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Performance and Failure Analysis of Thin Composite Ferrocement Panels

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Abstract
Ferrocement is fast becoming recognized as an alternative to reinforced concrete by recent studies. While ferrocement characteristic can be compared to reinforced cement concrete, the construction of the former is cheaper and easier. The study specifically investigates the characteristics of ferrocement such as its flexural strength and mode of failure of the composite with varying top bar quantity (1-, 2- and 3-bars) and thickness of the ferrocement (30mm, 35mm and 40mm). The diameter of the top bar is the same for all samples so the quantity of the top bar is varied due to spacing. Each composite of the Ferro-cement has the same quantity and ratio of cement, sand, water, welded wire mesh, and reinforcing steel bars. All samples utilize ten (10) bottom bars with eight (8) mm diameter. With the Universal Testing Machine (UTM) subjected to mid-point loading, the samples were tested after 28 days curing period. The result shows that panels with a thickness of 35 mm having three top bar (3-8mm) have reached the maximum flexural stress (σ_b) of 33.83Mpa indicating that the quantity of top bar is significantly affecting the flexural strength. The 35mm thickness of ferrocement yields better σ_b compared to both the 30 and 40mm which suggests that there is no direct relationship between thickness and the strength of the ferrocement. It is not necessary that it would have thicker panel and more steel bar reinforcement. Triangulation of data reveals that the higher flexural stress occurs when the mode of failure is flexure/bending.

Keywords: Ferrocement, Composite, Welded wire mesh, Flexural strength, Mode of failure

1. Introduction

Ferrocement is a composite material made of cement mortar and layers of small diameter rod or wire mesh. In details, it consists of closely spaced, multiple layers of rod or mesh that is embedded in cement mortar. It is comparatively a new material that has sufficient strength to carry loads, crack resistance, and low maintenance. When this kind of composite material is used for construction as a replacement of other members, it can provide some resistance to fire, earthquake, and corrosion compared to traditional materials like wood, stone, and adobe. [1], [2], [3], [4].

This composite material is similar to conventional reinforced concrete cement (RCC). Per se, some of advantages of using RCC in construction can be normally applied to ferrocement. Compared to conventional RCC, it is a type of low technology construction that it does not necessarily require highly technical skilled labor, complex construction methods, and heavy equipment or manufacturing in a plant. Furthermore, if proper procedures are followed, a good performance of ferrocement in construction can be achieved. [1], [2], [3], [4].

It has a variety of applications both building components and prefabricated construction elements used for multipurpose structure. Specific applications are slab, wall, tank, roof and other thin construction

membrane. Therefore, to examine and use this type of construction technology, characterization of thin composite Ferro-cement beam panel is necessary.
Many researchers analyzed the behavior of ferrocement beam. In the past study, Acma, Leoncio and Mariano, C [5] studied the Flexural Strength and Ductility Behavior of Ferrocement I Beam which found out that there is increased in the capacity of flexural strength if there is increased in number of layers of wire mesh reinforcement. Additionally, increasing the wire mesh reinforcement increases the cracks showing ductility behavior. M.Z. Hossain, A.S.M.A. Awal [6] observed that the flexural modulus of elasticity of thin cement composite depends on the elastic modulus of mortar. It has been found that the newly developed equations give relatively conservative results as compared to the typically used ones. Mohana Rajendran, Nagan Soundarapandian [7] studied the Flexural Behavior of Geopolymer Ferrocement Slabs which concluded that that there were direct relationships of the thickness of the composite and concentration of alkaline solution to the first crack pattern and ultimate load. Similarly, the load carrying capacities, energy absorption, deformation at ultimate load are high in the case of geopolymer ferrocement element. Mohamad N. Mahmood, Sura Majeed [8] found out that the flexural strength of folded ferrocement panel is 3.5 -5 times which of flat panel considering the same number of wire mesh layers. Moreover, increasing the number of layers of wire mesh from 1 to 3 layers significantly increases the ductility and capability to absorb energy of both types of the panel.

Research Objectives

The main objective of the study is to improve the applications of ferrocement by characterizing its flexural performance with varying thickness and spacing of bar.
Specifically, it aims: (a) to identify the properties of aggregates and compressive strength of cement mortar; (b) to examine the tensile property of wire mesh; (c) to evaluate the flexural capacity of the thin composite ferrocement panels; and (d) to inspect the mode of failure of the thin composite ferrocement panels.

2. Methodology

2.1. Materials

The cement used was made from Portland Pozzolana Cement, CES: 28, Grade: 32 5R CEM II. Approximately four kilograms of fine aggregates were prepared for sieve analysis. The grading requirements for fine aggregates were determined using sets of mechanical sieves [8]. Welded wire mesh (WWM) with 12mmx12mm opening and wire diameter of 0.8 mm and reinforcing steel bar (RSB) with 8mm diameter were used as the reinforcement.
Quartering was performed to determine the representative samples for the fine aggregates. Followed by silt test to determine the silt content as per Ethiopian Authority of Standards. Combining the cement, fine aggregate, and water will result to cement mortar. Six cubes samples were used to determine the compressive strength of the mortar. Its proportions and ratios used were 1.5 cement aggregate ratio and 0.45 water-cement ratio by weight [11], respectively. On the other hand, tensile property of the mesh was determined using Universal Testing Machine (UTM). Two types of WWM specimens were prepared. The first type is a mesh with a size of 75 mm width and 300 mm length. While, the second type is same dimension with the previous but it was encapsulated at the ends by a 75mm x 75mm surface area and 10mm thick of mortar. Both have allow a free welded wire mesh of 150 mm length that will be used for clamping. [9], [10]. Casting of the panel was made by the used of metal sheet and wooden molds. Each

wooden batten has variation of thickness from 30 mm- 40 mm that will serve as guide. After the wooden battens were arranged accordingly, it was attached to the metal sheet. The prepared molds were properly oiled before casting.

2.2 Modelling

The dimensions of the ferrocement specimens were based on ACI 549.1R-93 and specification of the UTM. Accordingly, the dimension of the panel is 100mmx 500mm. Considering three (3) different thickness (30mm, 35mm, 40mm) and three (3) different number of top bar (1-,2-,3-8mm) with constant number of bottom bar (10-8mm) attached together by tie wire, there were 9 different panels. Table 1 shows the details of ferrocement panels.

Table 1. Details of the thin composite ferrocement panel

s/n	Sample ID	Size (mm)	No. of Panel	Reinforcement Arrangement			
				No. of WWM at top	No. of bar at top	No. of bar at bottom	No. of WWM at bottom
1	S30-1	30x100x 500	3	1	1	10	1
2	S30-2	30x100x 500	3	1	2	10	1
3	S30-3	30x100x 500	3	1	3	10	1
4	S35-1	35x100x 500	3	1	1	10	1
5	S35-2	35x100x 500	3	1	2	10	1
6	S35-3	35x100x 500	3	1	3	10	1
7	S40-1	40x100x 500	3	1	1	10	1
8	S40-2	40x100x 500	3	1	2	10	1
9	S40-3	40x100x 500	3	1	3	10	1

The detailed drawing represents the assembly of ferrocement panel (S30-1) as shown in Figure 1. The side cover for all the panels was 4mmm. While, the top and bottom cover varies depending on the thickness of the panel. For particular, the 30 mm, 35mm, 40mm thick panel has a top and bottom cover of 6.2mm, 8.7mm, 11.2mm, respectively.

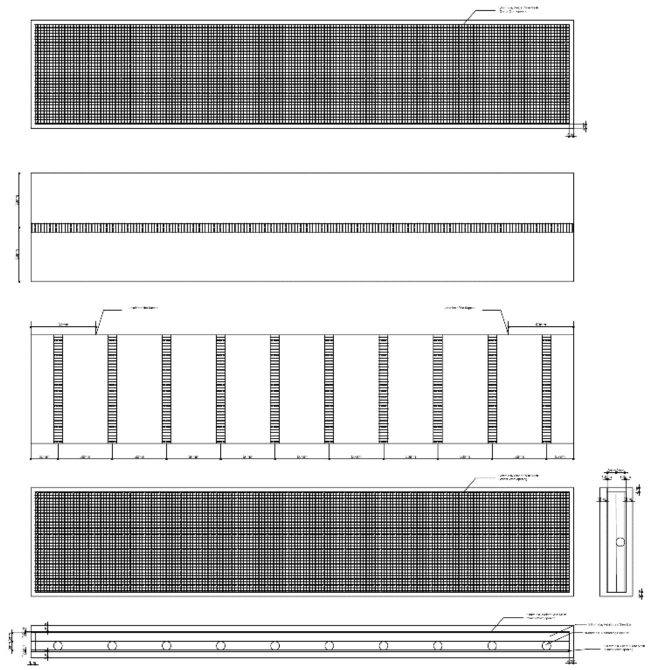

Figure 1. Detailed drawing of S30-1

Figure 2 shows the placement of mortar, bar arrangement, and mesh arrangement. The preparation started with placing the cement mortar on the wooded mold and was compacted to reduce the air void. WWM was placed on top of the mortar followed by placing the bar (top and bottom bar which are attached together by tie wire) on top of it. Then, WWD is placed on top of the bar. Finally, the mortar is placed on top of WWD and again was compacted in order to move the mortar within the mesh and bars.

Figure 2. Picture showing placement of mortar mesh layers, and reinforcing steel bar.

2.3 Testing

After 28 days curing, the flexural strength of the panel by mid-point loading and compressive strength of cement mortar were determined using UTM and compression machine, respectively. The provision of ACI C78 [12], ASTM C78-02 [13], and ASTM C109/C109M-02[14] were utilized to perform the different testing. As shown in Figure 3, the maximum moment was determined by sketching the load and shear diagram.

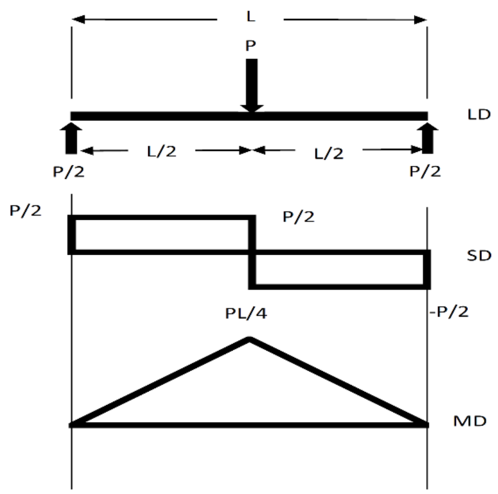

Figure 3. Diagrams of flexural strength.

The bending/ flexural strength was calculated using the following formula:

$$\sigma b = My = \frac{PL}{4} \times \frac{h}{2} \times \frac{1}{bh^3/12} = \frac{3PL}{2bh^2}$$

Where:

σb - Bending/ flexural stress

M -Maximum Bending Moment

I -Moment of Inertia
y -Location of centroid

3. Results and Discussion

3.1 Properties of Materials

Result of the actual sieve/grading of fine aggregates is shown in Table 2. It is noted that the fine aggregates used conformed to ACI 549.1-93 recommendation.

Table 2. Grading of Fine Aggregates as per ACI 549.1-93

Sieve size (g)	Wgt. of sieve (g)	Wgt. of sieve & retained (g)	Wgt. ret. (g)	% Ret.	Cumm. coarse,%	Cumm. pass,%	Reqt. passing,%
2.36	398.2	551.2	153	7.65	7.65	92.35	80-100
1.18	350.3	584.9	234.6	11.73	19.38	80.62	50-85
600	316.6	1117.6	801	40.05	59.43	40.57	25-60
300	282.1	504.7	222.6	11.13	70.56	29.44	10-30

150	268.6	777.2	508.6	25.43	95.99	4.01	2-10
pan	242.3	322.5	80.2	4.01	100	0	-
Total			2000				

3.2 Compression properties of cement mortar

As specified in ACI 549.1-93, the 28-day compressive strength of 3 by 6-in. (75 by 150-mm) moist-cured cylinders should not be less than 5000 psi (35 MPa). It shows in Table 3 that it passed the required strength. Hence, the average compressive stress is 38.54 MPa.

Table 3. Compressive Strength of Cement Mortar

Cube No.	Compressive Stress (MPa)
1	40.67
2	38.92
3	36.94
4	38.52
5	39.48
6	36.68
Average	38.54

3.3 Tension properties of welded wire mesh

The tensile strength of welded wire mesh (WWM) was determined using the UTM. Two types of WWM specimens were prepared as shown in Figure 4. Table 4 shows the summary of the results. Considering the constraints for the WWM, it passed the required tensile strength as per ACI 549.1-93.

Table 4. Summary of results of Tensile Test of WWD

Sample No.	Sample Size	Max. Load (KN)	Max. Stress (MPa)
Welded wire mesh (12mmx12mmx0.8mm diameter)			
1	7 strands of 0.8mm thk.	2.46	447.68
2	7 strands of 0.8mm thk.	2.56	465.88
3	7 strands of 0.8mm thk.	2.78	505.91
Average	7 strands of 0.8mm thk.	2.60	473.16
Welded wire mesh (12mmx12mmx0.8mm diameter) encapsulated at both ends by 75mmx75mmx10mm thk. Mortar			
1	7 strands of 0.8mm thk.	2.95	536.85
2	7 strands of 0.8mm thk.	2.45	445.86
3	7 strands of 0.8mm thk.	3.76	684.26
Average	7 strands of 0.8mm thk.	3.05	555.66

a. Welded wire mesh

b. Encapsulated with mortar

Figure 4. Tensile test of wire mesh (a) and (b)

3.3 Flexural strength of thin composite panel

Flexural load and stress are shown in Table 5. It indicates that the flexural load for all panels (30mm, 35mm, and 40mm) increases as the number of bar (top) in longitudinal direction increases. However, increasing the thickness has no direct effect on the flexural stress. This is seen in panel S30-1 (18.40MPa), S35-1 (13.52 MPa), and S40-1 (10.66 MPa). While the maximum flexural stress is found in panel S35-3 (36.83MPa). The flexural stresses are shown in Figure 6.

Table 5. Summary of flexural test results for the thin composite ferrocement panel

Sample ID	Size (mm)	Max. Load (KN)	Max. Stress (MPa)
S30-1	30x100x 500	2.20	16.50
S30-1	30x100x 500	2.30	17.25
S30-1	30x100x 500	2.28	17.10
Average	30x100x 500	2.26	16.95
S30-2	30x100x 500	4.20	31.50
S30-2	30x100x 500	4.00	30.00
S30-2	30x100x 500	4.15	31.13
Average	30x100x 500	4.12	30.88
S30-3	30x100x 500	4.60	34.50
S30-3	30x100x 500	4.30	32.25
S30-3	30x100x 500	4.50	33.75
Average	30x100x 500	4.47	33.50
S35-1	35x100x500	2.40	13.22
S35-1	35x100x500	2.45	13.50
S35-1	35x100x500	2.51	13.83
Average	35x100x500	2.45	13.52
S35-2	35x100x500	5.51	30.36
S35-2	35x100x500	5.70	31.41
S35-2	35x100x500	5.62	30.97
Average	35x100x500	5.61	30.91

S35-3	35x100x500	6.70	36.92
S35-3	35x100x500	6.60	36.37
S35-3	35x100x500	6.75	37.19
Average	35x100x500	6.68	36.83
S40-1	40x100x500	2.56	10.80
S40-1	40x100x500	2.54	10.72
S40-1	40x100x500	2.48	10.46
Average	40x100x500	2.53	10.66
S40-2	40x100x500	5.99	25.27
S40-2	40x100x500	5.60	23.63
S40-2	40x100x500	5.80	24.47
Average	40x100x500	5.80	24.45
S40-3	40x100x500	6.83	28.81
S40-3	40x100x500	6.90	29.11
S40-3	40x100x500	6.74	28.43
Average	40x100x500	6.82	28.79

Figure 5. Flexural test of ferrocement panel

Markings on the middle part and end supports of the panel were set before performing the flexural test as shown in Figure 5. These will be the guide for the application of load and location of support for the panel. Hence, improper placing of panel on the machine can affect the result of flexural load as well as the flexural stress.

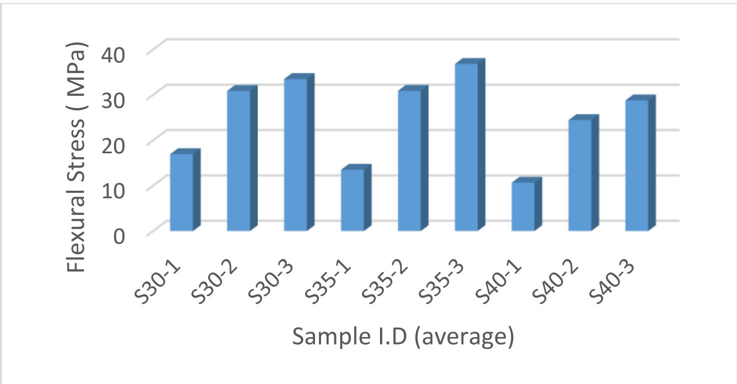

Figure 6. Flexural stress of thin composite ferrocement panels

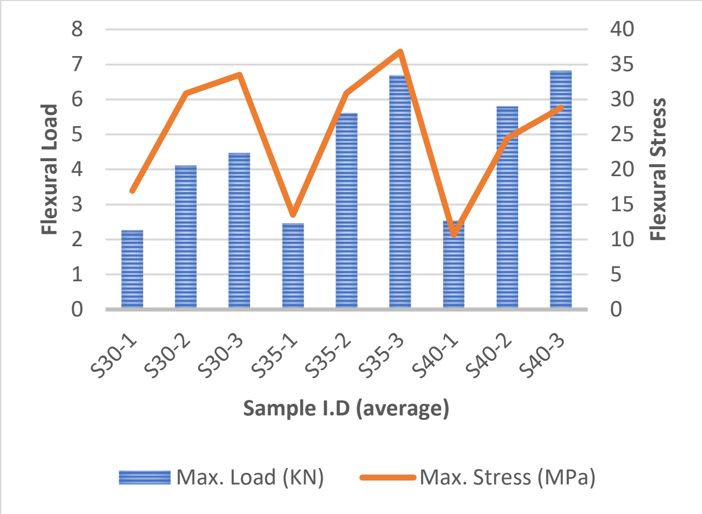

Figure 7. Flexural load and flexural stress of thin composite ferrocement panels

Based on Figure 7, maximum load occurs in S40-3 which is 6.82 KN. This means that increasing the thickness can increase the flexural load, respectively. However, as per formula, the flexural stress is affected by the cross-sectional area of the panel. Thus, at some instant, increasing load will not increase the stress directly.

3.4 Mode of Failure

Different modes of failure for the thin composite ferrocement panel are presented in Table 6. It shows that if the mode of failure is flexural/bending, higher flexural strength is expected. While, bond anchorage failure has the lowest flexural strength. Picture representing the mode of failure can be seen in Figure 8.

Table 6. Summary of mode of failure

Sample ID	Size (mm)	Mode of Failure
S30-1	30x100x 500	Bond anchorage
S30-1	30x100x 500	Shear
S30-1	30x100x 500	Shear
S30-2	30x100x 500	Flexure
S30-2	30x100x 500	Bond anchorage
S30-2	30x100x 500	Shear
S30-3	30x100x 500	Flexure
S30-3	30x100x 500	Flexure
S30-3	30x100x 500	Flexure
S35-1	35x100x500	Shear
S35-1	35x100x500	Bond anchorage
S35-1	35x100x500	Bond anchorage
S35-2	35x100x500	Shear
S35-2	35x100x500	Flexure
S35-2	35x100x500	Shear
S35-3	35x100x500	Flexure

S35-3	35x100x500	Flexure
S35-3	35x100x500	Flexure
S40-1	40x100x500	Shear
S40-1	40x100x500	Shear
S40-1	40x100x500	Bond anchorage
S40-2	40x100x500	Flexure
S40-2	40x100x500	Shear
S40-2	40x100x500	Flexure
S40-3	40x100x500	Flexure
S40-3	40x100x500	Flexure
S40-3	40x100x500	Flexure

a. Bond anchorage failure

b. Shear Failure

c. Flexure Failure

4. Conclusion and Recommendation

From the results of the experimental investigation conducted, the following conclusions were drawn:

A. The cement mortar passed the required compressive strength as per ACI 549.1-93 which is 35MPa;

B. The tensile strength of welded wire mesh encapsulated with mortar has higher strength compared with pure welded wire mesh. Considering both constraints, the welded wire mesh passed the required tensile strength as per ACI 549.1-93 which is 450MPa;

C. Increasing the top bar reinforcement increases the flexural load. However, thickness has no direct impact on the flexural stress. Besides, increasing the thickness will not yield the same result for flexural stress. The maximum flexural stress is 36.83 MPa, this is a panel of 35mm with three (3) top bar reinforcement; and,

D. Higher flexural load occurs when the mode of failure is by flexure/bending. Consequently, lower loads occur when the mode of failure is by bond anchorage or shear.

Further study is still essential to advance and improve the capability of thin composite ferrocement. These include the use of other type of wire mesh, providing additional number of layers of welded wire mesh, arrangement(spacing) of the bar, large size of beam panel to make it more reliable, and finite element analysis (FEM) of the panel.

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