TEXTILE REINFORCED CEMENT COMPOSITES: COMPETITIVE STATUS AND RESEARCH DIRECTIONS

A. E. Naaman, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, USA

ABSTRACT: This paper summarizes the author's opinion as to where we are and where we should go in the near future in the field of thin reinforced cementitious composites. Pointing out the similarities between ferrocement and thin TRC composites an attempt is made to provide a definition for TRC using that of ferrocement as a reference base. Then the paper summarizes the performance status of ferrocement (reinforced with conventional steel wire meshes), thin reinforced cement composites and thin textile reinforced concrete composites (reinforced with fiber reinforced polymer (FRP) meshes or textiles or fabrics) using their bending resistance (modulus of rupture) as a basis of comparison. The bending resistance is first normalized by the volume fraction of reinforcement to compare mechanical performance, then it is used in combination with the density of the reinforcement to derive a willingness-to-pay price for such reinforcement. It is first observed that not all FRP or textiles or fabrics can be economically justified, at time of this writing, on the basis of their mechanical performance. However, since labor cost can be significant, the use of 3D textiles may prove to be the breaking point for textile reinforcements to become cost competitive with steel. Some research directions are suggested and include the development of 3D textiles specifically tailored for thin and larger scale products, the use of very lightweight matrices with FRP meshes or fabrics or textiles, the use of hybrid 3D textiles incorporating steel wires or strands in additions to FRP fibers, the use of self-stressing composites using shape memory materials with deformation recovery property, the use of ultra-high performance cementitious (UHPC) matrices with textiles and a combination of these such as self stressing and UHPC.

1 DEFINITIONS

The term Textile Reinforced Concrete (TRC) has been first introduced in the late 1990's. Since then several symposia and sessions at a number of conventions have been devoted to TRC. Moreover a very comprehensive state-of-the-art report on TRC was developed by *RILEM Technical Committee 201-TRC,* in 2006 [5]. While the scope of the report is well defined, a clear definition of TRC is not given in it. It may thus be useful to refer to the established definition of a similar composite, ferrocement, given by the American Concrete Institute, and attempt to offer a suitable definition for TRC. Figure 1 shows a typical cross section of ferrocement and should be distinguished from what is generally defined as reinforced Stucco (Fig. 2).

1.1 Ferrocement

Committee 549 of the American Concrete Institute (ACI) provides the following definition [2]:

> *"Ferrocement is a type of thin-wall reinforced concrete commonly constructed of hydraulic-cement mortar reinforced with closely spaced layers of continuous and relatively small-size wire mesh. The mesh may be made of metallic or other suitable materials."*

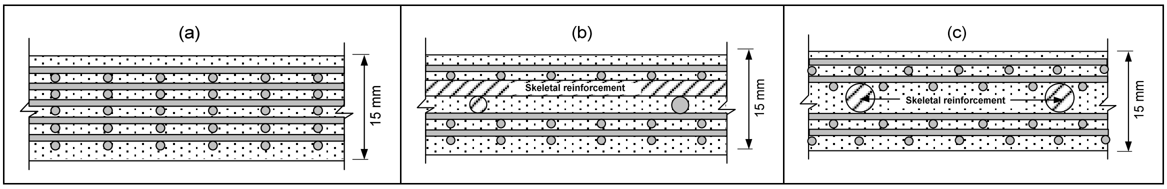


Fig. 1 Typical sections of ferrocement: a) showing several layers of distributed welded wire mesh reinforcement; b) showing a combination of wire mesh and skeletal steel reinforcement in the form of a two-directional grid; and c) showing a combination of wire mesh and small diameter reinforcing bars in only one direction.

This last sentence in the ACI definition opens the field to the use of polymer reinforcements such as high-performance carbon or aramid fibers, and thus also encompasses, in principle, some modern applications such as textile-reinforced concrete (TRC). In a classic book on the subject of ferrocement and cementitious composite laminates, *Naaman* [23] suggested extending the above definition by adding the following two sentences:

> *"The fineness of the mortar matrix and its composition should be compatible with the mesh and armature systems it is meant to encapsulate. The matrix may contain discontinuous fibers."*

These sentences were added: 1) to ascertain the compatibility of the matrix with the reinforcement system it is meant to infiltrate in order to build a sound composite, and 2) to accommodate, when desirable, the use of discontinuous fibers or microfibers to improve performance in hybrid composites.

It is stated in the above ACI definition that the reinforcement comprises "several layers" thus distinguishing ferrocement from conventional Stucco. Moreover, the term "thin" in "thin-wall" is not defined; however in numerous publications, Naaman [23] suggested to use about 50 mm as the upper limit, with the understanding that conventional reinforced concrete starts at about 100 mm and that the range between 50 mm and 100 mm is a transition area which is not very common to date, but will eventually provide continuity. Note finally that, unlike TRC, ferrocement is a mature technology which has been addressed in numerous publications, including books, symposia proceedings, a Journal, and many research studies [1, 2, 3, 4, 6, 7, 11, 23, 29, 33].

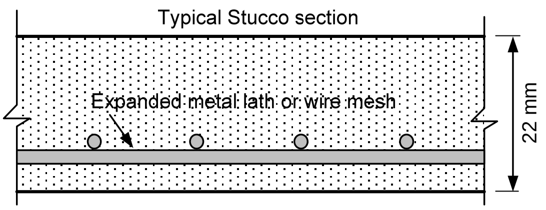


Fig. 2 Typical section of Stucco where one layer of metal lath or wire mesh is used in a matrix about 7/8 in (22 mm) thick (note differences from Fig. 1)

1.2 Textile Reinforced Concrete - TRC

If we assume, hypothetically, that a new structural composite called TRC (textile reinforced concrete) is to be defined in which "true concrete" is implied, such as in conventional large scale structural concrete applications, then the definition of TRC would be same as that of conventional Reinforced Concrete (RC) except that the reinforcement is made out of non-metallic or polymer-based bars or textiles instead of reinforcing steel bars.

However, if we restrict TRC to thin products, where it can be competitive in today's market, and if we have to define it assuming the definition of ferrocement is not available, what could that definition be? First we would have to define a textile in general terms, such as a 2D textile or a 3D textile without reference to any process of fabrication or material. Then perhaps we could use a definition such as suggested next:

> *"Textile reinforced concrete is a type of reinforced concrete commonly constructed of hydraulic-cement matrix reinforced with several layers of closely spaced continuous 2D textiles, or one or several layers of 3D textiles. At least one textile layer should be placed near each of the two extreme surfaces of the resulting structure. The textiles may be made of polymer, synthetic, metallic, organic or other suitable materials. The fineness of the cementitious matrix and its composition should be compatible with the textile armature system it is meant to encapsulate. The matrix may contain discontinuous fibers or microfibers of appropriate dimensions."*

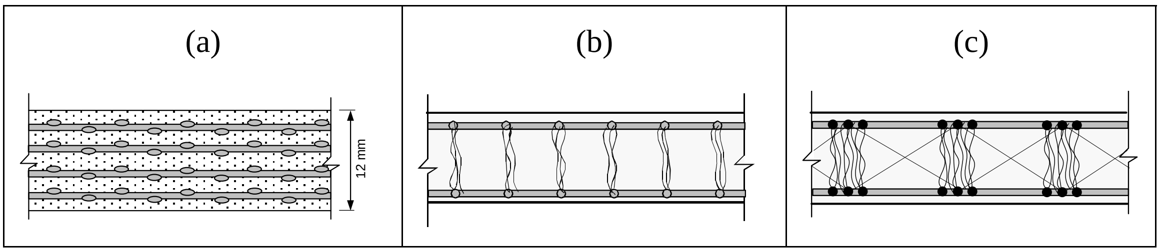


Fig. 3 Typical sections of thin textile reinforced concrete (TRC) products with: a) several layers of 2D textile reinforcements, or b,c) one layer of 3D textiles

By stating that the textile could be "metallic", TRC would allow the use of conventional steel wires meshes (woven or welded) and thus TRC could cover conventional ferrocement. The only issue we would have to explain is whether a TRC with a single layer of 2D reinforcement such as in Stucco (Fig. 2) is acceptable, or we would insist on at least two layers such as in a sandwich construction, where each layer is placed close to one extreme surface of the composite to optimize bending resistance. On the other hand a TRC could use a single 3D textile fulfilling the same function of reinforcing system as several 2D textiles. In such a case one layer of a 3D textile would be acceptable as stated in the proposed definition and shown in Figs. 3b and 3c.

2 CONDITIONS FOR COST COMPETITIVENESS OF TRC

So far textile reinforced concrete, if understood at the structural concrete level, such as in a conventional steel reinforced concrete slab or column, has had limited practical applications. Many cited applications stemmed from research or demonstration projects. Indeed it may be observed that: 1) the textiles needed for such applications are relatively large scale, thus out of the reach of current textile machinery, 2) the textiles needed are not cost competitive with conventional steel reinforcements, and/or 3) the relative performance of the resulting structure in comparison to conventional reinforced concrete does not justify their use [25]. Such measures are true for any new product.

Since the mid-1990's several studies have addressed the use of FRP meshes or textiles in thin reinforced cement composites [12, 18, 19, 20, 21, 22, 23, 26 to 33]**.** In particular, this writer has shown that in thin cement composite products such as similar to ferrocement, textile reinforced cement composites can be cost competitive and can also achieve a commendable level of performance [27]. Related studies may have used the term FRP mesh (or fiber reinforced polymer mesh) or ferrocement reinforced with FRP meshes, instead of textile reinforced concrete. A synthesis of some observations related to performance and cost is provided farther below.

3 SIMPLE MECHANICAL COMPATIBILITY RULES FOR TEXTILE SELECTION

Few practical rules derived from mechanics may dictate some preferential properties of textiles for use in cement matrices. For instance when using normal weight cementitious matrices, it is desirable to have textiles with relatively high equivalent elastic modulus as well as high strength. The equivalent modulus of the textile is different from the elastic modulus of the fiber from which it is made and depends on the production process of the textile. It is generally smaller than the fiber modulus. So a textile with Leno weave will show in the Leno direction a smaller equivalent modulus than in the other direction. Similarly, a high modulus high strength fiber such as for instance Kevlar, used in a jersey type textile, would likely lead to a textile of relatively low equivalent modulus simply because of the textile architecture itself. Finally, a textile made with high tensile strength brittle fibers may lead to significantly lower tensile strength due to the fabrication process if the fibers are not kept perfectly straight.

It is generally assumed that the textile material and the cement matrix are chemically compatible, and that perfect bond exists at the interface between the reinforcement and the matrix. More specifically it is desirable to have a bond stress versus slip relationship with a high initial stiffness, that undergoes little or not deterioration during cyclic service loads and for normal fluctuations in service temperature. While the issue of bond of conventional deformed reinforcing bars with concrete seems to be somewhat settled at the research level, bond in textile reinforced concrete will need significant research efforts and deeper understanding [13, 14, 17].

Assuming that a good bond (adhesive, frictional, mechanical or a combination of them) can be achieved for a particular reinforcement or textile, the author suggests the following simple two-parts rule based on mechanics to design cement composites with improved performance:

> *Increase both the ratio of tensile strength of the reinforcement to the compressive strength of the matrix, and the ratio of elastic modulus of the reinforcement to that of the matrix.*

The above rule assumes that cementitious composites will crack under tension (or bending tension) leaving the reinforcement in the cracked zone to contribute to both stiffness and strength while the matrix is cracked and thus contributes little in tension. The requirement related to the moduli ratio may explain why low-end polymer meshes or textiles made of polypropylene, for instance, were not widely or successfully used in normal weight cementitious matrices, although their tensile strength was comparable to that of conventional steel-wire meshes. However, based on the above simple rule, it can also be predicted that polypropylene based textiles may be compatible mechanically with very lightweight cementitious matrices, which show both low compressive strength and low elastic modulus.

4 PERFORMANCE COMPARISON BASED ON MOR

In this section, a synthesis of observations related to the maximum bending resistance (also termed modulus of rupture, MOR) of cement composites is provided as a comparative measure of performance. The issue of cost is addressed in the next section.

4.1 Ferrocement with Steel Reinforcement

In order to provide a basis and some measure of comparison, here are some facts about ferrocement using galvanized steel wire meshes, in thin cementitious matrices of thickness less than about 50 mm. The following results were obtained both experimentally and analytically using thin ferrocement bending plates [23, 28, 29].

- Using conventional square steel wire meshes (welded or woven) with tensile yield strength around 450 MPa, the value of modulus of rupture of such systems can attain about 50 MPa with 7% total reinforcement by volume of composite, that is about 7 MPa per 1% total volume fraction of reinforcement. This would apply to a ferrocement plate, with equal bending resistance in the two in plane directions, and with equal resistance for either positive or negative moments.

- Using high strength high performance steel reinforcing mats with tensile yield strength about 3100 MPa, the value of modulus of rupture can attain about 21 to 24 MPa per 1% total volume fraction of reinforcement. This volume fraction includes the amount of microfibers used in the matrix to improve its shear resistance. This would apply to a ferrocement plate, with equal bending resistance in the two in plane directions, and with equal resistance for either positive or negative moments.

4.2 Low-End Fiber Reinforced Polymer Meshes and Textiles

Starting in the early 1960’s, polymer based meshes (or 2-D textiles, or fabrics) became available on the market for various applications such as for carpet backing, netting, and the like. They include meshes made with polypropylene, nylon, and polyester fibers. They were of relatively low strength (compared to high performance fibers such as glass or carbon) and low elastic modulus (compared to normal strength concrete); they are described here as “low-end” in comparison to the high performance fiber reinforced yarns or 2-D fabrics (glass, carbon, Kevlar, Spectra) which were used in aerospace and defense applications in combination with polymeric matrices, identified here as “high-end”.

Several low-end type polymer meshes were tried as reinforcement in thin cement based applications such as ferrocement (or textile reinforced concrete). For all practical purposes, modulus of rupture (MOR) values in excess of 25 MPa were difficult to achieve even with high amount of reinforcement. The following base reference could be used [23, 12]:

- Typically, for PP meshes under best conditions, a MOR value of about 3.6 MPa could be achieved per 1% total volume fraction of reinforcement.

- Typically, for PVA meshes under best conditions, a MOR value of about 6.2 MPa could be achieved per 1% total volume fraction of reinforcement.

Note that the elastic modulus of PVA fibers used is about 29 GPa, that is, almost three times that of polypropylene fibers. While the above range (3.6-6.2 MPa per 1% reinforcement) can be viewed as competitive with that of conventional steel wire meshes (7 MPa for 1% reinforcement) other composite properties were not as good. By and large, composites with low-end FRP meshes or textiles led to a relatively poor performance in comparison to conventional steel wire meshes, namely: low elastic stiffness in the cracked state, large crack widths, large creep deformations, and being very prone to distress at relatively moderate levels of temperature.

4.3 High-End Fiber Reinforced Polymer Meshes and Textiles

Among high performance fibers (with relatively high tensile strength and high elastic modulus) glass fibers and glass-fiber fabrics were first considered as reinforcement for cement matrices. However, while the short term mechanical properties of the composite were competitive, long term behavior deteriorated due to the alkali reactivity of the glass fibers with the cement matrix. Although alkali resistant glass fibers were developed to minimize such reaction, glass fiber textiles or fabrics are not included in the following discussion.

While textiles and fabrics made with high performance polymer fibers such as carbon, Kevlar and Spectra were available for the aerospace industry as early as the 1960’s, they did not come in a form sufficiently acceptable (such as for instance for proper matrix infiltration) for cement composites until the late 1980’s and early 1990s. Both experimental and analytical studies have shown that the most efficient use of these reinforcements for bending resistance consists of a sandwich construction with two extreme layers of reinforcement and a cement matrix containing fibers (needed for vertical shear and interlaminar shear resistance) [20, 21, 22, 23, 31]. Experimental results observed lead to the following reference base to use for comparison with other reinforcements [27]:

- Using composites with high-end fiber reinforced polymer meshes or textiles, and a cement matrix without fibers, moduli of rupture ranging from 15.5 MPa to 18.3 MPa could be achieved per 1% total volume fraction of reinforcement.

- Using hybrid composites with high-end fiber reinforced polymer meshes or textiles, and a cement matrix containing fibers, moduli of rupture ranging from 13 MPa to 17 MPa could be achieved per 1% total volume fraction of reinforcement (which includes the fiber content).

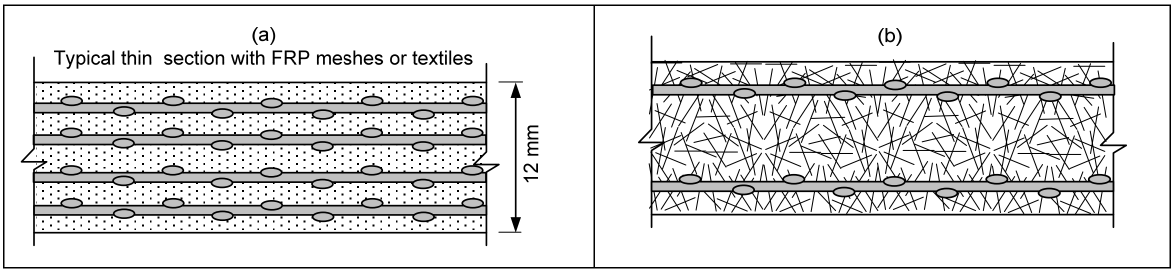


Fig. 4 a) Typical section with FRP meshes or textiles, and b) Most efficient section using high-end FRP meshes

Note that the use of discontinuous fibers in the matrix may increase the absolute value of MOR, but decreases the value of MOR per unit amount of reinforcement used; however, a host of other properties such as shear, cracking, durability are improved when fibers are added. Note also that the best observed case (about 26 MPa per 1% total reinforcement [27]) was that using carbon textiles in a machine-pultruded cement plate. It is not included in the range above, because of the different manufacturing process but should be considered as a potential value in future studies.

5 COMPARATIVE WILLINGNESS-TO-PAY PRICE

The cost of a typical mesh (steel, textile or other reinforcement) is based on unit weight while the mesh mechanical efficiency in the composite is based on volume fraction in the composite. Since the unit weight of steel ranges from 3 to 8 times that of most FRP materials, and since the composite properties are based on volume fraction (or volume) of reinforcing mesh instead of weight, cost comparison should be based on equal performance and may favor FRP meshes over steel meshes.

Table 1 provides typical properties of selected materials that have been used in ferrocement and thin cementitious composites. Table 2 provides a summary of performance comparison for thin cement composite plates (0.5 in or 12.5 mm thick) all tested in bending under the same conditions. Column (2) of Table 2 provides a summary of comparative performance based on modulus of rupture per 1% volume fraction of reinforcement. The modulus of rupture values shown are for a composite plate with equal bending resistance in the two in plane directions, and with equal resistance for either positive or negative moments. Column (5) of Table 2 shows the calculated willingness-to-pay price for a typical mesh reinforcement based on its performance compared to that of conventional steel wire mesh. Note that the willingness-to-pay price of a given mesh reinforcement represents the maximum price one should be willing to pay for using such a mesh. Details of the study are given in [27] where prices are given in $ reflecting prices in 2004. The willingness-to-pay price takes into consideration the fact that composite performance is based on volume fraction of reinforcement while reinforcement cost is per unit weight, not volume. To make the table more useful with time and geographic location, a unit price of 1 unit is taken here for one kilo of conventional steel galvanized wire mesh of the type used in typical ferrocement applications; it is considered a reference base. Such a value may correspond, for instance, to 3 Euro per kilo in Germany or $ 4 per kilo in the US. Other prices are relative to the 1 unit price of conventional galvanized steel wire mesh.

Table 1 Mechanical properties of typical fibers for use in concrete as compared to steel wires

Fiber Material	Specific gravity	Tensile strength, MPa	Elastic Modulus, GPa	Ultimate Elongation %	Qualitative Bond
Cellulose, kraft pulp	1.5	500	10-30		Good
Polypropylene, PP	0.93	200-700	4 – 10 GPa	15 - 8	Poor
Nylon	1.15		Up to 6.7 GPa		Poor
Polyester	1.38	800-1300	Up to 15 GPa	20 - 8	Poor
PVA	1.31	800-1500	23-40	10 - 6	Excellent
Glass, AR	2.7	1700	72	2	Moderate
Kevlar (aramid)	1.44	2700	130		Moderate
Spectra (high molecular weight polyethylene	0.97	2585	117	2.2	Moderate
Carbon, from polyacrylonitrile	1.6 – 1.8	2800-4500	210-290	2 - 1	Moderate
Carbon, isotropic pitch	1.6 – 1.8	590 - 840	28 - 35		Moderate
Carbon, meshophase pitch	1.8 – 2.1	1700 - 3200	170 - 520	Around 1%	Moderate
Steel	7.9	Up to 3100	200	> 2%	Poor to excellent depending on mecha-nical defor-mations

Table 2 Comparative performance of thin cement composites reinforced with various polymeric meshes based on MOR and willingness to pay price compared to conventional steel wire meshes

Reinforcement Type (1)	MOR per 1% total reinf., Vr, (MPa) (2)	Assumed density (3)	Reinforcement density ratio used (steel to fiber material) (4)	Willingness-to-pay price per unit weight assuming steel unit price is 1 unit / kg (5)
Conventional steel wire mesh	7	7.9	1	1
Very high strength steel mat (with micro fibers)	21 - 24	7.9	1	3-3.4
Low-End Polymer:				
PP	3.6	0.93	8.5	4.37
PVA	6.2	1.3	6.03	5.38
High-End Polymer:				
Carbon 1	13 - 18.3	1.8	4.36	8.1 - 11.4
Carbon 1 (machine pultruded)	26.7	1.8	4.36	16.6
Carbon 2	11 - 17.9	1.8	4.36	6.9 -11.1
Kevlar	16.7 - 18.1	1.44	5.45	13 - 14.1
Spectra	13.9 - 15.6	0.97	8.2	17.1 - 19.2
3D-Glass	5.28 - 10.4	2.6	3.02	2.28 – 4.48

In columns (2) and (5) of Table 2, when a range is shown, the lower value reflects the use of 1% PVA microfibers in the cement matrix. Microfibers improve the vertical and interlaminar shear resistance of the composite. The total reinforcement considered in the analysis includes the amount of microfibers when used. In that case, the corresponding willingness-to-pay price may be slightly biased because it assumes that the cost of fiber and mesh are equal. Since the cost per unit weight of PVA fibers is, at time of this writing, smaller than that of carbon, Kevlar, or Spectra meshes, the corresponding willingness-to-pay price calculated is slightly on the low side. Should there be need for a more precise evaluation, it is possible to separate the price of the fiber and mesh materials and provide an adjusted “willingness-to-pay price" for the mesh. Nevertheless the values given in Table 2 are very useful in providing a rough estimate.

Thus the last column of Table 2 suggests that one should be willing to 3 to 3.4 times more for a steel mesh or mat made with very high strength steel wires, than for a conventional galvanized steel wire mesh such as typically used in ferrocement. Similarly one should be willing to pay up to 14.1 times more for a Kevlar (aramid) mesh.

Table 3, also adapted from [27], provides a comparison between actual price ratios (column 2) in Germany in 2004 for some fiber reinforced polymer mesh (or textiles or fabrics) materials compared to conventional steel wire meshes, and the corresponding willingness-to-pay price ratio calculated from column (5) of Table 3. It can be observed for instance that while carbon and glass are cost competitive, aramid is not. The unit prices taken for the glass, carbon, and aramid fabrics were initially taken from *Kruger* [16] and were for the year 2004 in Germany.

Table 3 Price ratios for 2004 compared to willingness-to-pay prices (assuming the price of conventional galvanized steel wire mesh is 1 unit per kilo)$

Material (1)	Unit Price Ratio, 2004 unit / kg (2)	Willingness-to-pay price ratio (3)	Remark (4)
Conventional galvanized steel wire mesh	1	1	Reference base for comparison
Very high strength steel mats	2.25	3 – 3.4	Competitive
AR-Glass, 2500tex, 500 g/m^2	2.25	2.25 to 4.5	Competitive
Carbon, 1700tex, 320 g / m^2	7.8	6.75 to 11.5	Competitive
Aramid, 1288tex, 260 g/m^2	17.25	13 to 14	Not competitive
AR-Glass, 2500tex, 500 g/m2, Epoxy*	5	2.25 to 4.5	Almost competitive
Carbon, 1700tex, 333 / m^2, Epoxy*	11.6	6.75 to 11.5	Competitive
Aramid, 1288tex, 260 g/m^2, Epoxy*	22.5	13 to 14	Not competitive

* Epoxy: means yarns impregnated with epoxy

$ The base unit prices for glass, carbon and aramid textiles in Euro/kilo were taken from Kruger [16] before being normalized to the price of steel

In spite of the results of this preliminary analysis, FRP (Fiber Reinforced Polymeric) meshes (or textiles, or fabrics) may offer advantages in spite of their initial high cost. This is because, unlike steel wire meshes, they can be tailored to exact requirements (i.e. fiber denier or diameter, mesh opening, etc..) at little extra cost, they can be delivered in virtually any length, they are lightweight, and they can be easily shaped to requirements. It is thus likely that future developments and applications will make FRP meshes increasingly cost competitive, especially when labor cost and life-cycle cost analysis are considered.

6 THE CASE FOR 3D TEXTILES

6.1 Why 3D Reinforcements

The above performance comparison and willingness-to-pay price (Tables 2 and 3) was based on comparing only the different reinforcing materials. Other factors may have a sufficiently high influence to change the rankings observed. One of them is labor or manufacturing cost, and that brings the subject of 3D reinforcements.

3D reinforcement systems for ferrocement applications have been thought off by many users of ferrocement wishing to simplify the construction process and reduce construction labor cost. Typically, the reinforcement in ferrocement and laminated cementitious composites consists of several layers of equally spaced meshes. Similarly to reinforced concrete, the fabrication and placement of the mesh reinforcement require significant labor commitment. For instance, in ferrocement where steel meshes are used, the cost of labor can be as high as 50% of the total cost of the composite [23]. Using a pre-engineered 3D reinforcing system can thus have enormous impact on final cost. To the best of the writers' knowledge, only one 3D steel-type mesh (the Watson mesh from New Zealand [23]) was commercially manufactured in the late 1970's for thin cement products but was eventually terminated due to high production cost. Indeed it is not as easy to handle high strength stiff springy steel wires in a textile type machine as in the case of polymer fibers such as glass or aramid.

While 2D textiles or fabrics using high performance fibers (carbon, Kevlar, Spectra) were evaluated for ferrocement applications since the early 1990's, it is only in the late 1990's and early 2000 that 3D meshes (or textiles or fabrics) derived from the technology of textiles and fabrics became available for research studies in ferrocement and thin cement composite products [5]. In particular, the Institute of Textiles in Aachen (ITA), Germany, in collaboration with the Technical University in Dresden, Germany, have pioneered a number of 3D textiles for applications in thin cement and concrete composites. Note that the term Textile Reinforced Concrete (TRC) is used in Germany and most of Europe for such applications [5, 13, 14, 17]. Textile technology offers the advantage of placing as much reinforcement as needed by design (generally less than 4% by volume of composite), and exactly where it is needed, and tailoring the fabric properties and shell volume for particular applications. They also offer a tremendous advantage in simplifying the construction process and saving on labor cost. Essentially the 3D textile (now acting as an armature system) is placed into a mold and infiltrated or encapsulated by a cement based matrix. Thus, with an open box shaped mold, a thin flat reinforced cement sheet can be easily produced. 3D textiles can be readily manufactured in thicknesses from about 10 to 50 mm, a range perfectly suitable for ferrocement and laminated cementitious composites applications or equivalently thin TRC applications.

6.2 Status of Applicability of 2D and 3D Textiles to Conventional RC Structures

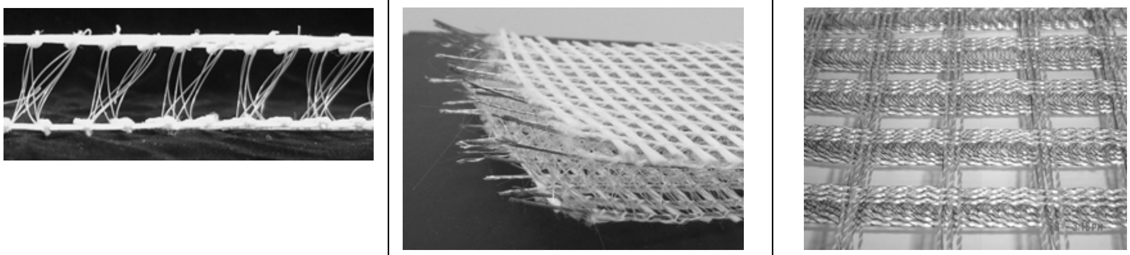
Reinforced concrete (RC) is the most commonly used structural and construction material in the world. It is typically a composite with two main components, the concrete matrix and the reinforcement. Here, the concrete matrix is taken in its broadest sense and includes all cement-based matrices, particularly matrices containing only fine particles. Most commonly the reinforcement in reinforced concrete is made out of steel reinforcing bars, with a proportion by volume ranging from about 0.7% to 3% of the composite. The placement and location of the reinforcement within the concrete matrix follow acceptable analysis and design procedures. Typically, reinforcing bars are assembled according to a design pattern and tied to other bars, generally along three orthogonal directions, eventually forming a self-standing armature system. This armature is placed inside a mold and fresh concrete is poured over it to entirely encapsulate it; upon hardening of the concrete with time, the reinforced concrete (RC) structure is formed. The labor cost associated with the fabrication of the armature system in RC structures represents a significant portion of the total cost of the composite. The armature system in a reinforced concrete structures can be envisioned as a 3D textile structure.

While 2D and 3D textiles of various architectures (braiding, spacer sandwich, weaving, etc…) are being increasingly used in aerospace structures, they have not yet made any impact on the world of conventional concrete. This may be primarily due to the scale of conventional reinforced concrete. Indeed, the least dimension (thickness) of conventional RC structures is generally of the order of 100 mm. Such a thickness may be too high to be covered competitively by current 3D textile technology but should be the objective of future developments in the field. Add to that the advantage of lightweight armature system versus steel, and there is a compelling case to be made for 3D textiles, once technically possible on a larger scale.

6.3 Status of Applicability to 2D and 3D Textiles to Thin Reinforced Cementitious Products

As suggested earlier, there is a whole family of cement based composites with significantly smaller thicknesses than conventional reinforced concrete. Typically, ferrocement and cementitious composite laminates range in thickness from about 5 to 50 mm [23]. While ferrocement uses primarily steel wire meshes as reinforcement, non-metallic reinforcement such as carbon, glass, aramid, and the like, primarily in the form of textiles or fabrics have been also used often in cement composites under the name of ferrocement [12, 18, 19, 20 21, 22, 23, 24, 26, 28, 29, 31, 32]. In such a case, the composite could be called textile reinforced concrete (TRC). Ferrocement and laminated cementitious composites comply with the same principles of mechanics as reinforced concrete; however, the cement matrix is made out of much finer components (such as containing fine sand versus coarse aggregates) and the reinforcement has much smaller diameter or denier, such as for a steel wire versus a reinforcing bar. These composites offer all the inherent benefits of using a concrete matrix, namely high compressive strength, stiffness, durability, fire resistance, abrasion resistance, unlimited availability, and safety (when properly designed).

Ferrocement and laminated cementitious composites (or thin textile reinforced concrete) can fulfill the double role of light manufactured structural elements (corrugated roofing panel), and protective skin (cladding) for other structures. Both analytical and experimental research have indicated that they can achieve a high level of performance (strength and ductility) at competitive cost (Section 5 and Table 3). In particular, it was observed that a hybrid combination with meshes (textiles) in sandwich construction combined with short discontinuous fibers reduces the need for multiple layers of reinforcement, while providing competitive bending and shear sufficient shear resistance (vertical shear and interlaminar or horizontal shear), and significantly reducing material and labor costs. Examples are shown in Tables 2 to 4 above and Fig. 4b. Note that fibers or micro-fibers added to the matrix also serve other functions such as improving first cracking strength, impact resistance, ductility, bond of main reinforcement, energy absorption and, in many cases, contribute to bending resistance as well.



(b) (c)

(a)

Fig. 5 Examples of 3D textile reinforcements produced at the ITA in Aachen Germany: a) spacer textile; b) hybrid spacer textile with steel strands incorporated; c) grid textile.

6.4 Steel versus Fiber Reinforced Polymer Reinforcements

Looking ahead, when comparing high performance textile reinforcements (made with high performance fibers) with steel reinforcements, it is likely that the advantage of one over the other will depend on criteria other than strength or moduli of rupture, including weight, ease of handling, and life-cycle cost. Moreover, the ease of producing 3D architectures and the possibility of using hybrid compositions of reinforcement (steel and FRP with or without fibers or microfibers in the matrix) may provide the best solution. Clearly the manufacture-ability of a particular 3D textile at reasonable cost will provide a key advantage.

Note that pre-engineered 3D textile reinforcement (say in the form of flat panels, corrugated sheets, or shells) can serve as light reinforcement for several applications. For instance, the weight of a 3D carbon or Kevlar reinforcement in a cement composite panel can be as little as 2% of the weight of the composite. The matrix, essentially made of cement, sand and water, can be cast in place where the structure or element is needed or in a nearby facility. Special cementitious matrices can harden sufficiently in less than 24 hours. This approach will offer enormous cost savings, for instance, for emergency shelters, in comparison to airlifting entire shelter systems, and the final product can be eventually turned into a permanent, durable, reliable, shelter.

7 SUGGESTED SPECIAL AREAS FOR FUTURE RESEARCH

7.1 Development of 3D Textiles

a. There should be continued development of 3D textiles particularly tailored for applications in thin cementitious composites. This is an area that is potentially cost competitive today and thus should be addressed first.

b. There should be continued development of 3D textiles with hybrid combinations of reinforcements including steel wires and strands. Examples include using low end polymer fibers to build the supporting armature for high end steel wires or strands. First priority should be given to thin cementitious composites.
c. There should be development of larger scale 3D textiles for application in true conventional reinforced concrete structures.

7.2 Self-Stressing Cement Composites

Cement and ceramic matrices are brittle in nature. They generally have a compressive strength much higher than their tensile strength, and thus tend to crack under tensile stresses induced by service loads. Prestressing these matrices, such as in the case of prestressed concrete, leads to a better composite in which higher tensile stresses can be applied, cracking can be avoided or delayed under service load conditions, and the structure becomes more impervious to penetration by liquids and gases, thus providing significantly higher durability.

Prestressing cementitious composite products such as thin sheets, boards, cladding, pipes and the like should bring an enormous impetus to their use and development. However, prestressing using conventional methods such as pre-tensioning or post-tensioning (by mechanical stretching and releasing of the reinforcement) requires relatively high technical skills, is labor intensive and necessitates very special care when thin polymer fibers are used. Thus, conventional prestressing methods are not cost-effective for thin cementitious products. Nevertheless, prestressing can be accomplished using the principles of internal prestressing or self-stressing.

In the self-stressing technique, the reinforcement is first placed in the mold and then encapsulated by a cement matrix similarly to conventional reinforced concrete. Self stressing of cement composites can be achieved (after the matrix has hardened) by one of three possible methods: expansion of the matrix, contraction of the reinforcement, and a combination of both.

Prestressing (by contraction of the reinforcement) is self-induced when needed by simple heating or radiation or other treatment of special reinforcing materials. Self stressing by expansion of the cement matrix occurs automatically with time. No labor is involved in stressing the reinforcement. Self-stressing incurs significant savings in labor cost and reduces the need for a highly technical labor force. Moreover the method of self-stressing allows the reinforcement to be formed in any shape in a two or three dimensional space without special devices.

For self-stressing by the reinforcement, there are today "smart" materials that allow us to envision self-stressing which produces sufficient prestress levels. Shape memory alloys (SMA) [17] and some special polymeric fibers such as liquid crystal polymers, possess the unique property of being able to be frozen temporarily in a particular state (imagine a stretched state); then, with proper heat or radiation treatment, go back to their previous equilibrium state (thus shortening elastically). This deformation controlled recovery property of a material is a property that produces a shortening of the material when it passes from one state to the other. In attempting to shrink back to its previous state, the reinforcement provides, through bond and/or anchorage, the needed prestressing. The treatment (heat or radiation or other exposure) to trigger shortening of the reinforcement can be applied any time after hardening of the cement matrix. The special reinforcement needed, a 2D or better a 3D textile or fabric or armature system can be machine manufactured, stored, shelved, placed in the composite, and triggered to recover its deformation (inducing prestressing) at any appropriate time.

7.3 Cement Composites with Lightweight Matrices

If we go back to the simple rule of mechanics described in Section 3, it is clear that it should be possible to successfully use low-end polymer fibers and fabrics which have a relatively high tensile strength (say in excess of 400 MPa) but low elastic modulus, provided the cement matrix has a low elastic modulus as well. Such matrices can be made from very lightweight or aerated cementitious matrices. Examples of strengths and elastic moduli are given in Table 4. Strength and moduli of potentially compatible low end fibers are given in Table 1. Note that the ratio of elastic modulus of a typical PP fiber (E_{PP} = 7 GPa) to the elastic modulus of mixture *B* in Table 4 (0.68 GPa) is about 10 and that is similar to the ratio of elastic modulus of steel (E_s = 200 GPa) to that of a typical normal weight concrete with a relatively low strength such as in a concrete slab or pavement (E_c = 20 GPa).

Table 4 Typical properties of lightweight aerated cement matrices *

Aerated Mixture ID*	Plastic Density pcf (specific gravity)	Dry Density psf (specific gravity)	Range of Compressive Strength f'c, psi (KPa)	Range of Elastic Modulus Ec, ksi, (MPa)
A	30 (0.48)	25 (0.40)	81 – 144 (559 – 994)	32.2 – 42.9 (222.2 – 296)
B	40 (0.64)	36 (0.58)	196 – 256 (1352 – 1766)	86.5 – 98.8 (596.9 – 681.7)
C	60 (0.96)	55 (0.88)	324 - 529 (2236 – 3650)	210 – 268.3 (1449 – 1851)

*Information obtained from Elastizell Corporation of America. Elastic modulus follows the following prediction equation using US units: $E_c = 28.6 \times w^{3/2} \sqrt{f_c'}$

7.4 Ultra-High Performance Cement Matrices in Thin Cement Composites

Cementitious materials with compressive strength over 150 MPa (22 ksi) produced in bulk quantities have aroused particular interest around the world since their introduction in the early 1990s. Known first as reactive powder concrete (RPC) [34], they are now more generally described as Ultra High Performance Concrete or UHPC. To date, two international technical symposia have specifically addressed UHPC [8, 9].

In order to achieve the high strength in UHPC, one objective is to optimize particle packing within the composite. In turn, dense particle packing, implies high durability, improved freeze-thaw resistance, increased resistance against various chemicals, and higher penetration resistance [10, 35, 36]. Thus the potential of UHPC in various applications, including blast and impact resistant structures, has attracted high interest by both the research and professional communities.

Note that most common UHPC mixtures so far developed should be called “mortar” not “concrete” because they do not use large aggregates. Instead they utilize very fine particles including cement, glass powder (or silica powder) silica fume, fly ash, and sand with a maximum particle size of less than about 1 mm. The finest particles in the mixture come from silica fume and are on average about 0.5 micron in diameter and generally less than 1 micron in diameter (1 micron = 10^{-3} mm). Moreover, even with a low water-to-binder ratio, given the help of superplasticizers (HWRA) and viscous agents, these mixtures are commonly self-consolidating or self-compacting, that is, they can easily flow on their own inside a mold and entirely encapsulate existing reinforcement without any vibration. Such self-consolidating UHPC mixtures are particularly compatible with and suitable for ferrocement, thin cement based composites products or textile reinforced concrete, constructed using molds, because the armature systems (multiple layers of mesh, 3D textile, etc…) in these composites have very small openings and thus require a matrix with very fine particles to pass through such openings.

Referring to the simple compatibility between reinforcement and matrix (Section 3), note that the modulus of UHPC matrices is of the order of 50 GPa and thus compatible reinforcement should preferably have as high an elastic modulus as possible. Assuming steel is acceptable, next potential reinforcement among high-end fiber reinforced polymer meshes or textiles or fabrics, is carbon.

Finally, looking ahead, it is conceivable today to envision the combination of ultra high performance cement matrices with self-stressing to produce truly outstanding composites which could show no cracking under service loads and a service life that can be measured in decades and centuries.

8 SUMMARY: CURRENT STATUS

1. **Compressive performance**. The compressive strength of cement composites including ferrocement, fiber reinforced concrete, and textile reinforced concrete is predominantly dictated by the strength of the matrix. Thus any advances in the matrix can be translated to the composite such as the use of high performance or ultra-high performance matrices of strength exceeding 150-200 MPa and where durability is expected to be significantly improved.
2. **Bending resistance**. According to several investigations of ferrocement and thin cement composite plates reinforced with either conventional steel wire meshes or high performance fiber reinforced polymeric meshes (or textiles or fabrics of Carbon, Kevlar, Spectra) a limit of about 50 MPa for the modulus of rupture or equivalent elastic bending strength was observed [23]. With FRP reinforcement, this limit was obtained when microfibers were used in the matrix to improve both vertical and interlaminar shear resistance [22, 27]. In prior studies involving low end polymeric meshes (or textiles or fabrics) such as polypropylene and nylon a modulus of rupture limit of 25 MPa was obtained even when the volume fraction of reinforcement was as high as reasonable. Moreover, with low end polymeric textiles and normal weight cement matrices, large crack width and large permanent (not recoverable) creep deformations were observed.

3. **Tensile resistance**. The tensile resistance of most cement composites with continuous reinforcement can be predicted directly from using the following simple relation [23]: $\sigma_{tu-composite} = \eta_o \times V_r \times \sigma_{ru}$ where η_o is the efficiency factor of reinforcement in the direction considered, V_r is the total volume fraction of reinforcement, and σ_{ru} is the ultimate tensile resistance of the reinforcement. It is assumed that the matrix is cracked and does not contribute any resistance. Note however, that a high tensile resistance does not imply good performance. Deformations and crack widths could be too large.
4. **Cost.** The cost of the matrix in typical thin reinforced cement composites is very small (5%) compared to that to the reinforcement and labor, which in most developing countries are of the same order [23, 29]. Thus cost reduction should focus on material cost and labor cost. The use of 3D textiles will have a significant impact on reducing labor cost.
5. **Lightweight matrices**. As suggested in the simple mechanical rule stated above, textiles or fabrics made with low-end polymeric fibers may be compatible with lightweight cement matrices. Lightweight implies here a density ranging between 0.5 and 1. The author is not aware of any systematic study involving such matrices. One can simply predict that their moduli of rupture will be less than 25 MPa (as obtained with polymeric meshes and normal weight cement matrices)
6. **Self stressing composites**. Very little has been done so far in that field. Prestress levels close to 1000 psi or 7 MPa were reported in [15] for thin cement specimens.

9 SUMMARY SUGGESTED RESEARCH DIRECTIONS

As expected, researchers will keep exploring new grounds, breaking existing barriers, and exceeding existing limits. Here are some areas of potential research at the material level to improve the composite performance:

1. High strength high modulus reinforcements used to produce the textiles or fabrics; most promising at this time are carbon based fibers or yarn based on carbon fibers. The general rule is to find a material with combined high strength, high elastic modulus, and good bond.
2. Textile architecture that favors achieving an equivalent elastic modulus as close as possible to the elastic modulus of the fiber material.
3. 3D textiles tailored for optimum performance in specific applications such as for thin plates or corrugated sheets or pipes or columns.
4. Textile with hybrid reinforcement such as steel and PP, steel for strength and modulus, and PP as armature support.
5. Large scale 3D textiles for applications in conventional reinforced concrete structures, starting with slabs and small beams.
6. 2D textiles designed for use in combination with fibers or fiber mats to produce sandwich construction.
7. Self-stressing composites using fibers or textile with useful deformation recovery property. Self stressing by a possible combination of controlled matrix expansion and fiber or textile deformation recovery.
8. High performance and ultra high performance cement matrices of compressive strength exceeding 150-200 MPa with and without addition of microfibers
9. Lightweight matrices and compatible low-end fibers and textiles (2D or 3D) designed for optimizing composite performance and cost.
10. New specialized products such as floating concrete, transparent concrete, which use special textile reinforcement.

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