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THIN CEMENTITIOUS PRODUCTS: PERFORMANCE COMPARISON BETWEEN STEEL AND TEXTILE REINFORCEMENTS

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ABSTRACT: Thin cementitious composites reinforced with steel wire mesh belong to the ferrocement family, that is, the first application of reinforced concrete. The use of textiles or fabrics or fiber reinforced polymeric (FRP) meshes adds another dimension to the reach of thin cement composites whether they are identified as ferrocement or textile reinforced concrete. The possible addition of discontinuous fibers or micro-fibers to the cement matrix and new availability in three-dimensional fabrics adapted for cement based applications offer unique opportunities for future developments and growth.

While material cost per unit weight is higher for FRP meshes than for steel meshes, FRP meshes can be tailored to exact requirements (that is, size, diameter, and opening) at little cost compared to steel wire mesh. Moreover, although high performance FRP reinforcements are brittle, the mesh configuration and progressive failure of the separate yarns in the composite under loading help achieve a reasonably ductile composite response. These advantages may give FRP meshes (or textiles or fabrics) some advantages over meshes made from steel wires. However, the main advantages of FRP reinforcements are increasingly challenged by new developments in steel reinforcement (wires and wire meshes).

This paper provides comparisons in terms of expected performance and cost of various reinforcing systems for thin cementitious products, including hybrids. The reinforcing systems evaluated include, respectively, 2D meshes, 2D meshes and fibers, 2D meshes and a fiber mat, 3D meshes, 3D meshes and fibers, and very high strength steel wires. Moduli of rupture close to 100 MPa were achieved with less than 3% total volume fraction of reinforcement. These composites are equally strong under both positive and negative bending and in the two principal directions.

1. BASIS FOR COMPARISON

So far the primary reinforcement in ferrocement (or thin cementitious products) consists of steel wire meshes or expanded metal mesh. Documented properties of ferrocement are almost entirely based on steel reinforcements [1].

FRP (Fiber Reinforced Polymeric) meshes (or textiles, or fabrics) may offer advantages in spite of their initial high cost. This is because, unlike steel wire meshes, they can be tailored to exact requirements (i.e. fiber denier or diameter, mesh opening, etc..) at little extra cost, they can be delivered in virtually any length, they are lightweight, and they can be easily shaped to requirements. Because generally the unit price of FRP reinforcements is significantly higher than the unit price of steel, there is need to provide a rational cost comparison of these reinforcement systems based on equal performance of composite.

In several prior publications, the author described results of bending tests on thin cement composites using different reinforcing materials and reinforcing systems [10 to 15]. Eighteen series from these tests conducted with similar specimen sizes under similar conditions are compared here and evaluated on the basis of performance and cost.

Because in many of the tests described, maximum strength was sought, the modulus of rupture (MOR) or maximum equivalent elastic bending stress obtained from the maximum load in bending is used as a reference for comparison. Although other properties can also be used separately or integrated with the modulus of rupture for performance evaluation, MOR provides a first measure which could be later expanded. Other characteristics such as toughness, cracking and crack width, and fragmentation, are not considered. However, note that all the series of tests selected lead to load-deflection response curves that had deflection-hardening behavior after first cracking accompanied by multiple cracking.

2. REINFORCING SCHEMES EVALUATED AND RESULTS

2.1 Definition

The term "ferrocement" is used here in its broadest meaning according to the following definition which is stated in Ref. [13] and adopted in Ref. [5].

> "*Ferrocement is a type of thin walled reinforced concrete commonly constructed of hydraulic cement mortar reinforced with closely spaced layers of relatively small wire diameter mesh. The mesh may be made of metallic or other suitable materials. The fineness of the mortar matrix and its composition should be compatible with the opening and tightness of the reinforcing system it is meant to encapsulate. The matrix may contain discontinuous fibers*".

Therefore the term ferrocement implies here steel reinforcement as well as FRP meshes and textiles or fabrics, and their hybrid combinations with fibers.

2.2 Test Series Description and Results

Several reinforcing schemes were evaluated in the eighteen series of tests selected. They include: 1) standard ferrocement plates with steel wire mesh of normal and high strength; 2) standard ferrocement plates using FRP meshes or textiles; 3) ferrocement plates using hybrid reinforcement of fibers and only two extreme layers of steel mesh; 4) ferrocement plates using hybrid reinforcement of fibers and only two extreme layers of FRP mesh or textile; 5) ferrocement plates using hybrid reinforcement consisting of a fiber mat taken in sandwich by two extreme layers of steel mesh or FRP meshes; 5) ferrocement plates consisting of a 3D textile infiltrated by a cement matrix; and 6) ferrocement plates consisting of a 3D textile infiltrated by a cement matrix containing micro fibers. Details for the various tests can be found in prior publications [10 to 15]

The average results of interest to this evaluation are summarized in Table 1. The following notation is used:

$V_{mesh} =$ Total volume fraction of mesh or continuous reinforcement

$V_f =$ Volume fraction of fibers

$V_r = V_{mesh} + V_f =$ Total volume fraction of reinforcement

Table 1 Test series properties and normalized values of modulus of rupture.

Series ID Number	Depth, mm	Mesh Type	Volume fraction of mesh, V_{mesh} (%)	Volume fraction of fibers[b], V_f (%)	MOR per 1% V_{mesh} (MPa)	MOR per 1% total reinf. V_r, (V_{mesh} + V_f) (MPa)
1	12.5	Steel (normal strength)	1.85%	0	7	7
2		Steel (high strength)[a]	3.526[c]	0	21	21
3		Carbon 1	1.31	0	18.32	18.32
4		Carbon 1 (Machine pultruded)	1.31	0	26.7	26.7
5		Carbon 2	1.4	0	17.86	17.86
6		Kevlar	1.44[c]	0	18.06	18.06
7		Spectra	1.67	0	15.57	15.57
8		3D-Glass	1.368	0	10.4	10.4
9	12.5	Steel (normal strength)	1.85%	1% (premix)	7	Use 7 (fibers are not needed.)
10		Steel (high strength)[a]	3.526[c]	1% (premix)	30.78	23.94
11		Carbon 1	1.31	1% (premix)	22.9	12.98
12		Carbon 2	1.4	1% (premix)	18.92	11.04
13		Kevlar	1.44[c]	1% (premix)	31.3	16.74
14		Spectra	1.67	1% (premix)	22.15	13.86
15		3D-Glass	1.368	1% (premix)	9.14	5.28
16	75	Steel (low strength)	0.831	1% (PVA mat)	Not[d] Applicable	4.35
17		Steel (high strength)	0.588[c]	1% (PVA mat)	Not[d] Applicable	8.94
18		Kevlar	0.040[c]	1% (PVA mat)	Not[d] Applicable	6.54

a. Hardwire® - made of five 0.3 mm wire strands with tensile strength of 3150 MPa
b. Fibers: PVA fibers
c. Since the volume fraction of reinforcement in the transverse direction was different from that in the longitudinal direction (or loading direction) the volume was adjusted accordingly.
d. Not applicable. The manufacturing process included the fiber mat and did not allow testing without fibers.

For each test series, Table 1 provides information on the mesh type, volume fraction of mesh reinforcement, volume fraction of fibers if any, modulus of rupture (MOR) observed, and a normalized value of the modulus of rupture per 1% total volume fraction of reinforcement in the composite.

2.3 Remarks Regarding the Tests Described in Table 1.

- It appears in some tests that the addition of fibers increases the modulus of rupture significantly; this is not necessarily due to the fiber contribution to bending resistance, but instead, to the fact that fibers improve shear and interlaminar shear properties, allowing the main mesh reinforcement to provide a higher resistance prior to failure.
- The addition of fibers generally improves first cracking strength and leads to smaller crack spacing and width.
- In the tests analyzed, it is assumed that the plate has equal resistance under positive and negative bending, and in the two principal directions. In instances where the mesh used did not have an equal volume of longitudinal and transverse reinforcement, the total volume was adjusted to provide an equal basis for comparison.
- Although many tests were available in which FRP meshes such as Polypropylene and Nylon were used [6, 10], high performance meshes (Carbon, Kevlar, Spectra) were selected for this study, because of better elastic modulus, less creep effect, smaller crack width, and superior performance.
- All meshes were more or less square (except for the Hardwire®) and most had about equal volume of reinforcement in each direction.
- Except for series 4, all series were hand-manufactured and tested under similar conditions.
- The modulus of rupture values for the normal strength steel mesh (that is, typical ferrocement), used as a reference for comparison, are considered common for this type of application and are extensively documented [1, 13].

For efficiency purposes, the plates could be designed to have less reinforcement in one direction than in another or be less strong in negative bending than in positive bending. These alternatives are not considered in this evaluation; however, they allow further optimization of a given system and should be eventually considered in the future.

The conventional steel mesh considered had a yield strength of the order of 450 MPa while the high strength steel reinforcement (Hardwire®) had a tensile strength of 3150 MPa. Information on the properties of the other FRP reinforcing meshes can be found in [12-15].

3. FIBER VOLUME FRACTION, WEIGHT FRACTION, AND COST

3.1 Background

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. Moreover, the cost of the mesh is based on unit weight while the mesh mechanical efficiency in the composite is based on volume fraction in the composite. Since the unit weight of steel ranges from 3 to 8 times that of most FRP materials, and since the composite properties are based on volume fraction (or volume) of mesh, cost comparison should be based on equal performance and may favor FRP meshes over steel 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. An attempt is made next to illustrate cost comparison based on performance where performance is essentially taken as the modulus of rupture of the plates tested.

3.2 Performance and Willingness-to-Pay Price

In order to generate the results described in Table 3, the following definitions and relations are used.

The unit weight (or specific gravity, or density) ratio of an FRP (or non-steel) mesh to a steel mesh is defined as follows:

$$r_{uw} = \gamma_{FRP} / \gamma_{Steel} \tag{1}$$

where:

$\gamma_{FRP} =$ unit weight or specific gravity or density of FRP (or non-steel) material

$\gamma_{Steel} =$ unit weight or specific gravity or density of steel

Values of the above ratio and its inverse are summarized in Table 2 for the fiber materials used in this study.

Table 2 Fiber characteristics and density considered in this study.

Mesh, Textile or Fiber Material	Density	Ratio density of fiber material to steel	Ratio density of steel to fiber material
Steel	7.85	1	1
Glass	2.60	0.3265	3.02
Carbon	1.8	0.2286	4.36
Kevlar	1.44	0.1835	5.45
Spectra	0.91	0.1159	8.62
PVA	1.3	0.1602	6.03

The performance ratio per unit volume of reinforcement is defined as:

$$(Performance\ Ratio)_{volume} = \frac{\left(\dfrac{MOR}{V_r}\right)_{Mesh\ Material}}{\left(\dfrac{MOR}{V_r}\right)_{Steel}} \tag{2}$$

The ratio MOR/V_r represents the increment in modulus of rupture contributed by 1% volume fraction of total reinforcement. It is equal for instance to 7 MPa and 18.32 MPa respectively for test series 1 and 3 in Table 1.

Since the modulus of rupture is based on volume fraction (thus volume) but the cost of reinforcement is per unit weight, let us define a performance ratio based on equal weight of reinforcement as follows:

$$(Performance\ Ratio)_{weight} = \frac{\left(\dfrac{MOR}{V_r}\right)_{FRP}}{\left(\dfrac{MOR}{V_r}\right)_{Steel}} \times \frac{\gamma_{Steel}}{\gamma_{Mesh\ Material}} \tag{3}$$

If the unit price of steel (such as $ / kg) is given as U_{Steel} and is considered a reference for comparing the cost of other reinforcements (here identified as mesh material), the maximum “willingness-to-pay” unit price for an FRP mesh, assuming equal performance, is given by:

$$(U_{FRP})_{\max} = (Performance\ Ratio)_{weight} \times U_{Steel} \tag{4}$$

In order to be competitive with steel wire mesh, the unit price of an FRP mesh or textile or fabric should be lower than the “willingness-to-pay price” based on equal performance, thus:

$$U_{FRP} \leq (Performance\ Ratio)_{weight} \times U_{Steel} \tag{5}$$

Calculations related to the above equations are summarized in Table 3. The maximum willingness-to-pay price from Eq. (4) is given in column (g); it assumes the cost of normal steel wire mesh (such as square welded or woven with a 6 to 13 mm wire spacing) to be equal to $ 4 per kilogram, (about $ 1.8 per lb). It can be observed, that everything else being equal, one should be willing to pay (Eq. 5) up to about $ 52 per kg for Kevlar mesh and $ 68 per kg for a Spectra mesh (series 13 and 14).

Note that the values given in column (g) of Table 3 are slightly biased for hybrid systems where fibers are used in combination with carbon, Kevlar and Spectra meshes, because they assume that the cost of fiber and mesh are equal. Since the cost per unit weight of PVA fibers used is, at time of this writing, smaller than that of carbon, Kevlar, or Spectra meshes, the corresponding willingness-to-pay price calculated is on the low side. Should there be need for a more precise evaluation, it is possible to separate the price of the fiber and mesh materials and provide an adjusted “willingness-to-pay price” for the mesh.

3.3 Remarks Regarding the Results in Table 3

Column (f) of Table 3 provides the performance ratio based on weight comparing the performance of a mesh made from non-steel material to that of a conventional steel mesh of normal strength. For instance, for equal MOR values, if the price per unit weight of a conventional steel mesh is 1 unit (series 1), one should be willing to pay up to 3 units for a high strength steel mesh (series 2), or up to about 14 units for a Kevlar mesh (series 6).

Series 1 to 8 had no fibers and series 9 to 15 were hybrids with 1% fiber content. While for carbon meshes, the willingness-to-pay price suffers significantly with fiber addition (compare series 3 and series 11 where the willingness-to-pay price decreases from11.41 to 8.08 units (column (f) of Table 3)), the willingness-to-pay price remains about the same for Kevlar and Spectra meshes (compare series 6 and 7 with series 13 and 14). One of the main reasons is that, in the case of carbon meshes, a brittle failure occurred at about the same load even when fibers where used, while for other meshes the fibers helped increase shear resistance improving the efficiency of the mesh.

Table 3 Performance index based on volume and weight of reinforcement.

Series ID Number	Depth, mm	Mesh Type	MOR per 1% total reinf. V_r (V_{mesh} + V_f) (MPa)	Perf. Index Volume (Eq. 2)	Perf. Index Weight (Eq. 3)	Willingness to pay price per kilogram, of fiber material assuming normal steel mesh price = $ 4 per kg.
(a)	(b)	(c)	(d)	(e)	(f)	(g)
1	12.5	Steel (normal strength)	7	1	1	4
2		Steel (high strength)	21	3	3	12
3		Carbon 1	18.32	2.62	11.41	45.64
4		Carbon 1 (Machine pultruded)	26.7	3.81	16.63	66.52
5		Carbon 2	17.86	2.55	11.12	44.48
6		Kevlar	18.06	2.58	14.06	56.24
7		Spectra	15.57	2.22	19.17	76.68
8		3D-Glass	10.4	1.48	4.48	17.92
9	12.5	Steel (normal strength)	Use 7 (fibers are not needed.)	1	1	4
10		Steel (high strength)	23.94	3.42	3.42	13.68
11		Carbon 1	12.98	1.85	8.08	32.32
12		Carbon 2	11.04	1.58	6.87	27.48
13		Kevlar	16.74	2.39	13.03	52.12
14		Spectra	13.86	1.98	17.07	68.28
15		3D-Glass	5.28	0.75	2.28	9.12
16	75	Steel (low strength)	4.35	1	1	4
17		Steel (high strength)	8.94	2.05	2.05	8.2
18		Kevlar	6.54	1.5	8.19	32.76

The unit price of conventional steel mesh assumed in column (g) of Table 3 is reasonable at time of this writing (US prices, 2005), leading to credible willingness-to-pay unit prices for the other meshes. Thus one should be willing to pay up to US $ 68 per kg for Spectra mesh (series 14) and up to US $ 52 per kg for Kevlar mesh (series 13).

If fibers are not needed for improved crack width and spacing, one should be willing to pay up to about US $ 18 per kg for a 3D glass mesh (series 8). Should crack width and spacing be of concern, the willingness to pay price drops to about US $ 9 per kg.

Series 16, 17 and 18 refer to plates thicker (75 mm) than series 1 to 15 (12.5 mm). For these series, the willingness-to-pay price for high performance meshes drops. For instance, the willingness to pay price for Kevlar mesh is US $ 32.76 for series 18 compared to US $ 52.12 for series 13. This is because the fiber mat used in the fabrication process introduces a volume fraction of fibers (V_f = 1%) higher than that of the mesh and induces a strong bias (or error) in the calculated price of the mesh. Reducing the volume of fiber mat say to 0.5% instead of 1% by volume, will strongly influence this result.

4. COMPARISON BETWEEN WILLINGNESS-TO-PAY PRICE AND CURRENT PRICES

The purchase price of FRP reinforcements or textiles varies widely depending on many factors, such as location, time, availability, size of order, supply and demand, and the like. For instance, depending on their properties and quality, carbon fibers in the US vary in cost form about US $ 20 per kilogram to US $ 1000 per kilogram. Glass fibers vary in price from US $ 1 to $ US 10 per kg, and Kevlar (aramid) from US $ 20 to US $ 30 per kg. These prices are likely to double the fibers are manufactured into textiles useful for reinforcing concrete.

Table 4. Prices for 2004 compared to willingness-to-pay prices derived from tests.

Material (1)	Price*, Euro / m^2 (2)	Price*, Euro / kg (3)	Willingness-to-pay price (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. 8).

In a study published in 2004, Kruger provides information about the quoted approximate market prices in Europe of different textiles used in his experiments [8]. The quoted price is based on a textile roll, one thousand meters long, and 1.27 meter wide. Three textiles (glass, carbon, aramid) were considered for two cases, one where the yarns are impregnated with epoxy, and one where they are not. Impregnating with epoxy leads to higher yarn performance but also higher cost. The prices given by Kruger are in Euro per square meter and are summarized in the second column of Table 4. Corresponding prices in Euro per kilogram are derived and given in the third column. The range of willingness-to-pay prices obtained in Table 3 for the three textile materials are summarized in the forth column. Although there is continuous currency fluctuation between the Euro and the US $, they are assumed equal for this comparison. The remark in the fifth column of Table 4 indicate whether a textile is competitive (at time of this writing) with steel meshes for thin cement products. It can be observed that only carbon is competitive whether the yarns are impregnated with epoxy or not. Glass is competitive if not impregnated and becomes too expensive (only within 10%) when impregnated. It seems that aramid is not competitive in the two cases. These results should be interpreted with a broad perspective as well as

precaution, keeping in mind that the performance of the composite only considered the modulus of rupture, that the meshes used had yarns not impregnated with epoxy, and that prices of advanced fibers such as aramid and carbon vary over a very wide range.
As mentioned above all the textiles used in this study had yarns not impregnated with epoxy. The textiles tested by Kruger [8] included yarns both impregnated with epoxy and without it, as shown in the first column of Table 4. However, Kruger also showed in his tests that the tensile resistance of the textile and equivalently the modulus of rupture of the composite changes significantly with epoxy impregnation. The improvement was highest for glass. It is therefore expected that the willingness-to-pay price for these textiles will be significantly higher and is likely to make them competitive in all cases of Table 4. A detailed evaluation is left for a future study.

5. CONCLUDING REMARKS

This investigation provides a good start for the evaluation of the cost-performance of FRP reinforcements (or textiles or fabrics) in comparison to steel reinforcements in thin reinforced concrete products. It has the advantage to be based on experimental results carried out under similar conditions in which failure may be due to several possible causes, instead of analytical predictions where only one mode of failure may be considered. The following conclusions can be drawn.

1. In non-hybrid reinforcement systems (that is, with no discontinuous fibers), if the cost of conventional steel mesh is US $ 4 per kilogram, one should be willing to pay roughly up to US $ 12 per kg for very high strength steel mesh, US $ 45 per kg for a carbon mesh, US $ 56 per kg for a Kevlar mesh, US $ 76 per kg for Spectra mesh, and US $ 18 per kg for a 3D glass mesh.

2. In hybrid systems (that is containing fibers) where other performance criteria (such as cracking, energy absorption, spalling, etc) are better than in non-hybrid systems, if the cost of conventional steel mesh is US $ 4 per kilogram, one should be willing to pay roughly up to US $ 13.7 per kg for very high strength steel mesh, US $ 32 per kg for a carbon mesh, US $ 52 per kg for a Kevlar mesh, US $ 68 per kg for Spectra mesh, and US $ 9 per kilo for a 3D glass mesh.

3. Generally hybrid reinforcement systems lead to lower values of “willingness-to-pay” price for the mesh reinforcement than non-hybrid systems. However, their performance with respect to criteria other than strength, such as cracking and crack width, shear and interlaminar shear resistance, ductility, energy absorption capacity, bond, and resistance to spalling and fragmentation, far out-weights the possible difference in price. The author recommends preferably hybrid systems when textiles or FRP reinforcements are used.

4. It should be noted that conventional steel meshes such as used in typical ferrocement did not need fiber reinforcement as for FRP textiles because the addition of fibers (1% PVA fibers by volume) does not influence much ferrocement performance. The modulus of rupture did not increase much and other criteria such as stress at first cracking, crack width and spacing were already good without fibers. Thus the reference price of $ 4 per kilogram for steel mesh (Table 3) was kept same as if fibers are not used. If the influence of fibers is considered, then the increment of MOR per unit weight of reinforcement decreases and leads to willingness-to-pay prices for non-steel materials higher than listed in Table 3 for series 9 to 15, by about one third.

5. The price values listed under conclusions 1 and 2 above provide a broad range of willingness-to-pay prices which can be compared with ongoing market prices to help

make rational decisions about whether or not to use FRP reinforcements and textiles as replacement to steel meshes in thin cement products.

Note finally that all FRP meshes and textiles used in this study had yarns not impregnated with epoxy. While epoxy impregnation increases the cost of the textile, it also makes it more effective, that is the resistance contributed by the textile increases. This should increase the willingness-pay-price for these materials.

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