Solid States

Concrete in Transition

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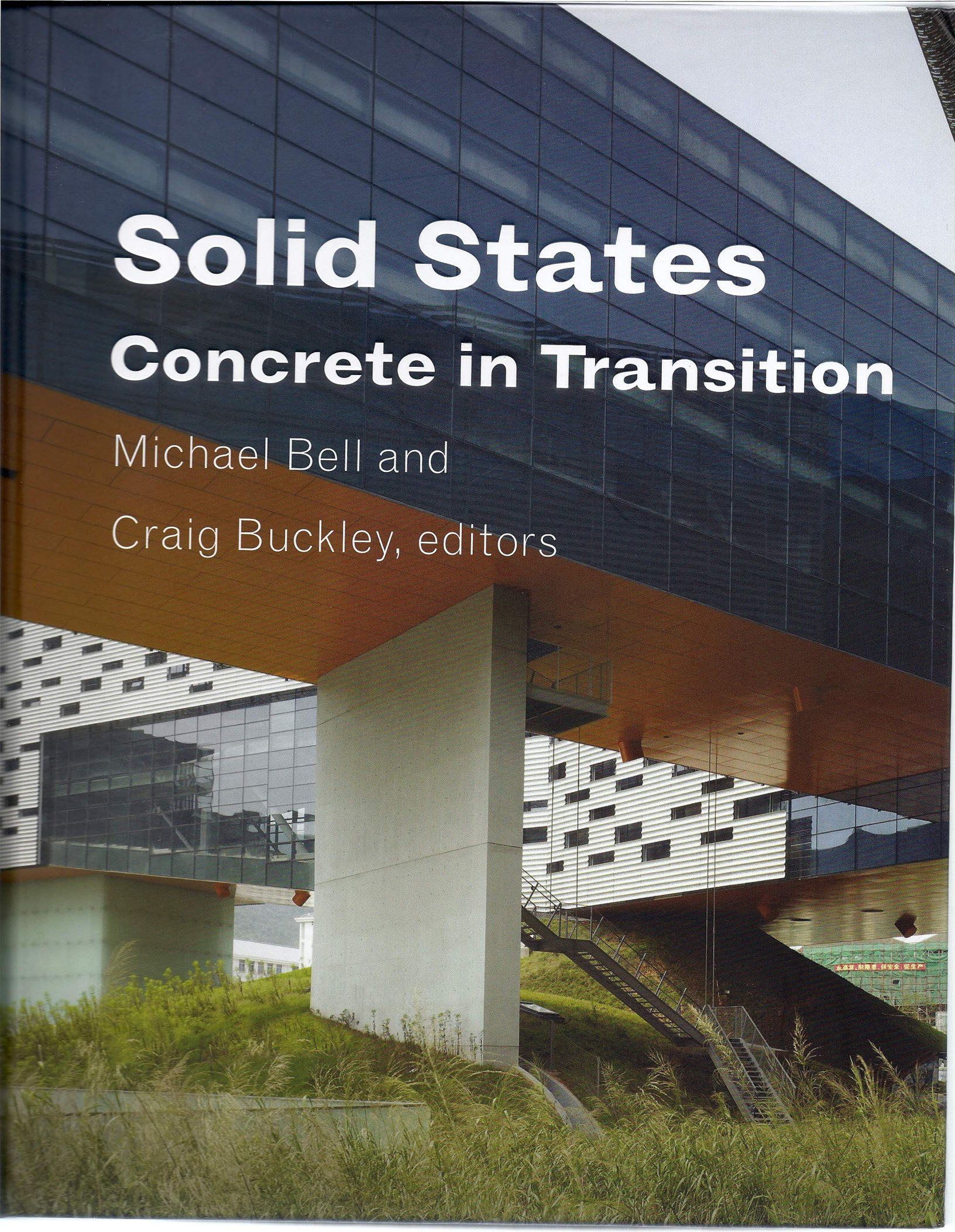

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From Wire Mesh to 3-D Textiles: Progress in New Reinforcements for Ferrocement and Thin-Cement Composites

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Background/Definition

This essay focuses on the evolution of reinforcements for thin, cement-based composites, defined here as products having less than about 50 millimeters (approximately 2 inches) in thickness. Such composites are composed of two main components: a cement-based matrix and reinforcement. The reinforcement may be made of different materials, which can be continuous, discontinuous, or a hybrid combination of both. Related products include cement boards, corrugated cement sheets, pipes, cladding, shells, water tanks, boats, housing elements, and the like. While conventional reinforcements for these products are steel-wire meshes or laths, new forms of reinforcements have emerged over the years with the objective of improving performance and minimizing total product cost. These include Fiber-Reinforced-Polymer (FRP) reinforcements, textiles, or fabrics, which use high-performance fibers such as carbon, Kevlar, Spectra, and the like; new steel-unidirectional-reinforcing mats made with extremely high-strength wires or strands; 3-D textiles or fabrics using polymer fibers; 3-D textiles using a combination of polymer fibers and steel; and reinforcement that uses shape-memory materials to induce self-stressing or internal prestressing.

The first thin-reinforced-cement material was invented by Joseph-Louis Lambot and patented in France as *Ferciment* in 1855. It can be considered the first patent on reinforced concrete. Today the commonly used English term is *ferrocement*. While ferrocement implies the use of cement and, initially, steel reinforcement (from the French *fer*), other reinforcements have been used in thin-cement products. The main difference between ferrocement and reinforced concrete relates mostly to scale. Reinforced concrete uses larger reinforcing bars instead of wires or meshes, and a concrete binder, which, unlike cement paste and mortar, contains large-size aggregates. Moreover, reinforcement in ferrocement is distributed throughout the thickness, while in reinforced concrete it is localized. The American Concrete Institute (ACI) provides the following definition: "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."[1] This last sentence opens the field to the use of polymer reinforcements such as high-performance carbon or aramid fibers, and also encompasses some modern applications such as textile-reinforced concrete (TRC). In a classic book on the subject of ferrocement and laminate-cementitious composites written by me in 2000, I suggested extending the definition by adding the two following 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."[2] These sentences were added to ascertain the compatibility of the matrix with the reinforcement in order to build a sound composite and to accommodate the use of discontinuous fibers or microfibers to improve performance in hybrid composites when desirable. Figure 1 shows a typical cross section of ferrocement and should be distinguished from what is generally defined as reinforced stucco. | figs. 1–2 While hundreds of references can be found to address these materials, a select number of recent reports and books is given at the end of this paper and should be considered a good starting point for further inquiry.[3–12]

Reference Materials of the 1960s and 1970s

In simple terms, a cement composite consists of two main components (as I mentioned earlier), the cementitious matrix and reinforcement, both of which have evolved enormously since Lambot's first patent. The evolution of the matrix—a colossal subject in its own right—will not be dealt with here. It is sufficient to say that the matrix, which in the time of Lambot may have achieved only 10 megapascals (MPa) compressive strength, today can be obtained with strengths of up

fig. 1 | Typical section of ferrocement, showing several layers of distributed welded wire-mesh reinforcement in a relatively thin section

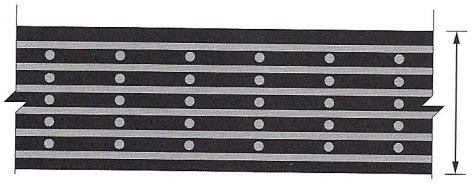


fig. 2 | Typical section of stucco, where one layer of metal lath or wire mesh is used in a matrix about 7/8-inch (22 millimeter) thick

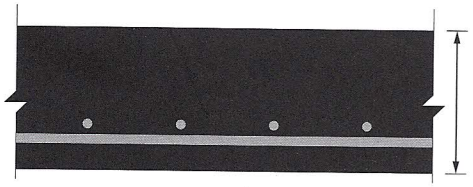
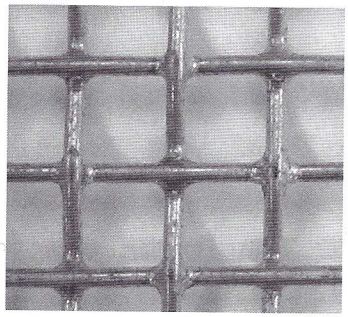
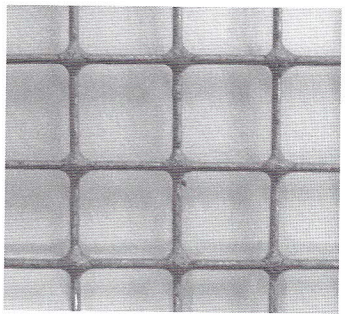
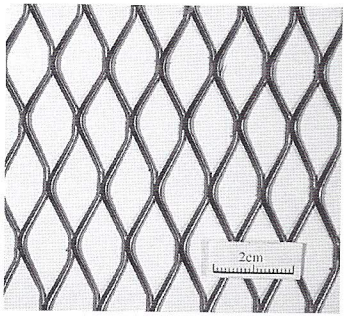
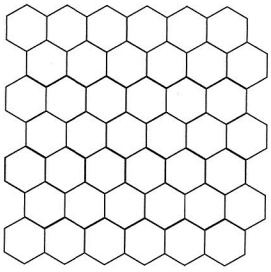


fig. 3 | Examples of steel meshes used as reinforcement for ferrocement and thin-cement composites

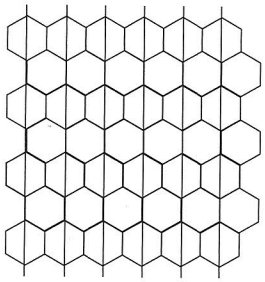






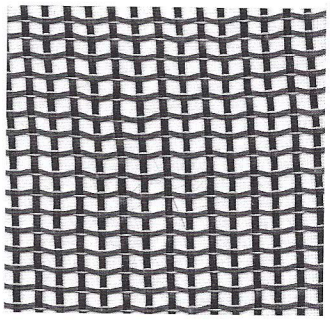


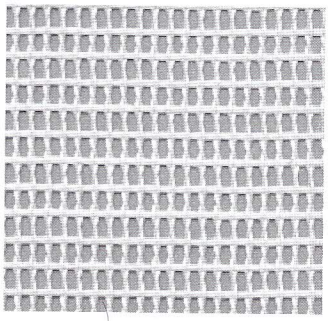
Hexagonal wire mesh

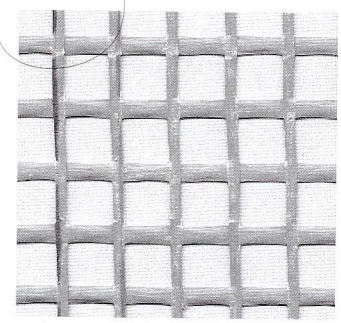


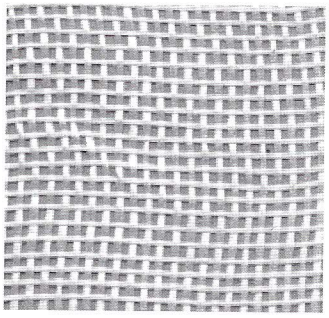
Improved hexagonal mesh

fig. 4 | Examples of high-performance 2-D polymeric meshes, textiles, or fabrics









to 20 times that value. The tensile-yield strength of the steel wires used by Lambot may not have been much more than about 240 MPa. Today, steel wires with a tensile strength of 15 times that or higher are available. Moreover, reinforcement materials include not only steel but also other high-performance polymer fibers such as glass, carbon, aramid, Kevlar, Spectra fibers, and others.

Since the initial idea of ferrocement quickly led to a thicker form that became conventional reinforced concrete, the use of ferrocement and related research fell relatively dormant shortly after the mid-1850s. Only about a century later, in the 1940s and '50s did the Italian engineer and architect Pier Luigi Nervi recognize the possible advantages of ferrocement, not only for boat building but for terrestrial applications as well, and he carried out some engineering-based experiments on its mechanical properties. What is considered modern ferrocement, however, was reborn in the 1960s, driven by interest from many amateur boat builders and small fisheries. Serious research on the subject followed in the mid-1970s, with the establishment of the ACI Committee on Ferrocement, as well as the International Ferrocement Information Center at the Asian Institute of Technology in Bangkok, Thailand.

Reviewing what was available in the 1960s and '70s in terms of reinforcement and the relative ability to produce a ferrocement-type product, one would find steel-wire meshes of different forms, such as woven- or welded-square mesh, hexagonal (chicken-wire mesh), and diamond shape (expanded metal used in stucco applications). | fig. 3 Other potential reinforcements were also available, including meshes made of natural fibers such as jute or sisal; and polymer meshes, textiles, or fabrics of various forms such as nylon, polypropylene, and polyester. These were considered of low performance because of their low elastic modulus in comparison to that of steel and concrete and their relatively low tensile strength in comparison to advanced synthetic fibers such as glass and carbon. The elastic modulus represents the stress needed to induce a unit deformation in a material. Thus, everything else being equal, the stress needed to extend a rubber band by 1 inch (2.5 centimeters), for example, is much smaller than the stress needed to extend a steel wire of the same length and cross section by 1 inch. From this example, it can be intuitively concluded that the elastic modulus of rubber is much smaller than that of steel. The yield strength of most widely available steel meshes ranges from about 240 MPa to about 600 MPa. While the elastic modulus of steel does not depend on its strength—that is, it remains almost constant at about 200 GPa—steel meshes may show an equivalent elastic modulus of lower value than that of steel because of the weaving or other manufacturing process. Thus, a woven-square steel-wire mesh could be considered to act as if its equivalent elastic modulus is half to two-thirds that of the steel from which it is made. A chicken-wire or aviary mesh would have an even lower equivalent modulus.

For all reinforced concrete and cement composites, there is a simple rule based on mechanics that can be followed to design a composite with higher 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. This requirement, related to the moduli ratio, may explain why low-end polymer meshes made of polypropylene, for instance, were not widely or successfully used, although polypropylene fibers had strengths comparable to that of conventional steel-wire meshes; however, based on the above simple rule, it can be concluded that polypropylene fibers may be compatible with very lightweight cementitious matrices, which show both low compressive strength and low elastic modulus.

Going back to the steel-wire meshes on the market in the 1970s, high-yield strengths were not available and could not be obtained beyond a certain strength. Indeed, in the production of woven-wire meshes, the use of high-strength wires leads to very "springy" wires that do not deform very much during alternate bending, making the weaving process difficult to control. In the case of welded meshes, the welds at the joints weakened the wires and thus again led to reduced strength. Thus in the 1970s, most available wire meshes on

the market showed tensile strengths less than 700 MPa, while tensile strengths close to 1,000 MPa could be obtained only exceptionally, such as in research experiments.

The volume fraction of steel-mesh reinforcement in ferrocement generally ranges from about 2 to 8 percent; the 8 percent threshold is exceeded only with difficulty.[2–3] Typically such a value may be obtained by packing together as many layers of mesh as possible within the composite; both the tensile and bending resistance of the composite increase with respect to the volume fraction of reinforcement. In particular, analysis of the section suggests that the bending resistance increases almost proportionately to the volume fraction of reinforcement (or the number of layers of mesh) primarily because the steel mesh has extensive yielding behavior. Under these conditions, modulus rupture values—that is, the equivalent elastic bending resistance in the cracked state—could reach about 50 MPa with 7 percent reinforcement content.[2] Until the 1990s, this was considered the mechanical limit of the material.

Advanced FRP Meshes, Textiles, or Fabrics—2-D Systems

During the mid-1980s and early '90s, polymer meshes, textiles, or fabrics made with high-performance fibers such as carbon, glass, Kevlar, or Spectra were tested for ferrocement applications. | **fig. 4** Since they exhibited high tensile strength in comparison to the conventional low yield strength of steel-wire meshes on the market, they were immediately viewed as a way to increase the performance of ferrocement composites.

Both analytical and experimental studies, however, show that adding FRP meshes, textiles, or fabrics in excess to the two extreme layers, with the goal of improving bending resistance, does not lead to a sufficient improvement to justify the additional cost of the intermediate layers. This is because, unlike steel meshes, FRP meshes using high-performance fibers such as carbon, Kevlar, or glass show a linear-elastic stress-strain response in tension up to failure, with no yielding. Thus the addition of intermediate layers of mesh for bending may lead to successive failures of the mesh layers at ultimate resistance, instead of allowing for the simultaneous combination of forces from different layers of mesh, as is the case with yielding steel-wire mesh.

Using only two extreme layers of reinforcement, however, FRP meshes demonstrated that their higher tensile strength could be an asset, and this led to composite moduli of rupture (equivalent elastic-bending resistance) of close to 25 MPa with less than 1.5 percent total volume fraction of reinforcing mesh. Furthermore, to remedy the absence of intermediate layers of FRP meshes and to improve shear resistance, discontinuous fibers were added to the mortar matrix, leading to hybrid combinations of reinforcement. The fibers were primarily needed to improve shear resistance, both vertical and interlaminar, and to help utilize the tensile strength of the mesh as much as possible by increasing the strain capacity of the mortar matrix in compression. Such an increase would allow for an increase in the compressive force within the compression zone, permitting the tensile force to maintain equilibrium and thus increasing the bending resistance. Moduli of rupture close to 40 MPa were thus obtained using only 2.26 percent total volume fraction of reinforcement, with two extreme layers of carbon mesh (1.26 percent reinforcement) and 1 percent discontinuous polyvinyl alcohol (PVA) microfibers.[11–12] Thus, comparing the maximum modulus of rupture of ferrocement with that of conventional steel meshes (50 MPa with 7 percent reinforcement) to that of hybrid ferrocement containing high-performance carbon meshes and fibers (40 MPa with 2.26 percent reinforcement), one can conclude that the hybrid combination offers a better overall efficiency of 250 percent in terms of volume of reinforcement used. Even with this improved efficiency, equivalent elastic-bending strengths (or moduli of rupture) in excess of 50 MPa could not be easily achieved with high-performance polymer reinforcements. Cost-related issues are not discussed here but should also be taken into consideration for real applications. In summary, the most efficient model for thin-cement composites reinforced with 2-D polymer meshes would have only two extreme layers of mesh reinforcement and a matrix reinforced with microfibers. | **figs. 5–6**

Advanced Steel Reinforcements for Thin-Cement Products—2-D Systems

Producing steel-wire mesh with high-strength wires, whether woven or welded, was not practical from the viewpoint of manufacturing, as explained earlier; however, pseudomeshes were developed for other purposes. Belgian manufacturer Bekaert S.A. marketed a meshlike product called *Fleximat* in the early 1990s, made in one direction from high-strength fine-steel strands, and in the other direction from low-end polymer yarns in a leno-weave process. Fleximat was used as reinforcement for conveyor belts used in quarries, mines, and similar applications. Fleximat fabric offered very high tensile strength in only one direction; one would have to place two layers of Fleximat, normal to each other, to obtain equally high strengths in two directions with a layout similar to a square-steel mesh. | fig. 7

In this decade, a high-strength steel-based product similar in purpose to the Fleximat mesh was introduced to the U.S. market with the trade name HardWire. It was initially marketed as a substitute to adhesively bonded FRP sheets, or plates such as carbon or Kevlar, used to repair reinforced-concrete members, where bonding is achieved through an epoxy resin. Hardwire is similar to a 2-D mesh. In the primary direction, it is composed of parallel steel strands spaced at approximately 6.25 millimeters (0.2 inches), although different spacing is also available; the strands are adhesively bonded by a square mesh made from glass fibers. Thus the product looks like a wire mesh. | fig. 8 The glass-fiber mesh, however, is neither strong nor significant, being used only as support to the steel strands. The strands are made each from five steel wires with an approximate diameter of 0.3 millimeters (0.01 inches) each. The wires have very high tensile strength of the order of 3,150 MPa and are typically used to fabricate tire cord for high-performance tires. Two layers of HardWire placed normal to each other can be used to simulate a 2-D square mesh similar to conventional steel-wire meshes used in ferrocement.

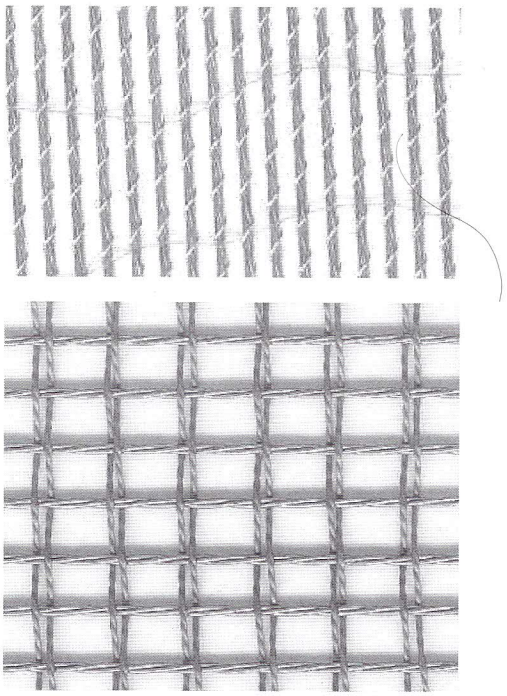
Tests carried out by the author on 12.5-millimeter (0.5-inch) thick ferrocement plates, reinforced only with two extreme layers of HardWire mesh and fibers, led to moduli of rupture in bending close to 105 MPa, with only 1.76 percent HardWire reinforcement (two layers) and 1 percent PVA fiber.[2, 11, and 13] If we adjust the reinforcement to include equal bending strength in two directions, it would lead to a total volume fraction of reinforcement of 4.52 percent, including the fibers. Similar tests using Fleximat fabric led to a modulus of rupture of 127 MPa, with an equivalent total volume of reinforcement of 3.7 percent. Adjusted to two directions, the total volume would become 6.4 percent. Thus, comparing the maximum modulus of rupture of ferrocement with conventional steel meshes (50 MPa with 7 percent reinforcement) with the above results (105 MPa at 4.52 percent reinforcement), one can almost achieve a double in modulus of rupture at about two-thirds the total volume of reinforcement. This is almost three times more efficiency. More importantly, this shows that a modulus of rupture of 125 MPa in thin cementitious products can be achieved, and it currently represents a record high-performance limit to exceed in the future.

Tri-Dimensional (3-D) Reinforcement—Cost Issues

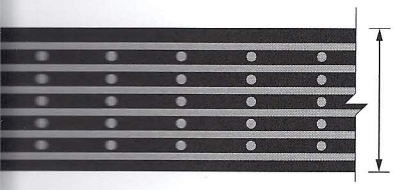
It is important to keep common cost issues encountered in the manufacturing of ferrocement and thin-concrete products in perspective. There are three main sources of cost for a typical product: cost of the cementitious matrix, cost of the reinforcement, and cost of labor. Typically the cost of the cementitious matrix is less than 10 percent of the total cost, even when several additives enhance the matrix. Most likely, the matrix cost is less than 5 percent. The combined cost of reinforcement and labor thus amounts to more than 90 percent of total cost.[2 and 13] In developing countries the cost of reinforcement and labor are almost equally divided. Placing several layers of mesh reinforcement and possibly spacing them according to design is labor intensive and thus costly. While some industrial processes were developed to handle the use of synthetic-mesh reinforcements, no such process exists to handle steel-wire meshes.

It becomes clear from the above that improvements in the efficiency of the reinforcement—for instance, by

fig. 7 | Fleximat fabric with unidirectional strength



ypical section of thin-cement composite with
layers of FRP mesh



ypical section of efficient, fiber-reinforced
hybrid composite with only two extreme layers of
d fibers to replace intermediate layers of mesh

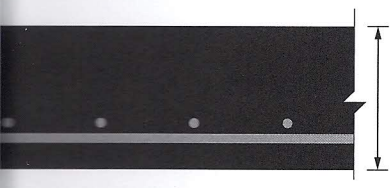
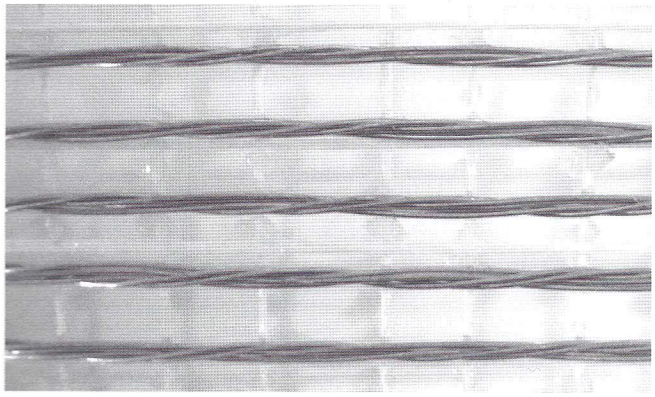


fig. 8 | HardWire reinforcement with unidirectional strength



reducing the number of mesh layers needed in the design—and improvements in the production process to reduce labor cost will have the most significant effect on the final cost of the product.

The first improvement, reducing the number of layers of mesh, can be resolved by using only two layers of high-performance steel-wire meshes or advanced FRP meshes and adding microfibers to the matrix, as described above. The second improvement, reducing labor cost, can be resolved by the use of 3-D instead of 2-D reinforcements. The idea behind the design of a 3-D reinforcement is to develop a single-armature system that, when placed in a mold and infiltrated by a cement matrix, will lead to the desired product. Three-dimensional reinforcement systems can also be designed and tailored to satisfy particular performance requirements.

3-D Reinforcement Systems Using Steel

Many users of ferrocement, wishing to simplify the construction process, have thought about 3-D reinforcement systems for ferrocement applications. This became particularly pressing in the late 1980s, as asbestos fibers were banned from use in cement boards and sheets due to health concerns. Tri-dimensional reinforcement systems in the form of 3-D meshes (Watson's mesh) were tried, as well as 3-D meshes made by simply connecting two parallel steel meshes (using welded links or coil spacers). | **fig. 9** These methods turned out to be costly and their use was limited. Watson's mesh was discontinued in the 1980s.

Another idea suitable for both steel- and fiber-reinforced polymer meshes was to use an armature system made out of a fiber mat sandwiched between two layers of reinforcing mesh. | **fig. 10** The sandwich is placed in a mold and infiltrated by a fine cement-based matrix. Besides the advantage of ease of construction, the system produces a composite with reinforcement spaced exactly as needed (with minimum labor), and the fiber mat improves the shear and bending resistance of the composite.

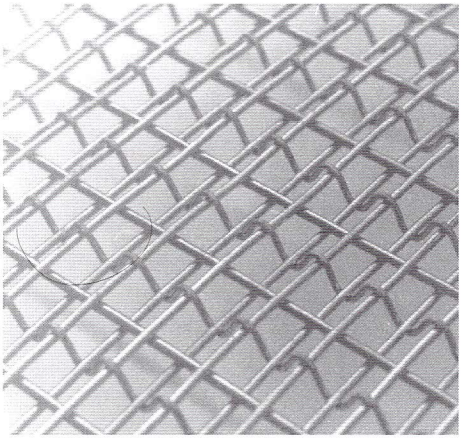
3-D Reinforcement Systems Using Polymer Fibers

It is only in the late 1990s and early 2000s that 3-D meshes—also described as 3-D fabrics or textiles—derived from the technology of textiles and fabrics became available for research studies in ferrocement-type products. In particular, the Institute of Textile Technology (ITA) at RWTH, Aachen University in collaboration with the Technical University of Dresden Germany, pioneered a number of 3-D textiles for applications in cement and concrete composites, which they have termed Textile-Reinforced Concrete (TRC).[9 and 12] The 3-D fabrics have the advantage of placing the reinforcement exactly where it is needed and tailoring its properties to particular applications. They also offer tremendous advantages in simplifying construction and saving on labor cost. Such 3-D meshes can be readily produced in thicknesses ranging from approximately 10 to 50 millimeters (0.4 to 2 inches), which is perfectly suitable for ferrocement and thin-cement composite applications. Moreover, textile technology offers the advantage of placing as much reinforcement as needed by design (generally less than 4 percent by volume) exactly where it is needed, and tailoring the fabric properties and shell volume for particular applications. | **figs. 11–12** The 3-D textiles allow for the production of composites with holes or cavities, thus leading to a reduction in weight for the final product. Analytical modeling suggests that bending resistance close to 30 MPa can be achieved with these 3-D systems using current FRP materials.

Thus, these 3-D systems, while definitely reducing production labor, have not demonstrated high performance such as high bending resistance, as expected. This is because, as a group, bundles of fibers, strands, or yarns made from high-performance polymer fibers do not show the same tensile strength as the individual fibers from which they are made. Typically a glass fiber may have a tensile strength of 3,500 MPa. Textiles, fabrics, or meshes use strands containing a large number of fibers, typically ranging from 200 to 12,000 fibers. A glass fabric made with strands containing approximately 200 fibers per strand and used in cement composite may show an equivalent tensile strength of only 800 MPa. This

fig. 9 | Examples of 3-D mesh systems with steel reinforcement: **a:** Watson's mesh (discontinued production), **b:** two square steel meshes joined by welded link, **c:** two square steel meshes joined by coiled links

a.



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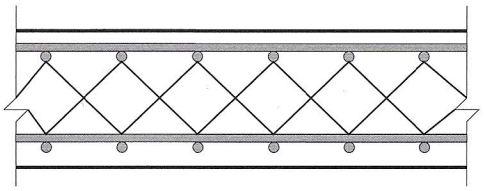

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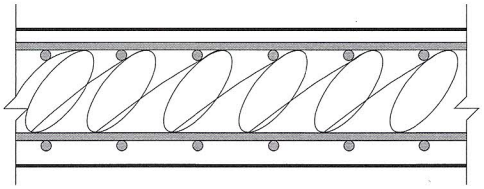
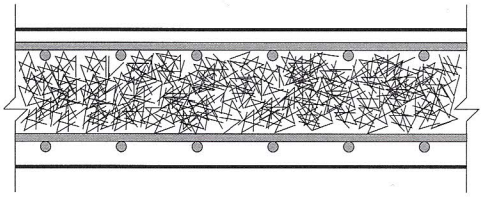


fig. 10 | Typical sandwich-type reinforcing system using a fiber mat core between two extreme layers of mesh: **a:** concept, **b:** example with steel mesh and PVA fiber mat

a.



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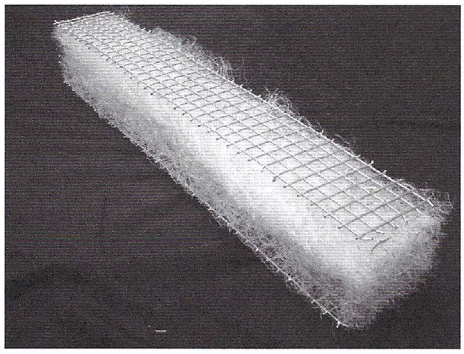
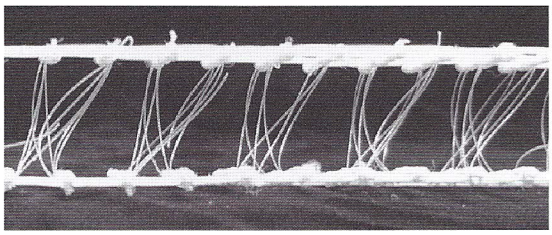


fig. 11 | Examples of 3-D mesh systems with FRP textile reinforcements fabricated at the ITA in Aachen, Germany, **a:** 3-D spacer textile, **b:** 3-D spacer stiff textile, both approximately 15 millimeters (0.6 inches) thick

a.



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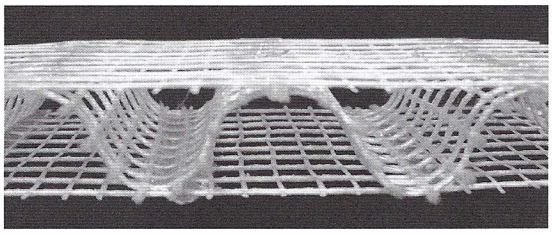


fig. 12 | a: 3-D ribbed textile sketch and sample produced by ITA in Aachen, Germany, for preliminary testing, **b:** The resulting thin-cement composite can be either solid or with cavities that can be filled with Styrofoam to reduce its weight (the panel can be made to float)

a.

b.

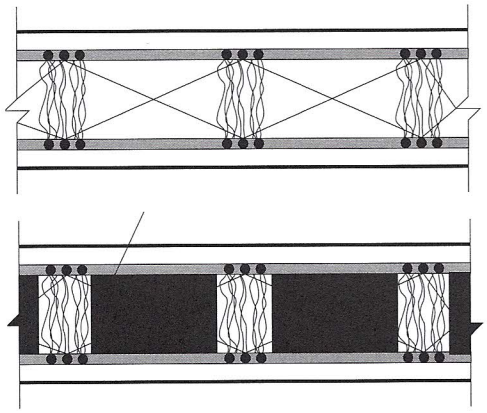
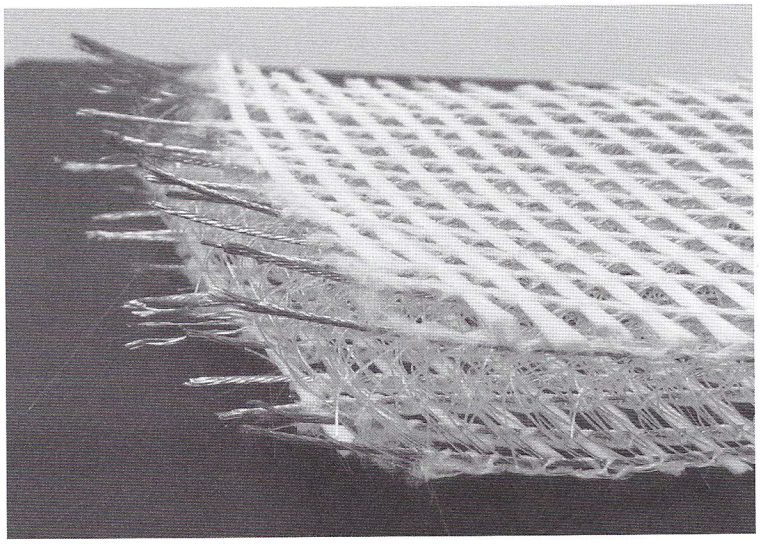


fig. 13 | New 3-D textile incorporating steel strands produced by ITA in Aachen, Germany (note the steel strands showing at the left end of the textile)



is because, under tensile loading, the fibers are not loaded simultaneously at the same level, and progressive fiber fracture occurs. If the strand is made with fibers embedded in a polymer resin, it is likely that the equivalent strength would increase to 1,200 MPa. On the other hand, if the fibers are perfectly aligned and embedded in a resin—leading to a rigid and perfectly straight strand structure—a much higher tensile strength can be achieved similar to a conventional FRP bar. One can get roughly 60 to 70 percent of the strength of the fiber; however, in such a case the 3-D fabric will be extremely costly and very difficult to manufacture.

This prompted the investigators at the D\ITA in Aachen and at the University of Michigan to look at introducing high-strength steel cord into the textile to replace some of the glass yarns, in order to take advantage of the strength and toughness of steel, while preserving the inherent constructional advantages offered by the 3-D textile. Recently the research team at ITA was able to produce such a 3-D textile, a world first in the integration of steel and FRP reinforcements. The textile uses glass fibers for the fill (transverse direction), polypropylene fibers for the vertical spacing (acting as spacers and shear reinforcement), and high-strength steel strands inserted in the weft (longitudinal direction). The vertical polypropylene fibers can be made to protrude beyond the plane of the main longitudinal reinforcing wires, thus allowing for the desired net cover of cement matrix desired over the main reinforcement. Such a textile offers the best possible performance by taking advantage of the strength and ductility of steel while using conventional polymer fibers and permitting a 3-D textile machine to fabricate the textile. The contribution of the polymer fibers remains effective and provides the support armature for the steel reinforcement and the shell of the armature. A typical 3-D FRP steel-hybrid textile is shown in figure 13. | fig. 13

Looking Ahead: Passive and Active Reinforcements

It is evident that cement composites with higher performance—qualified here as high strength and high ductility—necessitate the use of high-performance cement matrices on the one hand and high-performance reinforcement characterized by both a high tensile strength and a high-tensile elastic modulus on the other hand. Such criteria favor high-strength steel products and high-performance polymer fibers such as carbon, Kevlar, Spectra, and the like. Since manufacturing and labor cost consume a large portion of the cost of these composites, the use of 3-D reinforcing systems may play a key role in future expansion and developments.[13]

In comparing high-performance FRP meshes, textiles, or fabrics with steel meshes, it is likely that the competition will be very close and that the advantages of one over the other will depend on criteria other than strength or moduli of rupture. For instance, the fact that FRP materials can (at the present time) be made into 3-D textiles that form the armature system and can be simply placed into a mold and infiltrated by a mortar matrix gives FRPs a significant advantage in terms of savings on labor cost. FRPs are also significantly lighter in weight than steel, and thus easier to handle in the field. The bottom line, however, is total cost, and steel remains very competitive not only in terms of performance, such as equivalent bending strength, but also in terms of total cost of the product. Manufactured 3-D steel meshes or hybrid-combination steel and textile 3-D meshes may offer optimized solutions in the future. Clearly the ability to manufacture a particular 3-D textile at reasonable cost will provide a key advantage.

In most of the above discussion, it was assumed that the reinforcement remains relatively passive; that is, the reinforcement is stressed only when the structure is stressed. It is possible, however, to make the reinforcement more active by creating self-stressing thin-cement composites. Self-stressing in cement composites can be obtained by either an expansion of the matrix, a contraction of the reinforcement, or both. Bond and/or anchorage between the two components is assumed to be perfect. The advantages of prestressing are similar to those of conventional prestressed concrete and include a higher resistance to cracking and thus improved corrosion resistance, impermeability, and durability. Smart

reinforcing materials currently available include shape-memory alloys (SMAs) and some special polymer fibers that possess the unique property of being able to be frozen temporarily in a particular state and then, with proper heat or radiation treatment, reverted to their previous equilibrium condition. For instance, an SMA wire mesh is first stretched to a certain strain level and stabilized in that state; then it is used in a cement-based matrix. Once the matrix has hardened, the reinforcement is relaxed from its induced deformation by heat or radiation; in attempting to shrink back to its previous state, it provides, through bond and or anchorage, the needed stress in the matrix. In some tests carried out on thin-cement sheets, an initial prestress of about 7 MPa was achieved.[14] The challenge, of course, is to go much higher.

Concluding Remarks

This paper has presented some of the progress in the reinforcement of ferrocement and thin-cement composites since their inception; one hopes that the results will inspire new researchers to take up the challenge and introduce improvements in the future, raising the limits achieved thus far. We need to exceed a modulus of rupture of about 125 MPa to minimize the cost-performance ratio; to produce optimized 3-D reinforcements at minimal cost; to take advantage of self-stressing reinforcement by inducing internal prestress levels exceeding 7 MPa; and to inform and educate the public and the profession about the advantages and potential applications of these composites. We need to keep dreaming at least slightly beyond the borders of reality.

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The potential list of references would be too long and would still not do justice to all those who contributed ideas and advances in the development of ferrocement, laminated cement composites, and thin-cement composite products. The following endnotes contain a large number of further references within their pages, and should be consulted for further inquiry.

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