**International Journal of Research in Advanced Engineering and Technology**
**ISSN: 2455-0876**
**Impact Factor: RJIF 5.44**
**www.newengineeringjournal.in**
**Volume 4; Issue 2; May 2018; Page No. 41-48**

# Different studies on ferrocement channel units under compression, flexure, fatigue and impact effect

**Ali Kadhim Sallal**
Department of Hydraulic Structures/College of Water Resource Engineering, Lecturer at Al-Qasim Green University, Al-Hula, Iraq

**Abstract**
Ferro-cement is often believed to be a form of reinforced concrete. However, in spite of the similarities between the two materials there are still major differences, indicating that Ferro-cement requires a separate study to establish its structural performances. On the other hand, a large amount of research has been carried out on Ferro-cement panels. This research included study the compression, flexural, fatigue and impact effect on Ferro-cement panels.

**Keywords:** introduction, review of literature, ferro-cement as construction material, conclusions references

## 1. Introduction
Ferro-cement is a term given by **"Nervi"** to describe a thin slab which consists of Portland Cement Mortar reinforced with multiple layers of steel wire mesh on both sides of the slab, usually with steel reinforcing bars called skeletal steel sandwiched in the middle of the slab [1]. Ferro-cement has many advantages over conventional reinforced concrete, such as improvement in tensile and flexural strengths, ductility, impact resistance and crack arresting properties [2, 3] although the concept of Ferro-cement is almost as old as reinforced concrete, the real development took place in recent years. The mechanical properties and hence the technical information are now fairly well established [4, 5, 6]. This has given an impetus to its application in various structures and structural elements such as boats, sail and folded plate structures, silos, water tanks slabs etc.

## 2. Literature Review
**[The Flexural Behavior of RCC Slab with Ferro-cement Tension Cover] was studied by (M.A. Al-Kubaisy, Mohd Zamin Jumaat) [10].**

The results of tests this project included casted 12 simply supported slabs. The effect of the following parameters: percentage of wire mesh reinforcement in the Ferro-cement cover layer, the thickness of the Ferro-cement layer and the type of connection between the Ferro-cement layer and the reinforced concrete slab on the ultimate flexural load, first crack load, crack width and spacing and the load deflection relationship was examined. All the slabs of rectangular shape with (500 mm) width, (75-85) mm depth and a length of (1500) mm. The specimens that covered by Ferro-cement material exhibited greater stiffness than the control specimens. The decrease in the value of deflection was higher for specimens provided with shear connectors. Reducing the volume fraction of reinforcement in the Ferro-cement cover from (0.90%) to (0.30%) didn't influence the total deflection near ultimate load. The Ferro-cement layer thickness and the connection type influenced the reduction in deflection. The results of investigation work showed, the use of Ferro-cement cover slightly increases the ultimate flexural load also increases the first crack load. The first crack load increased with the increase in the number of mesh reinforcement and thickness of Ferro-cement layer. Considerable decrease in crack width and spacing (64 - 84%) was observed for the specimens that contains Ferro-cement layer. The presence of a cold joint between the reinforced concrete slab and the Ferro-cement layer showed decrease in the ultimate flexural load by (34%). However, the cracks width and spacing were reduced. The specimens that casted without structural connection, provided that the concrete was cast within (1-1.5) hour of casting the Ferro-cement cover, behaved in a very similar manner to those with structural connection. The deflections at a service load and near ultimate load were smaller for the specimens that contain Ferro-cement layer.

**[An Appraisal of the Shear Resistance of Ferro-cement Elements] was studied by (T. Chandrasekhar Rao, T.D. Gunneswara Rao and N.V. Ramana Rao) [11].**

This project include study the effect of shear strength on simply supported Ferro-cement rectangular plates subjected to four points loading. Limited literature is available on the shear behavior of Ferro-cement elements, as the span to depth ratio of these elements is very high. However, the studies on shear response of Ferro-cement material assume importance to understand the behavior of material. In this study, the tests on Ferro-cement elements varying the shear span to depth ratio (a/d) and the different layers of mesh are conducted. It's observed from this work that is an increase in the volume fraction of the mesh reinforcement with wire mesh also showed that is increased the shear capacity of the member and found that up to shear span to depth ratio was (3), shear behavior is predominant. Beyond shear span to depth ratio was (3), the flexural behavior is predominant and the design of the elements based on flexure is sufficient.

## 3. Ferro cement as construction material
### 3.1 Definition of Ferro-cement
Although Ferro-cement has been in use since the (1940's),

still, it's a definition isn't yet established. The reasons for this may be several.

1. Ferro-cement material has been considered as a form of reinforced concrete and therefore, there was no real need for its definition.
2. The lack of investigation of the material which meant that its potentials and superior properties aren't known.
3. The very many different types of reinforcement used in Ferro-cement material led to uncertainty of the established properties. Until more data is established about Ferro-cement will have no exact definition.

Ramouldi [3] stated [Among the more pressing problems relating to the development of Ferro-cement material is the question of its very definition]. In what follows, some of the available definitions of Ferro-cement are reviewed.

Bigg [4] reported a definition on Ferro-cement according to the American Bureau of Shipping which define is a thin, highly reinforced concrete in which the steel reinforcement is distributed widely throughout the concrete, so that the material under stress, acts approximately as homogeneous material. The strength properties of this material are to be determined by testing a significant number of samples. It has been argued that the words thin, highly reinforced and the homogeneous may suggest different meanings to different people.

The Russians [5] definition, which was also adopted by Bigg [4] emphasized on the subdivision of the reinforcement. The definition was true Ferro-cement is considered to be a mesh reinforced mortar with a compressive strength at least (39.3 $N/mm^2$) and a specific surface K (ratio of surface area of steel wire to the volume of the composite) between (2.0 $cm^2/cm^3$) and (3.0 $cm^2/cm^3$). This definition seems to lack the description of the material itself. Moreover, the restriction in the specific surface of reinforcement requires more experimental verification.

The definition of Ferro-cement by (ACI) Committee 549 [7] was: (Ferro-cement is a type of thin wall reinforced concrete construction where usually hydraulic cement is reinforced with layers of continuous and relatively small diameter mesh. The mesh may be made of metallic materials or other suitable materials). In this definition, Ferro-cement isn't confined to only steel wire mesh but other types of meshes as well. However, the definition ignores an important type of reinforcement currently in use the Ferro-cement, i.e. the combination of steel rods and wire mesh. In addition, it doesn't emphasize the properties of the mesh reinforcement. These properties, as will be seen later, are important factors in producing sections of the superior properties of reinforced concrete also it can be seen from the above discussion that research is needed before reaching a truly representative definition for Ferro-cement.

### 3.2 Ferro-cement Technology

Shelter is one of the basic needs of human being but more than 80 developing countries in the world suffer from housing shortages resulting from population growth, internal migration, war, natural disaster, to mention a few. Most dwellings in rural areas are made of cheap local materials, including low quality wood (which is easily attacked by termites), scrap metal, thatch or earth products (like clay, mud, sand, rock or stone) which are temporary and unsafe. There is an urgent need to explore a building material that is structurally efficient, but at the same time, should be lightweight, eco-friendly, cost effective and especially the ones that can perform the desired functions (Akhtar *et al*. 2009) [17]. Ferro-cement is such a material that is slim and slender but at the same time strong and elegant, which provides a potential solution to roofing problems (Abdullah and Takiguchi, 2003) [13], with a history of ancient and universal method of building huts by using reeds to reinforce dried mud (wattle and daub) (ACI Committee 549-R97) [14]. Small Ferro-cement tanks of less than (18.9 $m^3$) or (5000 gal) capacity were being factory built in New Zealand (Bulletin CP-10, 1968) [18] and elevated water tanks of (47.3 $m^3$) or (12500 gal) capacity was successfully constructed in Bangladesh in 1989 (Mansur, 1990) [24]. Ferro-cement silos can hold up to a capacity of (10 metric tons) or (22400 lb) of grain/ food stuffs, fertilizer, cement and pesticide (Naaman, 2000) [58].

#### 3.2.1 Uniqueness of Ferro-cement

Ferro-cement is a thin construction element with thickness in the order of (10-25 mm) or (3/8–1 in.) and uses rich cement mortar no coarse aggregate is used and the reinforcement consists of one or more layers of continuous/ small diameter steel wire/ weld mesh netting. It requires no skilled labor for casting and employs only little or no formwork (Ferro 7, 2001) [22]. In Ferro-cement, cement matrix hasn't cracked since cracking forces are taken over by wire mesh reinforcement immediately below the surface (Desai, 2011) [20]. (Husain Doshi Gufa), an underground Ferro-cement shell structure which was built in (1993) in Ahmedabad in India hasn't only withstood the (2001) earthquake but also has remained crack-free till date (Doshi *et al*. 2011) [21]. Such a structure involving complex curvatures can be constructed in a reliable manner using Ferro-cement technology giving free reign to architectural expression. Ferro-cement construction technology is being popularized throughout the world in many countries like (Canada- USA- Australia- New Zealand- United Kingdom- Mexico- Brazil- the former USSR, Eastern European countries- China- Thailand- India- Indonesia) and in other developing countries due to its uniqueness and versatility (Shannag and Ziyyad, 2007) [27].

#### 3.2.2 Ferro-cement Structures World-Wide

There are many structures built of Ferro-cement housing units- shell roofs- water tanks and swimming pools, biogas digesters, silos, food storage units and for some specialized applications such as floating marine structures for which reinforced concrete is too heavy, Ferro-cement is a preferred choice over reinforced concrete (Naaman, 2000; Hago *et al*., 2005; Abasolo *et al*., 2009) [26, 23, 12]. In the early (1960s), Ferro-cement construction was widely accepted in many countries like (Australia- New Zealand- and the United Kingdom). From then on, 1000 of Ferro-cement vessels and structures were built in quite a number of countries. For example in Israel, Ferro-cement is used to improve existing houses (Adajar *et al*., 2006) [16]. Ferro-cement houses utilizing local materials such as wood, bamboo or bush sticks as equivalent steel replacements have been constructed in Bangladesh, Indonesia and Papua New Guinea. Also in SriLanka, Ferro-cement houses resistant to cyclones are developed and constructed (Adajar *et al*. 2006) [16] and corrugated Ferro-cement sheets have been developed and tested by the building research institute, The state engineering corporation, Colombo, SriLanka, these sheets are developed as a replacement for asbestos cement corrugated sheets which are widely used as a roofing material (Naaman and Shah, 1976, ACI Committee 549R-97) [25, 15]. In India, many Ferro-cement structures implemented by The Auroville Centre for Scientific Research (CSR) are testimony of durability of the Ferro-cement technology (CoP, 1997) [13].

### 3.3 Practical Applications

During the past ten years, Ferro-cement applications have been extended widely. These were especially helped by publishing a report on the uses of the material in developing countries by the National Academy of Sciences [2] of the United States of America. The report explored many advantages of the material such as (ease of fabrication, low skill and adaptability of the material for complicated shapes). On the other hand, research progress helped developed countries to find many new potential uses of the material. In marine applications, it includes a wide range of boat building varying in size between (10) to (30) m. It also includes [18] docks, buoys, floating breakwaters, submarine structures, floating and submerged oil reservoirs, offshore tanker terminals and floating bridges. The inland applications of the material, both in developing and developed countries, vary widely. The developing countries, making use of the low skill required and the availability of the constituents used the material in low cost housing, roofing, grain storage bins, agricultural buildings and similar applications [28, 56]. In developed countries applications include shell structures, water tanks, tunnel lining, Permanent formwork, etc. A good amount of literature is available [57, 58, 59] on both the possible applications of Ferro-cement and its manufacturing techniques. Moreover, it would be expected that the material will find even a greater range of application when its characteristics and theoretical prediction are fully established.

### 3.4 Ferro-cement Constituents

#### 3.4.1 Matrix

The matrix of Ferro-cement is usually cemented mortar consisting of (cement, sand, water and perhaps some additive). The matrix should have some or all of the following requirements depending on the use of the structure. High compressive strength, impermeability, hardness, resistance to chemical attack, low shrinkage and workability. Most of the available specifications concerning the properties of the mortar used in Ferro-cement depend on the observation and practical consideration of the Ferro-cement uses with some aid from the knowledge of concrete technology. From a concrete technology point of view, the main factors which affect the properties of the mortar are:

1. Water: cement ratio.
2. Sand: cement ratio.
3. Gradation, shape, maximum size, and purity of sand.
4. Quality, age, and type of cement.
5. Additives.
6. Curing condition.
7. Mixing, placing *and compaction.*

The limits of the above factors are affected by the requirements of the mortar which in turn depend on the use of Ferro-cement. In marine structures, more

**Table 1:** Details of Mix design

| Mix Design | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Grade of Concrete** | **ratio used** | **Cement brand and grade** | **Admixture** | **Proportion used for design** | | | |
| | | | | **Cement** | **C.sand** | **W/C ratio** | **Admixture** |
| M30 Grade (Mortar Mix) | 01:03.5 | Vasudatta OPC Cement grade -43 | BASF1125 | 5 kg | 17.5 kg | 0.6 | 60 ml/1.2% |

Restrictions are generally required [5, 6] than in civil engineering structures. In most applications, high strength and low shrinkage are required and therefore low (water: cement) ratio between (0.35) to (0.55) [7] should be used. Workability of mix should be high and therefore a suitable compromise should be arrived at to increase the water content to take account of the decrease in strength. Rich cement mortar is required to give compressive strength between (35) to (50) N/$mm^2$. Additives have been used to reduce or decrease the water content. Proper gradation [8] of sand could help provide workable mixes. On the other hand, (gradation of ordinary sand, lightweight sand, expanded shale or vermiculite) has no effect on the tensile strength of Ferro-cement [9].

#### 3.4.2 Reinforcement

Ferro-cement reinforcement is characterized by high the surface area as compared with those used in reinforced concrete. It usually consists of layers of continuous mesh. These generally results from the assembly of continuous filaments. Different or various types of meshes are available almost in every country in the world. The principal types of wire mesh currently being used are given below:

1. **Hexagonal or chicken wire mesh:** This type of mesh is readily available in most countries and it's known to be the cheapest and easiest to handle. This mesh is fabricated from cold drawn wire which is generally woven into hexagonal patterns. Special patterns may include hexagonal mesh with longitudinal wires.
2. **Welded wire mesh:** In this type of mesh a grid pattern is formed by welding or cementing the perpendicular, intersecting wires at their intersection. Although this type of mesh may have many advantages such as easy molding into the required shape also it has the disadvantage of the possibility of weak spots at the intersection of wires resulting from inadequate welding during the manufacture of the mesh [28].
3. **Woven Wire mesh:** In this type of mesh, the wires are interwoven to form the required grid and the intersections

aren't welded. The wires in this type of mesh aren't straight. They are bent in the shape of zig-zag lines and large angle of bending might cause cracks along the mesh **[29]**. However, the molding behavior of this mesh is as good as compared with hexagonal and welded wire mesh [28]

4. **Expanded Metal Mesh:** This type of mesh is formed by cutting a thin sheet of expanded metal to produce diamond shape openings. This type of mesh isn't as popular as the previous three types and weight for weight comparison, it's not as strong as woven mesh but on cost to strength ratio, expanded metal has the advantage [28].
5. **Watson Mesh:** A specially designed three dimensional space frame mesh. It consists of straight high tensile wires and a transverse crimped wire which holds the high tensile wire together. The high tensile wires are placed in two parallel planes and are separated from mild steel wires transverse to the high tensile wires. Most of the mesh wires are straight, without twists, crimps or welds. The result is a very strong mesh and completely flexible to conform to any shape. The above mentioned types of meshes are mainly metallic materials. Vegetable Fiber and Glass Fiber meshes are also available. At the same time, there is a wide variation or different in the properties of each type of mesh. This includes different mesh size, strength, ductility, manufacture and treatment. Research shows that the properties of the resulting Ferro-cement product are affected by the properties of the mesh. Steel rods have been used together with wire mesh in the reinforcement of Ferro-cement. The rods could be used for making the framework of the structure upon which layers of mesh are laid. Longitudinal and transverse rods usually vary in diameter between (4) to (9) mm and they are mainly of mild steel. Steel rods are sometimes used a main reinforcing component. Bezukladov *et al* [5] reported that the middle- third of the mesh in Ferro-cement members can be replaced by steel rods without affecting the structural behavior of the member. Finally, Steel Fibers have been used [30, 31] with wire mesh reinforcement to improve some of the properties of Ferro-cement.

### 3.5 Mechanical Properties of Ferro-cement

#### 3.5.1 General

Ferro-cement is often thought of as a variety of conventional reinforced concrete. However, **Nervi's [1]** description of Ferro-cement in which he identifies the material by the high subdivision and distribution of the reinforcement may be the basic difference between Ferro-cement and reinforced concrete. No theoretical support was provided by Nervi, but later on the importance of the subdivision of reinforcement was confirmed by experimental and theoretical studies **[32, 33]** on closely spaced wire reinforcement. In addition to the subdivision, the amount of the reinforcement was believed, from the early experiments on Ferro-cement to be very important.

Oberti found from his study that steel content of (120) to (240 kg/m$^3$) of mortar will not practically improve the elongation of the mortar. But increasing it to a range of (480) to (640 kg/m$^3$) increased the elongation to (5) times that of the mortar. Recently, the subdivision and the amount of reinforcement have been described using the terms specific surface which is defined as the ratio of the surface area of reinforcement to the volume of the composite and the fractional volume, which is defined as the percentage of the volume of the reinforcement to the volume of the composite. These two terms have been found to give good correlation to the load response of Ferro-cement.

Bezukladov found from his study that Ferro-cement superior behavior compared to reinforced concrete can be achieved when the specific surface of reinforcement exceeds (2.0 $cm^2/cm^3$). However, in most previous practical uses of Ferro-cement, the reinforcement had less specific surface. This, in addition to the many available types of meshes may result in a confusing picture about the properties of Ferro-cement.

#### 3.5.2 Behavior of Ferro-cement under Compression

Behavior of Ferro-cement under compression is reported [5, 39, 40, 41] to be mainly affected by the mortar characteristics. Although the modulus of elasticity increases [42] with the increase in the fractional volume of reinforcement and the ultimate strength is mainly determined by the compressive strength of the mortar. Bezukladov *et al* [5] reported that the specific surface and the fractional volume of reinforcement don't exert appreciable influence upon the compressive strength of Ferro-cement. Varying steel content from (0.7%) to (2.8%) increase the compressive strength by (15%) and this strength is determined chiefly by the prismatic strength of the mortar. Rao and Gowder [42] showed from his study that the increase in the compressive strength with an increase in the percentage area of reinforcement isn't significant and in any case steel area of more than (2-2.5 %) wasn't economical as it results in reduction in strength. Pama and Lee [42] concluded from his tests, that the ultimate compressive strength of Ferro-cement depends on the fraction volume of mortar and is lower than that of equivalent pure mortar. However, Johnston and Martar [36] showed recently that the significant compressive strength gains can be realized by using mesh reinforcement in closed box or cylindrical arrangement which restrains the matrix. The transverse wires of the mesh contribute relatively more to the overall strength than the longitudinal wires, which is probably why the welded mesh showed better behavior than expanded metal mesh. Therefore, it seems that in addition to the mortar characteristics, the compressive strength is influenced by the type, orientation and mode of arrangement of meshes. Both the modulus of elasticity and the compressive strength of Ferro-cement can be predicted using the composite theory **[28].**

#### 3.5.3 Behavior of Ferro-cement under Flexure

#### 3.5.3.1 Load-Deflection and Stress-Strain Relationships

The load-deflection and the stress-strain relationship for sections under bending are, as the case for section under tension, characterized by three stages [5, 31, 43, 44, 45], namely, the elastic, the elastic to plastic and plastic stages. The end of the steeper linear portion of the load deflection curve corresponds to the first cracking of the mortar. No cracking was optically observed before this point, while the cracking was always observed soon after this load. The second part of the curve represents the elastic to plastic stage in which the multiple cracking takes place and the steel strain is less than the yield strain. The range and the slope at this stage increases with increase in steel content [45, 46]. The end of this stage is at the yielding of the steel which marks the beginning of the plastic stage. The load-deflection curve can be idealized [40, 43] to a tri-linear curve with each of the above three stages considered as a straight line. Near ultimate load, the deflection can be approximated by an elastic-perfectly plastic bilinear analysis. Walkus [35] had divided the behavior of Ferro-cement section under bending, as he did in the section under tension, according to the serviceability and in connection with the crack width, see (Table 1) and (Table 2).

**Table 2:** Properties of Ferro-cement section under Bending/ (20) Tensile zone

| Measured Value | Technological State | | | |
|---|---|---|---|---|
| | Tight | Anti-Corrosive I | Anti-Corrosive II | Corrosive |
| Permissible Width of Micro-Cracks (Microns) | 0-20 | 20-50 | 50-100 | >100 |
| Stress, σ (Kg/$cm^2$) | 43 | 49.5 | 56 | ----- |
| Unit elongation ε x $10^{-6}$ | 130 | 325 | 650 | ----- |
| Coefficient of deformability E x $10^{-3}$(kg/$cm^2$) | 330 | 33 | 20 | ----- |

**3.5.3.2 Cracking**

The cracking behavior of Ferro-cement was studied mainly by observing the crack number at first cracking, and at failure and the factors which influenced them. The more appropriate and systematic approach of measuring the crack width and separating the influences of the different factors on it was neglected. Consequently, there are no experimental data to initiate or verify crack width prediction equations. Recently, tests were carried out [40, 47] to measure the crack width and present prediction equations for the crack width in connection with the factors considered. However, the amount of data in this field is far from enough. In fact, from the above mentioned tests it was concluded [38] that an extensive amount of work is required to decide the effect of the different factors on the cracking of Ferro-cement. In general, it was believed that the cracking behavior in bending is similar to that in tension [5, 34, 44]**.** The subdivision, amount, type and ductility of the reinforcement are most important factors that effect on the cracking behavior. Increasing the specific surface decreases the crack width and spacing [44]. Logan & Shah [34] presented a formula to predict the crack spacing depending mainly on the specific surface. However, Naaman [38] from later tests concluded that the specific surface didn't seem to have as strong an influence on the cracking behavior in flexure as in the tension. This less pronounced effect found by Naaman could be explained by noticing that additional layers of meshes are placed away from the extreme fiber where the highest tensile stress takes place. Therefore, they contribute less to the crack arresting mechanism which will be mainly provided by the outermost meshes. A more pronounced effect of the specific surface may be found by considering samples of different specific surface of the outermost layers. According to Balaguru, Naaman and Shah [45], the crack width is mainly influenced by the strain level in the outermost layer of mesh and the spacing of the transverse wires as they are favorable positions for cracks. A design equation based on the above mentioned two factors was suggested.

**3.5.3.3 Strength**

As in tension, the strength in flexure for a Ferro-cement member was considered in two stages of its life. They are the strength at first crack and the ultimate strength. In any case, none of these methods are fully accepted as a rationalized design method and more work is needed in this context. The factors which influence the strength at first cracking and a failure are discussed separately as follows:

**a) Strength at first cracking**

There are several definitions of the first cracking load. Depending on the definition adopted, first cracking represents a certain point in the elastic -plastic stage of the life of the section. It's non-uniqueness of the first cracking definition which has led to the uncertainty of the factors affecting it. Some researchers [29, 45] have found that the strength at first cracking increases with increase in steel content. Logan and Shah [34] concluded that the strength at first cracking increases with an increase in the specific surface of reinforcement. However, Balaguru, Naaman, & Shah [45] couldn't find a clear relationship between the first cracking load and the specific surface. It appears that the term first cracking it's not suitable unless all are agreed on its definition. If it's defined as the instance of the first movement of the existing flaws, then there is a doubt whether there is a factor other than the ultimate tensile strength of the mortar which will enhance it. But if it's defined as the instance in which a crack of a certain width appears, then the factors affecting the cracking behavior will be expected to influence it. It, therefore, follows that the term first cracking whenever used should be associated closely with its definition.

**b) Ultimate Strength**

The ultimate strength in bending is expected to reflect the combined influences of factors governing the tensile and compressive strength. Therefore, and as far as reinforcement is concerned, the amount, type, orientation and inherent geometry of the reinforcing meshes, in addition to their position relative to the neutral axis and to each other are factors influencing the ultimate strength. As for the mortar, its strength was found to be of relative little importance [47] on the ultimate bending moment. Thus, a mortar of the medium compressive strength of (35) to (50) N/mm$^2$ is adequate [5, 47]. The thickness of the section has little influence on the ultimate strength, aside from the influence of depth as expected from analytical principles [47]. It follows, therefore, that the reinforcement characteristics have the greatest influence on the ultimate bending strength. Increasing the reinforcement content increases the ultimate strength but the specific surface has no effect on it [5]. The type of mesh also effects on the ultimate strength. For example, members reinforced with expanded metal or welded wire mesh of a given cross sectional area and used in their normal orientation and perform better than those reinforced with woven wire mesh or standard bars of the same cross sectional area. Orientation and geometry of the mesh have a significant effect on the ultimate strength. ACI Committee 549 [7], reported that different meshes exhibit weaknesses in different directions and therefore orientation become is particularly important when strength under biaxial loading is considered. Expanded metal mesh imparts a considerable weakness in the secondary direction [47]. Welded wire mesh, while having equal strength in both longitudinal and transverse directions has a weakness along planes at (450) to the directions of the wires. Large weaving angles in woven wire mesh result in cracks along the mesh [29]. This could result in premature failure. In the Ferro-cement, unlike in reinforced concrete, uniform distribution of the mesh along the section gives better ultimate strength than concentrating them near the fibers [47]. The steel strength was reported [47] to have relatively minor importance in the ultimate strength and it's controlled by the degree of cold working employed in the manufacturing process of the mesh. This result seems to be illogical especially for specimens reinforced with small numbers of meshes where flexural failure takes place due to fracture of the mesh [29].

### 3.5.4 Behavior of Ferro-cement under Fatigue and Impact Effect

#### 3.5.4.1 Fatigue Effect

The fatigue behavior of Ferro-cement is very important. Most of the structural members will be subjected to a certain type of repeated loading. Picard and Lachance reported [48] that the load which causes failure on a Ferro-cement member after lx$10^6$cycles was only (27%) of the ultimate load. Also, the residual deflection during the unloading of the first cycle was noticed and this deflection increases with increase in the amplitude of the loading cycle. It's**,** therefore, essential to establish enough data on fatigue behavior of Ferro-cement before setting its serviceability criteria. Preliminary flexural fatigue tests by wind boats limited [49] showed the following results: It was reported [28] that Karasudhi, Mathew, and Himityongskul (in their fatigue tests) showed that the fatigue strength of Ferro-cement is dependent on the fatigue properties of the reinforcement including both the wire mesh and the skeletal steel. The load-cycle curves for Ferro-cement specimens reinforced with three different meshes were given in the following form:

*Log10 N = 12.27 - 0.128S (Welded wire mesh) ----1*
*Log10 N = 7.417 - 0.031S (Expanded metal mesh)-2*
*Log10 N = 9.750 - 0.073S (Hexagonal wire mesh)--3*

Where (N and S) denote the number of cycles to failure and the maximum repeated load expressed as percentage of the ultimate static load. Using equation (for welded mesh) on data from Picard & Lachance [48] gave (S = 49%) while the experimental value was (27%). This indicates that there are other factors apart from the type of mesh which affect the load cycle curves.

McKinnon and Simpson [50] reported from his work that Ferro-cement specimens reinforced with un galvanized welded mesh and water cured showed better flexural fatigue results than those reinforced with galvanized welded mesh and steam cured. The deterioration in the fatigue properties due to galvanization of the mesh was confirmed by Bannet *et al*. [51].

Balaguru, Naaman and Shah [52] suggested an analytical model to predict the fatigue properties of Ferro-cement from the fatigue properties of its constituents, i.e., mortar and reinforcement. Expressions for the increase in the crack width and deflections and the deterioration of the flexural rigidity due to repeated loads, were given. These expressions disparately require more experimental verification.

Singh [53], recently, from the comparison of his and other investigators results found that the behavior of Ferro-cement under repeated loading is a function of such factors as:

1. Amount, type and disposition of reinforcement.
2. Mode and method of testing as well as criterion of failure.
3. Specimen form and size.
4. Type of cement and method of curing.

#### 3.5.4.2 Impact Effect

Because of the importance of the impact resistance in the application of the Ferro-cement material in marine structures, impact tests were some of the very early experiments carried out on Ferro-cement. Impact tests **[49]** on Ferro-cement slabs demonstrated the high impact resistance of the material and showed that the failure didn't consist of the development of an actual hole in the slab but rather a weakening of the wire mesh and a relatively dispersed breaking a way of the Ferro-cement material. This property is one of the advantages which encouraged the use of Ferro-cement in boat building. Impact tests necessary to compare the behavior of Ferro-cement with reinforced concrete were carried out by Bezukladov *et al*. [5] They found that a (25) mm thick of Ferro-cement plate could give the same impact strength as (50) mm thick reinforced concrete plate.

Shah and Key [9] carried out impact tests to investigate the effect of the specific surface and tensile strength of the wire mesh. The rate of flow of water through the sample was used to measure the damage in the specimen due to impact loading. They found that the higher specific surface or the tensile strength of the mesh lower damage induced by impact loadings.

Nathan & Paramasivam [37] carried out tests and showed when increasing the fraction volume of reinforcement increases the absorbed energy required to cause the impact failure. It was reported **[30, 54, 55]** that inclusion of short Steel Fibers with wire mesh reinforcement in Ferro-cement greatly improved the impact strength of panels.

## 4. Conclusions

1. Ferro-cement has many advantages over conventional reinforced concrete such as improvement in tensile and flexural strengths, ductility, impact resistance and crack arresting properties.
2. Ferro-cement construction was widely accepted in the (Australia- New Zealand- and the United Kingdom). For example In Israel, Ferro-cement is used to improve existing houses and In the SriLanka, Ferro-cement houses resistant to cyclones are developed and constructed.

3. The matrix of Ferro-cement is usually cemented mortar, consisting of cement, sand, water and perhaps some additive.
4. The modulus of elasticity of Ferro-cement increases with the increase in the fractional volume of reinforcement and the ultimate strength is mainly determined by the compressive strength of the mortar.
5. Ferro-cement specimens reinforced with un-galvanized welded mesh and water cured showed better flexural fatigue results than those reinforced with galvanized welded mesh and steam cured.

**References**


1. Nervi PL. [Structures], Translation by Giuseppina and Mario Salvadori, F.W. Dodge Corporation, New York, 1956.
2. National Academy of Sciences, [Ferro-cement: Applications in Developing Countries], Washington, February, 1973.
3. Romualdi JP. [Research Needs and The Future of Ferro-Cement], Ref. 1956; 71:173-177.
4. Bigg GW. [An Introduction To Design For Ferro-cement Vessels], Vessels and Engineering Division, Industries Development Branch, Fisheries Services, Ottawa, Canada, 1972, 224.
5. Bezukladov VF, Vanovich A. [Ship Hulls Made of Reinforced Concrete], Translated from Russian as Navships translation No. 1148, U.S. Department of the Navy, 1968.
6. Shah SP. [New Reinforcing Materials in Concrete], J. Amer. Concrete Institute. 1974; 71(5):257-262.
7. ACI Committee 549, [State Of The Art, Report on Ferro-cement].
8. Raichvarger Z, Raphael M. Grading Design of Sand for Ferro-cement Mixes. 1956; 71:115-132.
9. Shah SP, Key WH. [Impact Resistance of Ferro-cement], Journal ASCE, Structure Division. 1972; 98(1):111-123.
10. Al-Kubaisy MA. Mohd Zamin Jumaat; [Flexural Behavior of Reinforced Concrete Slabs with Ferro-cement Tension Zone Cover] Received 10 June 1999; received in revised form, 1999, 20.
11. Chandrasekhar T, Raoa TD. Gunneswara Rao b and N.V. Ramana Raoc [An Appraisal of the Shear Resistance of Ferro-cement Elements]; Asian Journal of Civil Engineering (Building and Housing. 2006; 7(6):591-602.
12. Abasolo R, Bandivas C, Guinita JV, Palen J, Parners E, Apor G. Utilization of Ferro-cement As Flexural Building Member (Applied as a Hollow Box Joist)], Student Working Paper, Xiraadman Research Center, Xavier University, Philippines, 2009, 29.
13. Abdullah Takiguchi K. [An Investigation in to the Behavior and Strength of Reinforced Concrete Columns Strengthened with Ferro-cement Jackets], Cement & Concrete Composites. 2003; 25:233-242.
14. ACI Committee 549-1R-88 and 1R-93: [Guide For The Design, Construction, And Repair Of Ferro-cement], ACI 549-1R-88 and 1R-93, In Manual of Concrete Practice, American Concrete Institute, Farmington Hills, Michigan, 2003; 1988-199.
15. ACI Committee. [State-Of-The-Art Report on Ferro-cement], ACI 549-R97, in Manual of Concrete Practice, American Concrete Institute, Farmington Hills, Michigan, 1997, 26.
16. Adajar JC, Hogue T, Jordan C. Ferro-cement for Hurricane-Prone State of Florida‖, Proceedings of the Conference on Structural Faults + Repair, June 2006, Edinburgh, Scotland, U.K, 2006, 13-15.
17. Akhtar S, Arif M, Quraishi MA. Use of Chemical Corrosion Inhibitors for Protection of Metallic Fiber Reinforcement in Ferro-cement Composites], the Arabian Journal for Science and Engineering, 2009; 34(2C):105-113.
18. Bulletin CP-10 [Ferro-cement Tanks and Utility Buildings], New Zealand Portland Cement Association, Wellington, 1968, 5.
19. CoP. [For Production and Use, Ferro-cement Roofing Channels, Jointly Developed by Auroville Center & Development Alternatives, 1997.
20. Desai JA. Corrosion and Ferro-cement, Proceedings of the National Conference on Ferro-Cement], FS, 2011, 13.
21. Doshi VD, Rangarao VV, Baetens T, Rajaratnam D. [Ribbed Ferro-cement Shells – Construction Using Unconventional Approaches], Proceedings of the National Conference on Ferro-cement, FS. 2011, 13-14, 165-172.
22. Ferro, [Proceedings of the Seventh International Symposium on Ferro-cement and Thin Reinforced Cement Composites], Mansur & Ong (Eds.), the National University of Singapore, 2001.
23. Hago AW, Al-Jabri KS, Alnuaimi AS, Al-Moqbali H, Al-Kubaisy MA. [Ultimate and Service Behavior of Ferro-cement Roof Slab Panels], Construction and Building Materials. 2005; 19:31-37.
24. Mansur MA. [Design and Construction of an Elevated Ferro-cement Water Tank], Concrete International: Design and Construction. 1990; 12(4):37-41.
25. Naaman AE, Shah SP. Evaluation of Ferro-cement in Some Structural Applications], Proceedings, 4th IAHS International Symposium on Housing Problems Atlanta, May 1976, Pergamon Press, Elmsford, 1976, 1069-1085.
26. Naaman AE. Ferro-cement & Laminated Cementitious Composites Techno Press 3000, Ann Arbor, Michigan, USA, 2000.
27. Shannag MJ, Ziyyad TB. [Flexural Response of Ferro-cement with Fibrous Cementitious Matrices], Construction Build Mater. 2007; 21:1198-1205.
28. Paul BK, Pama RP. [Ferro-Cement International Ferro-cement Centre] IFIC Pub. 1978-2007, 149.
29. Alwash AA. [Flexural Characteristics Of Ferro-cement], M.Sc. Thesis, College of Engineering, University of Baghdad, Iraq, 1974.
30. Atcheson M, Alexander D. [Development of Fibrous Ferro-cement], Ref. 2007; 71:81-102.
31. Alexander D, Atcheson M. Fibrous Ferro-cement for Commercial Vessels], Journal of Ferro-cement. 1976; 5(2):25-48.
32. Ramouldi JP, Batson GB. Mechanics of Crack Arrest in Concrete], Journal ASCE; 89 EM3, 1963-1976, 147.

33. Ramouldi JP, Batson GB. [Behavior of Reinforced Concrete Beams with Closely Spaced Reinforcement], ACI Journal. 1963; 60(6):775-790.
34. Logan D, Shah SP. [Moment Capacity and Cracking Behavior of Ferro-cement in Flexure], ACI Journal. 1976; 70(12):799-804.
35. Walkus BR, Mackiewicz A. [Application of Ferro-cement Shells in Marine Structures], IASS, Symposium on Industrial Spatial and Shell Structures, Held at Kielec, Poland, 1973, 385-398.
36. Johnston CD, Mattar SG. [Ferro-cement Behavior in Tension and Compression], Journal of the Structural Division, ASCE. 1976; 102(ST5):875-899.
37. Nathan GK, Paramasivam P. [Mechanical Properties of Ferro-cement Material], First Australian Conference on Engineering Materials, Sydney, 1974-1976, 309.
38. Naaman AE. [Design Prediction of Crack Width], Ref, 1976; 71:25-42.
39. Rajagopalan K, Parameswaran VS. [Cracking and Ultimate Strength Characteristics of Ferro-cement in Direct Tension and Pure Bending], Indian Concrete Journal. 1974; 48(12):387-395.
40. Pama RP, Sutharatanachaiyaporn C, Lee SL. [Rigidities and Strength of Ferro-cement], First Australian Conference on Engineering Materials, Sydney, 1974, 287-308.
41. Desayi P, Joshi AD. [Ferro-cement Load Bearing Wall Elements], ASCE Journal, Structure. Div. 1976; 102(ST9):1903-1916.
42. Rao A, Gowdar CS. [A Study of Behavior of Ferro-cement in Direct Compression], Cement and Concrete Journal. 1969; 10(3):231-237.
43. Austeriaco NC, Lee SL, Pama RP. [Inelastic Behavior of Ferro-cement Slabs in Bending], Magazine of Concrete Research. 1975-1976; 27(93):193-209.
44. Walkus BR. [The Behavior of Ferro-cement in Bending], Journal of Structural Engineering. 1975; 3(3):113-125.
45. Balaguru PN, Naaman AE, Shah SP. [Analysis and Behavior of Ferro-cement in Flexure], Journal of the Structural Division, ASCE. 1977; 103(ST10):1937-1951.
46. Kamaswadara A, Kallapa CS. [A Study of the Behavior of Ferro-cement in Flexure], Indian Concrete Journal, 1971.
47. Johnston CD, Mowat DN. [Ferro-cement Material Behavior in Flexure], Journal of the Structural Division, ASCE, Vol.100, No. ST10. 1974-1977, 2053-2069.
48. Picard A, LaChance L. [Preliminary Fatigue Tests on Ferro-cement Plates], Cement and Concrete Research. 1974; 4(6):967-978.
49. Thomas G. [Ferro-cement Boats], Indian Concrete Journal. 1971; 45(7):329-332.
50. McKinnon EA, Simpson MG. [Fatigue of Ferro-cement], Journal of Testing and Evaluation, JTEUA. 1975; 3(5):359-363.
51. Bennett EW, Fakhri NA, Singh G. [Fatigue of Ferro-cement in Unidirectional Bending], International Symposium on Ferro-cement, ISMES, Bergamo, Italy,. 1981, 1/37-1/47.
52. Balaguru PN, Naaman AE, Shah SP. [Serviceability of Ferro-cement Subjected to Flexural Fatigue], The International Journal of Cement Composites. 1979; 1(1):3-9.
53. Singh G. [Flexural Response of a Ferro-cement to Constant Deflection Repeated Loading], International Symposium on Ferro-cement, ISMES, Bergamo, Italy, 1981, 211-216.
54. Surya Kumar GV, Narayanaswamy VP, Sharma PC. [Ferro-cement–A Survey of Experimental Investigations], Journal of Structural Engineering. 1981; l(1):4
55. Claman, J.S., [Bending Of Ferro-cement Plates], M.Sc. Thesis, Massachusetts Institute of Technology, May 1969.
56. Pama RP, *et al*. (Editor), [Materials of Construction for Developing Countries], Asian Institute of Technology, Bangkok Thailand, 1978, 2.
57. Pama RP, Lee SL, Vietmeyer ND. [Ferro-cement, A Versatile Construction Material: It's Increasing Use in Asia], Asian Institute of Technology, Bangkok, Thailand, 1976.
58. Pama RP, Phromratanaporgse O. [The Potentials of Ferro-cement and Related Materials for Rural Indonesia - A Feasibility Study], Asian Institute of Technology, Bankok, Thailand, 1977, 20.
59. Jorgensen SL. [Effect of Multi-Stage Plastering On Ferro-cement], M.Sc. Thesis, Berkeley, U.S.A, 1971.