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NON-TRADITIONAL REINFORCEMENT FOR CONCRETE COMPOSITES - STATE OF THE ART

NETRADICIONĀLAIS BETONA STIEGROJUMS – MŪSDIENU PROBLĒMAS STĀVOKLIS

Andrejs Krasnikovs, *Dr.sc.ing., professor*
Head of Concrete Mechanics laboratory
http://www.bml.rtu.lv
Riga Technical University, Institute of Mechanics
Address: 16 Azenes Street, Riga LV-1048, Latvia
Phone: +371 29436518; Fax: + 371 67089159
E-mail: akrasn@latnet.lv

Videvuds Lapsa, *Dr.sc.ing., Senior researcher*
Concrete Mechanics laboratory
http://www.bml.rtu.lv
Riga Technical University,
Address: 16 Azenes Street, Riga LV-1048, Latvia
Phone: +371 67089296; Fax: + 371 67089159
E-mail: valapsa@latnet.lv

Māris Eiduks, *M.sc.ing., PhD student*
Concrete mechanics laboratory
http://www.bml.rtu.lv
Riga Technical University, Institute of mechanics
Address: 16 Azenes Street, Riga LV-1048, Latvia
Phone: +371 67089294; Fax: + 371 67089159
E-mail: maris.eiduks@gmail.com

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1. Introduction

Main building material –concrete- is strong in compression, but weak in tension. The tensile strength of concrete is only about 10 % (for conventional concretes) of its compressive strength. To compensate concrete's low tensile strength, concrete members are reinforced to carry tensile

loads. Mechanically two different reinforcement acting mechanisms can be recognized (Figure 1.):
long fiber or bars reinforcement;
short fibers reinforcement.
Long fibers (bars, nets, cage parts) are bearing tensile stress in reinforced concrete till fibers rupture in one of the beam's cross section. Tensile beam's strength is fibers (bars) strength (in tensioned beams part).
Short fibers are working according to pull-out mechanism bridging cracks. Tensile beam's strength is mixed mechanism of fibers strength and fiber-concrete matrix adhesion strength.

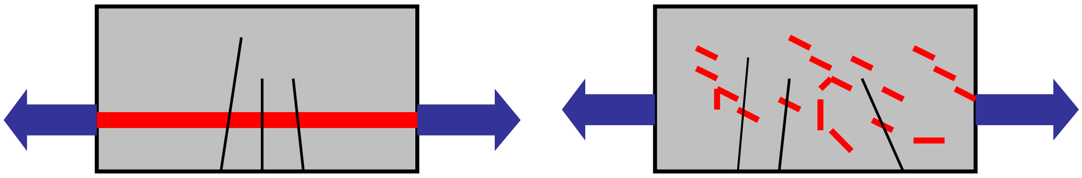

Figure 1. Long and short fibers reinforcement under tensile load in concrete (two different load bearing mechanisms)

2. Materials for reinforcement

Traditional material for concrete reinforcement is steel. However, at last times, non-metallic fibers (steel, glass, aramid, carbon, polyethylene and polypropylene) as dispersed short fibers (as well as different structures, yarn, chopped yarn, strings, nets, fabrics and polymer composite material reinforcement (bars and cages)) have been intensively investigated and some of them used for construction structures.

Non-metallic fibers
Commercially available non-metallic fibers are characterized by a tensile strength competitive with steel. In the same time such fibers have a lower density. Main physical and geometrical fibre characteristics are shown in Table 1.
Glass fibers
Idea to use glass fibers for concrete reinforcement arouse in the 1950's. Glass fibers are relatively cheap. Fibers are manufactured in the following way: molten glass is held in a container and allowed to emerge through plate having a number of small holes. Fibers are drawn off from the emerging drops at rates of about several tens of meters per second, depending on desired diameter. Fibers are cooled very rapidly and covered with an organic coating that protects the surface. Coating the glass fibers with a coupling agent will provide a flexible layer at the interface. This technology allows obtain fibers with low concentration of micro-defects potentially altering the tensile strength. Glass fibers are produced from E-glass and S-glass. E-glass has good strength, stiffness and wearing properties; S-glass is more expensive and has higher mechanical properties and temperature resistance. Unfortunately, properties of glass fibers decrease in presence of water, acid and concrete alkali environment (see Figure 2). Four alternatives are used for short fibers dispersed in concrete to overcome this situation:

Table 1. Main characteristics of non-metallic fibers

Property	E-glass	AR-glass	AR-glass (string)	HM carbon	HS carbon	Aramid “Kevlar 49”	polypropylene
Diameter range (microns)	8-20	12	110x 650	10	10	12	500-4000
Young modulus (GPa)	75	70-76	70	380	230	130	<8
Tensile strength (GPa)	2-4	1.8-3.5	1.4-1.9	2.4	3.4	3.6	0.4
Failure strain (%)	~2	~2	-	0.6	1.1	2-2.6	8
Compatibility with Cement paste	Low	Middle	Middle	Good	Good	Middle	Good

a) to use a special alkali resistant coating for the fibers; This solution is not suitable when a highly alkaline Portland cement is used, as the coating can be damaged during the mixing process;
b) to use alkalis resistant AR-glass fibers; Alkali- resistant fibers contain zirconium that prevents corrosion rising from alkali in the cement matrix. For example Cem-FIL AR Glass Fibre is a continuous filament, alkali resistant glass fibre with high durability in cement. The fibre composition is the Na2O CaO ZrO2 SiO2 system. Some typical properties of Cem-FIL AR Fibre are as follows: Single filament tensile strength 3.5 GN/m2 3.5 GN/m2. Strand tensile strength 1.7 GN/m2 1.7 GN/m2, Young’s Modulus of Elasticity 72 GN/m2, Specific Gravity 2.68 Strain at breaking point (strand) 2.4%, filament diameter 14 or 20 μm.
c) to use low alkali cement.
d) to use glass fibers in polymer composite products which are using for concrete reinforcement. A limited number of such products is commercially available, and special methods of placement precludes their use.
AR-glass fibers are commercially available products with high mechanical properties and attractive price.

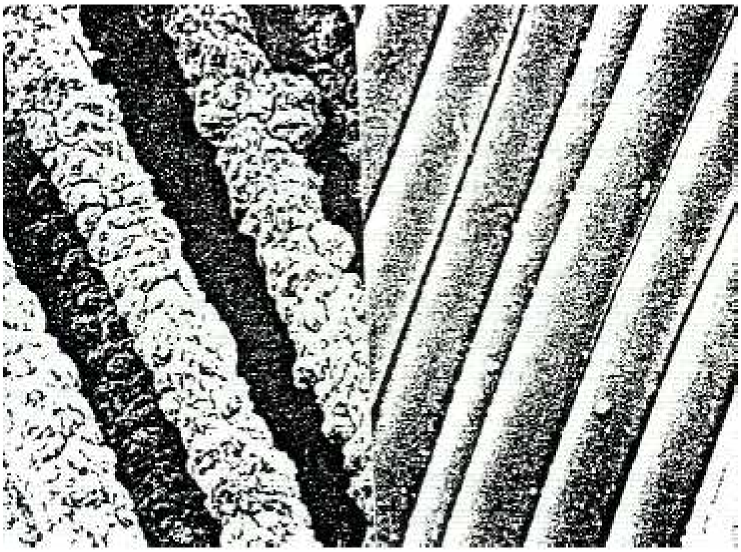

Figure 2. Surface of normal (left) glass fibers and AR fibers (right) after exposure to cement environment (picture from [1])

Carbon fibers

Carbon fibers are available on the market (traditionally) as strings, consisting of 3000 to 6000 fibers, as long and continuous ribbons (consisting of 1000 to 160 000 fibers) and weave fabrics (see Figure 3.). Two types of carbon fibers are available (HM) and (HS) (Table 1.). Fibers are stiff and strong. First reason why they are strong is that the dominating chemical bonds in the fibers have high strength and high density, the second, small fibers diameter reduce the probability to have a large defect in individual fibers. Carbon fibers are made in two technologies, out of pre-stretched polyacrylonitrile (PAN) fibers, further stretched and heat-treated and out of pitch, a product of petroleum. Strong covalent bonds act in the fibers direction creating high stiffness. The transverse stiffness of the fibers is low due to lack of covalent bonds. Carbon fibers are not absorbing water, have a low chemical activity, are stiff and have a high tensile strength. Fibers are chemically resistant to acid, alkali and organic solvents [2]. Negative properties are:

a) relatively high price comparing with glass (ten to thirty times more expensive than E-glass fibers) and steel fibers; this is the main argument against a common use of carbon fibers in the construction industry ;

b) fibers are brittle (important property for short fibers dispersed in concrete);

c) fibers are electric conductors, and will accelerate the corrosion of steel rebars placed in their proximity.

As a result, carbon fibers could be observed only as laboratory investigation objects.

Figure 3. Samples of commercially available carbon fibre products (picture from [3])

Aramid fibers.

Aramid fibers are polymer fibers (a family of nylons) formed by stretching high molecular weight polymers in solution. Subsequent heat treatment leads to higher molecular orientation in the fibre direction. More commonly used fibre trade names are: Kevlar, Technora, Twaron and Nomex. Du Pont Company developed the most popular of these fibers under the trade names Kevlar 29 and Kevlar 49 in 1966. Briefly afterwards, Akzo Nobel developed aramid fibers under the trade name Twaron. In early 2001, the Teijin Corporation acquired Twaron Products and since then has been the producer of Twaron fibers and another aramid fibers, called Technora. The polymer used contains within its molecule the aromatic carbon ring structure, which has a strong carbon-carbon bond (see Figure 4). There are several types of Kevlar fibers: Kevlar 29, Kevlar 49, and Kevlar 149.

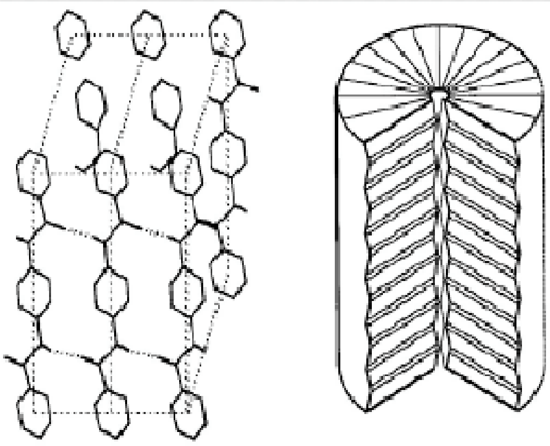

Figure 4. Aramid unit cell and fibre structure [5]

(picture from [6])

Kevlar 149 has the highest tensile modulus among all available aramid fibers. Kevlar 49 is widely used in composite plastics. It shows a large degree of yielding on compression side during bending [4]. This property is not observed in glass or carbon fibers. Polymer composites give Kevlar composites higher impact resistance. Kevlar fibers have low creep; the strength and longitudinal stiffness decrease linearly with temperature rise, still having 80% of their original strength at 180 °C [4]. Like carbon fibers, polymer fibers have low transverse stiffness. Compared to glass fibers, aramid fibers are relatively not sensitive to surface damage, which is considerable advantage in weaving and other fabrication processes. In concrete, aramid fibers are absorbing water and loosing strength. This property is increasing with increasing temperature. Relatively high price and mentioned properties are the reason why, at the moment, aramid fibers cannot be observed as fibers with wide application.

Polypropylene fibers
Polypropylene fibers are acid and alkali resistant with low water absorption. Commercially available fibers are much thicker compared to above mentioned glass, carbon and aramid fibers (see Table 1). Molten polypropylene is compressed and stretched forming sheets, tapes (or fibers). After this the tape is split into single fibers by mechanical means. Sometimes splitting is done in such a way that the edges of the fibers become uneven and frayed, hereby a mechanical bond between fibre and concrete can be achieved over the full surface of each fibre. Fibers obtained have mainly a rectangular cross section; their width varies considerably from fibre to fibre. After splitting, the material is chopped into suitable fibre length (traditionally 6, 12, 18, 24 … mm). In special cases the fibre material may be left in full length. Ordinary polypropylene have low bond with cement, low elastic modulus ad high Poisson's ratio. To improve compatibility with concrete, special surface and edges treatment are performed [7].

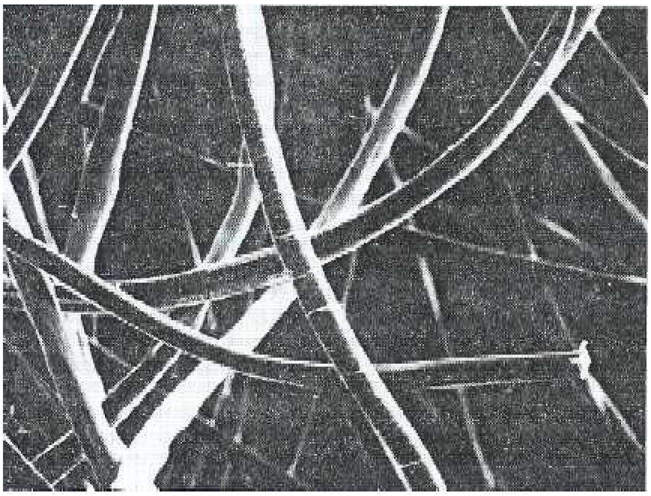
Figure 5. Extruded ordinary polypropylene fibers (picture from [7])

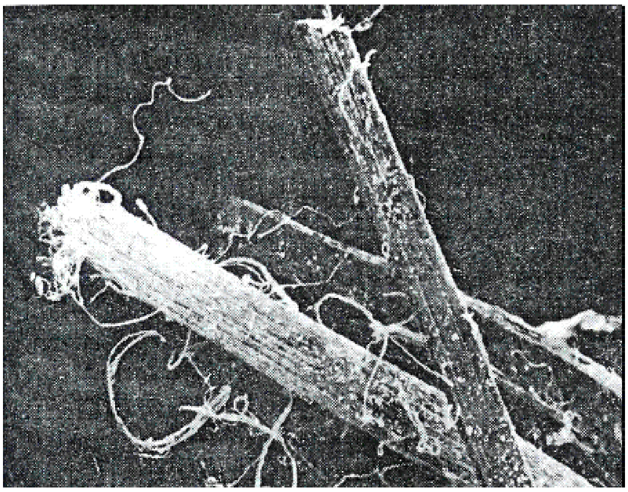
Figure 6. Specially developed polypropylene fibers with higher bond to cement and concrete matrix (picture from[7])

Polypropylene fibers are relatively cheap. Polypropylene short fibre size can be compared with short steel fibers as well as glass and carbon fibre polymer composite products (short polymer composite sticks). Polypropylene fibers are widely used for concrete properties improvement in different civil engineering applications. Negative point is that polypropylene fibers are softer than other non-metallic fibers. Polypropylene fibers cannot be considered as an efficient means to carry loads. Polypropylene fibers are cheap, commercially available and may be considered as a means to improve mechanical properties of reinforced concrete in combination with load bearing reinforcement.

Metal fibers. Steel fibers
Affordable price, possibility to use traditional technologies, high strength and stiffness and close to concrete thermal expansion coefficient are making this material still very competitive (using them as short fibre concrete reinforcement for concrete) when compared to novel polymer composite and non-metallic reinforcement. Highest strength may be obtained for steel wire

having diameter in microns range (such fibers are expensive and very sensitive to corrosion). Fibers used for concrete reinforcement have a diameter D between 0.15 and 1.5 mm. Steel fibers are produced out of cold or warm-drawn steel wire, steel thin tape or steel blocks [8]. Fibre length L varies from 30 to 150 times the diameter. Traditionally, the R=L/D ratio is used for fibre characterization. Increasing R will decrease the workability of fibre concrete and increase the efficiency of the fibre. Fibers cross section form may be round, or rectangular. Different producers are trying to deform fibers with the goal to improve fibre anchorage capacity. In Table 2 (from reference [9]) are shown steel fibers, suppliers and fibre "brand names" currently available on the market.

Table 2. Main types of steel fibers available on the market

Form	Manufacturing process	Company	Brand name
	Drawing Drawing	Trefil ARBED	Wirex Eurosteel
	Cutting, Slitting	Australien Wire	Fibresteel
	Drawing	Bekaert	Dramix
	Drawing	National-standard	Duoform
	Melt-extraction	National-standard	Melt-extracted
	Milling, Filing	Harex Stahlfaser-technik	Harex
	Drawing	Stax	
	Drawing	Thibo	
	Cutting, Slitting	US-Steel	Steel sheet fibres

Tensile strength of steel fibers is between 400 MPa and 1500 MPa. Strength of highly carbonated steel fibers may reach about 2000 MPa. Young modulus is about 200 GPa. Fibers are isotropic or may be slightly anisotropic. Steel fiber concrete is widely used in different civil engineering application, variety of fibers is commercially available, and this is the reason why practical engineers are more familiar with such fibers applications.

3. Continuous reinforcement elements

Steel reinforcement bars

Traditional material for concrete reinforcement is steel. All composite reinforcement variants can be compared with concrete reinforce by steel bars.

Composite reinforcement bars

There are two main reasons why composite bars (fibers in polymer matrix) are used for concrete reinforcement in lieu of steel:

a) Durability;

b) Electromagnetic neutrality, high strength, predictable ductile properties and light weight.

The use of FRP bars in concrete for anti-corrosion purposes is expected to find applications in marine (or close) buildings, in chemical or other industrial plants and for thin structural elements [4]. Such bars have a high strength. Commercially available bars consisting of 70% glass fibers; 15% vinyl ester resin; 10% polyethilenterephthalate (PET) resin; 3,5% ceramic fibers and 1.5% corrosion inhibitor are shown on Figure 7. Nevertheless, many investigations must be done to clarify advantages and disadvantages of FRP fibers use in concrete constructions.

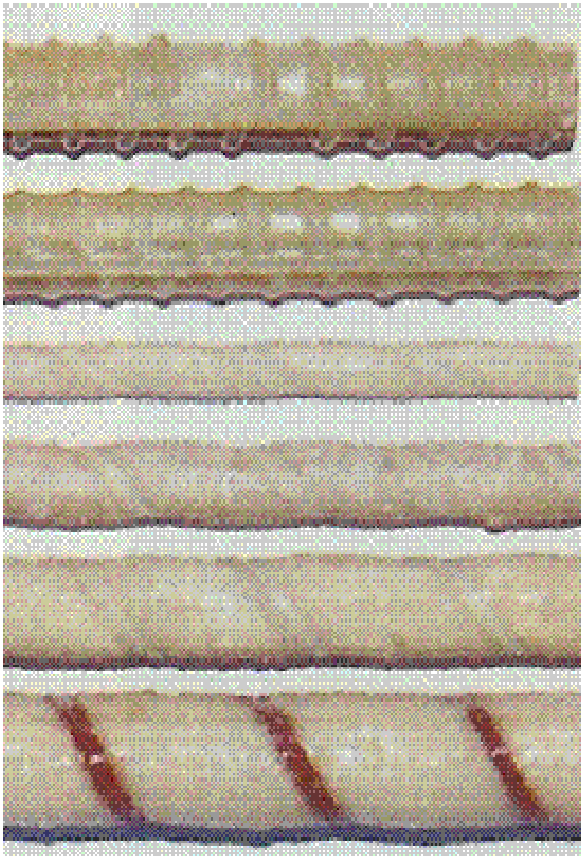

Figure 7. Glass fibre hybrid polymer composite bars (picture from [10])

a)
b)
c)
d)
e)
f)

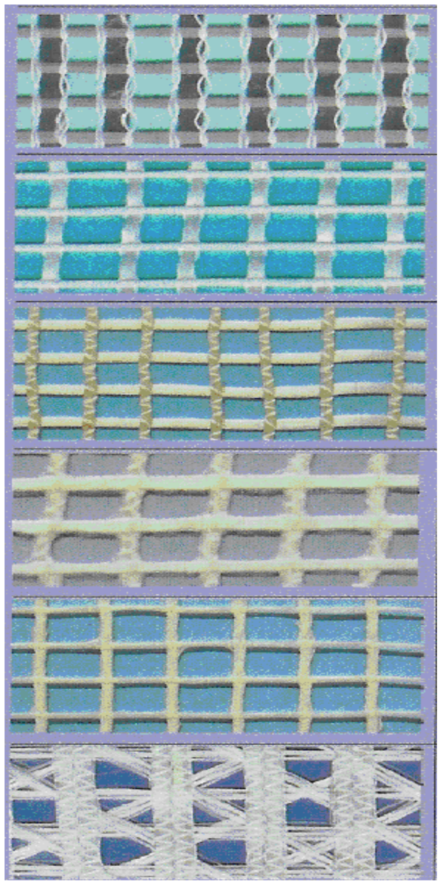

Figure 8. Fibre nets for concrete reinforcement (picture from [11])

Polymer composite nets

A very promising concrete reinforcing way is to use composite nets made of polymer composite bars, or composite yarn. Normal and priestesses concrete construction members may be obtained. Figure 8 shows different non-metallic fibre nets used for concrete reinforcement [11.]:

a) carbon fibers net (yarn spacing: 0 direction – 10mm, 90 direction -10mm);

b) AR-glass fibers, linen weave (yarn spacing: 0 direction – 8mm, 90 direction – 8mm);

c) AR-glass fibers tricot weave (yarn spacing: 0 direction – 8mm, 90 direction – 8mm);

d) AR yarn with sheath of polypropylene fibers hot-pressed (yarn spacing: 0 direction – 8mm, 90 direction – 8mm);

e) AR-glass fibers coated (yarn spacing: 0 direction – 8mm, 90 direction – 8mm);

f) AR-glass fibers (yarn spacing: 0 direction – 20mm, 90 direction – 17mm, 45 direction 18mm). These last times, various investigations were made using composite yarn and non metallic fibre fabrics, 3D composite nets and different fibers combinations for concrete reinforcement.

Conclusions

Successes in concrete matrix production new technologies (use of micro powders, super plasticizers and other modern chemical admixtures) leads to new possibilities in concrete reinforcement use. New types of reinforcement are changing traditional concrete mechanical behavior as well as concrete construction member's production technology.

Acknowledgement

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Krasņikovs A., Lapsa V., Eiduks M. Netradicionālais betona stiegrojums – mūsdienu problēmas stāvoklis

Rakstā dots apskats netradicionālā betona stiegrojuma pielietošanā konstrukcijās un konstruktīvajos materiālos mūsdienās. Galvenais uzsvars likts uz šķiedru un šķiedraino materiālu produktiem. Tiek aplūkotas metāla (tērauda) un nemetāla (stikla, oglekļa, sintētiskās (aramīdu) un polimēru) šķiedras. Katrai šķiedru grupai dots īss raksturojums. Atzīmēti arī attiecīgie komerciāli pieejamie produkti (uz šķiedru bāzes). Analizēta dažādu šķiedru

materiālu ķīmiskā uzbūve. Apskatīta šķiedru savstarpējā saderība ar betona matricu no fizikāliem un mehāniskiem aspektiem un uzrādītas šķiedru mehāniskās īpašības - stiprība, stingums un ģeometriskie izmēri. Atzīmēts, ka šķiedras kā armējumu betonā var izmantot īso šķiedru veidā, kompozīto stieņu vai hibrīdo tīklu veidā. Kompozītie stieņi sastāv no viena vai vairākiem šķiedru tipiem, kas savienoti ar polimēru matricu. Hibrīdo tīklu sastāvā tiek lietoti stieņi, kūļi, vai virves no viena vai vairākiem šķiedru tipiem. Uzrādītos armējuma paveidus var pielietot vienus pašus vai kombinējot vienus ar otriem, vai arī kopā ar tradicionālo armējumu. Ir atzīmēts jauno, netradicionālo armējumu pielietojuma daudzsološais raksturs.

Krasnikovs A., Lapsa V., Eiduks M., Non-traditional reinforcement for concrete composites - state of the art
In the article can be found problem's state of the art for a new non-traditional reinforcement use (and types) in building industry. Main attention is focused on the fibers and fiber materials. Under discussion are metallic (steel) and non-metallic (glass, carbon, synthetic (aramid) and polymer) fibers. Each type of fibers is comprehensively characterized, as well as commercially available products made on the base of fibers. Peculiarities of fiber material's internal structure and chemical form are discussed. Compatibility with concrete matrix is important parameter for all fiber materials. Mechanical behavior parameters: strength, stiffness, size and geometry were analyzed and discussed. Fibers can be used for concrete reinforcement as short monofilaments or multifilaments. Another possibility is composite bars, wires and nets. In composite bars (wires) one type fibers may be combined with other types, forming composite rods glued by polymer matrix. Hybrid nets can be produced using one type, or different fiber type rods, wires and yarn. All mentioned non-traditional reinforcement can be combined with traditional one. In the article was emphasized highly promising character of new reinforcement.

Красников А., Лапса В., Ейдукс М. Нетрадиционная арматура для бетонов – состояние проблемы на данное время
В статье дан обзор современного состояния проблемы применения нетрадиционного армирования бетонных конструкций. Основное внимание уделяется применению волокон и волокнистых материалов. Выделяются металлические (стальные) и неметаллические (стеклянные, угольные, синтетические (арамидные) и полимерные волокна). Дается краткая характеристика каждому типу волокон наряду с соответствующими коммерчески доступными продуктами. Отмечаются особенности внутренней структуры и химического строения материала волокон. Характеризуется совместимость волокон с бетонной матрицей, приводятся механические характеристики - прочность, жесткость и геометрические размеры. Волокна используются в виде коротковолоконного армирования, в виде композиционных (состоящих из волокон разного происхождения и полимерной матрицы) стержней, а также в виде гибридных композиционных сеток. Указанные армирующие элементы могут использоваться как самостоятельно, так и совместно с традиционным армированием. Отмечается эффективность нетрадиционного армирования.