Towards Prestressed Thin-Sheet Glass Concrete Products

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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 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 Vilkner 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 μm[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.

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.

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Table 1. Mechanical Properties of Polyamid Fibers (MatWeb)

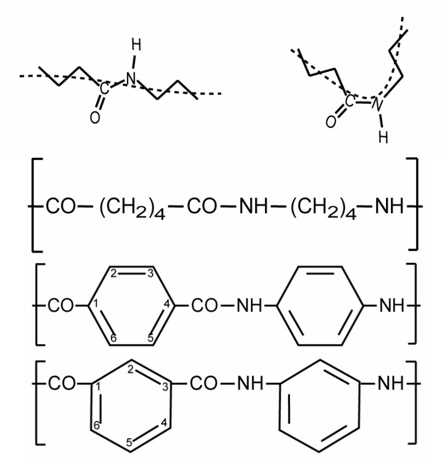
	Nylon 6,6	Nomex	Kevlar 29	Kevlar 49	Twaron
Tensile Modulus (Gpa)	3.3	N/A	70	112	45
Tensile Strength (Mpa)	80	300-600	3600	3000	2030
Ultimate Strain (%)	80	20-30	3.7	2.4	4.5
Density (g/cm^3)	1.14	1.38	1.44	1.44	1.45

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



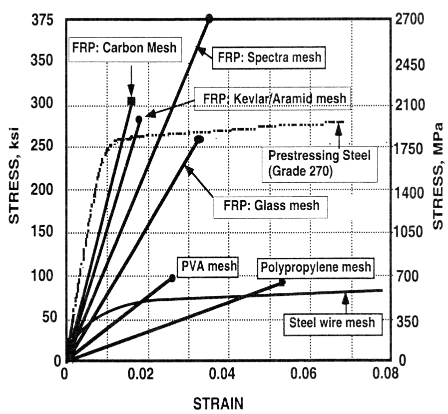
Amid
(trans- and cis- configuration)

Nylon 6,6
(a non-aromatic polyamid)

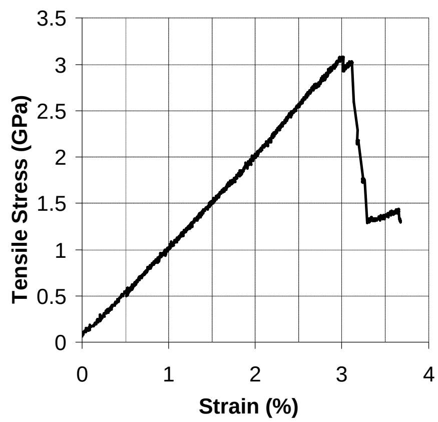
Para-Aramid Fiber (i.e. Kevlar)

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

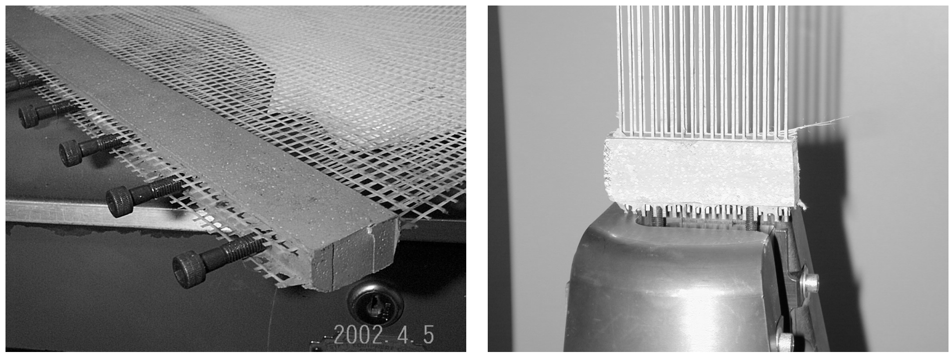
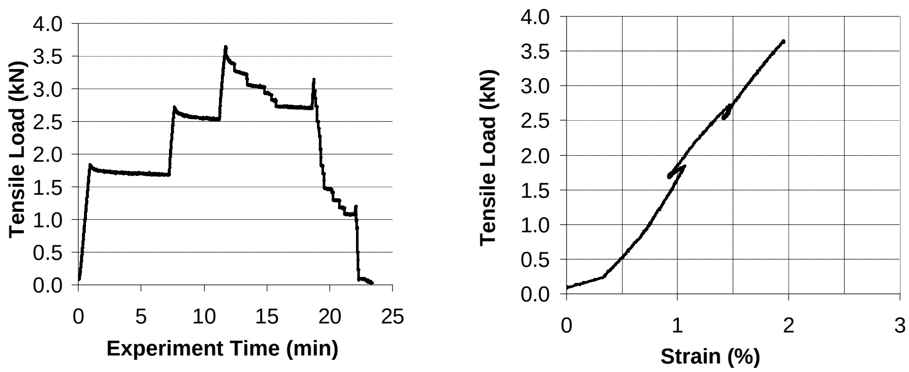


Figure 3. Epoxy Anchorage for Aramid Textile Fabric



a) Load vs. Time

b) Load vs. Strain

Figure 4. Response of Aramid Textile Fabric

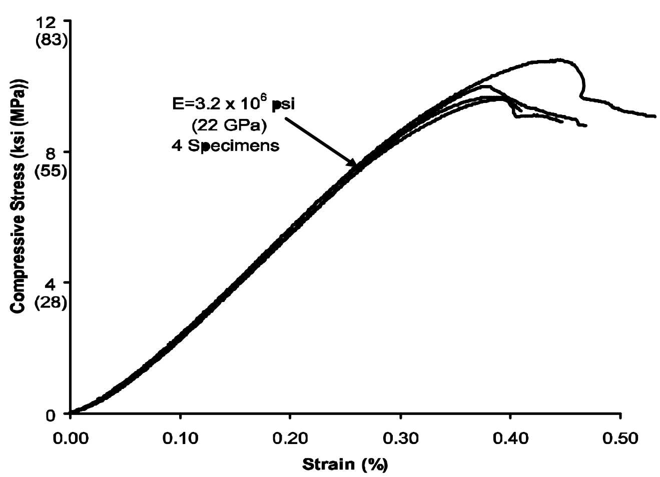


Figure 5. Glass Concrete Stress-Strain Curve