FERROCEMENT AND THIN REINFORCED CEMENT COMPOSITES: FOUR DECADES OF PROGRESS

Antoine E. Naaman
University of Michigan, Ann Arbor, USA

Naaman, A.E., "Ferrocement: Four Decades of Progress," Journal of Ferrocement, Vol. 36, No. 1, January 2006, pp. 741-756. Also published in Proceedings of International Symposium on Ferrocement and Thin Cement Products, Thai Concrete Society, Bangkok, Thailand, February 2006.

Abstract
The main purpose of this paper is to set the stage for the state of progress, at the beginning of this 21st century, in ferrocement and generally thin reinforced cement composites which can be considered part of the same family as ferrocement. For practical purposes the discussion is limited to composites with thicknesses less than about 50 mm. These include, in particular, thin composites utilizing high performance fiber reinforced polymeric meshes also identified as textiles or fabrics. Progress since the modern development of ferrocement in related materials and activities is reviewed. It focuces on evolution in the mesh reinforcement, the cementitious matrix, construction methods, tools, analytical methods, guidelines, educational and professional activities and the like. Cost comparison between steel and FRP meshes is provided based on equal bending resistance; it suggests that the race between steel and FRP meshes is close and could favor FRP meshes should they offer the opportunity to reduce the cost of labor significantly such as by utilizing 3D reinforcement systems.

1. Introduction

The history of ferrocement dates back to its first invention by Joseph Louis Lambot in 1849 and has been reported in numerous publications. This paper is an attempt to set the stage at the beginning of the 21 century, by reviewing about four decades of progress.

Significant interest by amateur boat builders in ferrocement and its applications grew in the early 1960's. Increased scientific approach to studying and predicting ferrocement properties started in the late 1060's and was encouraged by a panel of the US National Academy of Sciences in 1973 [32, 33, and 44]. This led to the formation of the American Concrete Institute's Committee on Ferrocement, in 1975, and the establishment, shortly thereafter, in 1976, of the International Ferrocement Information Center (IFIC) in Bangkok, Thailand. Publication of the Journal of Ferrocment was then consolidated at IFIC. A RILEM scientific committee on ferrocement was later formed in 1979. Progress accelerated during the 1980's through fundamental research, publications, symposia, short courses and applications [1, 2, 3, 5, 7, 8, 12, 19, 20, 22, 23, 24, 25, 26, 27, 34, 35, 46, 48, 49, 50, 51, 55, 56, 57, 59, 60, 62, and 63]. The International Ferrocement Society (IFS) was founded in 1991 with the objective to foster development, disseminate knowledge, and encourage practical applications of ferrocement. The most urgent need of this new professional society was to develop a building code for ferrocement. The first Ferrocement Model Code was published in 2001 essentially setting the stage for guided expansion, imagineering and developments [16]

2. Evolution in Reinforcement

2.1 Steel mesh

The reinforcement used in the first research studies on ferrocement properties consisted of hexagonal (aviary or chicken) or square woven steel wire mesh. Yield strength of such meshes varied from about 240 to 450 MPa. Bending tests on ferrocement beams (plates) led to moduli of rupture of up to 20 MPa with hexagonal meshes and up to 40 MPa with square meshes, at the highest practical volume fraction of mesh reinforcement, that is, of the order of 6% to 7%. Analytical evaluation clearly indicated that the bending resistance would improve with increased tensile strength of the reinforcement, and there were attempt in the early 1970's to press for higher strength reinforcement to improve overall performance [32]. However, manufacturer of steel meshes did not follow suite. Exceptionally, special orders of welded square mesh of yield strength as high as 800 to 900 MPa could be obtained for research purposes. Moduli of rupture close to 50 MPa could then be achieved.

With conventional steel meshes, increasing the number of mesh layers led to almost a proportionate increase in bending resistance [8, 32]. This is because steel meshes had low yield strengths and most layers of mesh yielded at nominal bending resistance, allowing essentially maximal contribution of the reinforcement. As a result, in a typical ferrocement plate under bending, practically all layers of mesh yielded at nominal resistance except the top layer which happens to be in the compression zone or near it.

Early during the first decade of the 21st century, a new very high strength steel-based product trade-named Hardwire© was introduced on the market in the US. It was initially marketed as a substitute to adhesively bonded fiber reinforced polymeric (FRP) sheets or plates such as carbon or Kevlar, used for repair of reinforced concrete members, where bonding is achieved through an epoxy resin. Hardwire© is similar to a 2D mesh. In the primary direction it comprises parallel steel strands spaced at approximately 6.25 mm (different spacing is also available); the strands are held in place (adhesively bonded) by a square mesh made from glass fibers. Thus the product looks like a wire mesh (Fig. 1a). However the glass fiber mesh is not strong or significant and is used only as support to the steel strands. The strands are made each from five steel wires with approximate diameter of 0.3 mm each. The wires have very high tensile strength of the order of 3150 MPa and are typically produced to fabricate tire cord for high performance tires. To simulate a two dimensional mesh similar to conventional steel wire meshes used in ferrocement, two layers of Hardwire© placed normal to each other can be used. Tests carried out by the author on 12.5 mm thick ferrocement plates reinforced with only two extreme layers of Hardwire© mesh and fibers led to moduli of rupture in bending exceeding 100 MPa (Fig. 1b).

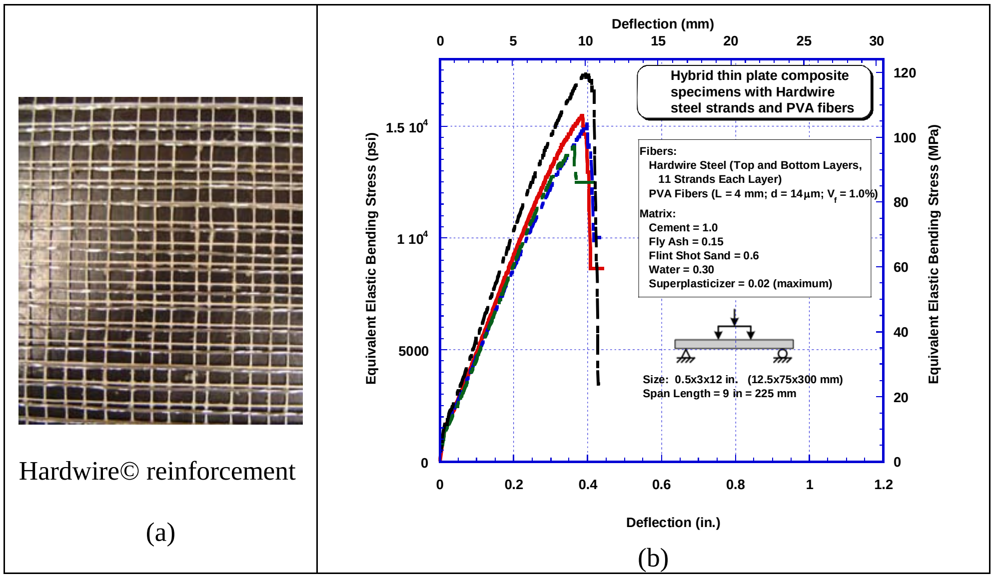


Figure 1 – Equivalent elastic bending stress versus deflection response of ferrocement plates reinforced with Hardwire© reinforcement

2.2 Fiber reinforced polymeric meshes or textiles

Low performance polymeric meshes and geotextiles made out of polypropylene, nylon, polyester fibers and the like were used with mortar matrices during the early 1980's [**20, 35**]. However, due to their low modulus of elasticity compared to that of concrete, they did not lead to performance comparable to steel meshes, in spite of comparable tensile strength. Moreover, in comparison to steel meshes, the ferrocement composites with low modulus polymeric meshes showed larger deflections or deformations, larger crack width and larger crack spacing, upon loading, and larger non-recoverable (or permanent) deformations upon unloading. A typical example is shown if Fig. 2 [40] for a thin plate 12.5 mm thick, where the non-recoverable deflection at maximum load varies from about 40% to about 90% of the plate thickness.

Analytical predictions using non-linear analysis suggest that higher values of bending strength can be achieved using meshes made with high performance fibers such as carbon or Kevlar. Figure 3 indicates that moduli of rupture close to 80 MPa can be obtained with only 4.5% of carbon or Kevlar reinforcement.

It is only during the late 1980's and early 1990's that polymeric meshes (or fabrics or textiles) made with high performance fibers such as carbon, glass, or Kevlar, were tested for ferrocement applications [36, 37, 38, 39, 40, 54, and 61]. A typical tensile stress strain response of ferrocement plates reinforced with carbon meshes (C3000 grid from TechFab) is shown in Fig. 4. A direct tensile strength in excess of 15 MPa is observed suggesting that an equivalent modulus of rupture in excess of 40 MPa (that is about 2.5 times the tensile strength) can be achieved with a volume fraction **of mesh of xx%.** In comparison, the tensile strength of ferrocement reinforced with Hardwire© reached about 40 MPa suggesting a modulus of rupture in excess of 100 MPa as confirmed in Fig. 1.

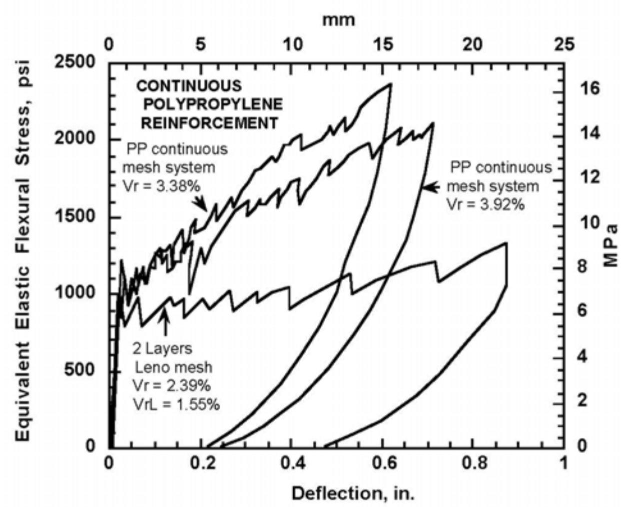


Figure 2 – Typical response of ferrocement plates reinforced with low modulus polymeric meshes

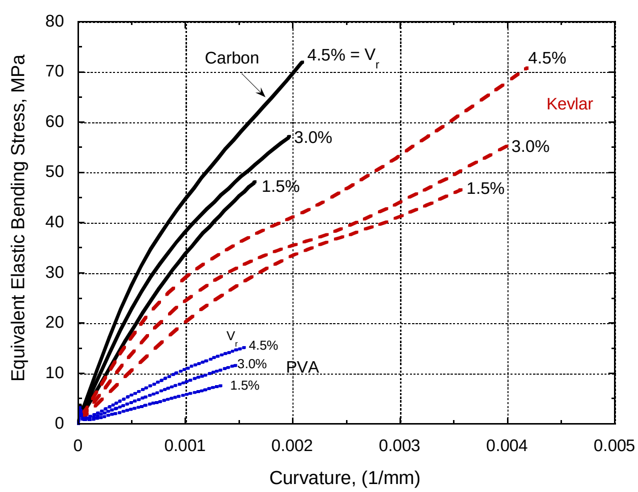


Figure 3 – Analytically predicted bending response of ferrocement plates reinforced with FRP meshes [53]

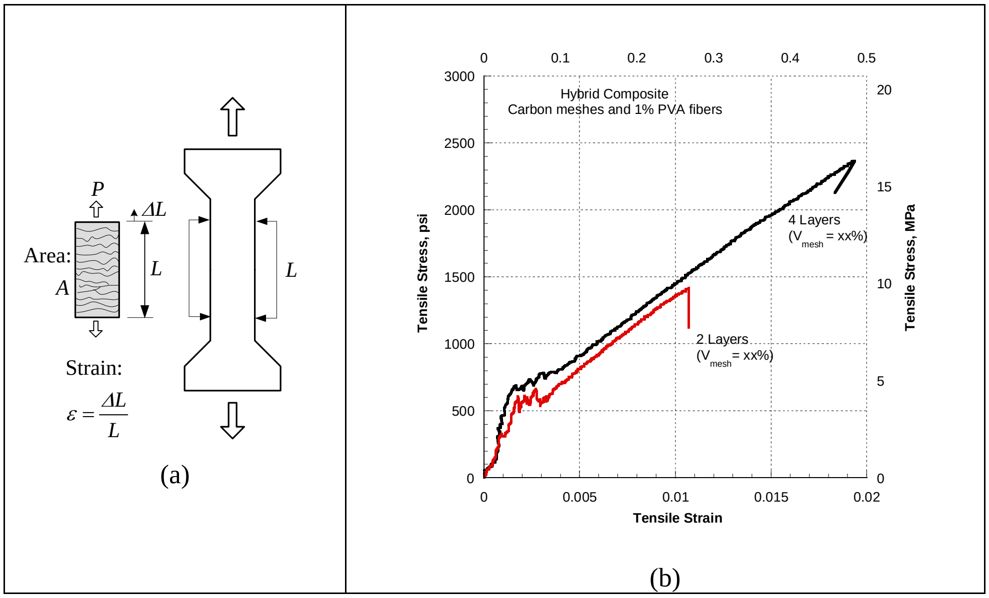


Figure 4 – Tensile stress-strain response of thin hybrid cement composites reinforced with carbon meshes and PVA fibers

Fiber reinforced polymeric meshes demonstrated that the higher tensile strength can be indeed an asset and led to composite moduli of rupture close to 25 MPa with less than 1.5% total volume fraction of reinforcing mesh. However, both analytical and experimental studies showed that adding FRP meshes (or textiles or fabrics), in excess to the two extreme layers, with the goal to improve performance did not lead to a sufficient improvement in bending resistance to justify the additional cost (Fig. 3). This is because, unlike steel meshes, fiber reinforced polymeric 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, instead of allowing for the simultaneous combination of forces from different layers of mesh. This is illustrated in Fig. 5 where the strain compatibility (Fig. 5a) shows different load contribution of each layer of mesh when the extreme layer is nearing failure, and their effect (Fig. 5b) on the failure mode and the corresponding load-deflection response where progressive failure of each layer occurs.

To remedy for the poor performance of the intermediate layers of high strength high modulus FRP meshes, discontinuous fibers were added to the mortar matrix leading to hybrid combinations of reinforcement [37 to 42]. The fibers were primarily needed to improve shear resistance, both vertical and interlaminar, and help utilize the tensile strength of the mesh as much as possible by increasing the strain capacity of the mortar matrix in compression. This effect of increasing compression strain capacity is illustrated in Fig. 6; the strain diagram at nominal resistance is plotted in Fig. 6a for the reference matrix, and in Fig. 6b for a hypothetical fiber reinforced matrix where the addition of fibers leads to an increase of 100% in the compression strain capacity. Such an increase would allow increasing the compressive force in the compression zone, thus the tensile force to maintain equilibrium, and thus the bending resistance.

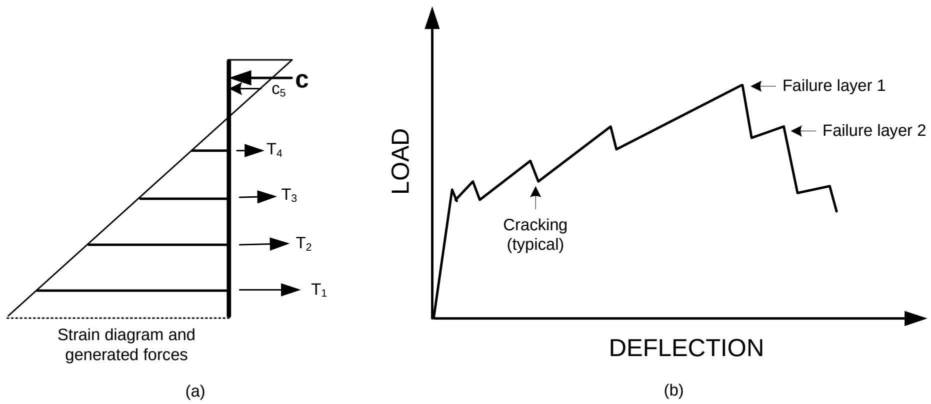


Figure 5 – Typical strain compatibility diagram for ferrocement plates reinforced with high performance FRP meshes and effect on load deflection response.

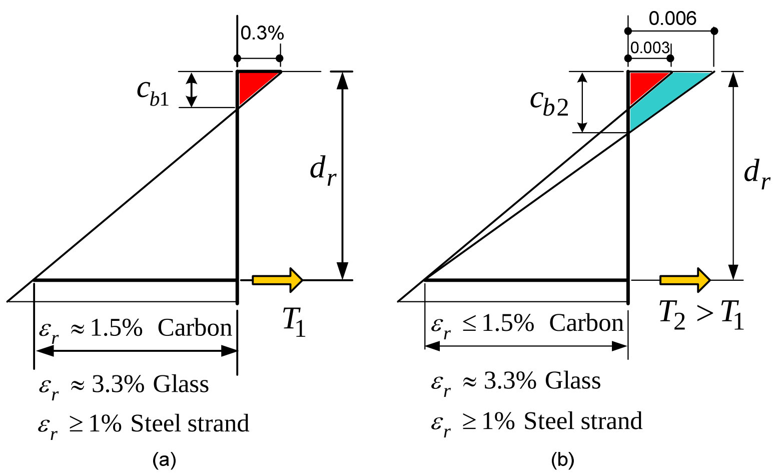


Figure 6 – (a) Typical strain diagram for balanced conditions using a plain mortar matrix. (b) Typical strain diagram illustrating the effect of doubling the strain capacity in compression by addition of fibers

Fibers also serve other functions such as improving first cracking strength, ductility, energy absorption and in many cases contribute to bending strength as well. The combination of continuous mesh reinforcement and discontinuous fibers led to various hybrid composites. To be most effective, the fiber had to be of rather fine diameter (micro fibers of 10 to 50 microns in diameter), short length (4 to 12 mm to allow effective penetration of the armature system), and in content exceeding about 1% by volume. Fibers used successfully included PVA, Spectra and carbon fibers.

The most efficient hybrid combination for bending was achieved with only two extreme layers of mesh and fibers (Fig. 7b). Experimental tests showed that the modulus of rupture can be increased from about 25 MPa to 40 MPa by addition of micro polymeric fibers to the mortar matrix in the amount of 1% by volume. This was achieved with only two layers of carbon mesh, placed one at each extreme fiber of a typical ferrocement plate, leading to a volume fraction of mesh of only 1.31% [39 to 41].

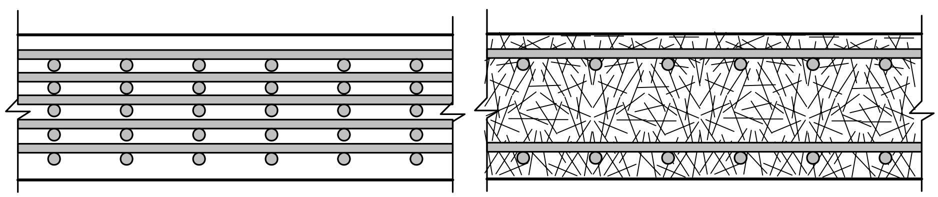

(a) (b)

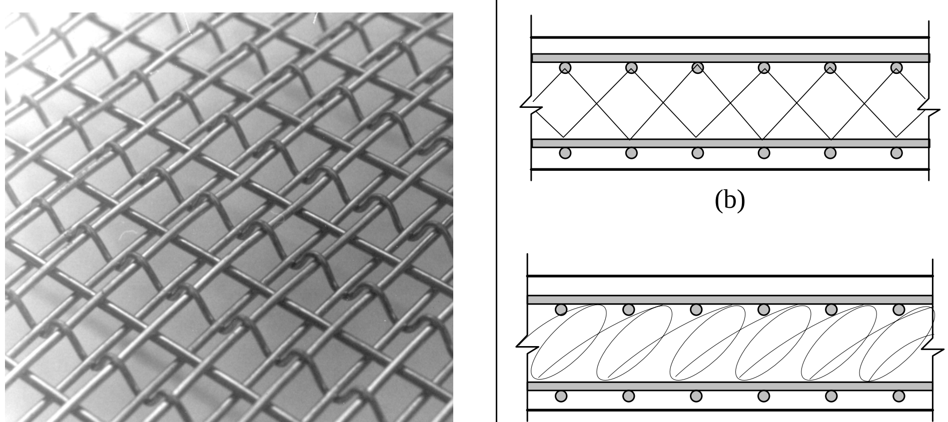
Figure 7 – (a) Typical section of ferrocement with several layers of mesh. (b) Typical section of efficient FRP hybrid composite with only two extreme layers of mesh and fibers

However, in a hybrid composite where the high performance mesh reinforcement (that is, two extreme layers of mesh) occupied less than 1.5% by volume, the addition of 1% micro-fibers represents a significant addition to the total cost. Other solutions had to be found, while keeping as design objective to minimize premature shear failure, both vertical and interlaminar. Tri-dimensional (3D) reinforcement systems (or meshes, textiles, or fabrics) were sought.

2.3 Tri-dimensional (3D) reinforcement

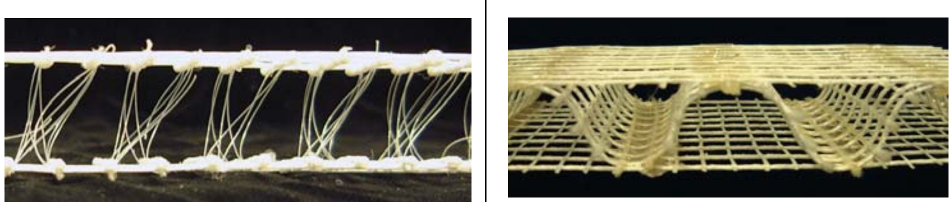
3D reinforcement systems for ferrocement applications have been thought off by many users of ferrocement wishing to simplify the construction process. This became particularly pressing in the 1980's since asbestos fibers were being banned from use in cement boards and sheets due to health reasons. Tri-dimensional reinforcement systems in the form of "fiber-mat" [35], fiber mat taken in sandwich between continuous meshes, special 3D meshes (Watson mesh, [12]), and 3D meshes made simply by connecting two parallel steel meshes together [welded links [64] or coil spacers] were tried (Fig. 8). Besides the fact that 3D reinforcement systems could be designed and tailored to satisfy particular performance requirements, they offer the advantage of significant saving in labor cost since they provide a single reinforcing armature system to handle. That is, they can be pre-placed in a mold and infiltrated by a cement matrix.

It is only in the late 1990's and early 2000 that 3D meshes derived from the technology of textiles and fabrics became available for research studies in ferrocement type products. In particular, the Institute of Textiles in Aachen (ITA), Germany, in collaboration with the Technical University in Dresden, Germany, is pioneering a number of 3D textiles for applications in cement and concrete composites [**21, 29**]. These have the advantage of placing the reinforcement exactly where it is needed and tailoring its properties for particular applications. They also offer a tremendous advantage in simplifying construction and saving on labor cost. Such 3D meshes can be readily produced in thicknesses from about 10 to 50 mm, a range perfectly suitable for ferrocement applications. Examples are shown in Figs. 9 and 10. Analytical modeling suggests that bending resistance close to 50 MPa can be achieved with 3D systems using current FRP materials.



(a) (b) (c)

Figure 8 – Examples of three-dimensional (3D) mesh systems with steel reinforcement: a) Watson mesh [12]; b) Two square steel meshes joined by welded links [61]; c) Two square steel meshes joined by coiled links



(a) (b)

Figure 9 – Examples of three-dimensional (3D) mesh systems with FRP (textile) reinforcements fabricated at the ITA in Aachen, Germany: a) 3D spacer-sandwich textile; b) 3D spacer stiff textile

Looking ahead in comparing high performance FRP meshes with steel meshes, it is likely that the race will be very close and that the advantage of one over the other will depend on criteria other than strength or moduli of rupture. For instance the fact that, at time of this writing, FRP materials can be made into 3D 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. However, manufactured 3D steel meshes may become available in the future.

(a) (b)

Figure 10 – Examples of three-dimensional (3D) mesh systems with FRP reinforcements fabricated at the ITA in Aachen, Germany: a) 3D ribbed textile; b) 3D joist-type textile

3. Evolution in Matrix

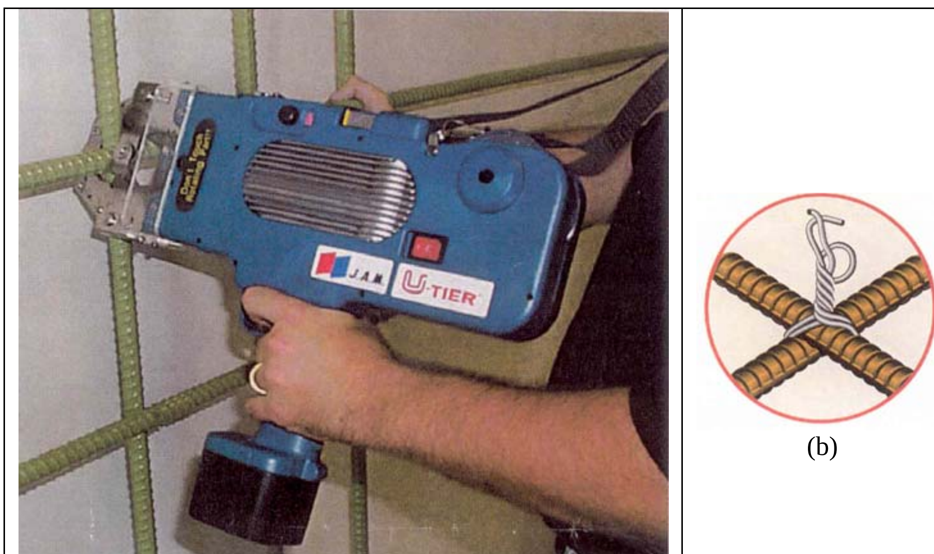
While the evolution of reinforcement has been impressive over the past four decades, the evolution of the matrix has been as impressive, all but less visibly spectacular. Typically the mortar matrix for ferrocement is made of cement, water, and sand; various proportions have been used depending on application, but a proportion containing 1 cement, 0.5 water, and 2 to 3 sand was often a starting trial mixture.

The cement matrix has however evolved enormously. Today the cement itself may be blended, that is, containing supplementary cementitious materials, such as flash ash, ground furnace slag etc.. Mineral components such as silica fume and fly ash are now commonly used either as additives to or as replacement of cement. They help provide a denser composite, reduce porosity, improve fresh properties, improve strength, corrosion resistance, durability, etc. Chemical admixtures, such as water reducing agents, superplasticizers, and viscosity agents, help control and improve a host of other properties in the fresh state to help in the fabrication and manufacturing phase. Today, self consolidating and self compacting cementitious mixtures allow us to rethink construction procedures for ferrocement. Such mixtures, for instance, allow us to use closed molds to produce thin products, which otherwise would have been troweled by hand.

In spite of all these technical advances, the cost of the matrix in ferrocement and thin reinforced cement products remains less than 10% of their total cost (matrix, reinforcement, and labor). Therefore, there is advantage in utilizing the best possible matrix for the conditions of use of the final structure.

4. Evolution in Equipment

Steel wire meshes of various types (woven square, welded square, aviary, or expanded metal mesh) remain available on the market; equipment to produce them has significantly evolved since the early 1970's. For steel wire mesh, there seems to be a bigger shift in production of welded meshes with a wide range of mesh opening and wire diameter. For FRP meshes (or textiles or fabrics), the development of textile machines to produce 3D products at competitive cost seems to represent, at time of this writing, the biggest game in town. Textile machines can be programmed to produce optimized reinforcing systems similar to the examples shown in Figs. 9 and 10.



(a) (b)

Figure 11 – U-Tier® automatic rebar tying machine and typical tie

Very few modern tools were developed to help in the fabrication of ferrocement with steel meshes. The biggest need is for a "tying" tool that would tie the various layers of steel meshes together using a steel wire or other connector. Such a tool exists for reinforcing bars, but is too bulky to use for wire meshes with small opening. It was nominated in 2003 for the Nova 2003 award for construction innovation (Fig. 11). It is likely that, with the proper engineering and investment, such a tool could be modified in the near future to apply to ferrocement construction.

5. Evolution in Construction Methods

Several methods of construction were identified during the early applications of ferrocement and were described first in the ACI Guide for the Design, Construction and Repair of Ferrocement [2]: 1) the skeletal armature method; 2) the closed mold method; 3) the integral mold method; and 4) the open mold method. These were mostly suitable for the construction of a single structure. Martin Iorns of California, introduced a variance of the closed mold method described as the lay-up technique for mortar application which proved to be cost-effective in terms of labor [22 to 26]. He went on building economical and competitive ferrocement structures worldwide. Additional manufacturing methods described in [40] are suitable for large scale industrial production of cement sheets or small ferrocement U-shaped or shell-shaped elements. These methods include pultrusion and are mostly used for cement sheets reinforced with polymeric fibers and/or FRP meshes [68]. The author is not aware of any other new method of construction applied to ferrocement.

6. Evolution in Education

Education on ferrocement was one of the main objectives for establishing the International Ferrocement Information Center in Bangkok, Thailand, in 1976. The center offered seminars and short courses on design and how-to-do construction of typical products, organized international symposia, and served as a warehouse for information on ferrocement. The center also immediately consolidated the Journal of Ferrocement into a periodical journal with a review board to help disseminate research information and practical results. Thereafter, several technical reports, research thesis, and papers on ferrocement were written [5, 6, 7, 8, 47, 48, and 49]. State-of-the-Art reports by ACI and Rile committees were developed as early as 1982 [3]. The first guide on Ferrocement Design, Construction and Repair was published by ACI in 1988 and became a widely referred and used publication [2]. Thereafter, numerous monographs or special publications related to ferrocement and thin cement composites were published [9, 10, 11, 13, and 14].

Meanwhile, the study of ferrocement as a special laminated composite appeared in some courses on concrete materials at universities throughout the world; some books addressing fiber reinforced concrete alluded to ferrocement as well [19]. A continuing series of conferences and symposia dealing with ferrocement and thin cement products was organized [1, 27, 31, 38, 45, 46, 49, 56, and 65]. The author introduced and first taught a course encompassing ferrocement, laminated cement composites, and fiber reinforced cement composites at the University of Michigan, in 1985. It may have been the first such graduate level course at a university worldwide, and is still continuing today with expanded material. It is further supported by a textbook on the subject published in 2000 [40]. Web sites addressing ferrocement and/or particular applications of, have sprung out. It is believed that increased penetration of education in ferrocement analysis, design, and construction will continue. Interest in thin reinforced concrete products which are dominated by ferrocement is developing worldwide.

7. Evolution in Guidelines and Codes

Ever since the beginning of modern ferrocement, there was a dire need by users and practitioners to find and rely on some guidelines or code dealing particularly with fibrocement. While codes for reinforced concrete were widely available, they were insufficient for ferrocement. Indeed, issues related to net cover to the reinforcement, fire rating, crack width and the like could not apply to ferrocement. Furthermore, using same analysis and design techniques as reinforced concrete, designers were faced with lack of information on the steel mesh properties (yield strength, apparent elastic modulus, directional efficiency, etc.). Many such questions were answered by initial efforts of members of ACI Committee 549 in a couple of early publications [34, 62] and implemented in the first draft of the ACI Guide for the Design, Construction and Repair of Ferrocement [2]. Still the guide was insufficient to represent a code of practice. Immediately after the founding of the International Ferrocement Society (IFS) in 1991, and its review of most urgent needs by the users, the first item on the agenda and priority task was to develop a code for ferrocement. An IFS committee was formed and after several years of work, the first Ferrocement Model Code was published in 2001 [16]. It was the first such document worldwide and is now copied in part and integrated in many local codes. Like any other code, the Ferrocement Model Code will see numerous modifications and improved versions in the future.

8. Evolution in Technical Professional Activities

The ACI Committee 549, initially titled Ferrocement has changed its name to Ferrocement and Thin Cement Products to reflect a broader interest in fiber reinforced cement composites (with continuous, discontinuous and/or hybrid reinforcements) and related applications. During the mid-1990's, the International Ferrocement Society formed a number of technical committees to address various important issues such as housing and terrestrial structures, education, corrosion and durability, tools and equipments, seismic applications, and the like. While progress has been slow, the goals of these committees remain valid and current.

9. Evolution in Analysis and Modeling

The initial introduction and subsequent widespread use of computers has affected the analysis, modeling and design of ferrocement to the same extent as other structural materials such as reinforced and prestressed concrete. Today finite element modeling allows detailed analysis accounting for non-linearities at the material level, as well as geometric nonlinearity at the structural level. Static and dynamic analyses are widely used. It is comforting to say that today's available analytical tools allow for modeling essentially most of what is needed for the current applications of ferrocement.

10. Evolution in Performance and Cost/Performance Ratio

An example of evolution in performance can be given by reviewing the increase in the modulus of rupture (or bending strength) of ferrocement. From about 40 MPa at about 7% total steel mesh content, to about 100 MPa at about 4.5% total reinforcement content. The 100 MPa is obtained using very high strength steel wires or strands (Fig. 1) and a high strength cementitious matrix reinforced with micro-fibers. This improvement represents almost a 400% increase in efficiency. With FRP meshes, a hybrid combination of meshes and fibers has been reported to achieve about 40 MPa at 2.5% total reinforcement content. Analytical models predict that 80 MPa can be achieved at about 4.5% reinforcement content **(**Fig. 3). Similarly to the case for steel, a high strength cementitious matrix reinforced with fibers is assumed. It should be observed that while only the modulus of rupture is mentioned in the above comparisons, all the systems described developed sufficient ductility and good cracking characteristics for structural applications [41 to 43].

Typically, per unit weight, a steel wire mesh costs 6 to 10 times as much as a conventional reinforcing bar for reinforced concrete. Also, for instance, if a carbon mesh is used, the weight ratio between steel and carbon is 4.36. Assuming equal performance, one should be willing to pay 4.36 times more for a carbon mesh than for a steel mesh; this is equivalent to saying that one should be willing to pay for a carbon mesh 26 to 44 times as much as for a conventional reinforcing bar.

Table 1 – Willingness-to-pay price based on equal performance [43]

Mesh Type	Willingness to pay price per kilogram of reinforcement material assuming conventional steel mesh price = $ 4 per kg.
(a)	(b)
Steel (normal strength)	4 $/kg
Steel (high strength)	12 – 13.68
Carbon 1	33.32 - 45.64
Carbon 1 (Machine pultruded)	66.52
Carbon 2	27.48 - 44.48
Kevlar	52.12 - 56.24
Spectra	68.28 - 76.68
3D-Glass	9.12 - 17.92

Note: The reference for conventional steel mesh was MOR = 7 MPa per 1% total volume fraction of mesh reinforcement

Cost/Performance ratio has been recently addressed in a study to compare steel with FRP meshes or textiles in thin cement products [43]. It illustrated that while steel remains very competitive, meshes or textiles made from high performance fibers such as glass and carbon are competitive as well in thin cement applications (Tables 1 and 2).

Table 2 – Prices for 2004 compared to willingness-to-pay prices derived from tests, based on equal performance in bending [43]

Material (1)	Price*, Euro / m^2 (2)	Price*, Euro / kg (3)	Willingness-to-pay price range (4)	Remark (5)
AR-Glass, 2500tex, 500 g/m^2	4.5	9	9 to 18	Competitive
Carbon, 1700tex, 320 g / m^2	10	31.25	27 to 46	Competitive
Aramid, 1288tex, 260 g/m^2	18	69	52 to 56	Not competitive
AR-Glass, 2500tex, 500 g/m2, Epoxy	10	20	9 to 18	Almost competitive
Carbon, 1700tex, 333 / m^2, Epoxy	15.5	46.5	27 to 46	Competitive
Aramid, 1288tex, 260 g/m^2, Epoxy	23.5	90	52 to 56	Not competitive

* From Kruger [Ref. 28].

This is because the basic cost of high performance fibers is not sensitive to their diameter as in the case of steel. Indeed, reducing the diameter of steel rods to sizes used in ferrocement (from 0.5 to 1 mm) increases the cost of steel mesh significantly. To develop Tables 1 and 2, the reference price for conventional steel mesh (square woven or welded with 0.7 to 1 mm in diameter, and 6 to 12.5 mm spacing**)** was taken as $ 4/kilogram.

12. Evolution in Applications

Traditional applications of ferrocement are numerous and encompass marine applications (boats, pontoons, etc…), terrestrial applications (water tanks, silos, housing, etc…), and support applications such as in repair and rehabilitation. The utilization of high performance matrices and high performance steel meshes combined with fibers offers opportunities for new applications such as protective panels against projectiles (bullet proof panels) and blast resistant membranes.

11. Concluding Remarks

While the term ferrocement implies a "ferrous" reinforcement, that is essentially steel, the definition of ferrocement should be seen as comprehensive. Indeed ACI committee on ferrocement recognized this point and suggested that the mesh system in ferrocement can be non-metallic as well. A more modern term for ferrocement could be "laminated cementitious composite" and will tie up with similar terms used in the aerospace industry. Since the reinforcement can be made of steel, high performance polymeric fibers (carbon, Kevlar, glass, Spectra), or natural fibers (jute, sisal, etc.), in the form of meshes, textiles, fabrics, fiber mats, or 3D systems, ferrocement offers enormous versatility in applications for various products. Moreover, 3D textiles can be optimally designed for targeted applications and should lead to savings in labor cost.

With the introduction of 3D textile technology and advanced matrices (high strength, self consolidating, etc.) ferrocement remains one of the most versatile construction materials available today. It offers a wide range of alternatives: from low tech materials to advanced high performance materials; from self-help construction to industrial prefabrication; from steel meshes to FRP meshes to natural organic meshes; from normal weight to lightweight, to sandwich construction; from stand-alone material to hybrid composition with or without fibers; from structural stand-alone material to support material in combination with reinforced and prestressed concrete (permanent molds, confinement, repair, etc.)

Ferrocement has been in existence since more that 150 years. However, for all practical purposes, progress in ferrocement has been almost at a standstill for more than 100 years, and picked up at an exceptional pace only during the last four decades. This may be partly due to fundamental research, better understanding of the reinforcing mechanisms of ferrocement, developments in advanced materials, economic competitiveness, and global circumstances. A solid foundation has thus been built. Progress is achieved one step at a time. By looking back, one can better appreciate the difficulties encountered and prepare for the next challenges. It is likely that every area mentioned in the above discussion will see progress in the future. However, economic considerations will keep playing a major role.

12. Acknowledgments

The research described herein was sponsored by the National Science Foundation under Grant No. CMS 0408623 and by the University of Michigan. The opinion expressed in this paper are those of the author and do not necessarily reflect the views of the sponsor.

13. References

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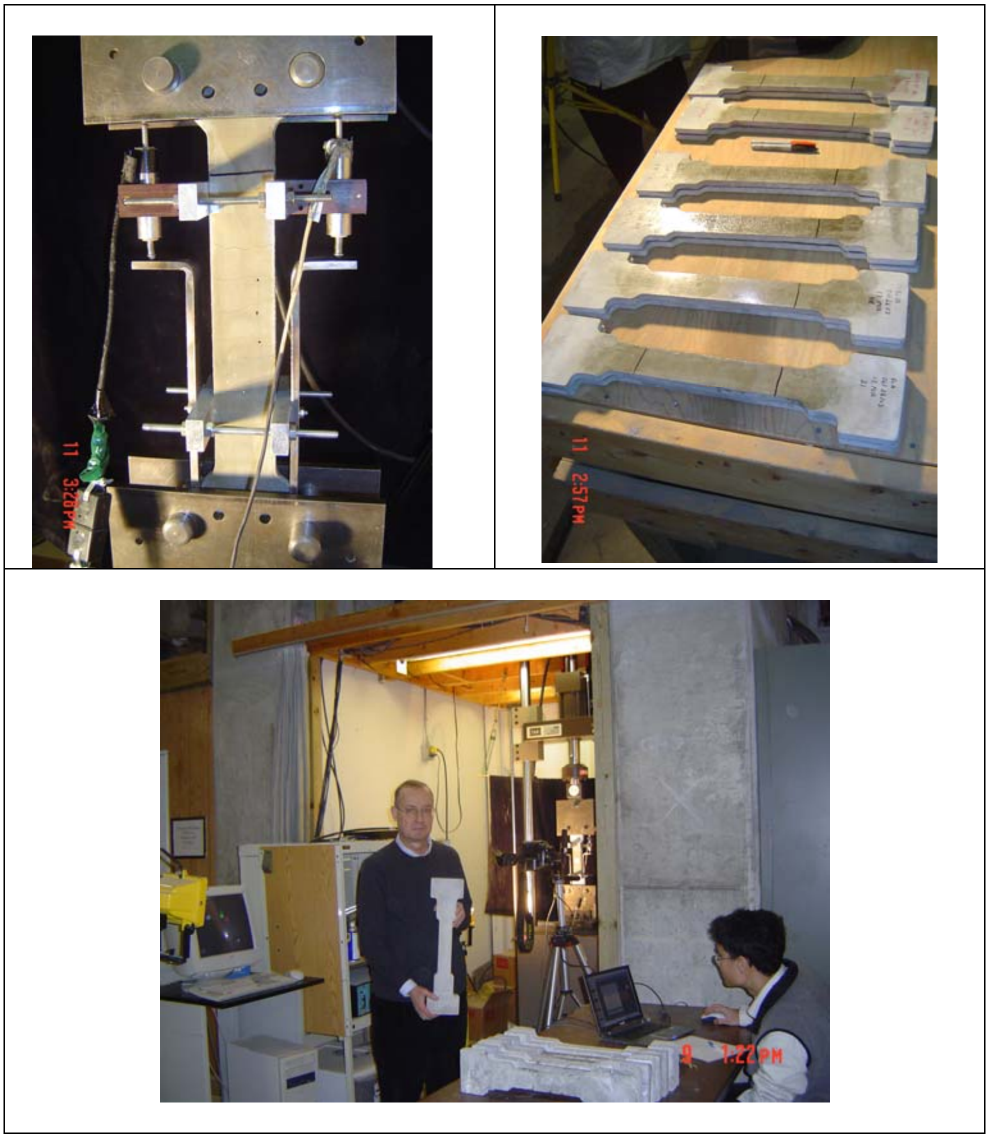

Tensile testing of ferrocement and FRC composites at the University of Michigan