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MORTAR REINFORCED WITH STEEL MESHES AND FIBRES: A SUITABLE MATERIAL FOR THIN-WALLED CONCRETE ELEMENTS

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ABSTRACT

Thin-walled concrete elements are defined as structural elements, manufactured from cement-based materials, whose walls have conventional thickness from 15 mm up to 40 mm. These kinds of elements have been used in shell and folded plate roofs and panels for housing construction. The materials currently used in these elements are Fibre Reinforced Concrete and Ferrocement. The most common product is GRC - Glass fibre Reinforced Concrete. Ferrocement is a Portland cement mortar reinforced with closely spaced multiple layers. As ferrocement has continuous reinforcement, it has, in general, a good mechanical performance. However, the high steel meshes consumption (and consequently, a high man-labour) has inhibited the full development and dissemination of ferrocement technology. Portland cement mortar reinforced with large opening meshes, or only single wires, of high strength steel, and short fibres, such as polypropylene, PVA (polyvinylalcohol) or glass can be a suitable alternative for ferrocement in Civil Construction. In this case, a proper mechanical performance level for Civil Construction can be reached and, as the steel reinforcement is placed only in tension parts, the cost is significantly lower than ferrocement. This paper presents experimental results of mechanical behaviour (bending and tension tests) and a cost analysis in order to demonstrate that this material can be a suitable alternative to thin-walled concrete elements.

INTRODUCTION

Thin-walled concrete units are defined as structural elements, manufactured from cement-based materials, whose walls have thickness of 15-40 mm [6]. This kind of elements has been used in shell and folded plate roofs and panels for housing construction. Although they can be cast-in-place, these elements are particularly suitable for precast constructions. As these units are more lightweight than conventional concrete ones, this means a great convenience for prefabricated constructions.

The materials currently used in these elements are Fibre Reinforced Concrete and Ferrocement. The use of fibre reinforced concrete in thin-walled elements is reported in technical literature. The most common product is glass fibre reinforced concrete. However, other types of fibres, like polypropylene, carbon and PVA (polyvinylalcohol) have been tried. Ferrocement is a type of thin-walled reinforced concrete made of hydraulic cement mortar reinforced with closely spaced layers of continuous and relatively small size wire mesh. The mesh may be made of metallic or other suitable materials [1].

The comparison among these materials shows that Ferrocement has high ductility, small crack width and improved impact resistance, but because of the high cost of steel wire mesh and the high labour cost associated with placing several layers of it, Ferrocement is considered uneconomical in numerous potential applications. On the other hand, in Fibre Reinforced Concrete the fibres are premixed with the matrix, leading to enormous savings in labour cost. However, discontinuous fibres are not mechanically as efficient as continuous meshes.

The aim of this paper is to demonstrate that mortar reinforced with large opening meshes, or only single wires, of high strength steel and short fibres, such as polypropylene, PVA (polyvinylalcohol) or glass can be a suitable alternative to thin-walled concrete elements, as this association can join the favourable characteristics of Fibre Reinforced Concrete and Ferrocement.

CONCEPTION OF MATERIAL AND POTENTIALITIES

Several studies have reported on the use of fibres in combination with wire mesh as reinforcement of thin mortar elements [2] [8] [9]. The focus of these studies is generally on the improvement of the mechanical properties of ferrocement.

The association of continuous and discontinuous reinforcements in a composite material for thin-walled reinforced concrete products is here 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 the ultimate strength limit states, and short fibres as a secondary reinforcement to control cracking and give toughness to cement mortar. This leads to the following features: 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 the one commonly used in ferrocement; and c) the use of a relatively low volume fraction of fibres in order to promote crack control and toughness increasing.

The main advantage of this approach is a possible overall reduction in cost, maintaining the appropriate mechanical performance for Civil Construction. Indeed, the same reinforcement ratio in both directions, as generally in the case of ferrocement, is 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 labour cost, which is an important fraction of the cost of ferrocement.

This kind of association is suitable for prefabrication and industrialisation, because it leads to lightweight precast elements that can be handled and erected without special equipment.

This approach is particularly important in Brazil because ferrocement has been used since the 60's. The most important experience of ferrocement application in Brazil was the construction of about 500 school units (about 500,000 m^2 construction) by means of a prefabricated construction system, between 1992 and 1995, sponsored by the Brazilian Federal Government [7].

BENDING TESTS

To support this idea, an experimental program has been developed at the University of Michigan. This program is described in detail in a paper [5].

This program comprised more than seventy thin-walled mortar beam tests. The following variables were investigated: a) type of fibres, namely polyvinylalcohol (PVA) or polypropylene (PP); b) volume fraction of fibres, namely 1% and 2% for PVA fibres and 0.5% and 1% for PP fibres; c) reference mesh size 25.4x25.4 mm and 50.8x50.8 mm, and d) transverse wire spacing (TWS) 25.4, 50.8 mm, and infinity, i.e. no transverse wire. Table 1 summarise the bending experimental program.

Table. 1 -- Experimental Program of bending tests

Fiber Type	***Fiber Volume Fraction***	***Reference Mesh Size (mm x mm)***	***Transverse Wire Spacing (TWS) (mm)***	***Specimen ID***
None	none	none	none	**N-N**
		25.4 x 25.4	25.4	**N-1-1**
			50.8	**N-1-2**
			Infinite	**N-1-f**
		50.8 x 50.8	50.8	**N-2-2**
			Infinite	**N-2-f**
PVA	1%	none	none	**A1-N**
		25.4 x 25.4	25.4	**A1-1-1**
			50.8	**A1-1-2**
			Infinite	**A1-1-f**
		50.8 x 50.8	50.8	**A1-2-2**
			Infinite	**A1-2-f**
	2%	none	none	**A2-N**
		25.4 x 25.4	25.4	**A2-1-1**
			50.8	**A2-1-2**
			Infinite	**A2-1-f**
		50.8 x 50.8	50.8	**A2-2-2**
			Infinite	**A2-2-f**
PP	0.5%	none	none	**P0.5-N**
		50.8 x 50.8	50.8	**P0.5-2-2**
	1%	none	none	**P1-N**
		50.8 x 50.8	50.8	**P1-2-2**
SPECIAL ESPECIMENS				
None	none	25.4 x 25.4	25.4	**N-1-1(S)**
PVA	2%	50.8 x 50.8	Infinite	**A2-2-f(S)**

All specimens were 127 mm wide, 457 mm long and 12.7 mm thick. The net cover to the steel reinforcement was 2.3 mm (0.09 in). In this investigation, commercially available galvanised steel welded square meshes were used. The PVA fibres were 12 mm long and 0.2 mm diameter and PP fibres were 12,7 mm long and 0.095 mm diameter, monofilament type.

The mortar mix proportion was the same for all specimens (by weight): 1 for portland cement (Type I - ASTM); 2 for sand (ASTM 20/30 silica sand); 0.2 for fly ash; 0.02 for superplasticizer (Melment); and 0.6 for water. The average compressive strengths of plain mortar and mortar with different volume fractions of PVA and PP fibres were, in MPa, 43 (without fibre), 41 (1% PVA), 35 (2% PVA), 39 (0,5% PP) and 41 (1% PP).

All specimens were cast in vertical Plexiglas moulds. The moulds were placed on a vibrating table during the pouring of the mortar matrix. In addition to the vibration, the matrix was sometimes pushed in with a rod to improve penetration. This was particularly true for the matrices containing 2% PVA fibres or 1% PP fibres.

A four-point loading fixture with 355 mm span and 152 mm constant bending moment zone was used (see Fig. 1).

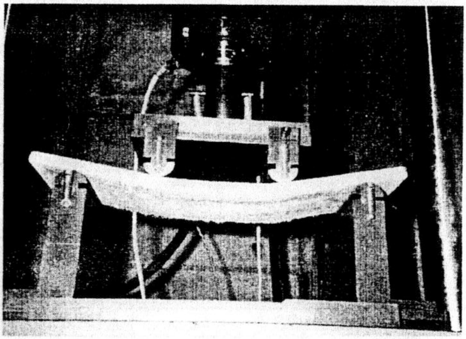

Fig. 1 -- Bending test set-up

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. Table 2 shows the number of the main cracks (without their branches) in the constant moment region.

Table 2 -- Average number of cracks in the constant moment region

Mesh	TWS	MATRIX				
(mm)	(mm)	no fibres	(1% PVA)	(2% PVA)	(0.5%PP)	(1% PP)
25.4 x 25.4	25.4	7.0	10.6	9.6	—	—
	50.8	7.0	9.0	10.3	—	—
	infinite	6.0	8.3	10.3	—	—
50.8 x 50.8	50.8	5.3	8.6	9.0	6.0	8.0
	infinite	5.0	9.0	9.0	—	—

TWS- Transversal wire spacing

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

a) The addition of PVA (1% and 2% by volume) leads to an increase in the cracking moment of up to 30% and a decrease in the crack spacing and width of up to 80%.

b) The addition of 1% PP fibres to the mortar matrix leads to a significant improvement in the cracking behaviour as illustrated by a decrease in the average crack spacing of about 60%.

c) No significant influence was observed on either the cracking behaviour, or the yield and ultimate moments when 0.5% PP fibres was added.

d) The presence of transverse wires or their spacing seems to become unnecessary for crack control when either 1% or 2% PVA fibres are used, that is, the addition of fibres leads to an average crack spacing smaller than the transverse wire spacing. In this case, the need for transverse wire vanishes, except for its function of keeping the longitudinal wires in position.

e) The behaviour (load-deflection response curve and cracking behaviour) of beams reinforced with one mesh layer in the tension zone is identical to the behaviour of beams reinforced with two symmetrical layers placed in the tension and compression zone. This implies that substantial savings can be achieved by eliminating the mesh layer from the compression zone.

The number of cracks and the corresponding average crack spacing obtained from these tests can be compared with the results of conventional ferrocement beams like those given by Balaguru, Naaman and Shah [3]. They report an average crack spacing of 12.7 mm in ferrocement beams with four layers of 12.7 mm opening square welded mesh. From the test results of this study, a slightly larger crack spacing (17 mm) is observed in specimens with one layer of 50,8 x 50,8 mesh and 2% PVA fibres.

TENSION TESTS

These tests were carried out in the Department of Structural Engineering of the University of São Paulo at São Carlos, Brazil [4]. As far as possible, it was intended to maintain the same variables of previous tests. Thus, the variables of this experimental program were: a) type of fibers - polyvinylalcohol (PVA) and polypropylene (PP), and b) volume fraction of fibers - 1% and 2% for PVA fibers and 0.5% and 1% for PP fibers. The steel mesh opening at 50mm x 50mm and the transverse wire spacing at 50 mm were kept constant. A special arrangement was included in the present program consisting of only longitudinal continuous wires without transversal wires, which implies infinite transverse spacing. This experimental program is summarized in table 3. For each arrangement two plates were cast.

The specimen width of 125 mm and thickness of 12.7 mm of the previous experimental program were maintained. However, some changes were made in the current program due to the type of test: the specimens had two heads in order to provide the fixture in the reaction frame (see Fig. 2); the specimen length of constant cross section was 810 mm and the predicted position of longitudinal wires was in the middle plane of the specimens.

The steel mesh reinforcement used in the current program was a welded mesh used in ferrocement elements in Brazil, with high strength steel. The wires of special specimens were also of high strength steel. These wires have the smallest diameter available for concrete reinforcement in Brazil.

As previously mentioned, polyvinylalcohol (PVA) and polypropylene (PP) fibers were used. The PVA fibers are the same of the previous tests, although polypropylene fibers changed from monofilament to multifilament ones, which were available.

The mortar mix proportion by weight was 1 part of high early strength cement, 2 parts of natural river sand with maximum characteristic diameter of 2.4 mm, 0.02 parts of superplasticizer and 0.6 parts of water. Despite the difference in the mortar composition between the current program and the previous one, it was intended to maintain the same matrix strength at the age of testing. The compressive strengths for the cylindrical test sample of 50 mm of diameter and 100 mm of length were, in MPa, 46 (without fibre), 43 (1% PVA), 43 (2% PVA), 38 (0,5% PP) and 34 (1% PP).

Some reinforcement parameters of the composite material studied are presented here. The steel volume fraction of continuous reinforcement, in the direction of loading, for normal series was 1.04% for the specimen and 0.88% for the composite (the composite is considered here as a continuous element with diameter and wire spacing used in the specimen). The steel consumption corresponds to 163 kg/m^3 for the specimens, and 138 kg/m^3 in the composite. The reinforcement parameters for the special series with only wires were 1.69% and 1.43% steel volume fraction for the specimens and composite, respectively, and 132 kg/m^3 and 112 kg/m^3 steel consumption for the specimens and composite, respectively.

The fiber consumption was 13 kg/m^3 and 26 kg/m^3 for 1% and 2% PVA fiber volume fraction, respectively, and 4.6 kg/m^3 and 9.1 kg/m^3 for 0.5% and 1% PP fiber volume fraction, respectively.

The specimens were cast in a steel mold with wood inserts to make the two ending heads. The mold was filled in the horizontal position, which greatly facilitates the casting, in comparison with the previous experimental program. The compaction was done on a vibrating table. The specimens were removed from the molds after one day and cured in water tank for 5 days. After this period, they were kept in the laboratory environment for one day to dry and finally were tested on the seventh day. The tension test was conducted using a frame reaction system with metallic fixing (see Fig. 2). The tensile force was applied by a hydraulic cylinder. An electrical load cell measured the load.

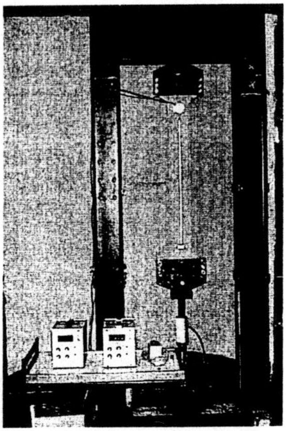

Fig. 2 --Tension test set-up

During the test, displacement measurements between two points of specimens were taken with mechanical dial gauges placed on two sides, with sensibility of 1/1000 mm. The crack width of three zones on each side of the specimens was also measured using an optical gauge, resulting in 6 crack width measuring per plate at each load stage. The total evolution of cracking mode was marked with black ink. The testing ended as soon as the rupture of the steel wires had occurred.

The crack width corresponding to the average of 6 measures for each plate, and consequently, 12 values for each series, for each stage of loading, is shown in figure 3.

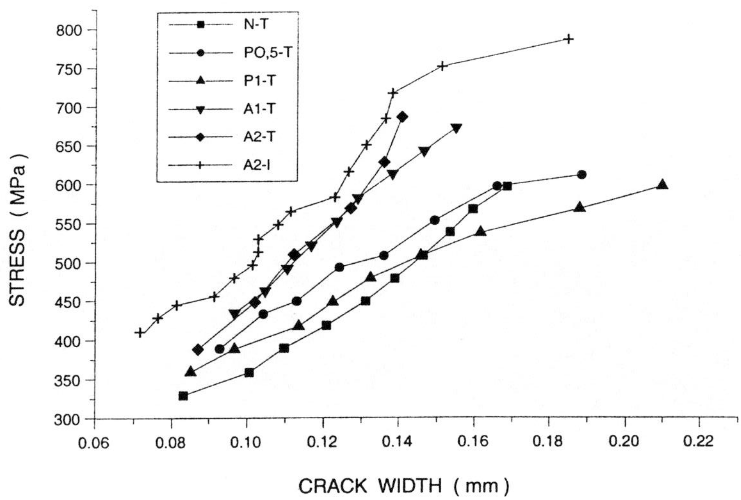

Fig. 3 -- Steel stress versus crack width curves

This figure shows the crack width x steel stress. The average spacing between cracks calculated by dividing the length of 810 mm by the number of main cracks without their branches is shown in table 4.

Table 4 -- Cracks spacing (mm)

Mesh	TWS (mm)	MATRIX no fibres	(1% PVA)	(2% PVA)	(0.5%PP)	(1% PP)
50 x 50	50	41.5	33.4	34.2	40.5	35.2
Special specimens	infinite	---	---	30.8	—	—

TWS- Transversal wire spacing

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

a. The addition of 1% PP and 1% and 2% PVA fibers leads to a reduction of crack spacing of about 20%, although the PVA fibers results in smaller crack widths than PP fibers;

b. The addition of 0.5% PP results in no significant influence, as bending tests demonstrate;

c. The special specimen with only steel wires and fibers achieved a better cracking behavior, in comparison with steel mesh only;

d. The PVA fiber leads to a better performance; it is easier to work than PP fibers, and there seems to be no need for more than 1% fiber by volume.

The results of both current and previous experimental programs point out that the proposed composite material is technically possible. That means that its use is feasible in thin reinforced concrete products of continuous steel reinforcement, as the primary reinforcement to satisfy the ultimate strength limit state, and fibers, as the secondary reinforcement to provide cracking control.

For practical applications, the following precautions should be considered: a) in this study, a constant thickness of 12.7 mm was used; results can be extrapolated to larger thickness as 25-38 mm. However, some adjustments must be made for the fiber orientation affected by the ratio of fiber length to specimen thickness; b) it is important to choose, an adequate wire with proper diameter/cover and diameter/thickness ratios as longitudinal reinforcement; i.e., a large diameter wire should not be used with a small cover and small thickness.

COST EVALUATION

To compare the reinforcement cost in conventional ferrocement and the proposed approach, an example of a typical wall panel is analysed. This panel is supposed to be U shaped, 18 mm flange thick, 0.60 m wide and 2,80 m long (0.037 m^3 of concrete volume). This panel is reinforced with one square mesh (50 mm x 50 mm opening, 2 mm wire diameter) and two 3.2 mm wires. The cost of this reinforcement is compared with the cost of a reinforcement with 3.2 mm wire and 1% PP fibre, commercially available in Brazil. Table 5 shows the results.

Table 5 -- Comparison of reinforcement cost

	Conventional		Wires and 1%PP	
	Mesh	Wire	Wire	Fibre
Quantity	2.16 m^2	0.38 kg	1.37 kg	0.33 kg
Unitary Cost (US$)	1.47	0.50	0.50	4.54
Total Cost (US$)	3.18	0.19	0.69	1.50
Reinforcement Cost (US$)	3.37		2.19	
Cost Reduction (%)			35	

It must be pointed out that labour cost is not included. However, this cost will be lower in the approach proposed. On the other hand, it is necessary to adjust the mix for the mortar with fibres and to provide additional care on pouring the elements.

Even the other expensive fibres, like PVA or glass, which cost almost twice as much as PP fibres, the cost of the material will be competitive, because the proportion of labour cost is very high.

CONCLUSION

The results confirm the idea that, in thin-walled reinforced concrete products is possible to apply a combination of continuous steel reinforcement as the primary reinforcement to satisfy the ultimate strength limit state, and short fibres, as the secondary reinforcement. This combination is able to provide toughness and cracking control with lower cost than with conventional ferrocement.

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