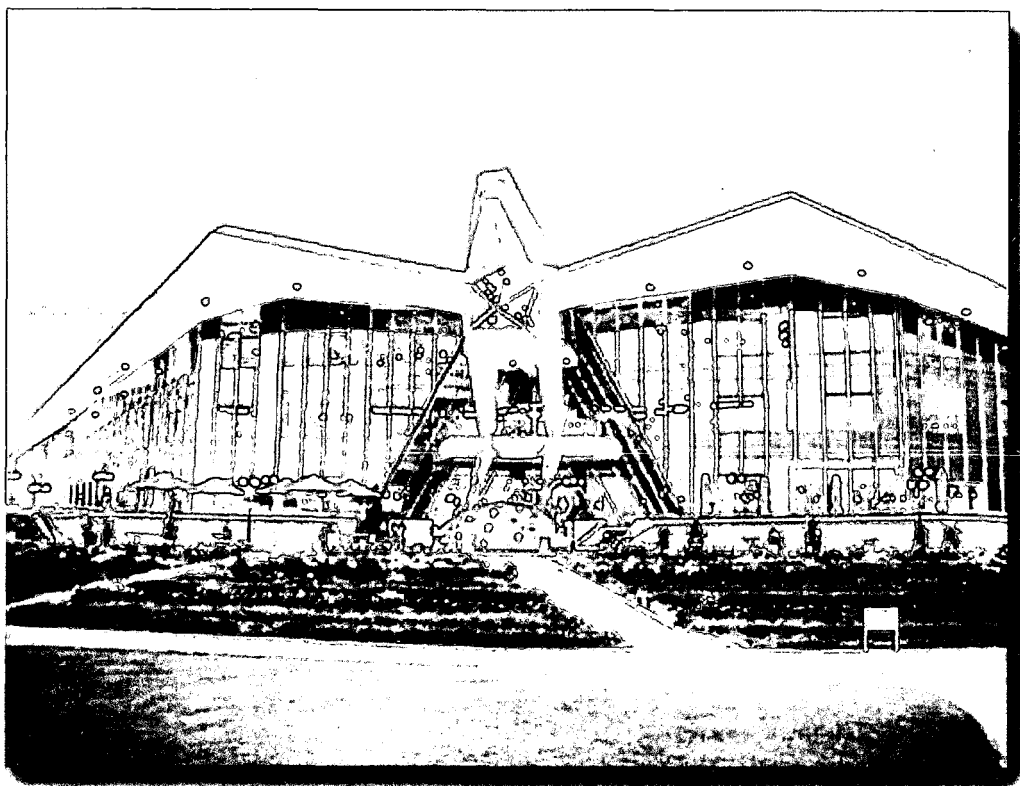


THIN REINFORCED CEMENT-BASED PRODUCTS AND CONSTRUCTION SYSTEMS



Editor
Ashish Dubey

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Thin Reinforced Cement-Based Products and Construction Systems

Editor
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Cover Page Photograph

The Clubhouse at Abu Dhabi - The building demonstrates the use of thin cementitious panels as exterior cladding.

Photograph courtesy of Fibrex LLC, Abu Dhabi

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PREFACE

The use of thin reinforced cementitious products continues to grow rapidly today in a variety of construction applications worldwide. Thin reinforced cementitious products are strong and tough, dimensionally stable, fire resistant, and possess excellent moisture resistance and environmental durability. With the continued rapid decline in the use of asbestos fibers as reinforcement in thin cementitious products, several advancements have occurred in the field as a result of the development of new types and forms of reinforcement for thin cementitious products. Also, several advancements have taken place in the material science and manufacturing methods of cementitious materials for thin reinforced cementitious products. This publication contains the papers originally presented in a symposium on the topic of thin reinforced cementitious products organized by ACI Committee 549 on Thin Reinforced Cementitious Products and Ferrocement during the ACI 2003 Spring Convention held in Vancouver, Canada. The symposium explored current state-of-the-art and recent advances in material science, manufacturing methods, and practical applications of thin reinforced cementitious products.

The topics covered in this publication include material science of textile reinforced concrete, use of textile reinforced concrete for integrated formwork and exterior cladding panels, prestressed thin-sheet concrete products, ultra-high-performance thin precast concrete products, production of concrete tubes by centrifugation method, freezing-and-thawing durability of commercial fiber-reinforced cement boards, structural evaluation of cement-skin sandwich building systems, microwave accelerated curing method for producing precast cementitious products, history of glass fiber-reinforced concrete (GFRP) products, and modeling of cement-based laminate composites. The papers presented in this publication have been peer reviewed by experts in the field, according to the guidelines established by the American Concrete Institute.

The future of thin reinforced cementitious products depends largely on their ability to compete cost effectively with similar products made using other materials such as metals and plastics. For future research and development, this entails understanding and optimizing fiber-reinforced cementitious compositions from a fundamental material science perspective; developing and implementing the use of cost-effective raw materials, particularly reinforcing fibers and other forms of reinforcement; and developing efficient manufacturing methods to produce thin reinforced cementitious products.

Ashish Dubey
Editor

*Chair, ACI Committee 549
Thin Reinforced Cementitious Products and Ferrocement*

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GFRC—30 Years of High Fiber Cement Composite Applications Worldwide

by G. T. Gilbert

Synopsis: Thin, fiber reinforced cementitious products offer a useful balance of properties such as strength, toughness, environmental durability, moisture resistance, dimensional stability, fire resistance, aesthetics and ease of handling and installation.

For more than 30 years, AR glass fibers have been at the forefront in the development of new applications of such products throughout the World. Glass Fiber Reinforced Concrete [GFRC] is a thin, cement composite based on AR glass fibers with an excellent strength to weight ratio.

Extensive early laboratory work produced a test method for determining long term strength. The validity of this work has been proven by the large number of buildings clad with GFRC, as well as a vast range of other GFRC products, used over a this 30 year period.

This paper explains the fundamental principles behind GFRC and gives examples of some of its uses. These applications range from high quality, architectural wall panels and decorative elements through to modular buildings down to low cost channel sections and utility components. New developments and techniques will also be discussed.

Keywords: AR glass fibers; AR mats; AR meshes; decorative elements; durability; engineering properties; fiber cement; fiber reinforcement; manufacturing methods; modular buildings; thin cementitious products; wall panels

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Based in the UK, he has worked on the use of AR Glass fibers as a fibrous reinforcement for cement based composites and concrete for more than 30 years. During this period, he has traveled extensively encompassing all the major European countries as well as the Middle East and North America providing techno-commercial support to both new and existing manufacturers.

He is also a member of the American Concrete Institute, The Precast/Prestressed Institute and the International Glassfibre Reinforced Concrete Association.

1.0 INTRODUCTION

Cement based materials have inherent defects such as flaws in the matrix due to shrinkage and debonding at interfaces. AR glass fibers in this brittle cementitious materials help to enhance the composite toughness and tensile strength by synergistically interacting with the micro cracks that develop when the composite is loaded. The AR glass fibers restrain crack opening and crack growth by effectively bridging across the micro cracks.

The most common form of glass fibers, E-glass, is used as a reinforcing material in resin composites referred to as FRP. However, when E-glass fibers are exposed to portland cement based mixtures, such as mortars or regular concrete, the alkaline nature of the cementitious mixtures rapidly deteriorates the glass fiber. Because of this, AR glass fibers were developed by intrinsically modifying the chemical composition of the glass fibers such that they are inherently more chemically resistant to the alkaline nature of cementitious matrix.

The actual dose rate used will determine the final composite properties with 0.6kg/cu.m. [11b/cu.yd] being used for plastic shrinkage cracking of regular concrete. However, thin section 12mm [1/2"] GFR Concrete will use much higher dose rates ranging from 2-5% of total weight being the normal range. Recently, dose rates as high as 15-18% of continuous filament have been used for newly developed filament wound poles. The exceptional high tensile strength of AR glass fibers imparts tensile properties to the resultant composite as well as improving its toughness and impact strength.

Because GFRC has both good tensile and compressive strength as well as being lightweight with good fire properties and low maintenance, it has been used throughout the World in a wide range of applications and these will be highlighted later in this paper.

2.0 AR GLASS FIBERS

2.1 General Data and Fiber Types

In order to make glass fibers resistant to the lime generated during the setting of Portland cement, zirconium is added to the glass mixture composition prior to melting and fiberising the raw materials. The added zirconium becomes part of the glass fiber molecular structure in the manufacturing process and is not just a protective coating. The minimum zirconium content in the composition for good durability is about 16% by weight. The glass fibers with this zirconium modification are usually referred to as alkali-resistant glass fibers or AR glass fibers. AR glass fibers are chemically stable resisting both alkali and acid conditions. Chemical composition of the AR glass fibers is shown in Table 1 and the physical and mechanical properties in Table 2.

AR glass fibers for use in concrete are available in three basic forms - discrete chopped strands [CS], continuous rovings and meshes.

2.1.1 AR Glass Fiber Discrete Chopped Strands-- are used primarily in premix glass fiber reinforced concrete [high dose rate] and in crack control of concrete [low dose rate] where the glass is added directly to the cement or concrete slurry. Typically, AR glass fiber CS are available in two types, integral and water dispersible. Glass fiber CS are made up of bundles of individual filaments with the typical diameter of these filaments being 12-20 microns.

2.1.2 Integral Chopped Strands-- are designed to stay as bundles of filaments through mixing and placing, with as little breakdown of the bundle as possible [Fig 1A]. Integral strand bundles can contain as many 400 and as few as 50 filaments. The number of filaments per bundle is usually referred as strand geometry. The diameter of the individual filaments, the number of filaments that are bundled together, and the integrity of the bundle are the key factors that determine performance characteristics of the strand. The typical length of discrete AR glass fiber strands used in thin-reinforced products ranges between 6 [1/4"] to 40 [1 3/4"] mm. The strand geometry, strand length, and glass fiber content all contribute to the processing characteristics of the composite and its final properties.

2.1.3 Water dispersible Chopped Strands-- are designed to disperse quickly into individual strands on contact with water or an aqueous cementitious mixture. These fibers are used in composites where a fine dispersion of individual monofilaments is desired rather than intact fiber bundles. In particular, water dispersible AR glass fibers are commonly used to reduce cracking in concrete, mortars and stucco application and in manufacturing processes that involve cementitious slurries with initial high water content such as modified Hatschek process or for calcium and sodium silicate applications frequently using the filter-press processes. Typical length of water dispersible AR glass fiber strands used in thin-reinforced cement products ranges between 6 [1/4"] to 25 [1"] mm.

2.1.4 Continuous AR Glass Fibers-- are available in the form of roving [Fig. 1B]. A roving is an assemblage of several continuous AR glass fiber monofilaments. The

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manner in which the monofilaments are assembled varies and differentiates one roving type from another. Fundamentally, the construction of an AR fiber roving is as follows:

- Several continuous alkali-resistant glass fiber monofilaments are gathered together to form a continuous strand. The typical diameter of the individual alkali-resistant glass fiber monofilaments ranges between 10 to 20 microns. Typically, the number of monofilaments that are gathered together to form a continuous strand ranges between 50 to 400.
- Several continuous strands as explained above are assembled together to form a continuous roving. Typically, the number of continuous strands that are assembled to form a continuous roving ranges between 20 to 100.

2.1.6 Glass Fiber Meshes and Mats-- are woven or dipped, non-woven products from assembled glass fiber rovings or strands whilst mats are chopped fibers bonded together with a polymeric coating. Traditionally they were woven products of heavily coated E-glass fiber yarn used mainly in the production of cement boards (Venta et al. 1995, 1997, 1998). As an alternative, an alkali-resistant (AR) glass fiber mesh can be used to reduce the need for the coating. The AR mesh has recently been used in a new system for seismic improvement of masonry walls.

3.0 PRODUCTION METHODS

3.1 Simultaneous Spray Process

In the simultaneous spray process, continuous AR glass fibers are chopped through a gun and air-sprayed simultaneously with the cement slurry onto a mold surface, [Figure 2]. To spray the entire mold area, both the fiber and cement slurry spray guns are moved to follow the contours of the mold. Successive 4-6mm [$\approx 1/4"$] layers are sprayed and roller compacted to form a typical 12-15 mm thick ($\approx 1/2"$) panel. The compaction removes air, helps bond and ensure a good quality finish.

The simultaneous spray process can be manual or automated. Spray process allows tremendous flexibility in manufacturing complex architectural shapes as well as producing a high strength product. Consequently, architects around the globe commonly design and specify architectural shapes manufactured using the spray process.

3.2 Premix Process

The premix process consists of first mixing together the other ingredients (cement, sand, admixtures, water, etc.) in a standard or specialized mixer to give a low viscosity mortar. The AR chopped strands are added to this mortar and cast to form a thin product of desired shape in a mold. The casting process may be similar to concrete casting or hand packing [lower strengths] or it may not involve spraying of fiber-cement slurry as a method to fill the mold and/or vibration to achieve satisfactory slurry compaction in the mold. In the premix process, the maximum amount of fibers that can be incorporated in the mixture is dependent upon the length and diameter of the fibers used. Additives such as polymers, pozzolans e.g. metakaolin, and/or flow aids such as water reducing agents are generally used to facilitate the mixing operation. The premix process typically yields a three-dimensional

random orientation of fibers in the mixture. Consequently, premix products are not as strong as simultaneous sprayed ones but the process has the advantage of ease of production and a lower level of skill required to produce the end product.

3.3 Filament Winding Process

Filament winding process was developed for FRP composites but has recently been used to produce GFRC poles.

Figure 3 shows a pole being wound onto a mandrel with AR glass fibers

The fiber roving strand passes over several round steel bars placed below the level of a specially modified mortar mix before being wound onto a mandrel.

Various continuous fiber cement based composites consisting of unidirectional lamina, cross ply and angle ply laminates can be manufactured with a typical AR glass volume fraction of 13%. Mechanical properties of wound tube test specimens gave tensile strengths higher than 300 MPa [50,000psi] and flexural strengths as high as 200 MPa [30,000psi]

The filament winding method has been refined commercially in the US for the production of a range of poles and inductively transparent, high temperature ladles with glass fiber volume fraction ranging from 10 to 25%. [Ref US Patents 5039345 (Mott 1991) and 5880404 (Stanley and Mott 1999).

3.4 Filter-press Process

In the filter-press process, first a wet fibrous mix is produced with an excess of water. Then this mix is charged into a mold, which has a perforated plate at the base. A filter material is laid on top of the mold base. The mix is then pressed by a top plate, which squeezes out the excess water through the base of the mold and through a small gap between the top plate and the sides of the mold. The compressed board or tile is then removed from the mold and stacked for curing. Depending on the shape, the product can be demolded immediately whilst in the unhardened state. It is also possible to use rapid setting cements to accomplish instant demolding. The filter-press process is well suited for mass production of products having simple or complex shapes.

4.0 GLASS FIBER REINFORCED PRODUCTS PROPERTIES

The physical and mechanical properties of glass fiber reinforced concrete are discussed more fully in ACI 544.1R-96. The following summarizes these properties.

The mechanical properties of GFRC composites depend upon the fiber content, water/cement ratio, density, sand content, fiber orientation, fiber length, and polymer content if used. Typical properties for traditional spray up GFRC containing 5% by weight of glass fibers are shown in Table 3 (PCI MNL-128-01). As shown in this table, GFRC composites have significant load and strain capacity. Whilst some of these properties reduce a little with time for standard GFRC their real time performance is well documented and all accepted

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design procedures allow for it in establishing design values. PCI publication MNL-128-01, 'Recommended Practice for Glass Fiber Reinforced Concrete Panels' details the most widely accepted design procedure in the industry.

If reduction in mechanical performance of composites is of concern, GFRC composition can be modified in several ways to prevent this from occurring. The formation of calcium hydroxide within the fiber strands has been held to be largely responsible for the change in properties with time (Bentur 1985). The measures that are used to arrest the change in properties generally attempt to prevent the formation of calcium hydroxide. The glass fiber manufacturers have made available alkali-resistant glass fibers with special coatings that reduce the affinity of the fibers for calcium hydroxide (Hayashi, Sato, and Fuji 1985). Most other methods to improve durability of GFRC rely on either the use of pozzolanic admixtures such as silica fume, metakaolin or fly ash, (Marikunte, Aldea, and Shah 1997; Soukatchoff 1999; Soukatchoff and Ridd 1991; Purnell et al. 1991) or use of special cements such as calcium sulphoaluminate cements that do not produce calcium hydroxide as a hydration product (Molloy, Jones, and Harmon 1993; Molloy and Jones 1993). Acrylic thermoplastic co-polymers have also been reported to reduce the extent of reduction in mechanical performance with time (Ball and Wackers 2001). Acrylic thermoplastic co-polymers are usually used in GFRC products because they improve the curing of the GFRC.

In addition to traditional spray up GFRC, premix glass fiber reinforced concrete is growing in use for certain products. Typical properties for premix GFRC are shown in Table 4 (PCI MNL-128-01). Generally premix GFRC has a lower fiber content, uses shorter fibers, and has significantly greater three dimensional fiber orientation than the largely two-dimensional orientation obtained with spray up GFRC, which all contribute to it having lower mechanical performance than the spray up GFRC.

5.0 APPLICATIONS OF GFRC

5.1 Cladding

5.1.1 Modular Buildings. -- Single- or two-storey modular buildings, have been constructed with AR glass fiber reinforced cementitious sandwich panels integrated into a lightweight steel structural frame during erection. Sandwich construction of the panel involves two 8 mm [$\approx 3/8$ in] thick AR fiber reinforced concrete skins attached onto both sides of a 155 mm [6in] thick core of lightweight concrete. This building system has been independently tested for load capacity, sound insulation, thermal conductivity, and fire resistance.

Figure 4 & 5 shows an example of such a system.

Much earlier, in the late 1970's, GFRC panels were used on exterior wall of prefabricated timber frame houses constructed to meet the shortage of dwellings in Scotland. The panels were typically 10 mm [0.4in] thick and had an aggregate finish surface. Simple cast-in washers for face fixing the panels were incorporated at 50mm [2in] on center.

Wind pull off tests conducted on the wall systems yielded results in excess of those needed for the 200 km/hour (125 mph) gusts found in that region. These houses were independently inspected by the GRCA (Glass Reinforced Concrete Association, UK) after 20 years and were found to be in good and serviceable condition. Figure 6 shows these dwellings after 20 years exposure in the Highlands of Scotland.

5.1.2 GFRC Architectural Façade Panels – these panels can be manufactured as wall and window units, spandrel, soffit and fascia panels, mansard roof elements as well as mullions, cornices and column covers. Figure 7 shows a photograph of the Cervantes Convention Center situated in St. Louis, Missouri in which 1670 m² [≈18000ft²] of the building exterior was clad with GFRC architectural façade panels. The panel size varied but the average was approx. 2.4 m x 6.0 m. [≈8 x 20ft] The panel skin consisted of 12.5 mm [1/2in] thick GFRC plus a 6 mm [1/4in] thick facing mix attached to a structural steel frame, which in turn was attached to the building. In several panels, two finishes were combined on the same panel. Brick red finish on the panels was achieved with the use of white cements, sands and pigments. The intricate architectural details on these panels were created by forming the panels over rubber liner molds. Some panels also had limestone finish. This was achieved with the use crushed stone, pigment and sandblasting. When using facing mixes, care is required to reduce incompatibility from thermal and moisture movement.

There are innumerable examples of high quality, architectural panels on buildings completed for over 30 years around the World. Fig 8 shows the recently completed Nile City Project in Cairo and Fig. 9 the San Francisco Towers complex in California, USA where 155 000 GFRC panels were used.

5.1.3 GFRC Decorative Elements- GFRC is capable of closely imitating natural materials, which tend to be expensive and in short supply. Thin complex shapes with excellent surface finish and surface details can be easily formed using AR glass fiber reinforced cementitious materials. Molds to form these shapes are frequently taken from deteriorated original carvings. GFRC architectural elements are relatively light in weight and require low maintenance. These attributes make GFRC architectural elements a sensible choice for both new and refurbished buildings. Figure 10a & b and Fig.11 show some applications.

5.2 Road and Rail Sound Walls

Throughout the world, new highways and mass transit rail systems compete for space in already developed urban areas. The result is that major traffic routes are found closer to commercial and residential areas and it becomes necessary to suppress noise pollution to the surroundings. GFRC noise barriers are being increasingly used since they are light in weight and offer simplicity and speed of erection without requiring the use of heavy lifting machinery. This gives reduced disruption to traffic and greatly reduced loads on any elevated structures allowing for the same material to be used throughout. The moldability of GFRC allows for aesthetically pleasing designs which are more attractive and acceptable to both residents and travelers as well as to bridge engineers and

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architects alike. In addition, GFRC has excellent resistance to salt attack, freeze-thaw and rotting thus reducing maintenance.

Figure 12 shows a GFRC reflective sound wall in Spain and Fig 13 a different design, absorbing, in South East Asia.

5.3. Ducts and Channels

5.3.1 Drainage Channels- GFRC has been used for drainage and transporting liquids represent another application for GFRC. Fig 14 shows a commercially available high volume, rain-water drainage channel used in parking lots, road and highway applications. These channels are designed for optimum flow capacity and are available in different cross-sectional sizes with lengths ranging up to 2 meters (6.6 feet). Further, these channels are lightweight, easy to install in long sections with reduced excavation, maintenance free, and require fewer silt traps or manholes due to their superior hydraulic performance. The channels are produced by vibration casting an AR fibers mix into a two-part mold.

5.4.2 Cable and Pipe Ducts and Conduits in GFRC are used in Europe, Japan and the USA. Figure 15 shows GFRC pipe trench liner in USA.

5.5 Tunnel and sewer Linings

5.5.1 Tunnel Liners --GFRC has been widely used for tunnel lining applications and Figure 16 & 17 shows Heathrow Express railway station at Heathrow Airport, London, UK. The panels used in this application are nominally 12 to 18 mm ($\frac{1}{2}$ " to $\frac{3}{4}$ ") thick and are made from a cementitious mixture reinforced with alkali-resistant glass. Lining within the stations consisted of 9000 acid-etched and sand-blasted panels of size 1.8 m (5.9') wide, 0.90 m (2.95') wide and 0.70 m (2.3') deep. A 50 mm (2") deep recess in each panel allowed enamelled glass advertising panels to be secured within.

5.5.2 Sewer Linings- Figure 18. shows a photograph of thin reinforced cementitious sewer lining application. GFRC sections are very versatile and cost effective, and thereby offer several significant advantages over FRP in sewer applications. They are stiffer and bond well with the grout lining, essentially becoming part of the sewer structure. Consequently, they are more resistant to the damaging influences of water pressure or ground movement.

5.5.3 Canal Bank Protection Linings in GFRC is demonstrated in Figure 19. Such linings are used to prevent erosion of the canal banks caused by different sources such as hydraulic discharge and incidental contact with passing boats. The panels are typically 6 to 9 mm thick, with ribs on rear face for strength and stiffness. The typical size of the panels is about 2 m x 1.36 m (6.5' x 4.5').

5.6 Pipes and Poles

Filament wound GFRC poles have recently been developed in North America. Figure 20 shows a pole manufactured using continuous alkali-resistant glass fibers. These poles can have a fiber volume fraction as high as 25%. In terms of their mechanical behavior, these products are exceptionally strong in tension (notched tensile strength of about 90 MPa), compression (compressive strength of about 175 MPa) and flexure (bending strengths of about 150 MPa). Using the filament winding process, the pole products can be easily manufactured in lengths of up to 15 meters (50 feet). Potential applications of the pole products include induction and wireless transmission-invisible poles and permanent formwork for seismic and marine columns.

5.7 Bridge Parapets

Fig. 21 shows GFRC panels used on the BTS Skytrain, Thailand's first mass transit system. The project extended about 23 km (14 miles) through the heart of the Bangkok and was entirely elevated. The parapets shown in this figure are typically 1.1 m high x 2.7 m [3' 6" x 8' 9"] long, and nominally 15 mm [2/3"] thick with ribbed top and bottom using expanded polystyrene void-formers. The ribbing provides the panels with additional strength and rigidity to resist the high wind loads caused by the passing trains. The parapet panels shown in this figure are reinforced with discrete, alkali-resistant glass fibers.

5.8 Landscaping Products

Glass fiber reinforced concrete is used widely for simulated rock installations in zoos, hotel and office lobbies, swimming pools, climbing walls, golf courses, and theme parks. Thin cementitious panels are usually factory prefabricated using the spray up process or sprayed premix. The molds are usually made of rubber that has been cast off an actual rock face. The cast panels are then assembled on the job site. The panels can be integrally colored or can be colored on the job site using acrylic stains.

6.0 SUMMARY

Glass fiber reinforced concrete, GFRC is a thin form of concrete with the high tensile strength of the AR glass fibers complimenting the high compressive strength of the cementitious matrix. The resulting composite, usually only 12-25mm [$\frac{1}{2}$ - 1"] thick, offers a unique balance of properties such as strength, toughness, dimensional stability, environmental durability, moisture resistance, freeze thaw resistance, fire resistance, esthetics, and ease of handling and installation.

Because of this blend of attractive properties, GFRC has found a wide range of uses in more than 40 countries spanning a period of more than 30 years.

The fibers are easy to incorporate using a variety of production methods to suit the end need.

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Applications range from the highly visible large architectural panels on low and high rise buildings to decorative elements to more mundane uses such as ducts and channels and tunnel linings.

Table 1-Chemical composition of AR-glass fibers, percent by weight (PCI MNL-128-01)

Component	AR-glass
SiO ₂	61.0-62.0
Na ₂ O	14.8-15.0
K ₂ O	0.0-2.0
Al ₂ O ₃	0.0-0.8
ZrO ₂	16.7-20.0
TiO ₂	0.0-0.1
Li ₂ O	0.0-1.0

Table 2-Properties AR-glass fibers (PCI MNL-128-01)

Property	AR-Glass
Specific Gravity	2.70-2.74
Tensile Strength, MPa [psi]	1700 [2.5 x 10 ⁵]
Modulus of Elasticity, GPa [psi]	72 [10.4 x 10 ⁶]
Strain at Break, %	2.0

Table 3: Typical range of traditional sprayed GFRC properties* (PCI MNL-128-01)

Property	28-day	Aged ^b
Dry Density Kg/cu.m. [pcf]	1900-2100 [120 to 140]	1900-2100 [120 to 140]
Compressive MPa [psi]	50-82 [7-12,000]	70-82 [10-> 12,000]
Flexural: MPa [psi]		
Yield (FY)	6-10 [900 ->1,500]	7-11 [1,000 to 1,600]
Ultimate strength (FU)	14-24 [2000 to 3,500]	9-17 [1300 to 2,500]
Modulus of elasticity GPa [psi]	7-21 [1->3.0x10 ⁶]	18-28 [2.5-> 4.0x10 ⁶]
Direct Tension: MPa [psi]		
Yield (TY)	5-7 [700 to 1,000]	5-7 [700 to 1,000]
Ultimate strength (TU)	7-11 [1,000 to 1,600]	5-8 [725 to 1,100]
Strain to failure %	0.6 to 1.2	0.03 to 0.08
Shear: MPa [psi]		
Interlaminar	3-6 [400 to 800]	3-6 [400 to 800]
In-plane	7-11 [1,000 to 1,600]	5-8 [725 to 1,100]
Coef. of thermal expansion ^o C (in./in. ^o F)	10-20 x 10 ⁻⁶ [≈12x10 ⁻⁶]	10-20 x 10 ⁻⁶ [≈12x10 ⁻⁶]
Thermal conductivity: W/m ^o C (Btu.in./hr.ft ² /°F)	0.5 to 1.0 [3.5 to 7.0]	0.5 to 1.0 [3.5 to 7.0]

Note:

*These are typical values and are not to be used for design or control purposes. Each manufacturer must test production composites to establish properties for design. The values achieved in practice will be dependent on mix design, quality control of materials, fabrication process and curing. Cement/sand ratio in the above composites ranges between 1:1 to 3:1.

^bDeveloped from accelerated testing programs on GFRC specimens immersed in 50 to 80°C (122 and 175°F) water. On the basis of comparisons between behavior in real weather and accelerated tests, predictions can be made of properties for 50+ years in different climates.

Table 4: Typical range of premix GFRC properties* (PCI MNL-128-01)

Property	Metric Equivalent	28 day
Density (dry)	1800-2000 kg/cu.m	110 to 130 pcf
Compressive Strength	40-60 MPa	6,000 to 9,000 psi
Flexural:		
Yield (FY)	50-80MPa	700 to 1,200 psi
Ultimate strength (FU)	10-14MPa	1,450 to 2,000 psi
Modulus of elasticity	7-20GPa	1.0x10 ⁶ to 2.9x10 ⁶ psi
Direct Tension: Yield (TY)	4-6Mpa	600 to 900 psi
Ultimate strength (TU)	4-7MPa	600 to 1,000 psi
Strain to failure	0.1-2%	0.1 to 0.2 percent
Shear: In-plane	4-7MPa	600 to 1000 psi
Coefficient of thermal expansion	10-20 x 10 ⁻⁶ /°C	Approx. 12x10 ⁻⁶ (in./in./°F)
Thermal conductivity	0.5 to 1.0 W/m° C	3.5 to 7.0 (Btu/in./hr/ft ² /°F)

Note: *These are typical values and are not to be used for design or control purposes. Each manufacturer must test production composites to establish properties for design. The values achieved in practice will be dependent on mix design, quality control of materials, fabrication process and curing.



Fig 1A AR Glass Fiber Chopped Strands

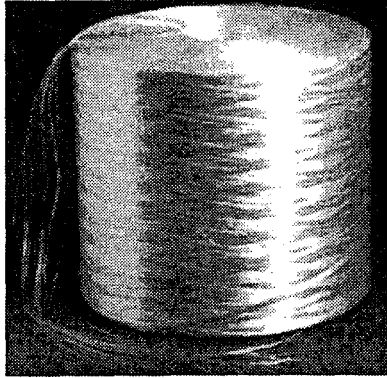


Fig 1B AR Glass Fiber Continuous Strand Roving

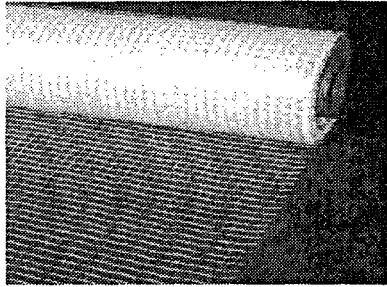


Fig 1C AR Glass Fiber Mesh



Fig 2 Simultaneous Spraying of GFRC

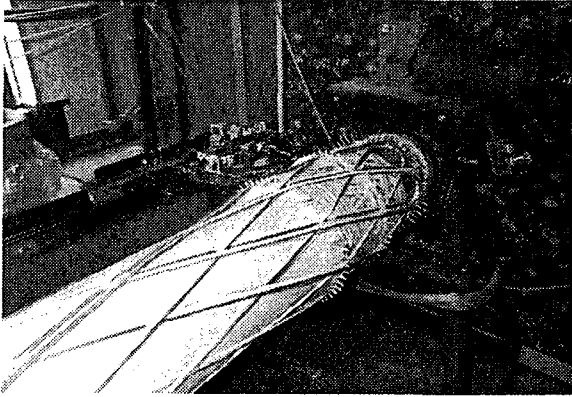


Fig 3 Filament Winding of a pole with AR Glass Fibers

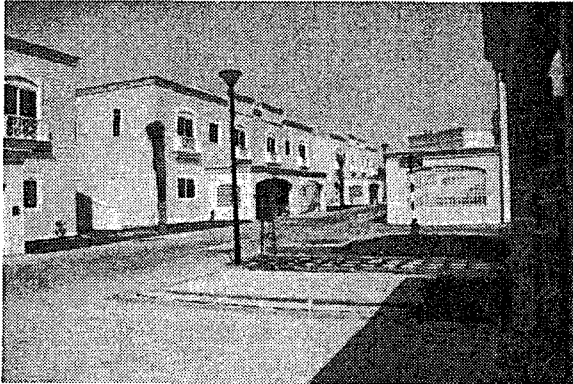


Fig 4 GFRC Insulated Wall Panels for Modular Housing in Dubai

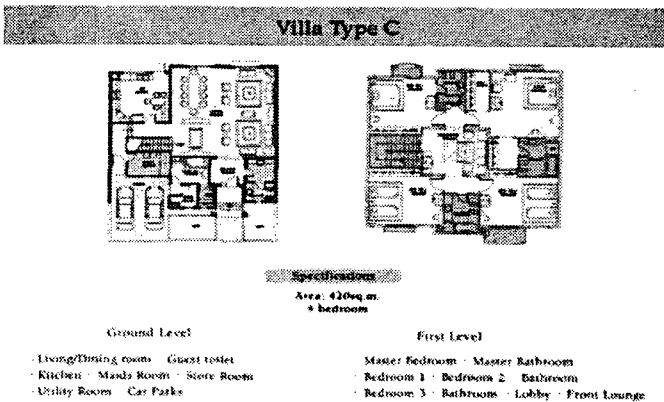


Fig 5 Floor Plan of Modular Construction House



Fig 6 Timber Frame Houses with Single Skin GFRP Panels. Built 1976, Scotland



Fig 7 1670 sq.m of GFRP panels on the Cervantes Convention Centre, St Louis, Missouri. 2 finishes – Ornate/pigmented and stone simulation

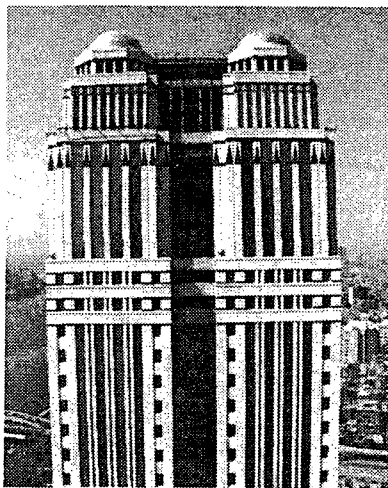


Fig 8 Nile City project, Cairo, Egypt. 2 x twin Towers



Fig 9 155 000 GFRC panels on San Francisco Towers, California, USA



Fig 10a Columns, Arches and Domes With Surface Details

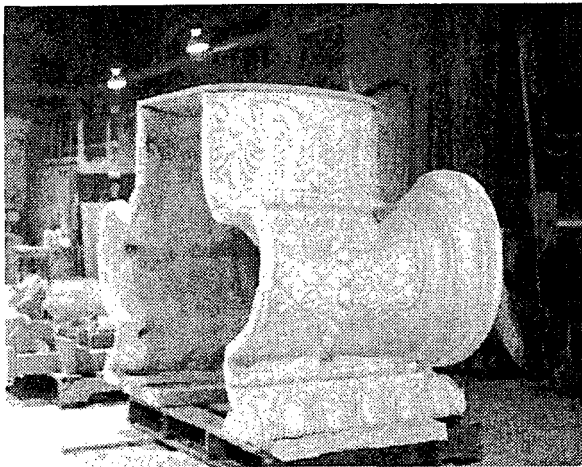


Fig 10b 1.3m [5ft] Capital Unit –View from Rear

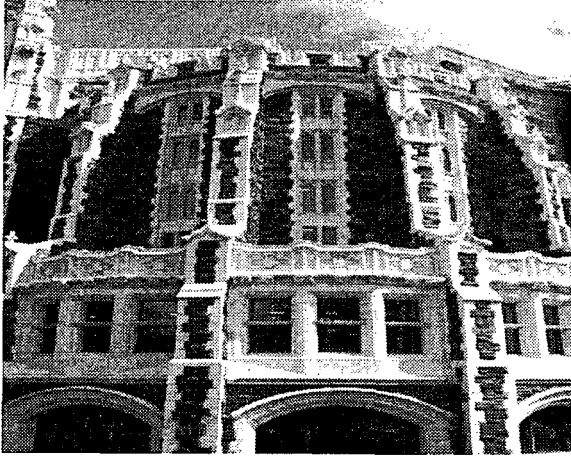


Fig 11 Terra Cotta Replacement on Shepard Hall, New York 72000 units with more than 4000 shapes inc. sculptures

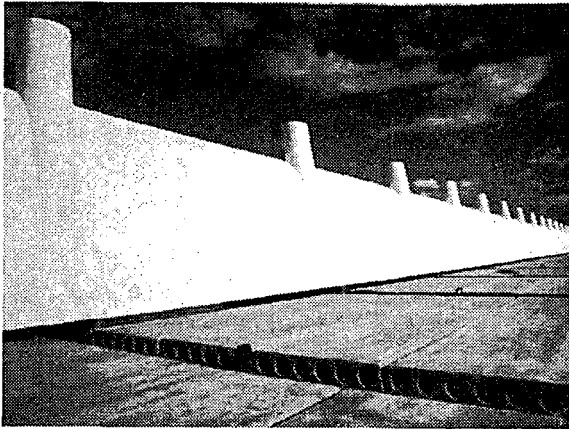


Fig 12 Reflecting Noise Barrier, Spain

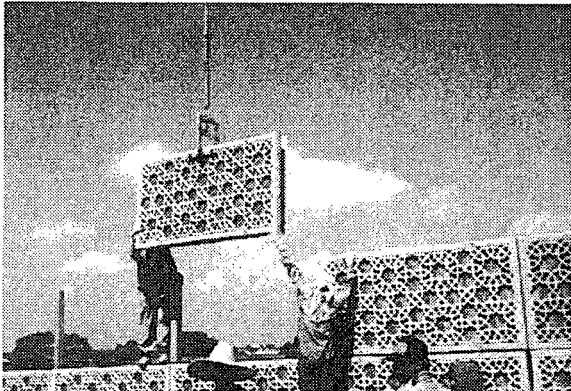


Fig 13 Absorbing Barrier S.E Asia

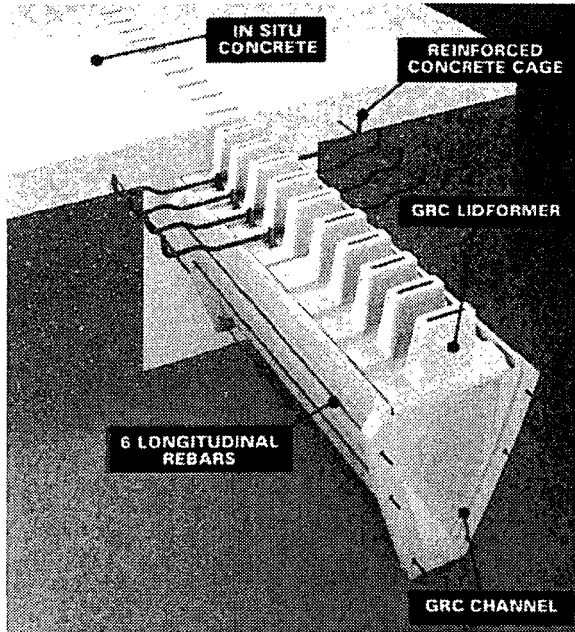


Fig 14 Engineered, Optimum Flow, Drainage Channels, UK



Fig 15 Pipe Trench Liners, USA

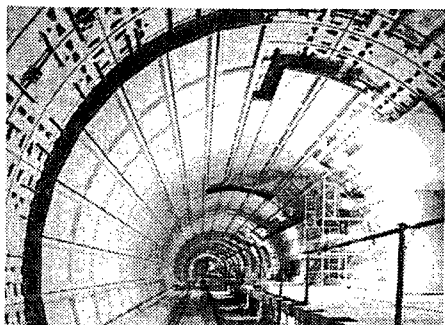


Fig 16 & 17 Heathrow, London

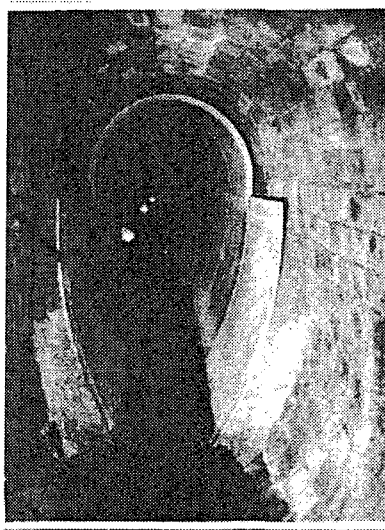


Fig 18 Sewer Re-lining

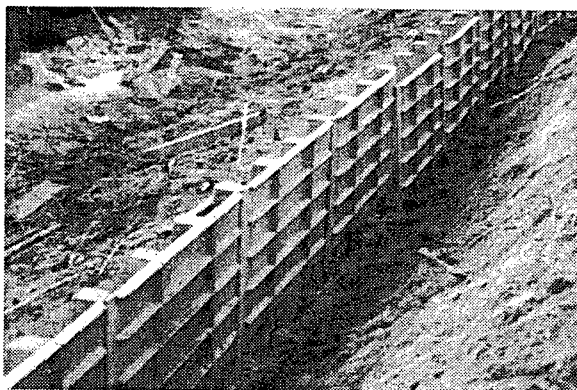


Fig 19 River Bank Protection, Holland

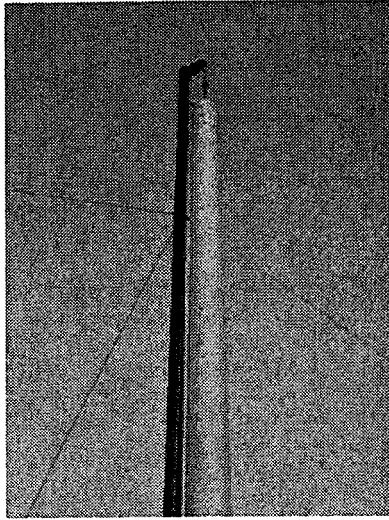


Fig 20 GFRC Pole 7.5m [25'], USA

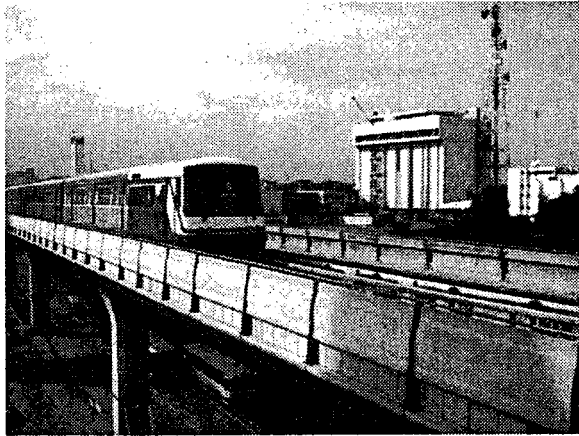


Fig 21 Bridge Parapets, Thailand

Towards Prestressed Thin-Sheet Glass Concrete Products

by G. Vilkner and C. Meyer

Synopsis: Thin sheet concrete products are receiving increased attention because of the large number of potential applications. By using crushed glass as aggregate, a multitude of different esthetic effects can be produced, which again open up numerous architectural and decorative uses. Such thin sheets are most effectively reinforced with fiber mesh, whether made of polypropylene, AR-glass, or other types of materials.

At Columbia University, a project is currently under way to explore the possibilities of prestressing thin sheet glass concrete products. There are numerous performance criteria that need to be satisfied by the fiber mesh material in order to qualify for the tasks on hand. Most promising to date are high-performance materials such as aramid and carbon fiber mesh.

This paper discusses the elimination process by which the most appropriate type of fiber mesh was selected. Various technical problems of prestressing and anchoring the fiber mesh are pointed out, as well as other issues that need to be resolved, before such products can be mass-produced commercially.

Keywords: aramid; fiber-reinforced concrete; glass concrete; prestressed concrete; textile reinforcement; thin sheets

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INTRODUCTION

Thin-sheet concrete products have attracted the attention of researchers and concrete producers alike in recent years because of their numerous potential applications. In conventional steel reinforced concrete elements, the cover needed to protect the steel against corrosion calls for a minimum sheet thickness of at least 5 to 7 cm. The tendency of the ribs of standard reinforcing bars to spall off thin concrete covers may require a further increase of the minimum plate thickness. For non-metallic reinforcement no corrosion protection is needed, and thicknesses of a few mm are theoretically possible. Woven fabrics or fiber mesh, also referred to as textile reinforcement, have proven to be a viable form of such reinforcement. The rovings are curved at points of intersection, caused by the weaving process. It has been observed by other researchers that woven fabrics, when stressed as ordinary reinforcement, need to be straightened before they contribute in the load carrying process (Curbach 1999). This delay inhibits distributed cracking to some extent, but if the fabrics are stretched slightly before being built in, such curvature effects become negligible. Prestressing the embedded reinforcement, whether provided in the form of single rovings or continuous fiber mesh, further improves the mechanical properties of structural members and enhances their durability because of the absence of cracks (Krüger 2004, Vilkner 2003).

The substitution of crushed glass for natural aggregate opens up additional options, primarily in the field of architectural concrete, because of the esthetic potential of colored glass. An important prerequisite is an effective measure to counter the potentially damaging effects of alkali-silica reaction (ASR). At Columbia University, a major research project has been under way for a number of years to utilize waste glass as aggregate in concrete products, and the work reported in this paper is a part of this ongoing larger effort. Some of the commercially available fiber mesh materials shall be described and compared and the various properties of prestressed thin sheets discussed. This paper describes work in progress, pointing out some of the issues of mechanical behavior involved and technical problems that need to be overcome, before such thin sheets can be mass-produced commercially.

PERFORMANCE SPECIFICATIONS FOR FIBER MESH

Fibers have been used in the concrete industry for some time to improve the tensile and flexural performance of concrete (Balaguru and Shah 1992). Also the beneficial effects of such fibers on shrinkage cracking and impact and fatigue resistance are well documented (Mindess et al. 1987, Ramakrishnan et al. 1995). While short randomly distributed fibers made of hydrophobic synthetic materials have some advantage during the mixing process, their relatively poor bond properties, combined with their random orientation in three dimensions, make their performance less than optimal. With continuous fiber mesh, some of these disadvantages are eliminated. Their use as reinforcement of thin cementitious sheets commenced in the mid-1980s (Gardiner and Currie 1983, Daniel and Shah 1990, Peled et al. 2000). In particular, the bond properties of textiles have been studied in detail in recent years (Bentur et al. 1997, Peled et al. 1998). When considering rovings instead of single fibers, as used in textiles, it is essential to address the question, if only the outer fibers of a roving develop bond to the matrix and how deep the matrix material penetrates into the rovings. Also the influence of the type of fabric, e.g., woven vs. knitted, is a major point of interest.

In order to select a fiber mesh material that is suitable for prestressing thin sheet glass concrete products, it is necessary to evaluate each potential candidate using the various performance specifications for the different applications. Foremost among such requirements is the chemical stability of the material in the alkaline environment of the cement paste. For prestressed concrete to achieve its traditional advantages, the reinforcing material has to be of high strength and show little stress relaxation at the intended prestress level. Related to this requirement is that of a reasonably high static fatigue strength. The melting point needs to be high enough as to cause no significant creep effects at elevated service temperatures, which would lead to an unacceptable lowering of the effective prestress. Good bond properties are required, in particular in the end zones, where otherwise separate anchorage mechanisms would be needed. Ideally, the material should also possess good ductility and have a large energy absorption capacity to assure gradual flexural failure modes.

FIBER MATERIAL SELECTION

All fibers are made of either inorganic or organic material. The inorganic category includes materials such as metals, minerals, ceramics, carbon and glass. The list of organic fiber materials, on the other hand, seems to be limited only by the creativity of nature and the chemical industry. Nature still holds the record for the strongest fibers, which are spun by spiders. Other natural fibers include cellulose, silk, and cotton. Man-made organic fibers include nylon, polypropylene, polyvinyl alcohol (PVA), polyethylene, and aramid, among many others.

High-strength steels, which traditionally have been the materials exclusively used for prestressed concrete applications, need to be protected against corrosion. Stainless steels are available, including piano wires. These are relatively expensive and are not being offered in the form of woven or knitted meshes. Therefore, they shall not be considered here any further. Most of the commonly used polymeric materials, such as

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polypropylene, nylon, and polyvinyl alcohol, have relatively low melting points and exhibit excessive creep and relaxation behavior, which makes these materials unsuitable for prestress applications. Alkali-resistant (AR) glass, aramid, and carbon are more suitable in those regards. Because of their very high unit strengths, relatively low creep deformations, and high melting points, these materials are now being studied for their suitability for prestressing thin-sheet glass concrete elements. All three materials have in common, in contrast to metals, that they exhibit highly linear-elastic brittle behavior, and they are available in the form of woven or knitted fiber mesh.

Alkali-resistant glass, although popular as short fiber reinforcement, has recently been shown to have a rather low static fatigue limit (Reinhardt 2002) and therefore is not likely to be suitable for applications in which the mesh is to be prestressed. Aramid and carbon fibers have reasonably high static fatigue limits, relative to their ultimate strengths. However, accounting for their low ductility requires comparably large safety factors against failure, such as for instance when glass is employed in structural applications. Especially in the case of carbon, its very high stiffness leads to very low strain levels, far below those common in conventional prestressed concrete applications. The costs of aramid and carbon fiber mesh are relatively high for typical thin-sheet applications, compared with some of the other available materials. However, manufacturers are steadily improving their production technologies. The expected price reductions will make new applications feasible, and the resulting increase in demand for these materials is likely to prompt further cost reductions due to the economy of scale. For these reasons, they are currently being considered for further study. The emphasis in this study was on aramid fiber mesh.

ARAMID

Aramids are a family of nylons, including high-strength fibers that are known under trade names like Kevlar and Nomex. Aramid is a short form for aromatic polyamides. Fig. 1 illustrates how amid groups connect phenyl rings to form monomers that build polymers. The aromatic rings differentiate them from non-aromatic polyamides that form fibers like Nylon 6,6. In the case of Nylon 6,6, the amid group is found in both illustrated forms, the cis- and trans-configuration. Single polymer chains can only form in a perfectly straight fashion in the trans-configuration. If the amid group forms in the cis-configuration it causes the path of the polymer to change. In aramids, the trans-configuration is formed almost exclusively, which allows for perfectly stretched polymer chains. A valid and often used analogy is comparing cooked (cis-) with uncooked (trans-) spaghetti. The small but important difference between para- and meta-amids, i.e. Kevlar and Nomex, is that in the first case, amid groups are attached to phenyl rings at carbon atoms directly across from each other, i.e. at positions 1 and 4, Fig. 1. In the second case, amid groups connect to phenyl rings at the 1 and 3 positions, which causes the polymer path to bend slightly. Both aramid forms are very resistant to high temperatures and chemical attack. The fact that para-aramids stretch out more perfectly allows them to form fibers in which the polymer chains are packed more closely, which is the reason for their higher strength. A more detailed description of the fiber production and the deformation mechanisms is given in (Meyer and Vilknér 2003). DuPont developed the most popular of these fibers

under the trade names Kevlar 29 and Kevlar 49 in 1966. In Europe, the AKZO Group fabricated the competing para-aramid fiber Twaron. Some representative technical data are summarized in Table 1.

Aramid fibers have basically good chemical resistance (Kasperkiewicz and Reinhardt 1992), except in environments with extreme pH values, where hydrolysis can degrade or literally dissolve fibers. Concerns do exist that the alkalinity of the pore solution in Portland cement paste can also cause their deterioration, so that the fibers are often provided with protective coatings such as PVC, polyester, or epoxy (Broadway 2002). It remains to be investigated whether the admixtures that are added to the cement matrix to suppress alkali-silica reaction in concrete with glass or other reactive aggregates are equally effective in preventing the deterioration of aramid fibers embedded in glass concrete thin sheets.

MECHANICAL BEHAVIOR OF ARAMID MESH

Aramid fibers have cross-sectional diameters of the order of $10\text{ }\mu\text{m}$ ¹. Several hundred of them form a roving or thread. The rovings tested in the present investigations, 700 denier Twaron fibers, failed at a tensile load of about 0.15 kN (35 lbs). Load-deformation curves for various fiber materials are reproduced in Fig. 2a (Naaman 2000), whereas Fig. 2b depicts the behavior of an aramid sample consisting of 8 rovings, as obtained in the present investigation.

Rovings are being woven or knitted into various textile patterns. For our purposes, orthogonal meshes appear to be most appropriate. The fiber mesh is woven like standard textile fabrics such that orthogonal sets of rovings are not interconnected at their points of intersection. If regular mortar is used, the number of rovings per inch can be quite large. In glass concrete, however, it is desirable to utilize aggregate particle sizes of at least 3 mm (1/8 inch) to achieve certain esthetic effects. The fiber spacing needs to be larger than the largest aggregate size, so that the concrete layers on both sides of the mesh are adequately connected. For this reason, the mesh sizes considered in the present investigation are 5 by 6 rovings per inch.

In welded wire mesh, orthogonal layers of wire are spot welded at each point of intersection, which provides excellent mechanical bond. In woven or knitted mesh of polypropylene or nylon fibers, the bond of weft or warp yarns is also improved by the anchorage provided by the fill yarns in the orthogonal direction. In the case of high-strength aramid fiber mesh, that added anchorage effect is all but negligible, and the only source of anchorage is an adequate development length. If such mesh is to be prestressed, it is necessary to provide a separate means of anchorage, which allows to stress and securely hold several layers of fabric. A first trial for such an external anchorage is shown in Fig. 3. The edges of two layers of mesh were encased in epoxy bars 12 mm (1/2 in) thick and 25 mm (1 in) wide, which were used to stress the mesh and stay in place as

¹ In the fiber industry, it is common to specify fibers in units of *tex* or *denier*, which indicate the weight in gram of a 1000 m or 9000 m long single fiber, respectively, i.e. 9 denier = 1 tex.

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permanent anchorage blocks. A commercial medium-strength epoxy mortar with a conventional filler was used. However, the choice of mortar becomes an issue of more importance, if more layers of fabric are to be utilized to generate higher prestress levels. The major problem with casting the scrim fabric into an epoxy end-block is to assure that all fibers are aligned parallel and are of equal length in their unstressed state. In practice, this is difficult to achieve. Therefore, in actual tests the ultimate strength (average stress per fiber at failure) dropped from 2800-3100 MPa (400-450 ksi), when few rovings were tested (e.g., 8 rovings, see Fig. 2b) to below 2100 MPa (300 ksi), when a specimen with 34 rovings was considered. The elastic modulus, i.e. the slope of the linear branch of the stress-strain diagram is in both cases equal at about 110 GPa (16,000 ksi) (Table 2).

The behavior of an aramid sample consisting of 34 rovings is depicted in Fig. 4, both as a load-versus-time curve and the standard load-deformation graph. The experiment was carried out on a mechanically driven INSTRON testing machine in displacement control without feedback control. Individual rovings are seen to fail before others reach their ultimate strength. Therefore the average strength decreases with the number of rovings tested in parallel. The reason is the different amounts of slack within the individual rovings prior to load application, coupled with the lack of ductility. If the rovings were made out of steel, their plastic deformations would assure load sharing between highly and lowly stressed rovings such that all of them would fail at the same time. Because of their brittleness, aramid fibers do not lend themselves towards such beneficial load sharing, and as a result, greatly lowered average strengths have to be accepted in addition to the relatively large factor of safety, which is a standard requirement for designs involving brittle materials. It remains to be seen whether under such constraints the cost-to-benefit ratio of high-strength fiber mesh still makes economical sense.

MECHANICAL PROPERTIES OF GLASS CONCRETE

Using glass aggregate in a concrete or mortar mix has fundamental effects on both the fresh and hardened concrete. The practically nonexistent water absorption of glass particles has a positive effect on the flow properties of the fresh concrete, whereas the admixtures necessary to suppress ASR have a negative influence on the workability. By careful mix design, very high-quality glass concrete can be produced. For example, concrete systems modified with metakaolin have been reported to profit from a superior Portlandite-free microstructure, which explains its excellent durability, low shrinkage and substantially lowered creep deformations (Sabir et al. 2001). Since no aggregate larger than 6 mm (¼ inch) is used, the material should be referred to as mortar instead of concrete, according to the strict definition of the American Concrete Institute. However, because of the arbitrariness of this definition we shall take the liberty of calling the material "glass concrete".

Table 3 summarizes the proportions of such a concrete mix, and a typical stress-strain diagram obtained after 7 days is shown in Fig. 5. Though the w/c ratio, adjusted to achieve exceptionally high flow, is higher than in other glass concrete applications, the material has a very high strength of about 35 MPa (5 ksi) after 20 hours and 70 MPa (10 ksi) after 7 days. Based on the 20 hour compressive strength an effective prestress of 14 MPa (2 ksi) was targeted for first trials of actually prestressed thin sheets. Glass concrete

is characterized by near-linear behavior up to about 80% of the ultimate strength. The Young's modulus is about 22 GPa (3200 ksi).

PRACTICAL CONSIDERATIONS

The selected epoxy endblock system proved to be suitable for investigative purposes, but could not sustain an effective prestress of 14 MPa (2 ksi). The 34 rovings were distributed in 2 layers. Selecting 50% of the failure load of 3.5kN (800 lbs) as prestressing force on a 75 mm x 12 mm (3 in x 1/2 in) cross section, the corresponding prestress was only 1.8 MPa (250 psi). The next step taken was the development of a 7 mm x 25 mm (1/4 in x 1 in) endblock containing 7 layers of fabric, totaling 35 rovings (Meyer and Vilkner 2003). Ultimately, larger rovings had to be considered.

Structural engineers familiar with prestressed concrete are used to deal with high-strength steels that undergo considerable plastic deformation before failure. Also, stress averaging is a common concept in structural engineering and justifies the neglect of many forms of stress concentrations for design purposes. But such stress averaging is possible only in conjunction with ductile materials. As pointed out previously, the brittle nature of high-strength non-metallic fiber material such as aramid or carbon prevents the utilization of a large fraction of this strength.

A separate set of problems is posed by the smooth surfaces of aramid fibers and the resulting low bond strength. This complicates both the stressing operation and the means of permanent anchorage. In standard prestressed concrete applications, these problems have been solved by a variety of commercial systems. But it took years to perfect those systems. It can be assumed that concentrated efforts will likewise result in practical schemes for high-performance fiber applications.

ACKNOWLEDGMENTS

The authors wish to express their gratitude towards Hexcel-Schwebel for supplying the fabrics used in this study. Waste glass was kindly provided by Strategic Materials. The reported progress would not have been possible without the active engagements of Dr. S. Shimanovich and Dr. S. Kozlova.

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Vilkner G. (2003). "Glass Concrete Thin Sheets Reinforced with Prestressed Aramid Fabrics", Ph.D. Thesis, Columbia University, New York.

Table 1. Mechanical Properties of Polyamid Fibers (MatWeb)

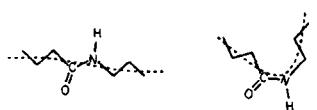
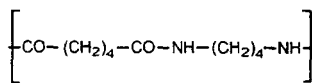
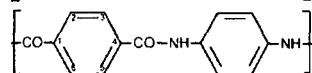
	Nylon 6,6	Nomex	Kevlar 29	Kevlar 49	Twaron
Tensile Modulus (Gpa)	3.3	N/A	70	112	45
Tensile Strength (Mpa)	80	300-600	3600	3000	2030
Ultimate Strain (%)	80	20-30	3.7	2.4	4.5
Density (g/cm³)	1.14	1.38	1.44	1.44	1.45

Table 2. Mechanical Properties of Roving Systems

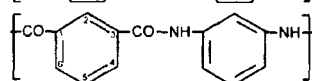
Test #	Ultimate Tensile Strength (GPa)	Elastic Modulus (GPa)
8 rovings in 1 row	2.75-3.1	103
34 rovings in 2 rows	1.95	110

Table 3. Glass Concrete Mix Design

Base Materials	Weight Ratios
Glass Aggregate	1.72
Type III Cement	0.8
Metakaolin	0.2
Water	0.38
Liquid Admixture	0.0125

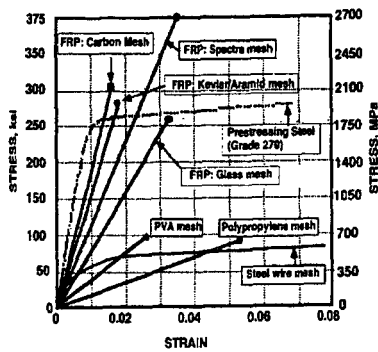
Amid
(trans- and cis- configuration)Nylon 6,6
(a non-aromatic polyamid)

Para-Aramid Fiber (i.e. Kevlar)

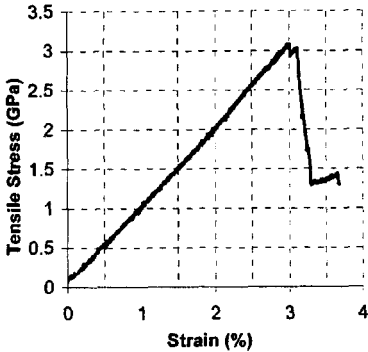


Meta-Aramid Fiber (i.e. Nomex)

Figure 1. Amid Configurations and Monomers that form Polyamids



a) Stress-Strain Behavior of Various Fiber Materials (Naaman 2000)



b) Stress-Strain Behavior of 8 Aramid Rovings

Figure 2. Typical Load-Deformation Curves

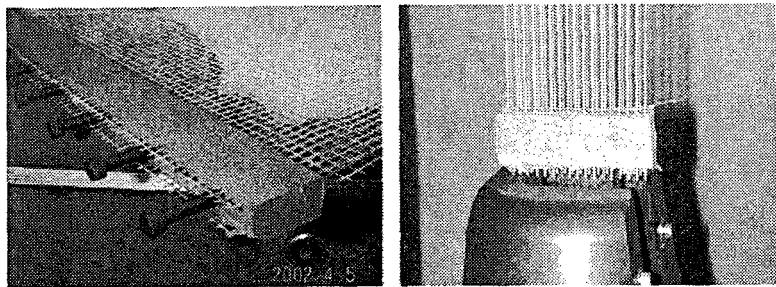
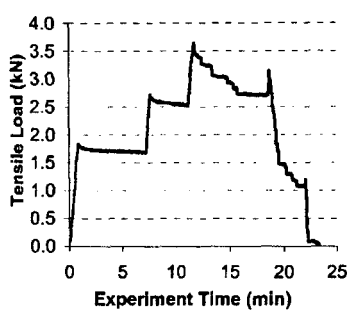
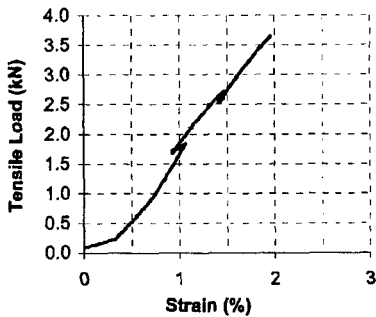


Figure 3. Epoxy Anchorage for Aramid Textile Fabric



a) Load vs. Time



b) Load vs. Strain

Figure 4. Response of Aramid Textile Fabric

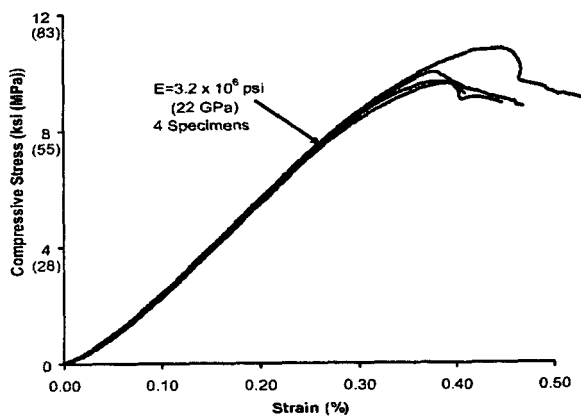


Figure 5. Glass Concrete Stress-Strain Curve

Textile Reinforced Concrete: Investigations at Different Levels

by J. Hegger, A. Sherif, O. Bruckermann and M. Konrad

Synopsis: Even though the knowledge about the load bearing behavior of Textile Reinforced Concrete (TRC) is still limited, there are already applications of TRC such as cladding panels and integrated framework systems. Up to the present, the design and dimensioning of TRC members is mainly based on extensive test series targeted to the particular application. Certainly, this approach is very goal-oriented. However, because design rules are not supported by mechanical models, high safety factors are incorporated. Within the scope of the collaborative research center “TRC: foundations for the development of a new technology” (SFB 532) at the Technical University of Aachen, Germany, the missing consistent description of the load bearing behavior of TRC is being developed. Thereby, experiments and numerical simulations at different levels, i.e., micro-, meso- and macro-levels, are performed. In this paper, the main results of the research program are presented.

Keywords: analysis; finite elements; material model; multi-level; textile reinforced concrete

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RESEARCH SIGNIFICANCE

The reinforcement of concrete with technical textiles extends its application to completely new fields. Because of the corrosion resistance of the textile materials, thick concrete covers as known in ordinary reinforced concrete are no longer needed. Thus, slender structural members with a wall thickness as low as ten millimeters are possible. In addition, fine grain concrete matrices guarantee an even and sharp-edged high quality surface, so that TRC is predestinated for architectural applications. Although the knowledge about the load bearing behavior of TRC is still limited, applications such as cladding panels [1] and an integrated framework system [2] have already been implemented.

The material models currently being developed and presented in this paper will lead to a better understanding of the failure mechanisms of TRC-structures. Based on these models, design rules and safety concepts can be set up in the future. Not until then TRC will become a versatile and cost-effective building material.

INTRODUCTION

Current investigations show that the failure process of TRC, which is observed at the macro level, cannot accurately be predicted based on the simple models known from ordinary steel reinforced concrete. This is primarily due to the inhomogeneous internal structure of the fiber strands (rovings) consisting of hundreds of separate filaments (Fig. 1). Furthermore, non-uniform bond conditions in the longitudinal direction and

within the cross-section of the rovings point out that developing a material model, capable of accurately describing the load bearing behavior of TRC is a non-trivial task.

Therefore, within the SFB 532 the investigations are being conducted at different levels. As shown in Table 1, these are the micro-, meso- and macro-levels. At each level, the material components have to be defined and modeled by an appropriate Finite Element model. Corresponding experiments provide the necessary data for calibrating the numerical models and obtaining the required mechanical properties of the components. The models at each level may conceptually either be coupled to an adaptive multi-level computation. Or as an alternative, the “smeared” material parameters used at one level are predefined at the previous smaller level. In the following, the main results for each level are described.

MICRO-LEVEL

The aim of the micro-level investigations is to completely cover the effects determining the behavior of single filaments as well as their mutual interaction and their interaction with the concrete matrix. In addition to the material properties, such as tensile strength and bond-slip relationship, the random distribution of several parameters has to be considered. Among these are the following [3]:

- Micro defects in the filament which lead to a statistical size-effect
- Cross-section of the filament
- Geometrical position of filaments within the roving cross-section and the change in the longitudinal direction (waviness)
- Bonding conditions, i.e., to what degree does matrix contact the filament’s perimeter and how does this vary in the longitudinal direction

The interaction between filament and matrix has been studied using pullout tests of single filaments (Fig. 2(a)) and the finite element model shown in Fig. 2(b). The resulting bond-slip relation (Fig. 3) is in agreement with the one obtained analytically by Banholzer [4, 5] based on the shear lag theory. The bond-slip curve can be divided into three parts. The first part is determined by elastic adhesional bond. Here, the bond layer is capable of taking up stresses of up to 4.8 N/mm^2 at a very small slip of 0.01 mm. If the value of the slip exceeds 0.01 mm, the adhesional bond is lost and only friction bond remains which is about four times smaller than the adhesional bond. In the second part (slip from 0.01 to 0.16 mm) the friction bond degrades due to “smoothing” of the interface between filament and matrix. In the third part the friction bond reaches a minimum and remains constant. This behavior is very different from steel reinforcement, because the maximum bond-stress can only be activated at a certain value of slip, i.e., there is no ductility. Therefore, the maximum force picked up by the filament, cannot be calculated just by the maximum bond stress times the available anchorage length.

MESO-LEVEL

The meso-level investigations aim at describing the behavior of the rovings within the composite material. Pullout tests, of which several types exist, are the main tools to study the characteristics of the bond between roving and matrix (Fig. 4). In contrast to steel reinforcement, the load-displacement curve does not feature a plastic plateau. Rupture of filaments or debonding over the entire embedment length lead to a rather quick decrease of the pullout force after the peak-load.

In order to simulate pullout tests the so-called bond layer model shown in Fig. 5 has been developed. This model considers a section of the roving idealized as layers and takes into account the deterioration of the bond with increasing distance between filament and matrix. The bond quality for each layer is defined by a function of the distance from the matrix. Any changes of these proportions in the longitudinal direction are neglected. In the Finite Element simulation each bond layer is represented by a one-dimensional element and is connected to the matrix by a zero-thickness interface element.

The parameters to be calibrated for the bond layer model are the bond quality distribution function and the effective tension strength of the filaments. In Fig. 6(a) the influence of a linear, a quadratic and a cubic bond quality distribution on the load-displacement curve of a roving pullout test is shown. Figure 6(b) indicates the calculated actual fraction of unbroken filaments. In the pullout experiment, this information was obtained by optical recording of the light transmission through the unbroken filaments [6]. Both, the linear and the quadratic approaches cannot accurately reproduce the smooth peak region of the measured curves. The cubic distribution leads to a more ductile curve and resembles the experimental data.

While the bond quality distribution function determines the post peak gradient, the maximum pullout force depends mainly on the tensile strength of the filaments. Preliminary calculations showed that the initial slope of the pullout curve is always overestimated by the model. Only a decrease in the maximum bond performance can reduce the initial stiffness, however this leads to a simultaneous decrease of the portion of filament fracture, because more filaments are pulled out completely. Therefore, the variation range of this parameter is limited, and the initial stiffness in the experiments cannot be reproduced by solely reducing the bond quality. As a consequence, this reduction can be explained by the existence of an internal free length between the macroscopic boundary of the matrix and the first contact of the filaments with the matrix inside the specimen, i.e., the start of the micro-bonding between filament and matrix, which is illustrated in Fig. 7. Using a cubic bond quality distribution function, a tensile strength of 1350 MPa and a maximum internal free length of 6 mm in the center of the roving, the simulation results in the pullout curve shown in Fig. 8.

MACRO-LEVEL

The tension tests on composite specimens reinforced with rovings and its simulation play an important role in the theoretical models. Based on the results of the pullout test described above (meso-level), the target is to explain the macro-response, i.e., the load

displacement curve of TRC under tension load. Pure rovings are used instead of textiles in order to avoid any influences resulting from the textile production process, the textile joints, and from the lateral reinforcement. Fig. 9 illustrates the geometry of the tensile test specimens and Fig. 10 shows the load-strain curve for the measurement length of a specimen reinforced with 12 rovings (2400 tex each). At the beginning, the load strain curve follows the usual linear-elastic increase. At a force of 3.1 kN the first crack occurs. This very early cracking can be explained by an initial bending moment in the specimen due to a small load eccentricity, which practically cannot be avoided. At a force of 4.8 kN the “real” cracking process starts, i.e., now the lower limit of the tensile strength of the concrete matrix within the specimen is reached (4.8 N/mm^2). Until a strain of 6 ‰ there is a continuous increase in the force and the number of cracks. The maximum load reaches 7.2 kN after which macroscopic failure can be observed. The specimen features a very satisfactory crack distribution (Fig. 11) with an average crack distance of about 14 mm and crack width of 0.09 mm. This is calculated from the elongation of the measurement length neglecting any elastic deformation of the non-cracked concrete.

The interpretation of the experimental data raises the following question: Why is there a substantial increase in the stress while cracking occurs? Normally, one would expect, similar to steel reinforced concrete, that cracking happens at a stress plateau, which is only determined by the tensile strength of the matrix.

In order to investigate this phenomenon a Finite Element analysis was conducted with the simple model shown in Fig. 12 (a). The model consists of linear elastic truss elements representing the uncracked concrete and of short crack elements ($l = 1 \text{ mm}$). The number of crack elements is chosen according to the number of cracks occurring in the experiment (35 cracks). For the crack elements a material law is used which can be split into two parts (Fig. 13):

- Concrete material law with mesh adjusted softening modulus [7]. The tension strength varies randomly (average = 5.0 N/mm^2 , standard deviation = 0.25 N/mm^2).
- Material law for the reinforcement, whereby the stiffness and the maximum load ($12 \times 430 \text{ N} = 5160 \text{ N}$) are taken from the linearly approximated pullout curve.

The result obtained is displayed in Fig. 14 (res_wo_core). Because the maximum load that can be picked up by the reinforcement is higher than the crack load, all 35 cracks open up. Finally, one of the cracks localizes and the reinforcement fails. The strain at failure of 6 ‰ matches the experiment. However, the model is not capable of predicting the linear load increase with increasing number of cracks.

In order to model this behavior, it is necessary to introduce a “core” of filaments, which are activated gradually with increasing crack number and strain, respectively (cf. [8]). This delayed activation is due to the following:

- Filaments in the center of the roving cross-section may have a waviness. Before they pick up load, they have to be stretched out.

- At the crack edge the core filaments do not have direct contact to the matrix. Therefore, their anchorage length is much longer than of those (sleeve-) filaments taking up the pullout force.

The bond force of the core is transmitted to the matrix not so much through friction bond between adjacent filaments as through matrix which has penetrated the roving at several points. These considerations lead to the modified Finite Element model shown in Fig. 12 (b). Of course, the introduction of a core, which is activated through bond elements, actually introduces several new unknown parameters, such as cross-section, stiffness and tension strength of the core. In addition, the friction law applied has to be defined. A curve-fitting of the experimental data leads to a portion of 35 % core filaments related to the whole roving cross-section and a tension strength of 600 N/mm². The increase of bond flow is 65 N/mm per 1 mm of slip. The load strain curve now matches the experimental curve much better (see res_w_core in Fig. 14).

It must be kept in mind that the so far obtained material laws may not be the only solution leading to these results. Further investigations on tension-tests with different lengths and different degrees of reinforcement must provide additional data for calibrating the model.

SUMMARY

The explanation of the load bearing behavior of TRC is a task that only can be handled if different resolution levels in the experiments as well as in the simulation are considered. In this research the behavior of TRC is investigated at three different levels: micro-, meso- and macro-level. It is shown how results obtained at one level can be used at the next higher level in order to reduce the number of unknown parameters. A finite element model is presented, and first results show its capability to simulate the experimental results. However, systematic experimental research has to provide further information in order to verify and optimize the models at each level. In addition, simulation techniques have to be developed at the macro-level taking into account the influences of the textile production process and the specific geometry of textiles. The demonstrated simulation of roving tension tests is only an intermediate step towards this final goal.

ACKNOWLEDGEMENTS

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CONVERSION FACTORS

1 in.	= 25.4 mm
1 ft	= 0.3048 m
1 kip	= 4.448 kN
1 tex	= 1 g/km

Table 1 -- Considered components at different resolution levels

Resolution level	Components
Micro-level	• filament • matrix • bond filament-matrix • bond filament-filament
Meso-level	• subroving (group of filaments) • matrix • bond subroving-matrix
Macro-level	• roving / textile • smeared concrete • smeared bond roving-matrix

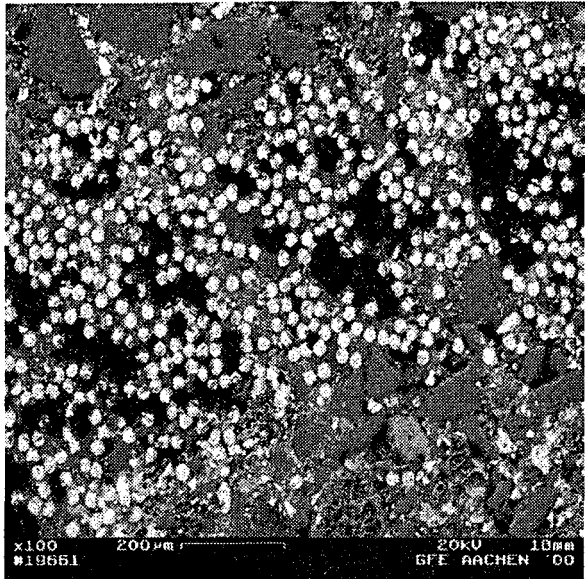


Fig. 1— X-section of a roving embedded in fine concrete

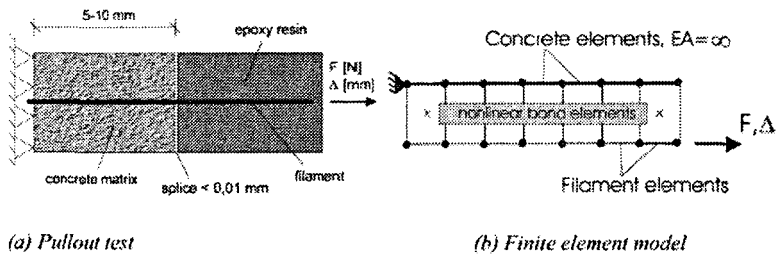


Fig. 2 — Filament pullout test and Finite Element model

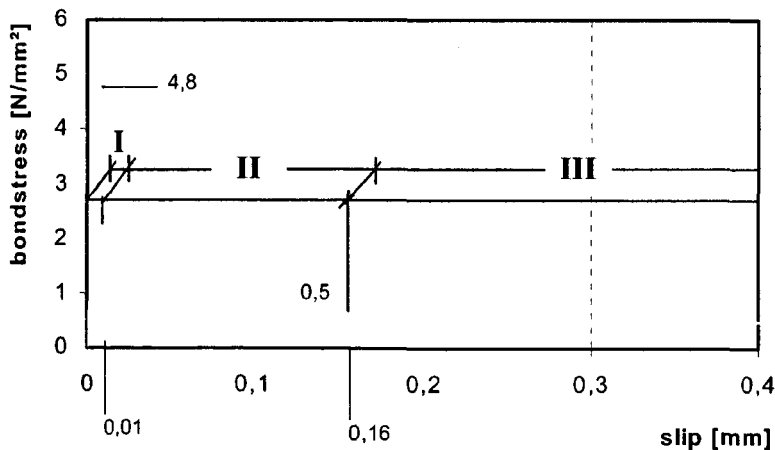


Fig. 3 — Bondstress-slip diagram for a single filament embedded in fine concrete

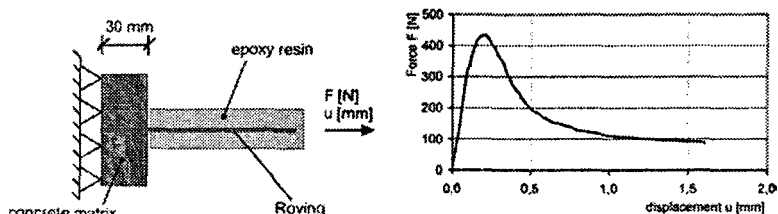
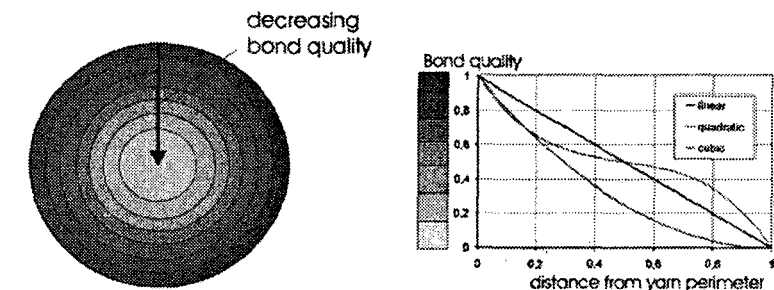


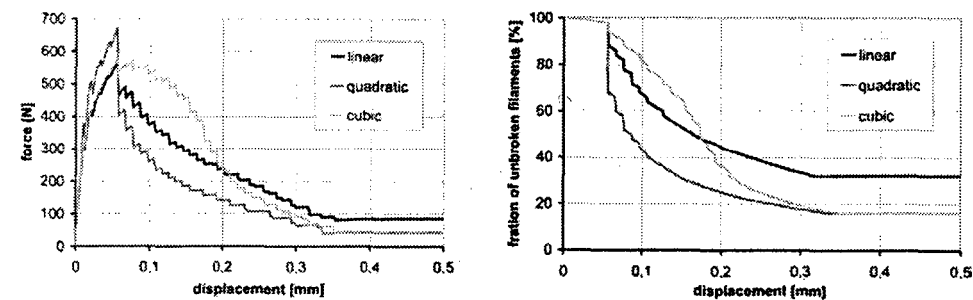
Fig. 4 — Roving pullout test and typical load displacement curve



(a) idealized roving x-section

(b) bond quality distribution functions

Fig. 5 — Bond layer model



(a) on the load-displacement curve

(b) on the fraction of unbroken filaments

Fig. 6 — Influence of the bond quality distribution function

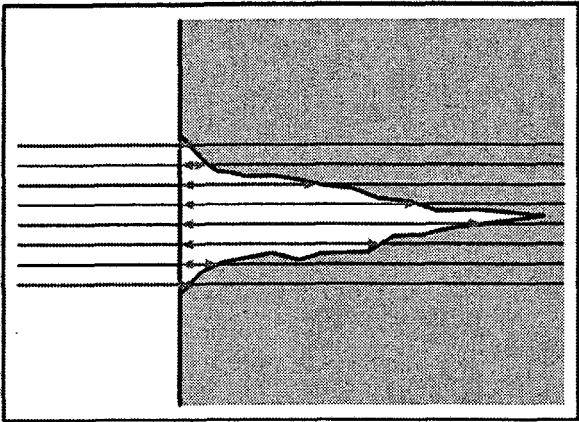


Fig. 7 — Internal free length between matrix boundary and begin of microbonding

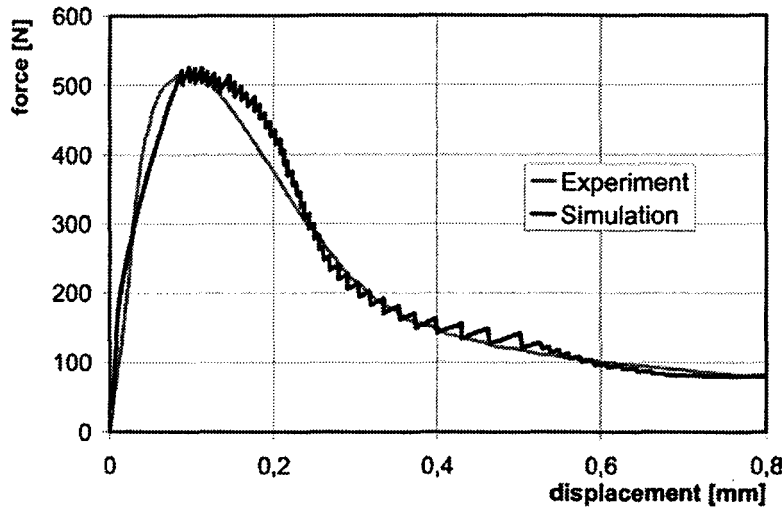


Fig.8 — Roving pullout test, experiment vs. simulation

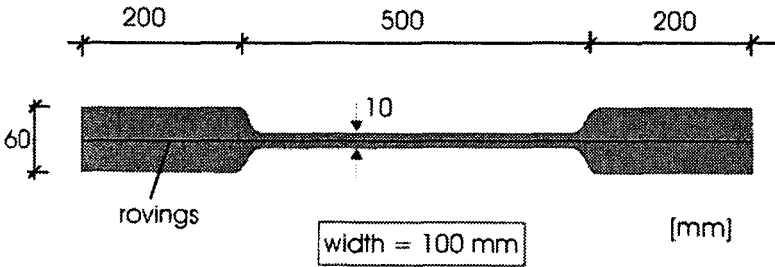


Fig. 9 — Geometry of tensile tests