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Progress in Ferrocement and Textile Hybrid Composites

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Summary: Background on advanced materials for ferrocement as well as new concepts to develop better ferrocement or laminated cementitious composites (LCC) are presented. The materials include fiber reinforced polymeric (FRP) meshes or textiles and high performance cementitious matrices. The concept of hybrid composites where advanced FRP meshes and discontinuous fibers are combined to achieve optimal performance is illustrated by several examples. Typical results of an investigation on the flexural response of hybrid cementitious composite laminates reinforced with meshes made from high performance FRP reinforcements, namely Kevlar, Aragrid, Spectra, and Carbon, are presented. Other meshes made with lower modulus fibers such as PVA and nylon are also described for comparison. The discontinuous fibers used were primarily PVA fibers premixed with the mortar matrix. Hybrid composite plates were prepared and tested under four point loading. Moduli of rupture close to 26 MPa were achieved with only 1.15% volume fraction of Kevlar mesh, and that was increased to about 38 MPa when 1% fiber by volume was added. The fibers, while contributing their share of resistance, also contribute to crack control, toughness and ductility, and helped change the failure mode from interlaminar shear to either shear or bending.

1. Definition

Ferrocement is truly the first invention of reinforced concrete, the most used construction material in the world. The main difference between them relates mostly to scale. Generally, ferrocement is a thin product made with a cement based mortar matrix reinforced with closely spaced layers of relatively small wire diameter steel mesh. Other reinforcing mesh materials and matrices containing fibers can be used.

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Ferrocement can be also considered a laminated composite made out of a number of laminae stacked on top of each other. A typical lamina comprises a layer of mesh embedded in a layer of matrix. The increasing availability for possible use in ferrocement of meshes (or textiles or fabrics) made with fiber reinforced polymers or plastics (FRP) materials of different types and properties, and high performance cementitious matrices, can add significantly to the strength, toughness, and ease of fabrication of the resulting composite.
Thus the term "ferrocement" which implies steel reinforcement is now extended to "laminated cementitious composite (LCC)" which includes: 1) all types of reinforcement including meshes, textiles, fabrics, and 2) modified cementitious matrices with fibers or micro-fibers leading to hybrid compositions.

2. Advanced or High Performance Materials

Generally the attribute "advanced" or "high performance" when applied to engineering materials is meant to differentiate them from the conventional materials used, given available technologies at the time and geographic location considered for the structure. It also implies an optimized combination of properties for a given application and should be generally viewed in its wider scope.

Cement based composites have made striking advances and gained enormous momentum in recent years. This is due in particular to several developments involving the mortar matrix, the mesh reinforcement, the bond between them, and the composite production process. Of particular interest are: 1) the increasing availability for possible use in ferrocement (and thin cement based laminated composites) of meshes made with fiber reinforced polymeric or plastic (FRP) materials of different types and properties (carbon, Kevlar, polyethylene) which can add significantly to the performance of the composite; and 2) the increasing availability of high performance microfibers (carbon, PVA, Spectra) to add to the cement matrix.

Combined properties of interest to civil engineering applications of ferrocement and laminated cementitious composites include strength, toughness, energy absorption, stiffness, durability, freeze-thaw and corrosion resistance, impermeability, non-flammability, tightness, appearance, stability, manufacturability, quality control, and last but not least, cost and user friendliness.

The potential use of high performance ferrocement (or more generally high performance laminated cementitious composites) is believed to be one possible way to improve the market penetration of ferrocement and its acceptance.

Some of these ideas are illustrated in the next sections.

3. Fiber Reinforced Polymeric Meshes

3.1 Introduction - Significance

Durability of concrete structures in general (and ferrocement in particular), and corrosion of steel reinforcement have been and will continue to be top priority issues for the civil engineering profession, both technically and economically. To reduce the risk of corrosion in ferrocement, the steel mesh reinforcement is generally galvanized and corrosion inhibitors are often added to the mortar matrix. However, to reliably insure long-term service life, corrosion must be not only delayed but also overcome. This can be achieved by using materials that are not susceptible to corrosion, such as for instance stainless steel or fiber reinforced polymeric (FRP) reinforcements.

FRP reinforcements, made from carbon, glass, aramid, or other high performance fibers embedded in polymeric matrices, in the form of bars, tendons, strands, and two or three dimensional meshes, are being produced and tested by numerous technical institutes around the world. Examples of FRP meshes that could be used in ferrocement applications include trade names such as Nefmac (Japan), Aragrid (Europe), Spectra (US) and the like. The Reticem (U.K. and Italy) process produces cement based laminated sheets reinforced by 20 to 30 thin layers of polypropylene mesh, which could be for all practical purposes considered a ferrocement reinforced with a non-metallic meshes.

3.2 Advantages and Drawbacks

Applications of FRP reinforcements in ferrocement and more generally thin reinforced concrete products, are bound to increase in order to solve special problems, especially those where corrosion is critical, non-magnetic properties are needed, and in order to improve some production processes for which steel meshes are not suitable. Other advantages of FRP meshes of particular interest to ferrocement and thin sheet applications, include high strength, lower unit weight, easiness in coiling and handling, and good damping and fatigue behavior. However, FRP materials are not without drawbacks which include high cost, low shear (transverse) strength, susceptibility to stress rupture effects, and low ductility [xx]. Indeed they show a linear elastic behavior in tension leading to a brittle type of failure without warning. Such drawbacks which are quite critical for conventional reinforced concrete structures, seem to be less critical for thin products applications such as ferrocement.

3.3 Type and Availability

Little information exists so far in the technical literature regarding the use of FRP reinforcements in ferrocement. However the term "textile concrete" is being used and could infer ferrocement when thin products are considered. Fiber reinforced polymeric reinforcements can take the form of continuous or discontinuous fibers, a combination of them, two or three dimensional (2-D and 3-D) meshes (fabrics and textiles) and mats. Fabrics, meshes, and mats made from fiber reinforced polymers have been extensively utilized in the aeronautics industry, as primary reinforcement of composites with polymeric matrices such as epoxy or polyester. While these fabrics, as produced at time of this writing, can be easily impregnated by a polymeric matrix, they are difficult to penetrate by a cement based matrix. Their opening and their tightness of weave are generally not suited for good impregnation or penetration by a cement matrix. This may explain why they have so far not been extensively used in combination with cement matrices. However, it should be quite easy to manufacture FRP meshes and mats with geometric and mechanical properties suitable, tailored, and optimized for use in cement based matrices

Some of the meshes tested by the author and described below, were picked up at best from existing meshes designed for applications other than ferrocement or thin cement products.

3.4 Cost Considerations

So far the primary reinforcement in ferrocement consists of steel wire meshes or expanded metal mesh. Documented properties of ferrocement are almost entirely based on steel reinforcements.

FRP meshes, may offer enormous 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, and they can be easily shaped to requirements.

Thin reinforced concrete products such as cement sheets, ferrocement elements, glass fiber reinforced cement cladding and the like, generally utilize a high percentage of reinforcement in comparison with conventional reinforced concrete; moreover the steel reinforcement in these products which consists of welded wire fabric, steel wire mesh, expanded metal mesh, or discontinuous fibers is two to eight times more expensive, on a unit weight basis, than conventional steel reinforcing bars.

Fabricating a smaller diameter steel wire from a steel rod, drives the cost of steel meshes very high. The smaller the diameter, the higher the cost. The cost of the mesh is based on unit weight while the mesh mechanical efficiency is based on volume fraction in the composite. Since the unit weight of steel ranges from 5 to 8 times that of FRP materials, and since the composite properties are based on volume fraction of mesh, cost comparison based on equal performance may eventually favor FRP meshes. Moreover, it is likely that future developments and applications will make FRP meshes increasingly cost competitive, especially when life-cycle cost analysis is considered.

3.5 Examples of FRP Meshes Tested

The author and co-workers at the University of Michigan have carried out a number of studies on the properties of ferrocement with FRP meshes [Refs.17-22]. Additional background information and other related studies can be found in the list of references provided at the end of the paper [Refs. 1-16, and 23-31]. The FRP meshes used have the following properties as supplied by their manufacturers.

- *Kevlar.* Aramids are a family of organic fibers developed by DuPont in 1966, in the US, under the tradename Kevlar. Two types are sold: Kevlar 29 and Kevlar 49, the latter being primarily for plastic reinforcements. The fabric style used had 10x6 fiber bundles per inch (i.e. a spacing of about 2.5 mm in the longitudinal direction and 3.5 mm in the transverse direction), and a bundle or yarn of 1500 denier in each direction. In the longitudinal direction, the yarn had a "leno" twist. Properties supplied by the manufacturer are as follows: tensile strength = 2800 MPa (406 ksi); elastic modulus = 124 GPa (18000 ksi); ultimate elongation = 2.8%; density of Kevlar material = 1.44 g/cc.

- *Aragrid.* Aragrid is a trade-mark for a mesh developed by AKZO in Europe, for masonry reinforcement. Its configuration seems very suitable for ferrocement applications. The fibers used are Twaron, a type of aramid. The square mesh is made from bundles (or yarns) of fibers embedded in a polymeric resin, with average spacing of about 10.5 mm in the two directions. Mechanical properties of the bundles are as follows: elastic modulus = 45 GPa (6500 ksi); tensile strength of bundle = 2030 MPa (293 ksi); elongation at failure = 4.5%; density = 1.45 g/cc.
- *Spectra.* Spectra fiber is a trademark of Allied Signal in the US. It is a high performance fiber made from polyethylene. Spectra fibers are mostly used in fiber reinforced plastics in the aeronautic and aerospace industries. They are not tailored for civil engineering applications. A mesh having 10x10 bundles per inch (i.e. bundle spacing of about 2.5 mm) was found for testing in ferrocement. It is identified as Spectra 901 fabric, with same fiber bundles in the two directions, and the following properties: elastic modulus = 118 GPa (17000 ksi); tensile strength = 2590 MPa (375 ksi); elongation at rupture = 3.5%; yarn denier = 1200 in each direction; density = 0.97 g/cc.
- *Carbon (PAN type).* Two of these meshes were tried. They were fabricated using carbon fiber yarns and looked like a very loose fabric or net. A small Kevlar fiber was used in addition in the transverse direction to stabilize the weave of the mesh. The first mesh had a clear opening of about 3 mm. One layer of mesh led to $V_r = 1.31\%$ assuming a ferrocement plate of thickness h = 12.7 mm. The second mesh had 5x5 fiber yarns per inch (i.e. center to center spacing of about 5 mm), and a yarn of 3500 denier in each direction. The density of carbon fibers is 1.72 g/cc. One layer of mesh led to $V_r = 1.40\%$. These meshes were sprayed with a latex solution and left to dry prior to using. The reason for spraying was to get the mesh to be stiffer and the fibers of each bundle to stay as much as possible together during handling.
- *PVA or Polyvinyl alcohol.* PVA (Poly Vinyl Alcohol) mesh was square with a yarn spacing of 5 mm, an elastic modulus of 29,000 MPa and a tensile strength of 400 MPa. The density was 1.3 g/cm3. The mesh weighted 111.13 grams per square meter.
- *Steel.* Steel meshes were used in control ferrocement specimens. The steel mesh was a welded square galvanized mesh with a wire spacing of 0.25 in. (6.3 mm) and a wire diameter of 0.025 in. (0.63 mm). It was tested in the laboratory and led to rather low values of tensile strength attributed to the effect of welding small diameter wires: equivalent yield strength = 238 MPa (34 ksi); ultimate strength = 350 MPa (50 ksi); ultimate elongation = 12%; elastic modulus = 200 GPa (29000 ksi); density = 7.8 gr./cc.

Other meshes tested included polypropylene, polyethylene and nylon based meshes. No mechanical properties could be obtained from the mesh supplier. However, because of their low elastic modulus in comparison to the mortar matrix modulus and because of their relatively low tensile strength in comparison to other advanced fibers (carbon, Kevlar, Spectra), everything else being equal, these meshes generally led to composite bending resistance lower than that obtained with the high modulus meshes (carbon, Kevlar, Spectra) described above. Moreover, their permanent deformation after cracking was too large and elastic recovery was small. One of the advantages of FRP reinforcements is that they offer a wide spectrum of mechanical properties particularly in terms of strength and elastic modulus. Reinforcing parameters can be chosen in function of the matrix material and the expected performance of the composite.

Most high performance fiber reinforced polymeric reinforcements (carbon, glass, aramid, spectra based) have a linear elastic stress-strain response in tension up to failure. Typical stress-strain curves are shown in Fig. 1 and compared with those of conventional steel meshes and high strength prestressing steel. A differentiating characteristics between these advanced fibers and steel is that they have no yielding behavior; unlike steel, they fail in a brittle manner without warning.

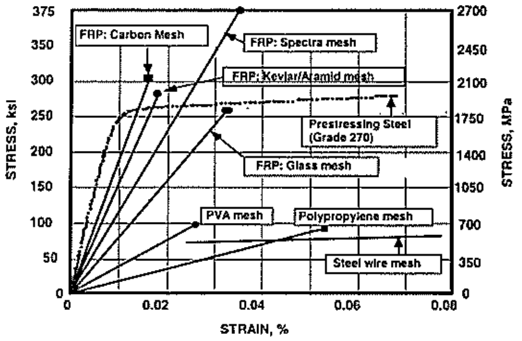

Fig. 1 Typical stress-strain curves in tension of FRP fibers (or yarns) and comparison with steel meshes and high strength prestressing steel

3.6 Test Parameters of Experimental Investigation

An extensive experimental study was carried out on thin mortar (ferrocement) plates reinforced with FRP meshes and tested in bending. All specimens were 3 in. (75 mm) wide, 12 in. (300 mm) long and, except in some special cases, 0.5 in. (12. 7 mm) thick. The two extreme mesh layers were placed close to the mold surfaces with a cover of about 2 mm. Other layers, when present, were distributed at best in between. Some specimens were reinforced with a combination of meshes and discontinuous fibers. Control plates without any mesh nor fibers were also prepared. The specimens were tested in bending, under four-point loading, over a span of 9 in. (228.6 mm) as shown in **Fig. 2**. At least four specimens were prepared and tested for each parameter. An averaging procedure was followed when average data are presented, otherwise representative curves are shown.

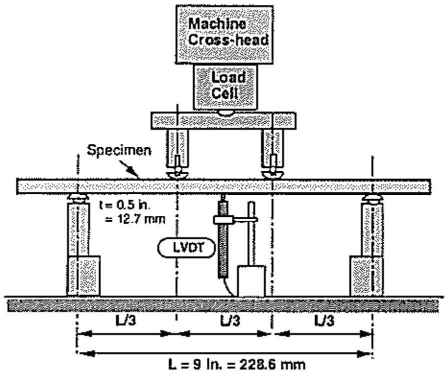

Fig. 2 Bending test set-up

Table 1: Properties of some FRP mesh reinforcements and reference steel mesh used in experimental study

Mesh Material	*Volume Fraction of Mesh**	*Diameter or denier*	*Density g/cc*	*Tensile Strength MPa*	*Elastic Modulus GPa*
Aragrid (square)	$V_r = 1.67\%$	na	1.45	2030	45
Kevlar (leno weave in L direction)	$V_r = 1.15\%$ $V_{rL} = 0.72\%$	1500 denier	1.44	2800	124
Spectra (square)	$V_r = 1.67\%$	1200 denier	0.97	2585	117
Carbon - type 1 (square)	$V_r = 1.31\%$		1.80	2800	240
Carbon - type 2	$V_r = 1.40\%$	3500 denier	1.80	2800	240
PVA	$V_r = 1.35\%$		1.31	400	29
Steel (square)	$V_r = 1.85\%$	0.63 mm	7.8	350	200

* Assuming 2 layers of mesh and h = 12.7 mm; a) embedded in resin.

The main parameters studied include the type of mesh, the volume fraction of reinforcement (number of layers of mesh), the compressive strength of the mortar matrix, and the addition of discontinuous fibers. When fibers were used, the ferrocement plates had only two extreme layers of mesh and their volume fraction, V_f, with respect to the matrix was either 1% or 2%.

For the steel mesh the volume fraction of reinforcement was calculated from the wire diameter. For the FRP meshes, the volume fraction of reinforcement was calculated from the denier of the yarn and/or from weighing the mesh. Typical values of V_r (total volume fraction of reinforcement for two layers of mesh) for the meshes used are given in Table 1.

3.7 Typical Results

Typical results of ferrocement bending tests using FRP meshes are shown in Figs. 3 to 8. Instead of plotting load versus deflection curves, the equivalent elastic flexural stress for a rectangular plate ($\sigma_e = \frac{6M}{bh^2}$), assuming uncracked section, was plotted versus the deflection. The equivalent elastic flexural stress accommodates automatically different geometric properties and test conditions, providing a good basis for comparison.

1. Influence of Number of Mesh Layers or V_r. Increasing the number of mesh layer is similar to increasing the total volume fraction of mesh reinforcement, V_r. However, unlike in a tensile test, the increase in the number of mesh layers does not lead to a proportional increase in bending resistance. This is because, every additional mesh layer will have a smaller lever arm under bending, and thus will contribute much less resistance than the mesh placed at the extreme layer.

Figure 3 shows typical results using 2,4,6 and 8 layers of steel mesh. Such curves can be used as a basis for comparison with other meshes. It can be observed that equivalent bending strength (MOR) of up to 5000 psi (35 MPa) were achieved with a longitudinal volume fraction of reinforcement of 3.7%, that is a total $V_r = 7.4\%$ (Table 1). The larger the number of mesh layers (or equivalently the larger the volume fraction of reinforcement) the higher the strength and the larger the deflection at maximum load. Increasing the number of mesh layers does not lead to a proportional increase in bending resistance. This is expected analytically. However, other factors such as actual location of the mesh layers within the section are also very important. Because it is very difficult in practice to control the spacing of meshes during pouring of the mortar matrix, it is likely in some cases that the mesh layers end up being closer to the tensile or to the compression zone leading to a significant variability in response. Cracks with the steel mesh were well distributed and generally of smaller widths than those observed with the FRP meshes. Failure of the specimens generally occurred when the mortar failed in compression.

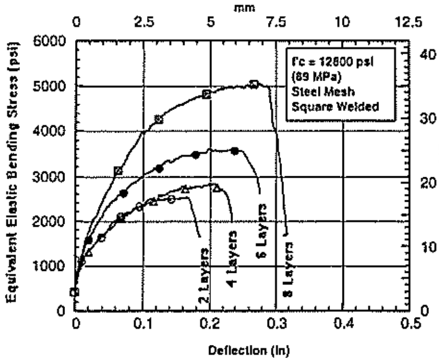

Fig. 3 Typical stress-deflection curves of ferrocement plates using steel meshes (V_r = 1.85% for two layers)

Figure 4 illustrates the response of two specimens reinforced with 6 layers of Aragrid mesh: one monotonically loaded and one with a couple of loading-unloading cycles. It can be noted that these meshes lead to equivalent bending stresses similar to those obtained with steel meshes (Fig. 3), but with a larger deflection due to their lower elastic modulus. Also larger crack widths were observed. For the maximum deflection applied, failure of the mesh did not occur. When failure occurred, it was initiated in the compression zone of the mortar at high deflections.

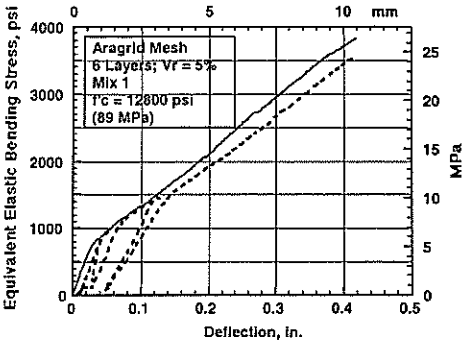

Fig. 4 Typical stress-deflection response curves of ferrocement plates using Aragrid FRP meshes showing some loading-unloading cycles

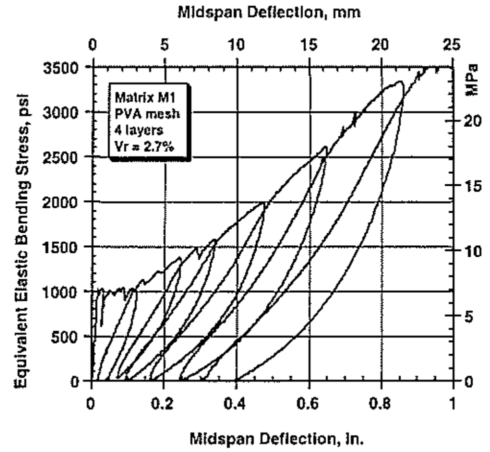

Fig. 5 Loading-unloading stress-deflection curves of ferrocement plates reinforced with PVA meshes

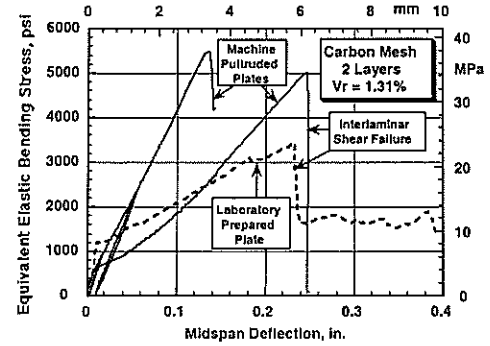

Fig. 6 Comparison of stress-deflection curves of machine pultruded ferrocement plates reinforced with carbon meshes and laboratory produced plate

2. Loading-Unloading Response. The curve of Fig. 5 illustrates the effects of loading-unloading on the bending response of specimens reinforced with PVA meshes. Thus the extent of the inelastic deformation at a given load can be clarified. Because fiber reinforced plastic meshes behave almost in a linear elastic manner up to failure, the permanent non-recoverable deflection at unloading is primarily due to cracking of the mortar matrix in tension and inelastic straining of the mortar in compression if any.

3. Effect of Production Process. Figure 6 illustrates the bending response of machine pultruded ferrocement plates using two layers of carbon mesh (one layer along each extreme fiber). In these specimens, unlike the others, the net cover to the mesh was very small and of the order of 0.5 to 1 mm. These plates failed by interlaminar shear between the mortar and the tensile layer of mesh. However, they developed a relatively high bending resistance. For comparison, the stress-deflection curve of a specimen prepared in the laboratory (instead of by machine pultrusion) is also given in Fig. 6. It modulus of rupture was almost 40% smaller than that of the pultruded specimens, but it also failed by interlaminar shear at the level of the tensile mesh layer.

4. Effect of Using Meshes with Low Elastic Modulus. Kevlar, carbon, and Spectra fibers can have high tensile strength, exceeding 2000 MPa, and high tensile modulus, exceeding 120 GPa (see Table 1). PVA fibers can have a tensile strengths up to 900 MPa and an elastic modulus of the order of 30 GPa. Polypropylene fibers can develop a strength close to 700 MPa and an elastic modulus close to 10 GPa. When used with normal weight mortar in ferrocement type applications, polypropylene fiber meshes provide good flexural resistance but poor cracking, not in terms of crack spacing, but particularly in terms of crack widths and permanent residual deflection after cracking. Typical examples of stress-deflection curves are shown in Fig. 7. It can be observed that moduli of rupture up to 16 MPa can be achieved with up to 4% volume of reinforcement. Note that with only two layers of mesh, and a volume fraction of reinforcement of 2.4%, an elastic strain hardening behavior can be developed with strengths exceeding 7 MPa.

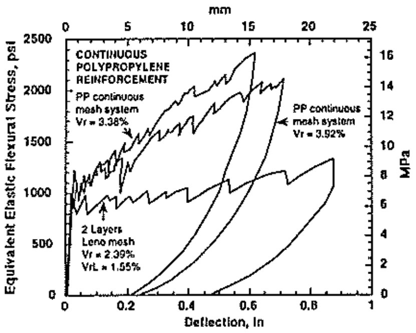

Fig. 7 Typical stress-deflection response curves of ferrocement plates with low modulus FRP meshes

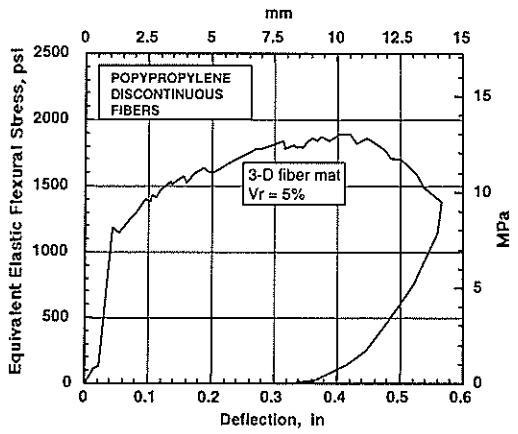

Fig. 8 Typical stress-deflection response curves of ferrocement plates reinforced with 3-D fiber mat made with polypropylene fibers

5. Effect of Using a Fiber Mat. Figure 8 illustrates the flexural response of ferrocement plates reinforced with fiber mats made with discontinuous polypropylene fibers. Bending resistance similar to that achieved using several layers of mesh is obtained using similar volume fraction of reinforcement. These results suggest that fiber mats may offer very attractive alternatives to the use of several layers of mesh in terms of savings on labor cost. Also, it is likely that using fiber mats made with more performant fibers, such as Kevlar or Spectra, will lead to results significantly better that those represented in Fig. 8 and should be explored in future studies. It should be noted that fiber mats made with steel fibers already exist and are used for special applications involving repair and retrofit. The technique is referred to as SIMCON or Slurry Infiltrated Mat Concrete. Fiber mats with PVA fibers leading to about 1% fiber content by volume have also been developed.

3.8 Conclusions on the Use of FRP Meshes with Conventional Cement Mortar Matrices

The following conclusions apply primarily to the use of FRP meshes with normal weight mortar matrices of compressive strength ranging from 20 to 100 MPa, and related elastic moduli.

a. Fiber reinforced polymeric meshes can be successfully used in ferrocement applications; they can lead to a bending response in par with that obtained with conventional steel meshes. Equivalent elastic bending strengths close to 4500 psi (30 MPa) were achieved with volume fractions of reinforcement similar to those with steel meshes.

b. Everything else being equal, the higher the strength of the mortar matrix, the higher the bending resistance at a given deflection.

c. For the mortar mixtures used in this study, best results were achieved with the stiffest meshes, i.e. the mesh with the highest modulus of elasticity. However, when carbon meshes (high strength and modulus) were used, interlaminar (horizontal) shear failure occurred in the mortar prior to failure of the extreme layer of mesh.

d. For the mortar mixtures used in this study (normal to high strength), the use of low modulus meshes leads to large crack widths, and large permanent non-recoverable deflections.

e. Because they are, lighter, easier to handle, easier to cut, and easier to bend than steel meshes, FRP meshes may offer numerous advantages over steel meshes, especially for structures with complex shapes and curvatures. Also, because they can be delivered in virtually any length, FRP meshes are very well suited for automated fabrication processes such as the manufacturing of thin sheets by pultrusion.

f. Fiber mats made with discontinuous fibers (or very long fibers) can offer a very attractive alternative in terms of labor cost savings, to the use of several layers of mesh.

This part of the study has indicated that FRP reinforcements in the form of meshes, can be successfully used for ferrocement applications and can achieve mechanical performance similar to that obtained using steel meshes.

4. Hybrid Composites with Meshes and Fibers

4.1 Justification

Most generally a hybrid composite may imply the use of meshes of different materials (such as carbon and PVA), fibers of different materials or properties (length, diameter, modulus, strength), and/or a combination of them. Here the term "hybrid composite" is used to indicate a combination of continuous meshes such as carbon or steel, with discontinuous fibers such as PVA or steel. The fibers are generally premixed with the mortar matrix. However, a prefabricated fiber mat used as core or spacer, or a fiber mat made of dispersed fibers allowing infiltration by the mortar matrix, can be used. One of the first proponents of the use of a hybrid ferrocement composite was Douglas Alexander of New Zealand. He combined high strength steel wires and steel meshes (as primary reinforcement) with discontinuous steel fibers premixed in the mortar matrix (as secondary reinforcement), to impart ferrocement composites with a combination of high strength and superior cracking and impact characteristics.

Several reasons have led to the idea of trying hybrid composites for ferrocement structural components:

1. For bending applications, increasing the number of layers of mesh (or the volume fraction of reinforcement) does not lead to a proportional increase in bending resistance. This is because the farther the layers of mesh are placed from the extreme tensile fiber the less efficient they are. Indeed meshes close to the neutral axis contribute very little. This is confirmed not only analytically but also experimentally. Thus the layer of mesh that contributes the most is the extreme layer; optimizing its properties has a strong impact on composite properties and cost efficiency. Therefore, it seems that using only two layers of mesh in a thin ferrocement sheet is the most cost effective way to use the mesh. However, this can also limit the maximum strength that could be achieved otherwise.
2. When high strengths, high moduli meshes are used with normal strength mortar matrices, failure under bending load seems to be primarily due to either shear delamination of the extreme layer of mesh and its mortar cover, or to vertical shear, unless extensive ties are used. Numerous experimental tests with carbon meshes augmented by analysis of the composite support such behavior.
3. In numerous situations, ferrocement sheets or structural elements need to be drilled either to attach other structural or non-structural elements, or simply to provide a hole for piping or wiring. Drilling is easier when the mortar matrix is made of fine particles and when meshes are FRP instead of steel. However, under best circumstances, drilling leads to numerous fracture sites in the matrix around the primary hole being drilled, leading to a poor bearing surface.

A remedy to the above three problems is the use of discontinuous fibers (or micro-fibers) in the matrix. Appropriately selected fibers will add to the strength and toughness of the composite in bending, will help increase both the vertical shear resistance and the interlaminar shear resistance at the interface of the extreme layer of mesh, and will help in allowing for a cleanly drilled hole in the composite. Fibers also impart other properties such as reduced crack width and spacing, and improved impact resistance. As a result of using fibers in combination with meshes, a hybrid composite with optimized properties can be obtained. In most of the tests described below, FRP meshes were used.

4.2 Experimental Results

The author with students at the University of Michigan has carried out a number of experimental studies on hybrid ferrocement composites in bending. The properties of the fibers used are given in Table 2. Typical results are illustrated in Figs. 9 to 13. Some results are discussed next.

1. Effect of Adding Discontinuous Fibers with PVA Mesh. In order to improve simultaneously cracking and strength, a fiber reinforced mortar matrix was used. Figure 9 shows the stress-deflection response of: 1) a composite with PVA fibers only, 2) a composite with 2 PVA mesh layers only, and 3) a composite with 2 PVA mesh layers and PVA fibers (2% by volume). From a load, stress, or strength viewpoint, the two effects were for all practical purposes additive. It can be observed that the addition of fibers leads to about a

60% increase in both bending resistance and energy absorption. Significant multiple cracking pattern was observed in the hybrid composite. The cracks were much finer than in the plates without fibers. The average crack spacing decreased from 0.78 in. (19.5 mm) for specimens without fibers to 0.3 in. (7.6 mm) for specimens with 2% PVA fibers.

Table 2: Properties of fibers used in experimental study

Fiber Type	*Diameter mm*	*Length mm*	*Density g/cc*	*Tensile Strength MPa*	*Elastic Modulus MPa*
PVA*	0.19	12	1.31	900	29,000
PVA*	0.014	6	1.31	900	29,000
Carbon	0.0095	6.35	1.80	2800	240,000

* Poly Vinyl Alcohol.

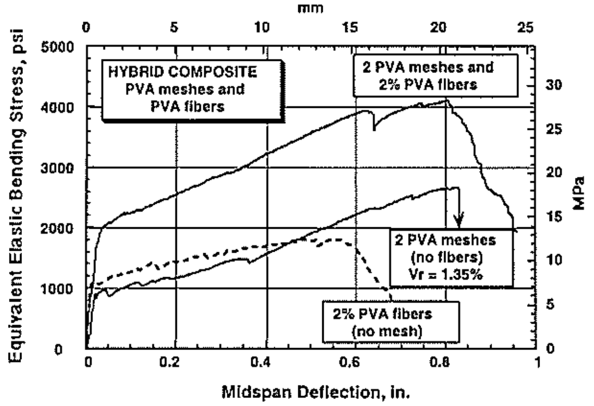

Fig. 9 Typical stress-deflection response curves of hybrid ferrocement plates reinforced PVA meshes and PVA fibers

2. Effect of Adding Discontinuous Fibers with Carbon Mesh. When only two layers of carbon mesh were used, horizontal or laminar shear failure occurred at the level of the tensile mesh at a load lower than expected from the bending resistance. In order to improve shear resistance, PVA fibers were added in amounts of 1% and 2% by volume of matrix. A comparison of the average stress-deflection curves is given in Fig. 10. Three observations can be made: 1) bending failure occurred when fibers were added, that is failure occurred when the tensile layer of mesh failed, 2) the addition of 1% PVA fibers was sufficient to improve the shear resistance, and 3) the PVA fibers contributed to increasing the bending resistance, and a slightly higher bending strength was achieved with 2% fibers than with 1% fibers. Note that the specimens of Fig. 10 were prepared in the lab and are different from the pultruded specimens described in Fig. 6.

3. Effect of Adding Discontinuous Fibers with Carbon, Kevlar and Spectra Meshes. Figure 11 (top) compares the stress-deflection response in bending of ferrocement plates containing only two layers of either carbon, or Kevlar or Spectra mesh. Since the two layers of each mesh correspond to different volume fractions of reinforcement, some scaling should be used in comparing the effects of different mesh materials. However, the upper graph of Fig. 11 should be compared with lower graph where the bending response of similar specimens now containing in addition 1% fibers by volume is shown. It can be observed that the addition of fibers, in specimens with Kevlar and Spectra meshes, is beneficial in many ways; it led to significant improvement in bending strength (more than 50%), deflection at maximum load, and toughness (measured as the area under the load-deflection curve). Fibers also led to finer crack widths and smaller crack spacing. Another important finding was that the addition of fibers increased significantly the stress at first structural cracking as illustrated in Fig. 12 which shows the initial portion of the curve for ferrocement plates reinforced with Kevlar meshes. Note finally that the addition of fibers was not as effective with carbon meshes, because of failure of the carbon yarns.

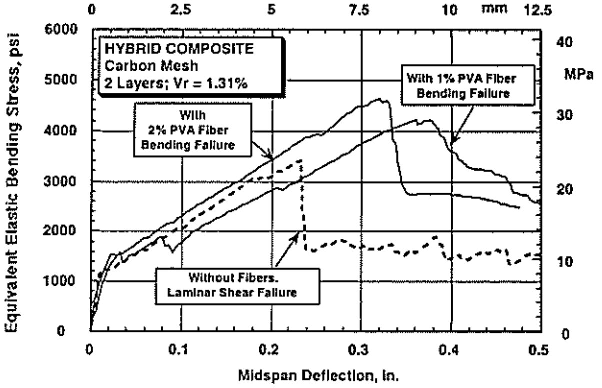

Fig. 10 Typical stress-deflection response curves of hybrid ferrocement plates reinforced carbon meshes and PVA fibers

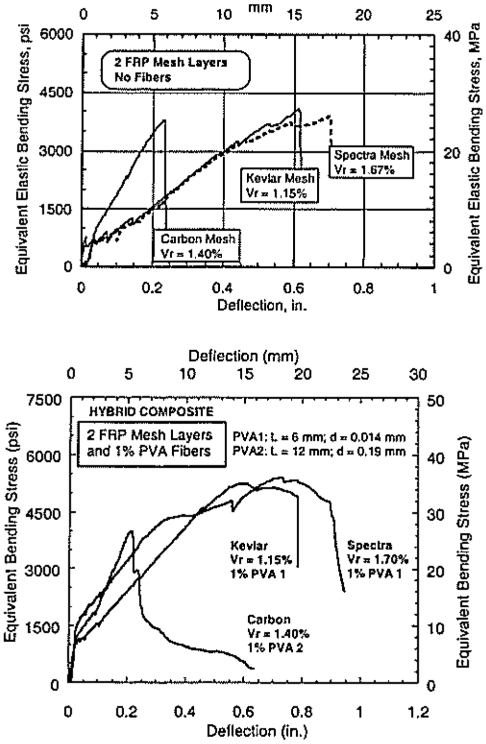

Fig. 11 Typical stress-deflection response curves of: top) ferrocement plates reinforced with two layers of either Kevlar, or carbon, or Spectra meshes, and bottom) similar hybrid plates with 1% PVA fibers

4.3 Conclusions from Using Hybrid Composites

1. The combination of discontinuous fibers and meshes (hybrid composite) leads to significantly improved flexural behavior, in terms of strength, toughness, increased shear resistance, and cracking.
2. The use of only two layers of FRP meshes such as carbon, Kevlar or Spectra, in combination with fibers, in 12.7 mm thick ferrocement plates, leads to equivalent elastic

bending strengths of about 40 MPa. Such strengths should cover most common applications of ferrocement and thin concrete products today.

3. The addition of fibers of up to 2% by volume to ferrocement composites lead to increases in composite first cracking stress ranging from 50 to 100% in comparison to identical specimens without fibers.

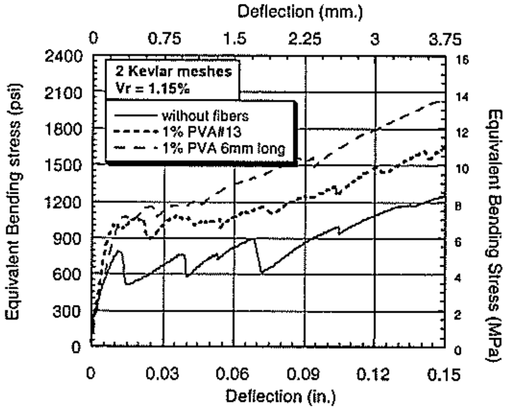

Fig. 12 Initial portion of the stress-deflection curves of hybrid ferrocement plates with Kevlar meshes illustrating the increase in first cracking strength due to fiber addition

4. A major drawback in the use of a combination of discontinuous fibers and meshes is the difficulty of production of the specimens. A poor matrix penetration of the mesh will affect the performance of ferrocement and may negate the benefits of using fibers. Superplasticizers and other additives are recommended to insure proper fiber dispersion and matrix penetration of the mesh system.

As observed from the above results, hybrid composites do achieve excellent mechanical performance; the discontinuous fibers fulfilled their function, by improving the shear resistance of the composite (vertical and interlaminar shear) and by taking a fair share of the resistance otherwise provided by intermediate meshes. Moreover, the author has shown in laboratory tests that, with the proper type and amount of fibers, direct drilling of the cement composite laminate is possible without significant fragmentation. That is, it is conceivable to visualize that, if needed, panels can be drilled on site (similarly to plywood) and bolted effectively together or to other elements (such as for the case of curtain walls and sunscreens).

5. General Concluding Remarks

The use of FRP meshes (or textiles or fabrics) in ferrocement seems logical in applications where corrosion and weight of the structure are of concern, where non-magnetic properties are desired, and where the production process can be simplified.

From a mechanical performance viewpoint, FRP meshes can be successfully used in ferrocement and other thin reinforced concrete (mortar) applications. They can lead to bending strengths similar to those achieved using steel meshes; however, the composite stiffness after cracking depends on the elastic modulus of the FRP mesh system. Generally a good cracking distribution and a good ductility or energy absorption before failure can be achieved. These conclusions are true for all the high performance FRP meshes tested by the author (carbon, Aragrid, Spectra, Kevlar, PVA).

Equivalent elastic bending strength close to 26 MPa was obtained using only two layers of carbon mesh or equivalently 1.40% total volume fraction of mesh. Machine pultruded plates with about same carbon mesh reinforcement led to a modulus of rupture close to 38 MPa. Such strength values are sufficient for many applications. The use of hybrid composites whereas intermediate meshes are replaced by discontinuous fibers may offer, in some cases, a better and more cost effective solution.

An increase in modulus of rupture from 26 MPa to about 38 MPa was obtained when in addition to two layers of Kevlar mesh (V_r = 1.15%), short discontinuous PVA fibers were added to the matrix in amount equal to 1% by volume. The combined use of only two layers of mesh reinforcement, placed near the extreme surfaces, with discontinuous fibers offered an optimum combination for bending behavior and should be further explored in future studies. The use of fibers improved significantly the interlaminar shear resistance of the matrix and thus allowed the extreme layer of mesh reinforcement to contribute its full capacity to the resistance of the member. Other benefits in using fibers in a hybrid configuration, include increased cracking strength, finer microcracks or shrinkage cracks, smaller crack widths under load, and improved "drill-ability" of the composite.

There is real need to develop FRP meshes with parameters especially optimized for thin concrete products. These include mechanical parameters such as strength, modulus, and ultimate elongation; geometric parameters such as yarn diameter, yarn spacing, specific surface; and practical parameters such as rigidity of the mesh for handling and placing, thickness and width of the mesh.

New materials and new concepts will make ferrocement and laminated cementitious composites increasingly competitive for particular applications such as in cement sheets, cement boards, claddings, or thin reinforced concrete products. There is need, on one hand, to develop new innovative structural systems that utilize the properties of these advanced cement composites and, on the other hand, to identify where they can be used to improve the performance of existing infrastructure systems.

However, It should be observed that the optimization of composite performance should involve the manipulation of not only the fundamental composite parameters (matrix and mesh parameters), but also variables related to the production process, the rheology of the fresh mix, the properties of the hardening composite and the final application of the material. A great deal of research and development is needed and is justified by current market potential worldwide.

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