Chapter 2

Literature Review

2.1 Introduction

The literature review presented in this chapter covers the research areas related to the objective of this thesis including the use of ferrocement sandwich panel system. Ferrocement technology is convenient for many applications especially construction buildings applications because of its ease of construction and its relating low cost. Therefore, many researches were conducted to investigate its performance and properties as a construction material. The current research focuses on the use of ferrocement sandwich panel system with core of AAC masonry construction to act as a wall bearing structural system.

The two thin outer layers in the proposed sandwich wall system are consisting of ferrocement. Actually, Ferrocement has been known since 1852 as a building material. Therefore, institutions and organizations made considerable and valuable technical information regarding ferrocement technology, and established design guidelines and design criteria. International Ferrocement Society (IFS Committee 10) is established by the Asian Institute of Technology, which is considered as one of the leading organizations in the ferrocement technology (IFS-Committee 10-2001). IFS Committee 10 established the criteria for material selection, quality control, repair and maintenance of ferrocement structures, and code provisions such as ACI 318 (ACI 318M-89).

The core martial in the proposed ferrocement sandwich panel system is AAC masonry construction. In fact, AAC was first produced commercially in Sweden, in 1923 by Swedish Architect Johann Axel Eriksson. Though, Autoclaved Aerated Concrete (AAC) is relatively new to the world-wide construction industry, yet it is available from different manufacturers throughout countries on all continents including the Middle East. Due to the wide applications of AAC blocks around world in different climates, many researches have been conducted on it and according to different building codes. The Code and Specification of the Masonry Standards Joint Committee (MSJC) illustrates the design provisions for AAC blocks, and background material on experience with AAC in Europe, as given in RILEM

(1993) (R. E. Klingner, 2010). The Autoclaved Aerated Concrete Products Association established a nationwide group of AAC manufacturers in 1998 (ww.aacpa.org). The web site of the AACPA includes the technical manuals and many technical materials of AAC blocks.

Thus, many researches have been conducted on ferrocement material and on AAC blocks to investigate their performance under different cases of loadings, and to formulate the criteria for design and construction. This chapter summarizes some of the previous investigations carried out on ferrocement and AAC blocks on the aspects of material, mechanical properties, and applications.

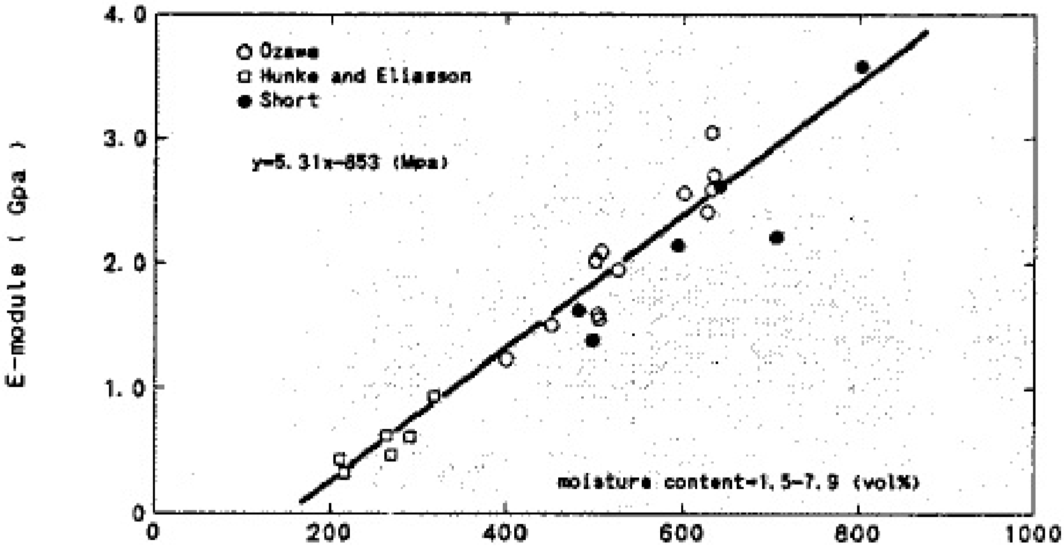
2.2 Autoclaved Aerated Concrete (AAC)

2.2.1 Materials Used in AAC

The material of AAC varies with manufacture and location, but it consists of some or all of the following: fine silica sand; Class F fly ash; hydraulic cements; calcined lime; gypsum; expansive agents such as finely ground aluminum powder or paste, and mixing water. However, as specified in ASTM C1386, it is a mixture of sand, lime, cement, gypsum, water and an expanding agent that is cured in a pressurized steam chamber, called an autoclave, producing a cellular lightweight material. Details of the mixture designs used by each producer depend on the available materials and the cost of the producing. AAC can also be reinforced internally in the manufacturing process with welded wire cages (R. E. Klingner, 2010).

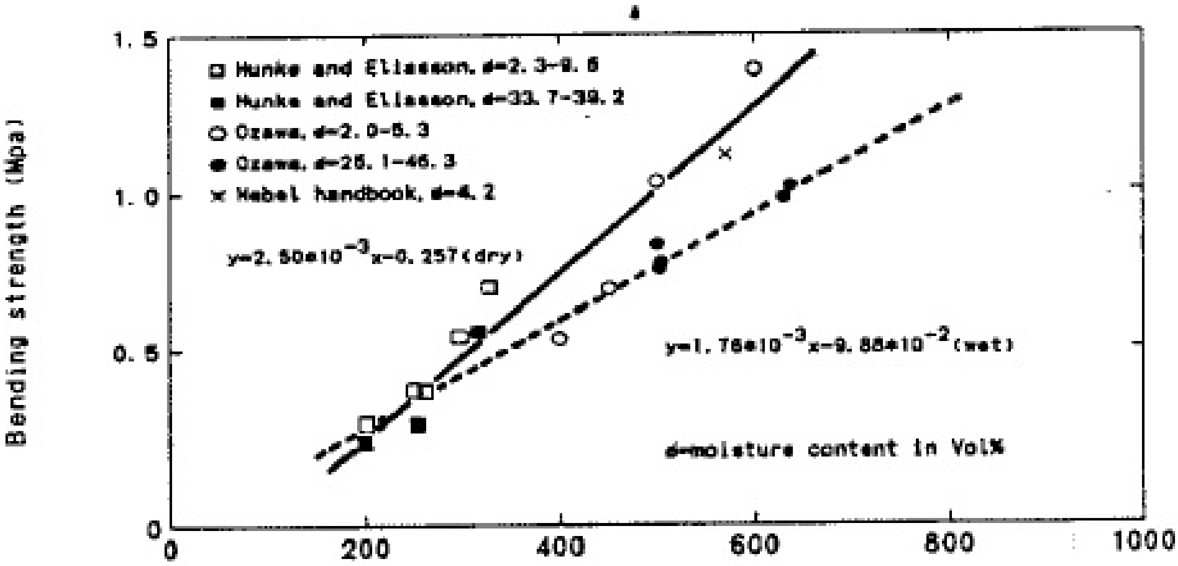
2.2.2 Mechanical Properties of AAC

In relation to its weight, Autoclaved Aerated Concrete (AAC) has a high compressive strength. Figure 2.1 shows the dependence of the mechanical properties of AAC on the bulk density (Tada, 1986).



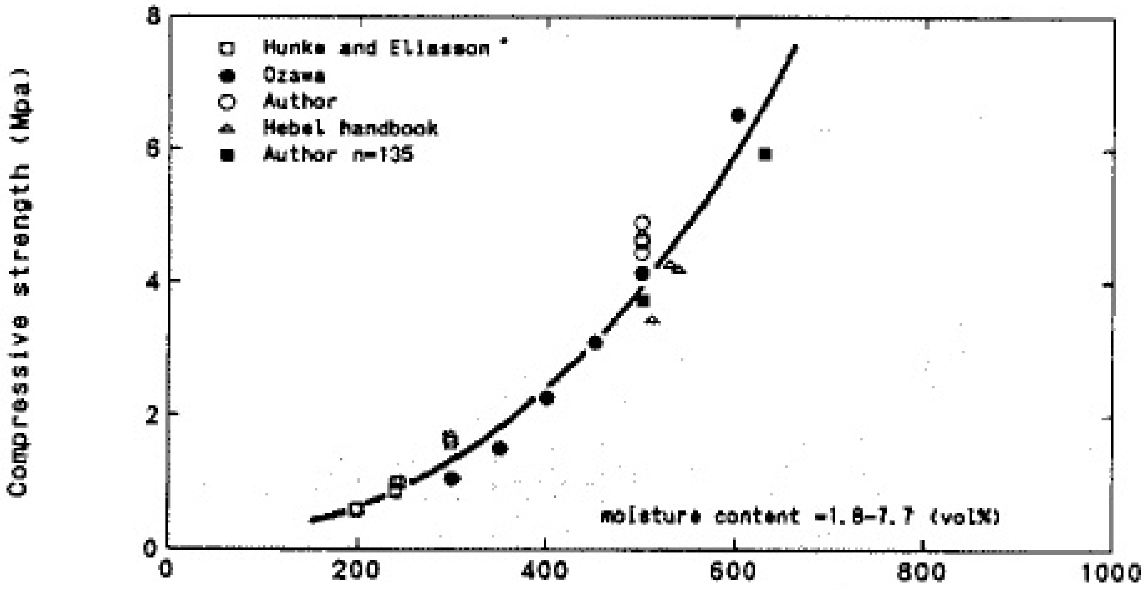
Bulk density (kg/m^3)

2.1a) Dependence of E-module on bulk density (Tada, 1986)



Bulk density (kg/m^3)

2.1b) Dependence of bending strength on bulk density (Tada, 1986)



Bulk density (kg/m^3)

2.1c) Dependence of compressive strength on bulk density (Tada, 1986)

Figure 2.1: Dependence of the mechanical properties of AAC on the bulk density (Tada, 1986)

AAC is produced in different densities and corresponding compressive strengths in accordance with ASTM C1386 (Precast Autoclaved Aerated Concrete Wall Construction Units) (R. E. Klingner, 2010). Table 2.1 shows typical material characteristics of AAC in Different Strength Classes.

Table 2.1: AAC in Different Strength Classes (R. E. Klingner, 2010)

Strength class	Specified compressive strength lb/in^2 (MPa)	Nominal dry bulk density lb/ft^3 (kg/m^3)	Density limits lb/ft^3 (kg/m^3)
AAC 2	290 (2)	25 (400) 31 (500)	22–28 (350–450) 28–34 (450–550)
AAC 4	580 (4)	31 (500) 37 (600) 44 (700) 50 (800)	28–34 (450–550) 34–41 (550–650) 41–47 (650–750) 47–53 (750–850)
AAC 6	870 (6)	44 (700) 50 (800)	41–47 (650–750) 47–53 (750–850)

2.3 Ferrocement

2.3.1 Ferrocement Constituent Material

According the IFS Committee 10, the ferrocement material is defined as a type of reinforced concrete commonly constructed of hydraulic cement mortal reinforced with closely spaced layers of relatively small wire diameter mesh. Therefore, the mechanical properties and characteristics of ferrocement like ductility, fine cracking, durability, and impermeability could be improved by proper selection and control of the reinforced mesh and matrix properties.

a) Cement

The cement should be used according to ASTM C 150-85a, ASTM C 595-85, or an equivalent standard. The cement should be supplied fresh and free of lumps and foreign matter, and it should be stored under dry conditions. The cement percent in ferrocement is higher than in the conventional reinforced concrete. Portland cement could be partially replaced in mortar matrix by adding Rice Husk Ash (RHA) cement with percent not exceed 35% by weight of the blended cement, and the compressive strength after 28 days is similar to the compressive strength of Type I Portland Cement Mortar. In order to maintain a higher volume fraction of fine filler material in the mortar, mineral admixtures should be added like silica fume or fly ash (www.set.ait.ac.th).

b) Fine Aggregates

The most common aggregate used in ferrocement is the normal weight fine aggregate (sand). The fine aggregates should be relatively free of organic materials, silt, and clay, and it should be clean, strong. The fine aggregates should be also inert with respect to other used materials in the mortar. Grading of the sand is to be such that a mortar of specified proportions is produced with a uniform distribution of the aggregate, which will have a high density and good workability and which will work into position without segregation and without use of high water content. The fineness of the sand should be such that 100% of it passes standard sieve no. 8. Table 2.2 shows some guideline on desirable grading (www.set.ait.ac.th).

Table 2.2: Guidelines on Desirable Sand Grading (www.set.ait.ac.th)

Sieve size	Percent passing
No. 8	80-100
No. 16	50-85
No. 30	25-60
No. 50	10-30
No. 100	2-10

c) Water

Water in the mortar should be free from any organic materials or any harmful or toxic solution, which may lead to deterioration in the properties of ferrocement. Water should also be free from salt solutions or harmful substances. Potable water is fit for use as mixing water. In addition, recycled water could be used as mixing water as well as for curing ferrocement structures (www.concrete.net). Table 2.3 shows the mandatory chemical and other limit for mortar mixing water according to ASTM standards.

Table 2.3: The mandatory chemical limits for mortar mixing water (www.concrete.net)

Chemical	Limit (ppm*)	Test method
Chloride Cl	500 : 1,000	ASTM D512
Sulfate SO_4	3,000	ASTM D516
Alkalies	1,500	ASTM C114 or EN 196-21
Total solids	50,000	ASTM C1603
Harmful substances	100	AS 1141.35
Harmful substances	100	Local Standard
Harmful substances	500	ISO 7890-1
Harmful substances	100	ASTM D3559
Harmful substances	100	ASTM D1691
pH	>5.0	AS 1580.505.1
Oil and grease	<50	APHA 5520

*1ppm=1mg/L, 0.1%=1000ppm

d) Admixture

Ferrocement may contain chemical admixtures such as superplasticizers and mineral admixtures like fly ash or silica fume in order to serve one of the following four purposes: water reduction, which increases strength and reduces permeability; air entrainment, which increases resistance to freezing and thawing; and suppression of reaction between galvanized reinforcement and cement. In order to increase workability and durability of ferrocement, mineral admixtures should be added. Normally, 15% of the cement can be replaced with mineral admixtures without reducing the strength. Pozzolanic admixtures are not added to reduce cement but to replace part of the fine aggregates to improve plasticity. According to Y. Korany (Y.S. Korany, 1996) research study, different mixes with different percentages of silica fume were conducted in order to investigate the effect of adding silica fume on the mortar properties and to determine its optimum replacement percentages such as 0, 5. 10. 15. 20. and 25% , and the water-cement ratio was kept constant at 0.35 for all mixes then results of mixes Slump, air content, and density were measured for each mix were measured and compared. All mixes with mineral admixtures results was agreed with IFS Committee 10 recommendations and showed that the optimum percent of silica fume as a cement replacement is 15%, and the compressive strength of the mixes is higher than the control mix after 28 days (Y.S. Korany, 1996).

e) Mortar Mix

The ferrocement mortar matrix is a homogeneous mix composed primarily of Portland cement, well graded fine aggregate (sand) passing sieve opening 2mm, and water; it may contain chemical admixtures such as super-plasticizers and mineral admixtures like fly ash or silica fume to improve its properties (IFS Committee 10, 2001). The mortar matrix usually comprises more than 95% of the ferrocement volume and has a great influence on the behavior of the final product; therefore, great care should be exercised in choosing the constituents materials of the mortar matrix and in mixing and placing the mortar. The chemical composition of the cement, the nature of the aggregate, the aggregate cement ratio, and the water cement ratio are the major parameters governing the properties of the mortar mix. The ranges of mix proportions recommended for common ferrocement applications are sand-cement ratio by weight, 1.5 to 2.5, and water-cement ratio by weight, 0.35 to 0.5. Fineness modulus of sand, water-cement ratio and sand-cement ratio should be determined from trial batches to insure a mix that can infiltrate the mesh and develop a strong and dense matrix. A research was conducted to investigate the permeability characteristic of ferrocement for water structures by Ravindrarajah and Tam. (R.S. Ravindrarajah and C. T. Tam, 1984) Superplasticizer was added to the mortar mix, while the water cement ratio was 0.3 to improve workability. It was found that adding Superplasticizer to the mortar results in low water cement ration, low permeability of the mortar matrix, and better crack resistance (R.S. Ravindrarajah and C. T. Tam, 1984).

f) Coating

In some cases, ferrocement structure elements, like marine structures, should be protected against chemical attack that might damage the structural integrity of their components. The most successful organic coatings are vinyl and epoxy coatings (www.set.ait.ac.th).

g) Reinforcing mesh

One of the most essential components of ferrocement is the reinforcing mesh. According to IFS Committee 10-01, wire mesh with closely spaced wires is the most commonly used reinforcement in ferrocement. Expanded metal, welded-wire fabric, wires or rods, and discontinuous fibers are also used in special applications. Wire mesh generally consists of thin wires, either woven or welded into a mesh, but the main requirement is that it must be easily handled and, if necessary, flexible enough to be bent around sharp corners. The function of the wire mesh and reinforcing rod in the first instance is to absorb the tensile stresses on the ferrocement structure which the mortar, on its own, would not be able to withstand, and to increase the tensile stress for the ferrocement structure. The mechanical behavior of ferrocement is highly dependent upon the type, quantity, orientation and strength properties of the mesh and reinforcing rod. Standards for the mechanical properties of steel meshes commonly used in ferrocement are not available; however, the values listed in the ACI 549 could be used. The American concrete Institute (ACI) committee 549 on

Ferrocement concluded that the definition of ferrocement is not limited to steel reinforcing only. The ACI definition of ferrocement included the statement "Mesh may be made of metallic material or other suitable materials." This definition allows other materials to be used for ferrocement structures like bamboo mesh (www.set.ait.ac.th).

A comparison between different steel types was conducted to investigate the effect of steel reinforcement on the ferrocement plates (Swamy and Shaheen, 1988). Mild steel bars, mild steel mesh with and without bars, and high tensile mesh were used in that research, and the results of deflection, first crack load, cracking pattern, and failure loads were recorded and analyzed. The results confirmed that the type of reinforcement has significant effect on the structural behavior of thin reinforced concrete plates. In addition, mild steel meshes showed better performance in terms of first crack load, cracking pattern, deflection, and failure loads, while the use of skeletal bars with mesh had some undesirable effect on ultimate loads and cracking (Swamy and Shaheen, 1988).

2.3.2 Structural Applications of Ferrocement

Ferrocement is considered as a special kind of conventional reinforced concrete. Therefore, most of tests, which are used for conventional reinforced concrete, are also applicable for ferrocement structures. However, these tests were modified in order to predict accurately the behavior of the ferrocement structures under different loading tests like flexural loading and axial compression loading.

a) Ferrocement as Flexural Units

A research was conducted by Fahmy, Shaheen, and Abou Zeid (2004) on the ferrocement panels for use as floor units (Fahmy et al, 2004). Ferrocement sandwich panels and hollow core panels were investigated as flexural slabs. Two different types of core materials were studied namely foam concrete and light brick core. Shear connectors Z-shape were used in order to transfer the load between the different layers across the whole section. The proposed panels were tested under flexural loadings and the following results were obtained:

- Shear connectors were recommended to be in a different pattern rather than Z-shape.
- Ferrocement hollow core panels yielded higher ultimate loads than the ferrocement sandwich panels.

- High ultimate and serviceability loads, crack resistance control, high ductility, and good energy absorption properties could be achieved by using the proposed panels.

Another research was conducted by Fahmy, Shaheen, Abou Zeid, and Hassan Gaafar (2005) on the behavior of ferrocement panels under axial and flexural loadings (Fahmy et al, 2005). In that research, two different types of core material were investigated the light brick core, and the hollow core panel. The proposed panels were tested under flexural loadings and the structural responses in terms of ultimate loads, mid-span deflections, energy absorption, serviceability loads, and ductility ratios were recorded, and the results drawn as follows:

- Increasing the thickness of the ferrocement layers leads to an increase in the ultimate load, energy absorption, ductility ratio, and service loads.
- Ferrocement hollow core panels under flexural loading yielded higher ultimate loads than ferrocement light brick sandwich panels without side reinforcement.
- Using side reinforcement in ferrocement light brick sandwich panels under flexural loading enhances the crack pattern remarkably.

I. A. Basunbul, Mohamed Saleem, and G. J. Al-Sulaimani conduct study on the flexural behavior of ferrocement sandwich panels in order to investigate the number of wire mesh layers, the skeletal steel, the web mesh reinforcement, and number of mesh (I.A. Basunbul et al, 1991). They proposed to add reinforced concrete ribs between the two facings for the ferrocement sandwich panels to act as a single unit and to transfer the shear forces in the cross section. Ultimate load was recorded experimentally, while ultimate moment capacities were computed theoretically using conventional reinforced concrete theory given by ACI code. The following conclusions were drawn:

- The number of ribs and the presence of web mesh reinforcement play an important role in developing full moment capacities.
- Conventional reinforced concrete theory predicts the ultimate moment capacities of ferrocement under flexural loading within reasonable limits.
- Failure pattern and cracking behavior depend on the volume of reinforcement and the shear connectors between the facings.

b) Ferrocement as Axial Compression Units

Several researches carried out investigate the ferrocement under axial compression loading in order to study the effect of number of mesh layers, the effect of buckling of ferrocement elements, and the effect of the compressive strength of the mortar.

A research was conducted to study the behavior of ferrocement under axial compression loading by Wail N. Al Rilaie and Ahlam A. Aziz (Al-Rifiaie and Aziz, 1995). The investigation aimed at studying the effect of the number of wire mesh layers, diameters of wires, and mortar strength. The failure happened when the mortar cover started to spall off over the surface, and a sudden rapid drop in load was also happened. However, the researcher proposed a theoretical model to calculate and predict the critical buckling load (Pc) as shown in Equation 2.1:

$$P_c = K \text{ x } A_g \text{ x } \{\pi^2 \text{ x } E/12 \text{ x } (1 - \upsilon^2)\} / (t/b)^2 \qquad (2.1)$$

Where,

Ag = the gross area, K = the buckling coefficient, E = the modulus of elasticity, υ = poisson ratio

The experimental test results were validated by the theoretical results, and it was matching with it. The following conclusions could be drawn:

- The proposed model could be used to predict the ultimate loads.
- The initial cracking load ranges between 40 to 60% of the ultimate compressive loads.
- The load carrying capacity is not affected by the number of mesh layers
- Having many layers of wire mesh will lead to an improper placement of the mortar which resulted in a lower load carrying capacity.
- Failure loads occurred by crushing top and bottom ends with spalling off the mortar cover around the mesh.

Another investigation was done by Mansur and Paramasvam to study to investigate the behavior of ferrocement short columns under axial compression loading (Mansur and Paramasvam, 1990). The major parameters in their research were types, arrangements, and volume fraction of reinforcement. In addition, they developed two theoretical models to predict the ultimate loads of the columns. The first model includes the contribution of steel reinforcement as shown in Equation 2.2:

$$P_u = 0.67\ F_{cu}\ (A_g - A_s) + A_s\ F_y \qquad (2.2)$$

Where,

Ag = gross cross-sectional area of column, A_s = Area of steel in direction of loading, F_{cu}= cube crushing strength of mortar, and F_y = yield strength of reinforcing steel.

The second model did not include the contribution of steel reinforcement as shown in Equation 2.3:

$$P_u = A_g\ F_f \qquad (2.3)$$

Where, F_f the ratio of the compressive strength of 20 mm thick ferrocement plates to that of 100 mm cubes. The following conclusions could be drawn:

- Welded wire mesh as reinforcement performs better than an equivalent amount of woven mesh in regard to both strength and post-ultimate behavior of the columns.
- Since the both theoretical models gave close results to those of the experimental, strength of the axially ferrocement loaded columns is not affected by the Volume fraction of reinforcement.

Kaushik et al conducted a research on ferrocement plates to study the buckling behavior of ferrocement plates (Kaushik et al, 1994). In this research, ACI empirical equations were used to predict the crushing load of the ferrocement plates as shown in Equations 2.4 and 2.5:

$$P_{ult} = \phi\ C_r\ (0.85\ f'_c)\ A_g \qquad (2.4)$$

Where;

ϕ is a reduction factor assumed to be 0.7, Cr = strength reduction factor.

Euler - Engeeser Tangen Modulus Formula was used to predict the buckling strength of tested columns.

$$F_{cr} = \pi^2\ E_c / (le/r)^2 \qquad (2.5)$$

Where;

F_{cr} is the critical buckling stress, E_c is the modulus of elasticity of the composite, l_e is the effective length, and r is the radius of gyration of the cross section. The following conclusions can be drawn:

- For slenderness ratio less than 100, failure is generally due to crushing and splitting of the plates; the ultimate crushing load could be predicted by Equation (2.4).
- For slenderness, ratio greater than 100, plates fail in buckling; the buckling strength can be predicted by Equation (2.5).

In 2005, Fahmy, Shaheen, Abou Zeid, and Hassan Gaafar conducted research on the behavior of ferrocement panels under axial and flexural loadings (Fahmy et al, 2005). In this research, two different types of core material were investigated the light brick core, and the hollow core panel. The proposed panels were tested under compressive axial loadings and the structural responses in terms of ultimate loads, mid-span deflections, energy absorption, serviceability loads, and ductility ratios were recorded. They developed and validated theoretical model to predict the ultimate loads of the ferrocement element to incorporate the effect of the strength of the ferrocement and the strength of the light core as shown in Equation 2.6:

$$P_u = 0.8\left[0.35\,f_{cu}\,A_{ferro} + 0.35\,f_{brick}\,A_{brick} + (f_y - f_{cu})\,A_{sv}\right]\left[1 - \left(\frac{k.H_c}{32\,t}\right)^2\right] \tag{2.6}$$

Where;

F_y is the yield stress of the vertical steel, f_{brick} is the specified characteristic compressive strength of the brick, A_{sv} is the total area of the vertical steel, A_{brick} is the gross area of the AAC brick cross section, A_{ferro} is the gross area of the two ferrocement layers, t is the thickness of the wall, H_c is the height of the wall, and K is the effective length factor. The following conclusions can be drawn:

- The proposed model could be used to predict the ultimate loads.
- Increasing the thickness of the ferrocement layers results in an increase in the maximum compression load. The load increased by about 26% as the results of increasing the thickness from 120mm to 140mm.