were not easy to demonstrate by the first pioneers in the field.

This is particularly so since deformation controlled testing was not available and proof-testing using beams loaded with sandbags (load controlled test) did not give any quantitative indication of the possible toughness of the composite. The concept of energy absorption or toughness was present only in some patents but was mostly emphasized later during the modern development of fiber reinforced concrete, where toughness could be measured and was needed in some modern structures.

It can be safely said today that the most obvious advantage of fiber reinforcement in concrete is the substantial increase in the toughness or energy absorption capacity of the composite. However, continuous efforts are being devoted and continuous progress is being achieved to increase the composite's tensile strength through improved fibers, fiber efficiency, fiber content, additives, and the like.

Reaching the pioneers' dream of producing a new concrete material with high tensile strength and toughness, while being homogeneous and isotropic (similarly to cast iron) is closer today than ever. This is possible in particular with SIFCON.

In the field of engineering materials, fiber reinforced concrete, supplemented by existing additives such as superplasticizers, silica fumes, and polymers, is on the way to becoming a "panacea" solution. Perhaps more than ever before concrete material engineers are confident that given a wide range of requirements for modern structures (earthquake resistant structures, offshore structures, blast resistant structures) they can design a fiber reinforced concrete material to satisfy them.

Acknowledgments

The research work of the author on fiber reinforced concrete is currently supported by Grant No. CEE-82-19774 from the National Science Foundation to the University of Michigan with John B. Scalzi as program director.

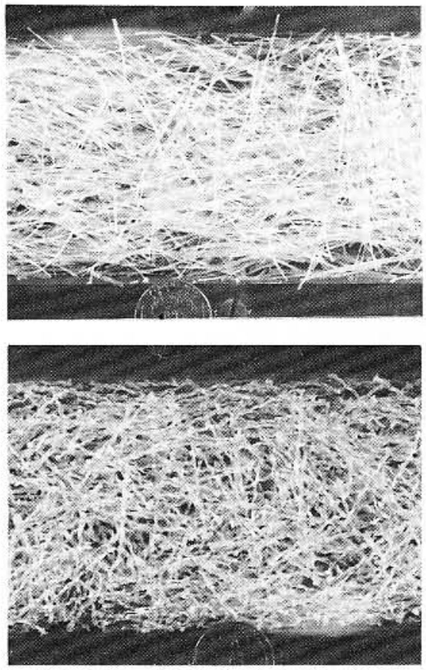

Fig. 6 — Examples of tridimensional fiber mats made with polypropylene fibers. Top is fiber mat V_f = 6.78 percent, two-ply twist. Bottom is mat V_f = 2.86 percent, one-ply twist.

***Antoine E. Naaman,** a Fellow of ACI, is professor of civil engineering, University of Michigan, Ann Arbor, Mich. He is currently chairman of Institute Committee 549, Ferrocement, and is a member of several other committees, including 544, Fiber Reinforced Concrete. He has done extensive analytical and experimental work on fiber reinforced concrete and his research has included advanced cementitious composites and prestressed concrete.*