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Bending Behavior of Mortar Reinforced with Steel Meshes and Polymeric Fibers

M. K. El Debs[a] & A. E. Naaman[b]

[a] Department of Structures, Engineering School at São Carlos, University of São Paulo, Av. Dr. Carlos Botelho, 1465-13560-250 São Carlos SP, Brazil
[b] Department of Civil and Environmental Engineering, The University of Michigan, 2340 GG Brown Building, Ann Arbor, Michigan 48109-2125, USA

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Abstract

The main purpose of this research was to study the effects of combining reinforcing steel meshes with discontinuous fibers as reinforcement in thin walled Portland cement based mortar beams. The term 'thin' implies thicknesses of less than about 25 mm. The underlying idea behind this combination is to satisfy the ultimate strength limit state through the steel mesh reinforcement (main reinforcement) and to control cracking under service loads through fiber reinforcement (secondary reinforcement).

An extensive experimental program with bending tests was undertaken. Specimens were 127 × 457 × 12·7 mm. The following variables were investigated: (a) the reference mesh size — 25·4 × 25·4 mm and 50·8 × 50·8 mm; (b) the transverse wire spacing — 25·4 mm, 50·8 mm, and no transverse wires; (c) the type of fibers — polyvinylalcohol (PVA) and polypropylene (PP); and (d) the fiber volume fraction — 1 and 2% for PVA fibers, and 0·5 and 1% for PP fibers.

Some of the main conclusions are: (a) for the same fiber volume fraction, the use of PVA fibers led to a better overall performance than that of PP fibers; (b) an increase in cracking moment and a decrease in crack spacing was observed when 1% PVA, 2% PVA, and 1% PP fibers were used; (c) when 0·5% PP fiber was used, no noticeable change in behavior was observed in comparison to specimens without fibers; and (d) for 1% PVA fibers the transverse wire spacing had little effect on the crack spacing and for 2% PVA fibers, the transverse wire had no influence.

INTRODUCTION

Definition

Portland cement based thin sheets or cladding elements are typically made with fiber reinforced concrete (mortar) or ferrocement. These materials have been used in construction applications and they are particularly suitable for prefabrication and industrialized production.[1]

According to ACI Committee 549,[2] ferrocement is a Portland cement mortar reinforced with closely spaced multiple layers of mesh and/or small diameter rods. Ferrocement is characterized by high ductility, small crack widths and improved impact resistance. Because of the high cost of steel wire mesh, and the high labor cost associated with placing several layers of it, ferrocement is considered uneconomical in numerous potential applications.

The use of fiber reinforced concrete in thin walled elements is reported in the technical literature, as for example in Balaguru & Shah.[3] The most common products are asbestos cement and glass fiber reinforced concrete; however, other types of fibers, like polypropylene, carbon and PVA (polyvinylalcohol), have been tried. One of the advantages of fiber reinforcement, compared to mesh reinforcement such as in ferrocement, is that fibers are premixed with the matrix, thus leading to enormous savings in labor cost. However, discontinuous fibers are mechanically not as efficient as continuous meshes. There is great hope that high performance fiber reinforced cement composites (using discontinuous fibers) will eventually achieve a performance similar to that of ferrocement.

Background information

Several studies have reported the use of fibers in combination with wire mesh as reinforcement for thin mortar elements. In most of these studies steel fibers and steel meshes were used. Studies particularly related to the experimental work of this investigation are briefly reviewed next.

Atcheson & Alexander[4] and Alexander[5] investigated ferrocement reinforced with a combination of steel wire meshes and steel fibers, with a volume fraction of fibers of about 5% by weight; they concluded that steel fibers allow the use of larger mesh opening than is possible with plain mortar.

Swamy & Spanos[6] studied the effects of combining steel meshes with several types of fibers, and concluded that 'the introduction of fibers in the matrix results in better cracking performance than that obtained by close-spaced mesh alone'. The important role of the fibers in crack control is also confirmed by Swamy & Hussin[7] and Hussin & Swamy[8] following studies where welded wire meshes were used with either 1·74% or 4·37% fibers by volume.

Several other experimental investigations by Kaushik & Menon,[9] Silva,[10] and Ohama & Shirai[11] have concluded that fibers improve the mechanical behavior of ferrocement.

Objectives and scope

In this investigation, the association of continuous and discontinuous reinforcements for thin reinforced concrete products is explored following a design philosophy different from that of previous studies.

The main idea is to extend the principles of reinforced concrete design by using continuous steel reinforcement as the main reinforcement to satisfy ultimate strength limit states, and the fibers as a secondary reinforcement to control cracking and satisfy the crack width limit state in service; improvement in shrinkage cracking is also expected. This leads to the following features of the experimental program as compared to typical investigations on ferrocement: (a) the use of steel wire mesh only in the tension zone, that is, generally only one mesh layer per specimen; (b) the use of steel meshes with opening and/or transverse wire spacing larger than commonly used in ferrocement; and (c) the use of a relatively low volume fraction of fibers in order to promote crack control. Differently from most prior investigations, instead of steel fibers, polymeric fibers were used.

The main advantage of this approach is a possible overall reduction in cost while improving performance. Indeed, including in a thin walled bending element a ratio of transverse reinforcement (transverse wire) equal to that of the longitudinal reinforcement, as is generally the case in ferrocement, is extremely inefficient. Similarly, adding reinforcement in the compression zone, which is not technically needed, is not cost effective. Moreover, decreasing the number of layers of steel meshes leads to a direct reduction in labor cost, which is an important factor of the cost of ferrocement.

The main objective of this study was to investigate the bending behavior of mortar reinforced simultaneously with only one layer of steel mesh (with various transverse wire spacing) and with polymeric fibers. The polymeric fibers used were polyvinylalcohol (PVA) and polypropylene fiber, both in monofilament form.

EXPERIMENTAL PROGRAM

Variables

The experimental program is described in detail in a report by El Debs and Naaman.[12] The program comprised more than 70 thin sheet mortar beam tests. It is summarized in Table 1. The following variables were investigated: (a) type of fibers, namely polyvinylalcohol (PVA) or polypropylene (PP); (b) volume fraction of fibers, namely 1 and 2% for PVA fibers and 0·5 and 1% for PP fibers; (c) reference mesh size $25{\cdot}4 \times 25{\cdot}4$ mm (1×1 in) and $50{\cdot}8 \times 50{\cdot}8$ mm (2×2 in); and (d) transverse wire spacing (TWS) 25·4 mm (1 in), 50·8 mm (2 in) and infinity, i.e. no transverse wire. This program also included two special specimens. One specimen had two steel layers, one in the tension zone and one in the compression zone (similarly to conventional ferrocement), and the other specimen had the transverse wire removed by a method different from that of the regular specimens. Additional information is given below.

Referring to Table 1, the specimen ID was generally defined according to four characteristics, such as XP-*m*-*n*: the first letter (X)

Table 1. Details of experimental program

Fiber type	*Fiber volume fraction*	*Reference mesh size*		*Transverse wire spacing (TWS)*		*Specimen ID*
		(mm × mm)	*(in × in)*	*(mm)*	*(in)*	
		None	None	None	None	N-N
				25·4	1	N-1-1
None	None	25·4 × 25·4	1 × 1	50·8	2	N-1-2
				Infinite	Infinite	N-1-f
		50·8 × 50·8	2 × 2	50·8	2	N-2-2
				Infinite	Infinite	N-2-f
		None	None	None	None	A1-N
				25·4	1	A1-1-1
	1%	25·4 × 25·4	1 × 1	50·8	2	A1-1-2
				Infinite	Infinite	A1-1-f
		50·8 × 50·8	2 × 2	50·8	2	A1-2-2
				Infinite	Infinite	A1-2-f
PVA		None	None	None	None	A2-N
				25·4	1	A2-1-1
	2%	25·4 × 25·4	1 × 1	50·8	2	A2-1-2
				Infinite	Infinite	A2-1-f
		50·8 × 50·8	2 × 2	50·8	2	A2-2-2
				Infinite	Infinite	A2-2-f
		None	None	None	None	P0·5-N
PP	0·5%	50·8 × 50·8	2 × 2	50·8	2	P0·5-2-2
		None	None	None	None	P1-N
	1%	50·8 × 50·8	2 × 2	50·8	2	P1-2-2
Special specimens						
None	None	25·4 × 25·4	1 × 1	25·4	1	N-1-1(S)
PVA	2%	50·8 × 50·8	2 × 2	Infinite	Infinite	A2-2-f(S)

identifies the type of fiber (A for PVA fiber and P for PP fiber); the second letter identifies the volume fraction of the fibers; the third letter (m) identifies the reference mesh size in inches, and the last letter (n) identifies the transverse wire spacing (TWS), in inches; for example A1-1-f, means PVA fibers with 1% volume fraction, 25·4 × 25·4 mm (or 1 × 1 in) reference mesh size, and a transverse wire spacing of infinity (i.e. no transverse wires).

The desired transverse wire spacing was obtained by cutting the transverse wire of the reference square mesh as close as possible to the longitudinal wire. However, for the special specimen N-2-f (S) the transverse wires were completely removed. The special specimen N-1-1 (S) had two meshes symmetrically placed in the tension and compression zones like traditional ferrocement.

Three specimens were tested for each variable, except for A2-2-f (S) which had only two specimens.

Specimen geometry

All specimens were 127 mm (5 in) wide, 457 mm (18 in) long and 12·7 mm (0·5 in) thick. The net cover to the steel reinforcement was 2·3 mm (0·09 in).

Materials

In this investigation, commercially available galvanized steel welded square meshes were used. Their characteristics are given in Table 2. At least five samples of steel wires were cut from each mesh and tested in a universal testing machine (Instron) to determine their stress–strain response in tension. A relatively large variability was observed in both the recorded strength and strain to failure. This may be because these meshes were not meant as reinforcement for concrete, only as fencing materials.

As mentioned earlier, polyvinylalcohol (PVA) and monofilament polypropylene (PP) fibers were used. Their characteristics are summarized in Table 3.

The mortar mix proportions were identical for all specimens. They were as follows, taken as proportion by weight of cement: 1 for Portland cement (Type I-ASTM); 2 for sand (ASTM 20/30 silica sand); 0·2 for fly ash; 0·02

Table 2. Characteristics of steel meshes used

Mesh ID	*Opening (mm × mm)*	*Wire diameter (mm)*	*Ultimate strength (MPa)*	*Fracture strain (× 1000)*
M1	25·4 × 25·4	2·03	364	119
M2	50·8 × 50·8	2·67	556	49·5

Table 3. Characteristics of fibers used

Fiber type	*Specific gravity (kg/m³)*	*Length (mm)*	*Diameter (mm)*	*Tensile strength (MPa)*	*E (GPa)*
PVA	1·3	12·0	0·2	900	29
PP	0·91	12·7	0·095	NA	NA

Note: Monofilament fibers used; E — modulus of elasticity; NA — not available.

Table 4. Compressive strength of matrices used

	Matrix				
	N (none)	*A1 (1% PVA)*	*A2 (2% PVA)*	*P0·5 (0·5% PP)*	*P1 (1% PP)*
Average (MPa)	43·01	40·97	35·00	38·55	41·39
Average (ksi)	6·24	5·92	5·08	5·59	6·00

Mixture proportions by weight: cement=1; sand=2; fly ash=0·2; superplasticizer=0·02; water=0·6.

for superplasticizer (Melment); and 0·6 for water.

The average compressive strength of the plain mortar mix and the fiber reinforced mortar with different volume fractions of PVA and PP fibers, were obtained from standard compression tests on 76 × 152 mm cylinders used four samples at an age of 35 days; they are given in Table 4. Note that the addition of fibers generally leads to a reduction in compressive strength; the decrease may be significant if high air entrapment due to fiber addition (such as in the case of 2% PVA fibers) is generated during mixing.

Reinforcement parameters

Table 5 summarizes the most important parameters. They are: (a) $1/S_l$ — this is the inverse of the specific surface of reinforcement S_l of the longitudinal reinforcement; it is the ratio of the surface area of the longitudinal reinforcement per unit volume of composite; (b) V_s — total volume fraction of steel reinforcement, that is, the volume of total steel wires (longitudinal and transverse) divided by the volume of the composite; (c) ρ_l — ratio of tension steel reinforcement, that is, the ratio of the sum of cross-sectional areas of the longitudinal wires to the product of the section width (127 mm for all specimens) by the section depth; the section depth is the distance from the extreme compression fiber to the centroid of longitudinal reinforcement (8·4 mm for specimens with M1 mesh and 7·9 mm for specimens with M2 mesh); (d) steel consumption — the weight of total steel reinforcement per unit volume of composite; and (e) fiber consumption — the weight of fibers per unit volume of composite.

Specimen preparation and testing procedure

All specimens were cast in vertical Plexiglass molds. The matrix components and the fibers were mixed using a special mixer for fiber concrete (Omni-type mixer). All materials were placed together and mixed for about 3 min. The molds were placed on a vibrating table during pouring of the mortar matrix. In addition to the vibration, it was sometimes necessary to push the matrix with a rod to improve penetration. This was particularly true for the matrices containing 2% PVA fibers or 1% PP fibers.

For the first 24 h, the molds with the speci-

Table 5. Reinforcement parameters

Specimen ID	$1/S_l$ (mm)	V_s (%)	ρ_l (%)	Steel consumption (kg/m^3)	Fiber consumption (kg/m^3)
N-N	—	None	—	None	
N-1-1				157·8	
N-1-2	50·5	1·005	1·523	118·3	None
N-1-f				78·9	
N-2-2	64·2	1·039	1·676	163·0	
N-2-f				81·5	
A1-N	—	None	—	None	
A1-1-1				157·8	
A1-1-2	50·5	1·005	1·523	118·3	13·0
A1-1-f				78·9	
A1-2-2	64·2	1·039	1·676	163·0	
A1-2-f				81·5	
A2-N	—	None	—	None	
A2-1-1				157·8	
A2-1-2	50·5	1·005	1·523	118·3	26·0
A2-1-f				78·9	
A2-2-2	64·2	1·039	1·676	163·0	
A2-2-f				81·5	
P0·5-N	—	None	—	None	4·6
P0·5-2-2	64·2	1·039	1·676	163·0	
P1-N	—	None	—	None	9·1
P1-2-2	64·2	1·039	1·676	163·0	
Special specimens					
N-1-1 (S)	50·5	2·010	1·523	315·6	None
A2-2-f (S)	64·2	1·039	1·676	81·5	26·0

S_l — specific surface of longitudinal reinforcement.
V_s — steel volume fraction; ρ_l — ratio of tension steel reinforcement.

mens were covered by a plastic sheet. Then, the specimens were removed from the molds and cured in a water tank for 27 days; they were then left in a laboratory environment until testing. All specimens were tested at 35 ± 2 days after casting.

The specimens were tested in an MTS servo-controlled hydraulic testing machine. A four-point loading fixture with a 355 mm span and a 152 mm constant bending moment zone was used. The cross head rate was 2·5 mm/min.

A computer based data acquisition system was used to record the load from the load cell of the machine, the cross head displacement of the machine, and the deflection from 3 LVDTs (linear voltage differential transducers) placed under the specimen. One LVDT was positioned under the mid-span section and the two others were placed under the two loading points.

The beam specimens were loaded until failure or to a maximum machine displacement of 30 mm, whichever occurred first. The LVDTs were removed when the mid-span deflection was close to 10–12·5 mm, after which only the LVDT of the machine was monitored.

RESULTS

General

The results obtained from the data acquisition system were processed and plotted as load (or equivalent elastic stress) versus deflection curves; the representative average curve of each series of identical specimens was obtained using an averaging technique developed at the University of Michigan and implemented in a computer program written by J. Alwan.

At first, it should be pointed out that the control specimens N-N (plain mortar without mesh or fibers) and specimens P05-N (without mesh and with 0·5% PP fibers) led to very inconsistent results. Some broke prematurely, very likely due to shrinkage cracking. For these specimens, only one sample curve was considered.

It should also be noted that for most specimens with M1 mesh the tests were interrupted when the machine displacement achieved about 30 mm, while most specimens with M2 mesh failed at a smaller deflection.

After testing, the tensile surface of the specimen in the constant moment zone was examined with a microscope and the cracks were marked with ink.

The results are analysed next with respect to three aspects: load versus midspan deflection, cracking behavior, and values of bending moments at cracking, yielding and ultimate.

Load versus average midspan deflection curves

For the purpose of evaluation and in order to allow comparison with ferrocement specimens of different geometries and from different investigations, the load was transformed into the equivalent elastic bending stress, assuming uncracked section behavior. The stress is computed from the following equation:

$$\sigma = \frac{M}{Z}$$

where M is the bending moment in constant moment and Z is the section modulus. For the given geometric properties of the specimen assumed uncracked, the equivalent elastic bending stress is given by:

$\sigma = 0{\cdot}0149P$ for σ in MPA and P in N;

$\sigma = 9{\cdot}60P$ for σ in psi and P in Lb.

The average bending stress versus mid-span deflection curves of the control beam as well as the beams with fibers but without meshes are shown in Fig. 1. It can be observed that, for the same volume fraction of fibers, PVA fibers lead to a better performance than PP fibers. For a volume fraction of 0·5% PP, there is very little resistance after first cracking. At 1% content of PP fibers, the beams showed a small post-cracking resistance that represents an equivalent bending stress of about 1·4 MPa. In the case of beams with 1% PVA fibers the equivalent stress was about 3·2 MPa. One of the three specimens showed multiple cracking behavior. All beams with 2% PVA fibers achieved ultimate moments larger than the cracking moment, developed by multiple cracking in the constant moment region, and sustained equivalent bending stresses of about 5·5 MPa.

Figure 2 shows a comparison of stress versus mid-span deflection curves for specimens with M1 mesh and transverse wire spacing (TWS) equal to 25·4 mm. It can be observed that the specimens with 1 and 2% PVA fibers developed higher resistance at equal deflections than those without fibers, whether one or two reinforcing meshes were used. The specimen with two reinforcing meshes had a higher strength than the specimen with one mesh; however, in the elastic cracked range of behavior, it had practically the same deformation.

In Fig. 3 the stress deflection curves of the specimens reinforced with M2 mesh and TWS

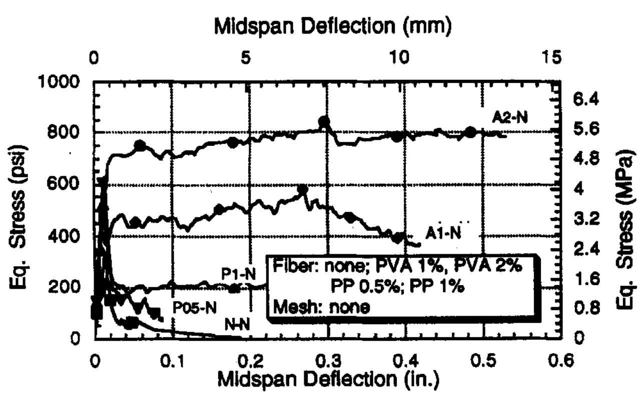

Fig. 1. Equivalent stress–midspan deflection curves of specimens without steel mesh.

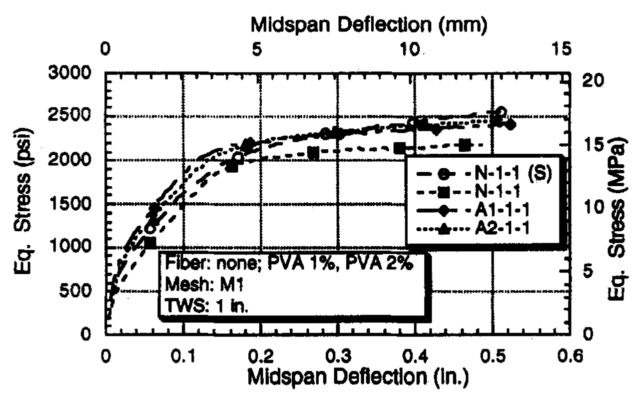

Fig. 2. Equivalent stress–midspan deflection curves of specimens with M1 mesh and 25·4 mm TWS.

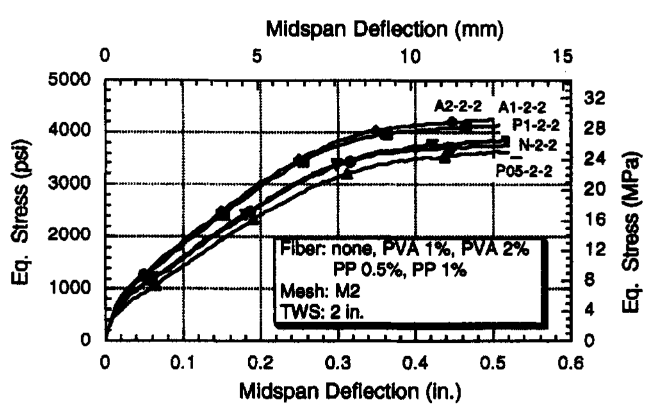

Fig. 3. Equivalent stress–midspan deflection curves of specimens with M2 mesh and 50·8 mm TWS.

(transverse wire spacing) equal to 50·8 mm, and different types of fibers are compared. It can be observed that, similarly to the case of specimens with M1 mesh, specimens with 1 and 2% PVA fibers were more resistant than the control without fibers and the specimen with 0·5 and 1% PP fibers.

Figure 4 provides a comparison for specimens with M2 mesh and without transverse wires (TWS=infinite) for different PVA fiber contents. The special specimen A2-2-f (S), whose transverse wires were completely removed, is also included. It can be seen that this specimen had an ultimate resistance lower than the others, but the initial portion of is stress–deflection curve is about the same. This is because the removal by grinding of the transverse wires weakened the longitudinal wires. Similar to

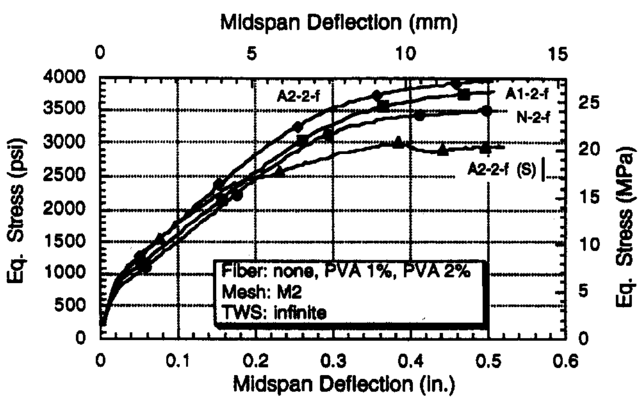

Fig. 4. Equivalent stress–midspan deflection curves of specimens with M2 mesh and without transversal wire (TWS=infinite).

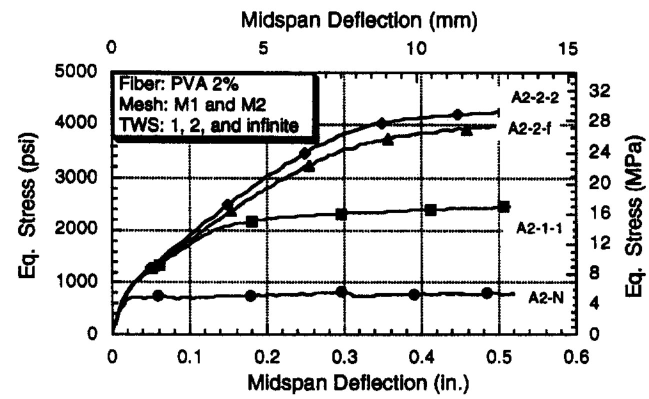

Fig. 5. Equivalent stress–midspan deflection curves of specimens with 2% PVA fibers.

Table 6. Number of cracks in the constant bending zone (152·4 mm)

(a) Counting all cracks along the two borders and the middle axis

Steel mesh	*TWS (mm)*	*Matrix*				
		N (None)	*A1 (1% PVA)*	*A2 (2% PVA)*	*P0·5 (0·5% PP)*	*P1 (1% PP)*
	25·4	8·7	11·3	11·5	—	—
M1	50·8	10·7	12·0	11·4	—	—
	Infinite	8·4	10·8	12·6	—	—
M2	50·8	8·6	10·6	11·8	9·0	9·9
	Infinite	7·6	11·0	13·4	—	—
Special specimens						
N-1-1 (S)	25·4	10·3	—	—	—	—
A2-2f (S)	Infinite	—	—	12·7	—	—

(b) Counting only main cracks without their branches

Steel mesh	*TWS (mm)*	*Matrix*				
		N (None)	*A1 (1% PVA)*	*A2 (2% PVA)*	*P0·5 (0·5% PP)*	*P1 (1% PP)*
	25·4	7·0	10·6	9·6	—	—
M1	50·8	7·0	9·0	10·3	—	—
	Infinite	6·0	8·3	10·3	—	—
M2	50·8	5·3	8·6	9·0	6·0	8·0
	Infinite	5·0	9·0	9·0	—	—
Special specimens						
N-1-1 (S)	25·4	7·6	—	—	—	—
A2-2f (S)	Infinite	—	—	8·5	—	—

other cases, the addition of PVA fibers led to higher bending stresses at any given deflection.

In Fig. 5 the stress–deflection curves of specimens with 2% PVA fibers, with different steel meshes, and different TWS are compared. Also included is the test series without steel mesh (specimens A2-N). It can be observed that the initial portion of curves is about the same for all specimens; however, the yield and ultimate moments of specimens with M1 mesh are lower than the others.

Cracking

After the tests, the cracks in the constant moment region of 152 mm were traced with a pencil and counted. Two approaches were used: (a) counting all cracks intersecting the two borders and the middle axis of the specimen; and (b) counting only main cracks without their branches. The results of this counting are summarized in Table 6. Note that for the first approach, the number of cracks is the average of nine measurements, while for the second approach it represents the average of three samples.

A representative sample of each series was selected and photographs were taken for the records and for comparison of cracking patterns. Some of these are shown in Figs 6–8. From these figures and from Table 6 the following observations were made: (a) for the range of parameters tested, the transverse wires (or transverse wire spacing) of 25·4 or 50·8 mm seem to have very little influence; (b) the addition of 1% PVA fibers leads to a decrease in crack spacing of about 30% for specimens with M1 mesh and 80% for specimens with M2 mesh, while the ultimate resistance remains of the same order; (c) the addition of 2% PVA fibers leads to a decrease in crack spacing of about 43% for specimens with M1 mesh and 80% for specimens with M2 mesh; (d) the addition of 0·5% PP fibers does not seem to have any noticeable effect on crack spacing and width; a clearer effect can be observed when 1% PP fibers are used; in this case the crack spacing decreases 60% for specimens with M2 mesh; (e) for the same fiber volume fraction of 1%, PVA fibers led to more cracks, thus smaller crack spacing, than PP fibers; (f) when 2% PVA fibers are used, there is practically no influence of transverse wire spacing; thus the transverse wires are not needed for crack control; (g) A2-2-f (S) specimens behaved very similarly to A-2-f specimens, implying that for 2% volume fraction of PVA fibers, the complete removal of transverse wires does not affect cracking behavior; and (h) the use of two symmetrical mesh layers in the tension and compression zones (specimen N-1-1 (S)) does not affect the crack distribution in the tensile zone.

The number of cracks and the corresponding average crack spacing obtained from these tests can be compared with results of conventional ferrocement beams such as those given by Balaguru *et al.*[13] They report an average crack

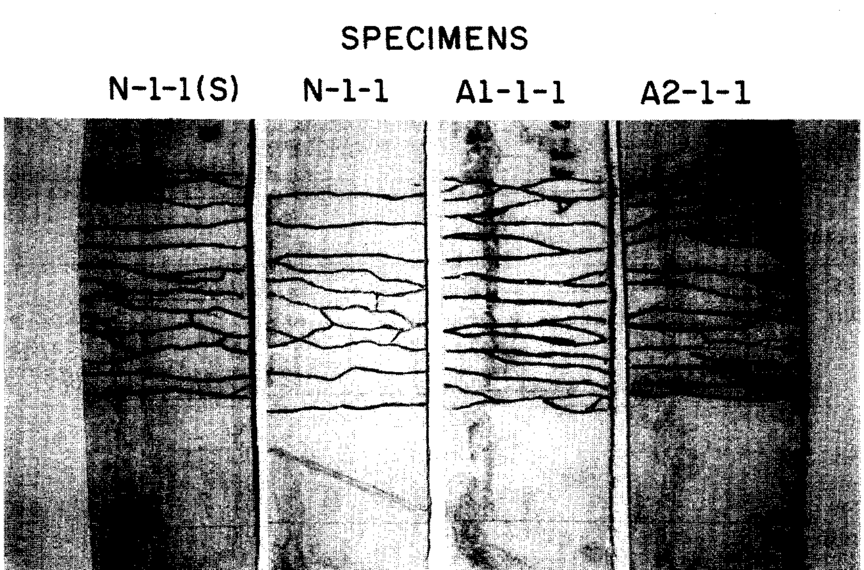

Fig. 6. Cracking pattern in specimens with M1 mesh and 25.4 mm transverse wire spacing — specimens: N-1-1 (S); N-1-1; A1-1-1; and A2-1-1.

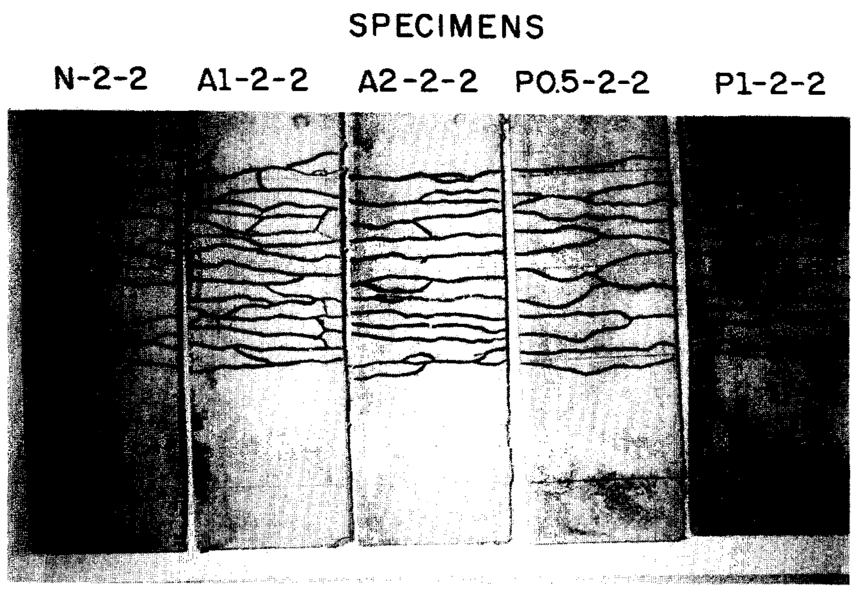

Fig. 7. Cracking pattern in specimens with M2 mesh and 50·8 mm transverse wire spacing — specimens: N-2-2; A1-2-2; A2-2-2; P0·5-2-2; and P1-2-2.

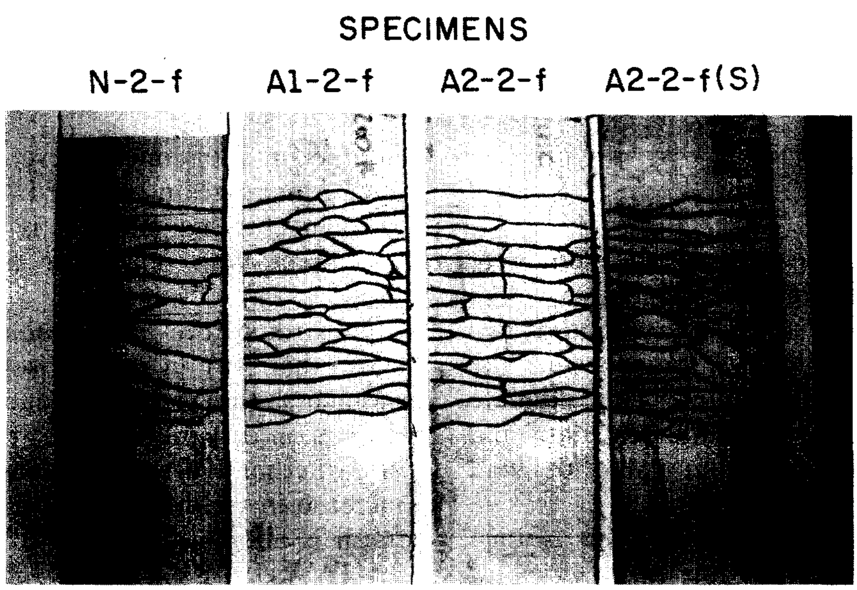

Fig. 8. Cracking pattern in specimens with M2 mesh and without transverse wire spacing — specimens; N-2-f; A1-2-f; A2-2-f; and A2-2-f (S).

spacing of 12·7 mm for ferrocement beams using four layers of 12·7 mm opening square welded mesh. From the test results of this study, a slightly larger crack spacing of 17 mm was observed for specimens with one layer of M2 mesh and 2% PVA fibers. The total volume fraction of mesh reinforcement in the tests of Balaguru *et al.* was 4·48% while the total volume for specimen A2-2-f was 3·04% including the 2% fiber content.

Moments at cracking, yielding of steel mesh and ultimate

The cracking moment was obtained directly from the load versus mid-span deflection curves; it corresponds to the point of first deviation from linearity, and generally indicates the propagation of one major crack across the section. The yield moment corresponds approximately to the second deviation point of the load–mid-span deflection curve. It was obtained

Table 7. Average bending moments observed

Specimen	*Moment (Nm)*		
	Cracking	*Yield*	*Ultimate*
N-N	7·8	7·8	7·8
N-1-1	13·0	47·4	54·6
N-1-2	15·6	48·5	57·4
N-1-f	13·8	45·7	54·0
N-2-2	16·5	83·0	89·8
N-2-f	17·7	78·2	83·1
A1-N	13·0	13·0	13·7
A1-1-1	19·5	52·3	61·7
A1-1-2	20·7	53·2	65·4
A1-1-f	18·3	43·8	56·1
A1-2-2	19·2	90·8	99·1
A1-2-f	19·8	89·9	96·9
A2-N	17·9	17·9	20·5
A2-1-1	20·7	52·0	62·0
A2-1-2	17·3	50·2	62·4
A2-1-f	18·2	46·3	55·4
A2-2-2	19·5	94·2	103·6
A2-2-f	23·3	89·6	97·7
P0·5-N	14·9	14·9	14·9
P0·5-2-2	11·6	79·7	87·0
P1-N	12·3	12·3	12·3
P1-2-2	17·1	85·8	92·8
Special specimens			
N-1-1 (S)	15·2	48·2	64·7
A2-2-f (S)	21·1	66·3	70·7

Table 8. Average bending moments for specimens with same characteristics

Specimen	*Moment (Nm)*		
	Cracking	*Yield*	*Ultimate*
N-1-1			
N-1-2		47·2	55·3
N-1-f	15·2		
N-2-2		80·7	86·5
N-2-f			
A1-1-1			
A1-1-2		49·7	61·1
A1-1-f	19·5		
A1-2-2		90·4	98·1
A1-2-f			
A2-1-1			
A2-1-2		49·5	60·0
A2-1-f	19·8		
A2-2-2		92·0	100·7
A2-2-f			
P0·5-2-2	12·3	79·7	87·0
P1-2-2	17·1	85·8	92·8
Special specimens			
N-1-1 (S)	15·2	48·2	64·7
A2-2-f (S)	21·1	66·3	70·7

directly from the curve in a manner similar to that recommended for ferrocement by ACI Committee 549;[2] that is, the intersection of two straight lines fitting the two branches of the curves adjacent to this point. The ultimate moment was obtained from the test data and corresponds to the maximum value of load recorded.

Tables 7 and 8 give, respectively, the average values of these moments for each series of specimens, and the average values of grouped series selected as follows: (a) for comparison of cracking moments, the test series without fibers, with 1% PVA, and with 2% PVA fibers; and (b) for comparison of yield and ultimate moments, the series without fibers, with 1% PVA fibers, and with 2% PVA fibers, for M1 mesh and M2 mesh. The following observations can be made.

For the cracking moments the results show that: (a) the cracking moments for the test series without fibers show great variability; (b) the average cracking moment increases, respectively, by 28 and 30% when 1 and 2% PVA fibers are added, in comparison with specimens without fibers; (c) the addition of 0·5% PP fibers does not lead to any noticeable increase in cracking moment; however, for 1% PP fibers a 12% increase in observed; and (d) no difference in cracking moment is observed between specimens with one layer and two layers of mesh.

Regarding the yield moments the results show that: (a) in comparison to the cracking moments, the yield moments have much less dispersion or variability; (b) the addition of fibers, whether PVA or PP, leads to a very slight increase in yield moments; the increase for M2 mesh is about 14, 12 and 6%, respectively for 2% PVA, 1% PVA and 1% PP fibers; and (c) a significant decrease in cracking moment is observed for specimen A2-2-f (S) in comparison with series A2-2-f, because of the possible reduction in longitudinal wire area due to the removal of transverse wires by grinding.

For the ultimate moments the results show that: (a) in comparing the control specimens without fibers to similar specimens with fibers, the addition of fibers generally leads to a slight increase in ultimate moment; the increase for M2 mesh is, respectively, 16, 13 and 7% for fiber contents of 2% PVA, 1% PVA and 1% PP; and (b) only a 17% increase in moment is observed when two symmetrical layers of mesh are used in the tension and compression zone instead of one layer in the tension zone.

CONCLUSIONS AND REMARKS

From the results of this experimental study, the following conclusions can be drawn:

(1) For an equal volume fraction of fibers, the addition of PVA fibers to ferrocement or thin reinforced mortar beams leads to a better overall performance (cracking behavior, yield and ultimate moments) than PP fibers;
(2) The addition of PVA (1 and 2% by volume) leads to an increase in cracking moment of up to 30% and a decrease in crack spacing and width of up to 80%.
(3) The addition of 1% PP fibers to the mortar matrix leads to a significant improvement in cracking behavior as illustrated by a decrease in average cracking spacing of about 60%.
(4) No significant influence was observed on either the cracking behavior or the yield and ultimate moments when 0·5% PP fibers were added.
(5) The presence of the transverse wires or their spacing seems to become unnecessary for crack control when either 1 or 2% PVA fibers are used. That is to say that the addition of the fibers leads to an average crack spacing smaller than the transverse wire spacing. In this case, the need for the transverse wire vanishes, except for its function of keeping the longitudinal wires in position.
(6) The behavior (load–deflection response curve and the cracking behavior) of beams reinforced with one mesh layer in the tension zone is identical to the behavior of beams reinforced with two symmetrical layers placed in the tension and compression zone. This implies that, for ferrocement elements acting as simple beams, substantial savings can be achieved by eliminating the mesh layer from the compression zone.

These conclusions confirm the idea that it is possible to use in thin reinforced concrete products continuous steel reinforcement as the primary reinforcement to satisfy the ultimate strength limit state, and fibers, as secondary reinforcement, to provide cracking control. Since cracking can be controlled by the fibers, the need for close transverse wire spacing to fulfil that role vanishes. In the present investigation the longitudinal wires used had a diameter substantially larger than those of typical meshes used in ferrocement. Thus their cost per unit weight will be significantly cheaper.

As mentioned earlier, the main advantage of exploring this idea is the decrease in overall steel (or reinforcement) consumption in comparison with traditional ferrocement where several layers of meshes are generally used. An overall reduction in cost should result. For instance the steel consumption in specimen N-1-1 (S) is 315·6 kg/m^3, while in specimen A2-2-f it is 81·5 kg/m^3 and 26·0 kg/m^3 of PVA fibers. These specimens gave comparable results in terms of strength and crack spacing. Assuming the cost of steel is 1 per unit weight, and the cost of fibers is 4 per unit weight (i.e. four times the cost of the steel), the total cost of the composite per unit volume not including labor would decrease from $(315{\cdot}6 \times 1) = 315{\cdot}6$ to $(81{\cdot}5 \times 1 + 26{\cdot}0 \times 4) = 185{\cdot}5$, or about 41%. Moreover, it is expected that a larger wire diameter and a larger transverse wire spacing would lead to a decrease in the unit cost of the mesh.

For practical applications, the following precautions should be considered: (a) it is necessary to use a steel mesh with good quality control unlike the steel mesh utilized in this investigation; this is because the mesh was meant for fencing not as reinforcement for concrete; it had a great variability in strength and strain capacity at failure; (b) in this study, a constant thickness of 12·7 mm was used; results can be extrapolated to larger thicknesses such as in the range of 25–38 mm; however, engineering judgement should be used and some adjustment must be made for the fiber orientation as affected by the ratio of fiber length to specimen thickness; and (c) it is important to choose for longitudinal reinforcement and adequate wire with proper diameter/cover and diameter/thickness ratios; that is, a large diameter wire should not be used with a small cover and a small thickness.

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