DESIGN AND BEHAVIOR ANALYSIS OF PREFABRICATED MODULAR FERROCEMENT FLOOR SLAB SYSTEM FOR INTERIOR APPLICATION

[1]JOEL GALUPO OPON, [2]GERONIDES P. ANCOG

[1,2]Department of Civil Engineering, MSU – Iligan Institute of Technology, Tibanga, Iligan City, Philippines, 9200
E-mail: joel.g.opon@gmail.com

Abstract- This research is focused on a new interior floor slab system, which can be prefabricated in modular form out of ferrocement technology. The design of the system is outlined using the mechanics of materials and the theory of plates, and the American Concrete Institute (ACI) guide for ferrocement design. All constituent materials were tested to conform to the ACI and applicable American Society for Testing and Materials (ASTM) standards. The cement mortar's water-cement ratio of 0.485, cement-sand ratio of 1:2.75, and the wire mesh reinforcement used was a galvanized square welded mesh ¾" x ¾" opening of 0.95mm diameter. The results from materials tests were used in the design, modeled to meet the geometric, serviceability, and strength requirements. A 600mm x 600mm x 40mm is the final design output, with 8mm skeletal steels that served as connection studs with two layers of wire mesh. The slab modules were tested to a central load using a universal testing machine (UTM) and based on the results, the behavior of the ferrocement modules conforms to the theoretical formulations and the requirements for serviceability and flexural strength are attained. An actual application was engaged to determine the material usage, productivity rates, and direct cost comparison with the ordinary reinforced concrete slab for an area of 2.52m x 2.95m that resulted to 7.47% construction cost savings. This is further supplemented by the additional savings from reduction of the dead weight of the slab system about 38.71% of the conventional. It is therefore concluded that ferrocement is an excellent and safe technology for an interior prefabricated modular slab design and there is economic savings in this technology.

Keywords- Interior Floor Slab; Prefabricated Ferrocement Slab; Slab Design; Reinforced Concrete Slab.

I. INTRODUCTION

1.1 Background of the Study

During the 19th century, the technology available at the time could not yet accommodate the efficient production of small diameter wires and meshes; hence ferrocement did not flourish until the end of the century. Presently thru proven researches and the wide availability of the constituent materials, it is known that ferrocement possesses a degree of toughness, ductility, durability, strength and crack resistance that is considerably greater than that found in other forms of concrete construction.

With such mechanical properties of the ferrocement, it found many marine and terrestrial applications such as in housing, sanitation, agriculture, fisheries, water resources, water transportation both in freshwater and marine environment, biogas structures, repair and strengthening of other structures, and including stand alone structures [14].

This study sought to discover the potential use of the ferrocement technology as a modular floor slab system. This type of flooring system presents easy mode of construction as the slabs can be constructed separately, and can be attached or detached conveniently from the structure, which will effectively cut off much construction time and complexity in the construction process. The installation procedure does not require heavy and sophisticated equipment since ferrocement is a lightweight composite compared to ordinary reinforced concrete slabs, and it requires less labor. This also increases the salvage value of the modules, which can be reused if its structural properties can still permit load applications.

1.2 Theoretical Framework

Ferrocement is a thin wall cement mortar reinforced with wire mesh and is now considered to be a very innovative construction material. It is for this reason that its application as major structural member is being considered in this paper.

The design of ferrocement structures follows the same design philosophy generally adopted in structural engineering, particularly for reinforced and prestressed concrete structures. The design is based on satisfying a number of limit states where a limit state is defined as the boundary between acceptable and unacceptable performance [12].The following codes such as theNational Structural Code of the Philippines 2010 (NSCP), the ACI as well as theACI 549, helped in the development of the theoretical framework of this research.The general assumptions used in the design of the modular ferrocement slab are:

1. The slab assumes the typical square area of 600mmx600mm as shown in Figure 1. However the thickness of the element is determined based on the requirement of strength and serviceability.
2. The matrix is reinforced with square mesh of which openings must not exceed 25mm, in

the case of this paper a galvanized square welded wire mesh with opening of ¾"x ¾" and an actual strand diameter of 0.95mm was used.

3. Dead and live loads are determined assuming the basic occupancy rating from the NSCP 2010, including the dead weight of the slab.
4. The design ultimate moment is calculated in accordance with the load factors suggested by the NSCP 2010.

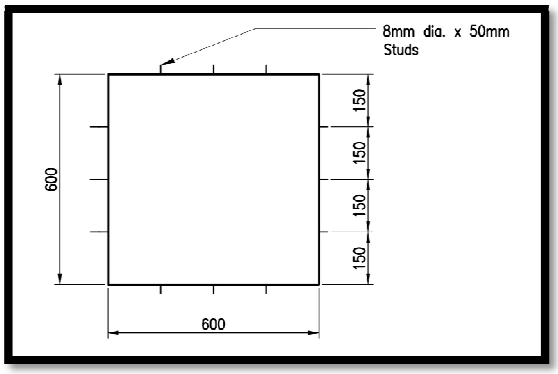

Figure 1 Typical Slab Used in the Design for Modular Ferrocement Slab Element

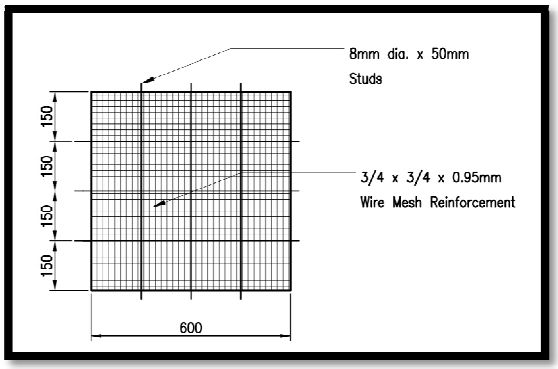

Figure 2Typical Reinforcing Arrangement

The major assumptions, which were the basis of the ultimate strength theory, used the exact method for nominal bending resistance, a method similar to that followed in the reinforced concrete columns. The applicable theory of plates was also incorporated in the formulation of the design criteria, because of the geometric properties of the ferrocement panels.

The design of the modular ferrocement slab was done by phases. The first phase dealt with the situation where the slab was reinforced with mesh alone to determine the minimum number of mesh layers required. The second phase took into account the contribution of skeletal bars in the analysis adopting the number of mesh layers obtained in the first phase.

1.2.1 Design of Modular Ferrocement Slab

The design approach employed was the exact method for nominal bending. The ultimate strength theory as applied to this framework has the following assumptions:

a. The distribution of stress across the section is linear.
b. The strength of mortar in tension is neglected.
c. Failure occurs only by breaking of the mesh reinforcement.

In summary, the order of design began with determining the right thickness that complied with the three major requirements, namely: the geometric requirement, the serviceability requirement and lastly the requirement for strength.

1.2.2 Geometric Requirement

To ensure good behavior of the ferrocement modules, the following figure shows the suggested placement of skeletal steel bars as well as the thickness required for a ferrocement panel.

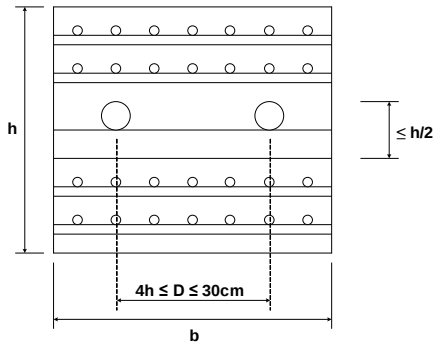

Figure 3 The Geometric Requirement to Ensure Good Behavior

$$h = 4\,(\Phi bar) \qquad (1)$$

1.2.3 The Serviceability Requirement

The serviceability requirement catered the deformation induced to the panels by the service loads as well as the combined loads, in the form of deflection. The thickness required to meet the condition for serviceability is given by the following equations for uniform load and equivalent central load, respectively.

$$h = 2.77\ L\ \left(\frac{Pu}{E}\right)^{1/3} (\text{in meters}) \qquad (2)$$

$$h = 3.93\ \left(\frac{V\,L}{E}\right)^{1/3}\ (\text{in meters}) \qquad (3)$$

1.2.4 Provision for Shear

Although, the ACI 549R Section 4.2.4 stated that no test data are available on the shear capacity of ferrocement slabs, this paper used the conventional analysis for ordinary reinforce concrete due to the similarity of the design process.

The design involves no shear reinforcement much like the ordinary reinforced slab design. From this analysis the following thickness is achieved, for uniform load.

$$V_{max} = 0.420\ P_u\ LW = 0.420\ V \quad (4)$$

$$h = \frac{6\ V_{max}}{\sqrt{f_c'}\ b_w} \quad (5)$$

For an equivalent central load,it is assumed to be distributed over some small circular area of radius c > 2h.

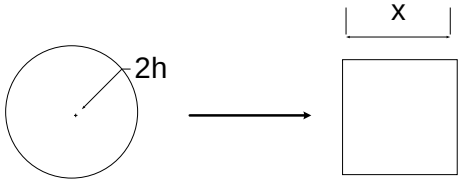

Figure 4Circular Area Replaced by Equivalent area of the UTM.

The following equations show the thickness of the modules, for this condition.

$$V_u = \frac{1}{3}\sqrt{f_c'}\ b_o\ h \quad (6)$$

$$h = \left[\frac{V_u}{6.06\ \sqrt{f_c'}}\right]^{1/2} \quad (7)$$

1.2.5 Strength Requirement

The strength criteria of the modular ferrocement slab design was evaluated using flexural strength analysis wherein a Maximum Bending Moment induced to the panel by the assumed load becomes the basis for calculating the Nominal Moment Capacity of the module itself.

The following equation is the maximum bending moment of the slab panels as calculated in the theory of plates for uniformly loading section simply supported on all sides.

$$M_u = 0.048\ P_u\ L^2 \quad (8)$$

$$M_{nreq} = \frac{0.048\ P_u\ L^2}{} \quad (9)$$

1.2.6 Exact Analysis of the Section

The following figure illustrates the nature of the exact method for rectangular element.

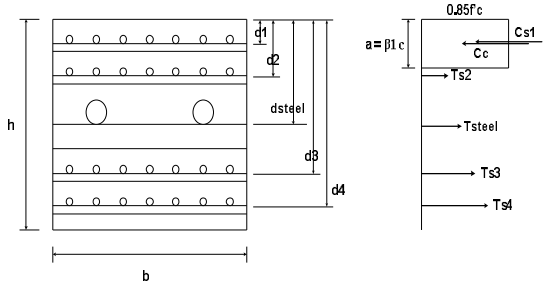

Figure 5 Force Diagram of the Transformed Area for the Exact Analysis

The first step in the exact analysis of the ferrocement panel was done by calculating the volume fraction of the mesh reinforcement, Vfmesh, and the Skeletal Steel reinforcement, Vfsteel, of the section. In this part, a trial number of mesh layer i was assumed.

The following expression details how the volume fraction of mesh and skeletal steel reinforcement is computed.

$$V_{fmesh} = \frac{N\ \pi\ d_{bmesh}^{\ 2}}{4\ h}\left[\frac{1}{D_{lmesh}} + \frac{1}{D_{tmesh}}\right] \quad (10)$$

$$V_{fsteel} = \frac{N_{steel}\ \pi\ d_{bsteel}^{\ 2}}{4\ h}\left[\frac{1}{D_{lsteel}} + \frac{1}{D_{tsteel}}\right] \quad (11)$$

The Nsteel for the above equations was taken as one (1), as there was only a single layer of steel for the ferrocement module in this design. The reader is reminded that the skeletal steel was not designed to contribute to the theoretical capacity of the ferrocement slab modules, and could be neglected in the exact analysis. However, because of its inevitable contribution in the actual performance of the slab to applied loading, it is shown here how its contribution can be computed together with the mesh layers.

After determining the volume fraction, the volume fraction per layer of mesh and the skeletal steel can be computed by the equations below.

$$V_{fmesh}' = \frac{V_{fmesh}}{N} \quad (12)$$

$$V_{fsteel}' = \frac{V_{fsteel}}{N_{steel}} \quad (13)$$

$$A_{smesh} = \eta_{mesh}\ V_{fmesh}'\ b\ h \quad (14)$$

$$A_{ssteel} = N_s\ (A_{sbar}) \quad (15)$$

$$C = 0.85\ f_c'\ a\ b \quad (16)$$

$$C = 0.85\ f_c'\ \beta_1\ c \quad (17)$$

Er which is the effective modulus of the reinforcement taken as Ersteel = 200,000MPa, however Ermesh is taken from the actual tensile test of the mesh reinforcement.

ηmesh = 0.50, this is the global efficiency factor for welded square mesh taken from ACI 549R, Table 4.2.

ηsteel = 1.0, this is the global efficiency factor for bars taken from ACI 549R, Table 4.2.

The the depths of each reinforcing layer is determined as is shown in Figure 5, d1, d2, …, dN, with dsteel reserve for the skeletal steel reinforcement.

A trial and error method is employed at this point in which the distance from extreme compression fiber to the neutral axis, c, is assumed. With the assumed value of c, the strain of the reinforcement layer i, can be calculated as:

$$\varepsilon_{ymesh} = \frac{f_{ymesh}}{E_{rmesh}} \quad (18)$$

$$\varepsilon_{ysteel} = \frac{f_{ysteel}}{E_r} \quad (19)$$

$$\varepsilon_{smeshi} = \left[\frac{d_i - c}{c}\right]\varepsilon_u \quad (20)$$

$$f_{smeshi} = E_{rmesh}\ \varepsilon_{smeshi} \quad (21)$$

if $\varepsilon_{smeshi} \leq \varepsilon_{ymesh}$

$$f_{smeshi} = f_{ymesh} \quad (22)$$

if $\varepsilon_{smeshi} > \varepsilon_{ymesh}$

$$\varepsilon_{ssteel} = \left[\frac{d_{steel} - c}{c}\right]\varepsilon_u \quad (23)$$

$$f_{ssteel} = E_r\ \varepsilon_{ssteel} \quad (24)$$

if □ssteel ≤ □ysteel
fssteel = fysteel (25)
if □ssteel > □steel

If the resulting value of the stress from the above expressions is negative, it signifies compression; otherwise tension.

Tsmeshi = fsmeshi Asmesh (26)
Tssteel = fssteel Assteel (27)

Whenever a compression stress is present for the reinforcement, the compression force can be evaluated as:

Csmeshi = (fsmeshi –0.85 fc')Asmesh(28)
Cssteel = (fssteel – 0.8 fc') Assteel(29)

The Compression and the Tension Forces are added using the following equations, such that both forces should be theoretically equal.

$\sum C = C + Csmeshi + Cssteel$ (30)
$\sum T = Tsmeshi + Tssteel$ (31)

If C = T results in the process, the nominal moment capacity, Mncomputed, can be determined using the following expressions. However, it might not be the case. In the event when C ≠ T, the value of c should be changed until an equality condition is met.

$$Mncomputed = \sum_1^N Csi \text{ or } Tsi \left[di - \frac{\beta 1\, c}{2}\right] \quad (32)$$

The following expression can be used to calculate Mncomputed using the mesh and steel reinforcement.

$$Mncomputed = \sum_1^N (Csmeshi + Tsmeshi)\left[di - \frac{\beta 1\, c}{2}\right] + (Cssteel + Tssteel)\left[dsteel - \frac{\beta 1\, c}{2}\right] \quad (33)$$

If Mncomputed is greater than or equal to Mnrequired, then the design is satisfactory. In the event that it falls below the required value, the author suggests considering another mesh layer until this condition is fully satisfied.

II. RESULTS

2.1Prototype Module Load Test Result

2.1.1 14-day old Ferrocement Slab Prototype Module
There were a total of six prototype ferrocement floor slab modules load tested using a Universal Testing Machine by applying a central load to the slabs induced by the plate of the UTM.

Three of these slabs were tested to determine the 14th day strength of the modules and the rest were tested for the 28th day strength.

From the test it can be observed that the first crack based on the arithmetic average of the three samples appeared at the application of 20.50kN load, with a corresponding deflection of 8.07mm.

The ultimate load that the slab can carry for 14th day curing period is 36.99kN with a corresponding deflection of 20.08mm.

With respect to the design load of 7.684kPa with an equivalent concentrated load of 2.77kN, the following figures illustrates that at such amount of applied load the prototypes were able to effectively handle it without so much deflection.

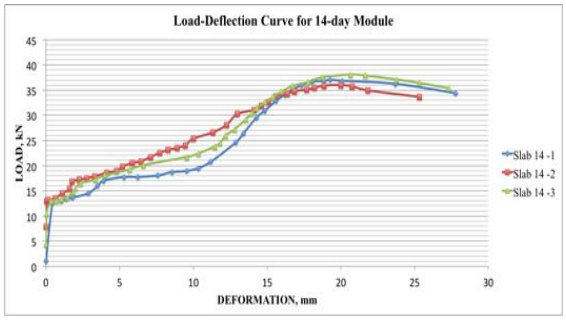

Figure 6Load-deflection Curve of the 14-day old Prototypes

2.1.2 28-day old Ferrocement Slab Prototype Module
Three prototype samples were load tested by way of central loading applied using the loading plate of the UTM for the 28-day curing period. From the test it can be observed that the first crack appeared upon the application of 25.24kN load on the center of the module, which is the arithmetic average of the three modules, with a corresponding deflection of 7.56mm on the average. The ultimate load recorded is 33.69kN with a deflection of 16.79mm.

The designed equivalent central load for the prototype is 2.77kN, and with this load, the theory of plate suggested a maximum deflection limit of 0.0802mm. With respect to the three modules that were tested for the 28-day curing period slab samples 1, 2 and 3, based on the following figure for a 2.77kN loading deflected at 0.00mm, 0.0079mm, 0.0122mm linearly interpolated between values containing 2.77kN. It can be inferred that the theory has been satisfactorily satisfied by the result of the load-testing phase.



Figure 7 Load-deflection Curve of the 28-day old Prototypes

2.1.3 Comparison

Continued loading of the specimen resulted in the crushing of the compression face of the ferrocement module prototypes and this phenomena was due to the compressive strength of the mortar matrix has been reached. Further loading only increased the deflection of the specimen but the force required to produce such deflection decreased after the ultimate load has been recorded.

The section used in this study has a moment capacity of 1.053kN-m, with this capacity a section was expected to carry an equivalent central load of 19.724kN at ultimate state, which has been surpassed by the two load-tested prototypes slabs which recorded a 36.99kN and 33.69kN, for the 14th and 28th day old modules, respectively.

However, it could be seen through the test result of the 28th-day old prototypes that the carrying capacity of the slab has been increased to 70.80%.

With respect to the deflection limit set forth by the NSCP 2010in this case a maximum deflection of L/480 was used as a limiting value for serviceability, equal to 1.25mm, the 14th-day old prototypes recorded a capacity in tern of the central load for the samples 1, 2, and 3 were 13.29kN, 13.79kN, and 13.50kN respectively, with an average arithmetic value of 13.53kN.

For the 28th-day curing period, the resulting capacity based on the deflection limit set forth by the NSCP 2010 for the prototype samples 1, 2, and 3, are, 17.34kN, 13.33kN, and 15.17kN respectively, with an average arithmetic value of 15.28kN.

This average value is almost twice as that of the designed load, which means that the section is very satisfactory to carry the projected load.

2.1.4 Behavior of Cracks

Figure 8 shows a sample of the behavior of cracks of the prototypes. Crack patterns appeared in a circular manner around the inner radius of the slabs and radiating out towards the edges of the slabs. The bottom of the prototype modules showed more severe and larger crack sizes because the bottom of the slab is under tensile forces.

Close inspection of the prototypes modules for both period of tests showed that some of the meshes reached their failing stages as indicated by the broken strands of wire mesh visible inside the bottom cracks.

In both tests, it could be observed also that the modules although infested by large cracks, the parts were still intact because of the presence of the meshes that tend of arrest the action of separation.

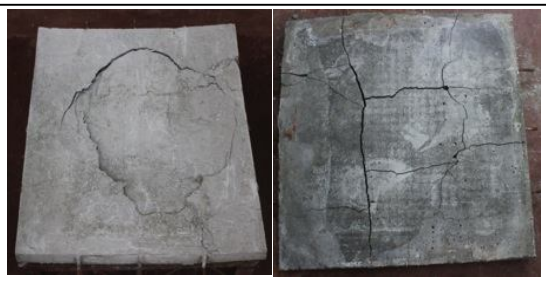

Figure 8 The Crack Patterns of the Top (Left) and Bottom (Right) of the Prototypes

2.2 Actual Application Phase

2.2.1 The Actual Construction

The first part that was done before the installation of the ferrocement floor slab system was the construction of the floor beams needed to hold the slab structure into place. This type of system employed another type of technology, which allowed the floor joist to be welded into its sides. However, the discussion of such work was not included in this paper. The following installation procedures were used on the actual construction.

1. The ferrocement modular slabs were constructed offsite at Dalipuga, Iligan City. An average of twenty (20) to twenty-four (24) modules can be produced in a day for a gang of one laborer and a semi-skilled individual.

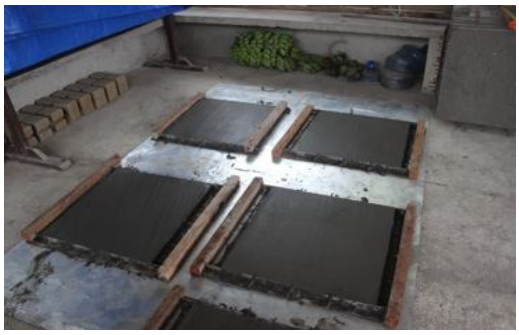

Figure 9 The Molded Prefabricated Slabs Readied for Curing

2. The floor joists were fabricated offsite through a local steel fabricator and were transported to site for installation and were then painted for protection. The rate of joist installation based on the actual performance of the gang of single welder and a helper is about $11m^2$/day.



Figure 11 The Application of the Red Metal Oxide to Joists

3. The slabs from stock were then individually welded for installation by welding. The installation part used a gang of a welder and a helper with a combined productivity rate based on actual observation of 15m^2/day.



Figure 12 Installation of the Modules by Welding

4. After the first slab was installed that served as guide for the level of other slabs, another single slab was brought and placed adjacent to the first slab that was already installed. The figures below show the interconnections that were created by fully welding the studs at the edges of the slab.



Figure 13 Installation of another Adjacent Slab

5. For corner slabs, and for slabs that did not fit the desired position, the remedy that was used was trimming and cutting some parts of the slab using a stonecutter.



Figure 14 Trimming of the Slab by using Stone Cutter

6. Methods 4 and 5 were repeated in cycle until all floor area was covered with the modules. This type of installation left an average of 50mm space between the slabs, which were filled with mortar.



Figure 15 Re-application of Red Metal Oxide to weld Connections

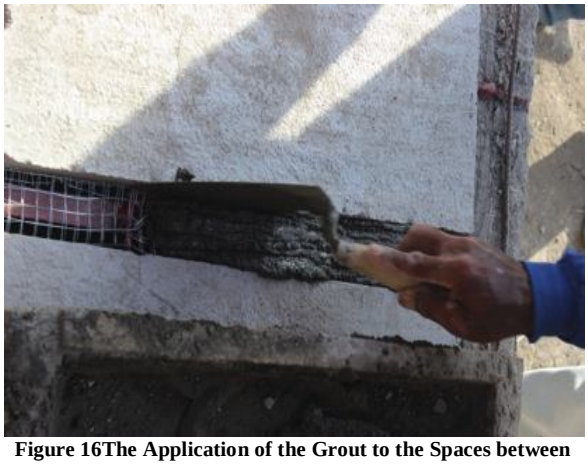

Figure 16The Application of the Grout to the Spaces between the Modules



Figure 17 The Finished System showing Freshly Placed Grout

2.3 Direct Cost Analysis

Based only on direct cost analysis of the two slab system it could be easily determined that for the floor area of 2.52m x 2.95m used in the prototype the prefabricated modular ferrocement floor slab system was lower by about 7.47% of the direct cost obtained for the conventional system. This small difference in cost might be due to the rates used in the evaluation of the prefabricated system, which was also based on the actual output of the labor that was

required to construct the floor system. Because the system was new to the labor hired for the purpose of evaluation, thus the ordinary productivity rates were greatly affected and consequently the direct cost of the whole system.

With the conventional system, its total dead weight is about 18.39kN, whereas the prefabricated modular ferrocement slab system is about 7.12kN, which was only about 38.71% of the weight of the conventional system. This means that the new prefabricated system need not have large supporting structure compared to the conventional system. The effect would be savings on the beams, the supporting pedestal or concrete columns, and on the structure's footing requirement.

CONCLUSIONS

1. The requirements for Serviceability and Strength in order to support ordinary household loadings as prescribed in the National Structural Code of the Philippines has been sufficiently attained and exceeded by the carrying capacity of the specimens.
2. There was substantial agreement between the theoretical approach made by the author and that of the results of the tests.
3. By mechanically testing the specimens, it was found out that a prefabricated modular slab made out of ferrocement technology for interior purposes was a viable and safe system that can address the basic house loading requirements.
4. There was sufficient economic savings in the ferrocement modular slab system.

REFERENCES

[1] Aboul-Anen, B., El-Shafey, A., & El-Shami, M. (2009). Experimental and Analytical Model of Ferrocement Slabs. International Journal of Recent Trends in Engneering. Vol. 1. No. 6.

[2] ACI Committee 549 (1999). Guide for the Design, Construction, and Repair of Ferrocement.

[3] Al-Rifaie, W.N. (2012). Modern Housing System using Ferrocement as Sustainable Construction Materials. University of Tikrit, Iraq.

[4] Alwash, A. S. (1982). Flexural Behavior of Ferrocment (Doctoral Thesis). Department of Civil and Structural Engineering, University of Sheffield.

[5] ASTM A 370 (2004). Standard Test Methods and Definitions for Mechanical Testing of Steel Products. ASTM International. West Conshohocken, United States.

[6] ASTM C 33 (2004). Standard Specification for Concrete Aggregates. ASTM International. West Conshohocken, United States.

[7] ChandraSekharRao, T., GunneswaraRao, T. D., RamanaRao, N. V., & Rambabu, C. (2008). An experimental Study on Ferro Cement Channel Units Under Flexural Loading. International Journal of Mechanics and Solids. Vol. 3. No. 2.

[8] Karmazinova, M., Melcher, J., Strba, M. (2012). Loading Tests of Thin-Walled Ferrocement Panels for Horizontal Slab Structures:Recent Advances in Engineering. Brno University of Technology.

[9] Laseima, S. Y. (2006). Structural Behavior of Ferrocement-Autoclave Block Composite Slab (Unpublished Master Thesis). Malaysia: Universiti Putra.

[10] Morton, E. C., Thompson, A. G., Villaescusa, E. Testing and alalysis of steel wire mesh for mining applications of rock surface support. School of Mines, Western Austrial.

[11] Mustapha, M. L., & Salihuddin, R. S. (2013). A Review Study on Cold-Formed-Ferrocment Composites. Austrialian Journal of Basic and Applied Sciences.

[12] Naaman, A. E. (2000). Ferrocement and Laminated Cementitious Composites. Michigan, USA: Techno Pess 3000.

[13] National Structural Code of the Philippines (2010). Association of Structural Engineers in the Philippines.

[14] Pama, R. P., & Paul, B. K. (1978). Ferrocement. Bangkok, Thailand: International Ferrocement Information Center (IFIC), Asian Institute of Technology.

[15] Pama, R. P. (1990). Research on Ferrocement – Global Perspective. Journal of Ferrocement. Vol. 20. No. 4.

[16] Raj, V. (1990) Large Span Bamboo Ferrocement Elements for Flooring and Roofing Purposes. Journal of Ferrocement. Vol. 20. No. 4.

[17] Saeed, J. A. et al (2010). Behavior and Flexural Strength of Ferrocement One-Way Slab with Square Openings. Journal of Zankoy Sulaimani. Vol. 1.

[18] Sakthivel, P. B., & Jagannathan, A. (July 2012). Study of Flexural Behavior of Ferrocement Slabs Reinforced with PVC-coated Welded Wire Mesh. International Journal of Engineering Research and Development. ISSN: 2278-067X, Vol. 1.

[19] Soranakom, C. & Mobasher B. (2006). Correlation of Tensile and Flexural Behavior of Fiber Reinforced Cement Composites. Ferro8, Proceedings of the 8th International Ferrocement and Thin Reinforced Cement Composites Conference. Bangkok, Thailand.

[20] Timoshenko S.P., & Krieger, S. (1959). Theory of Plates and Shells. Singapore: McGraw-Hill Book Co.

★★★