Ferrocement Technology & Quality Improvisation Techniques - A Review

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***Abstract*--Ferrocement is the best alternative to reinforced cement concrete and ferrocement technology is applied throughout the world in various building applications like roofs, swimming pools, sea walls and marine structures. Ferrocement has many advantages like thin construction elements which can be cast to any complicated shapes, but there are some quality issues relating to cement mortar composition, compaction and corrosion of reinforcing wire/ weld mesh which reduces its life span. Even though there has been a continuous development of ferrocement for several decades, researchers' feel that further research can still improve the behaviour of the material. This study therefore makes an attempt to identify critical quality problems in ferrocement and suggest techniques/ methods to improvise the quality. After thoroughly reviewing the literature, this study brings out the use of non-corrosive reinforcing materials like polymer or poly-vinyl alcohol (PVA) meshes and synthetic fibers (manufactured of polypropylene, polyolefin, poly-vinyl alcohol) in separate or hybrid composite forms that will improve the quality of ferrocement panels as well as prevent corrosion to a great extent. As this study is limited with review of literature, this study further recommends to the researchers that experimental investigations may be taken-up on the hybrid ferrocement composite slab panels with galvanized-iron weld meshes (with poly-vinyl chloride coating) as primary reinforcement and synthetic fibers made of materials such as PVA as secondary reinforcement and conduct research on flexure and impact and relevant applications be brought-out, which will help the construction industry to a great extent.**

***Index Terms*--Corrosion, Durability, Fibers, Weld Mesh.**

I. Introduction

FERROCEMENT is a superior construction material and the best alternative to Reinforced Cement Concrete (RCC) [1]. Ferrocement technology is gaining popularity worldwide due to its thin profile (thickness ranging in the order of 10-25 mm. reinforced with wire/ weld mesh) that can be cast in flexible and complicated shapes, using less energy (men and materials) resulting in less pollution as well as protecting the environment [2]. Sometimes, ferrocement is described as a modified form of RCC, with elimination of coarse aggregate but ferrocement behaves in a manner so different from conventional concrete (reinforced with steel) in terms of strength, deformation, and potential applications that it can be termed as a distinct material. There has been an increasing activity with ferrocement in Canada, USA, Australia, China, India, Thailand, Mexico, Indonesia and other developing countries [3] viz., roofing applications in Egypt [1], the biggest ferrocement swimming pool (with irregular shape and wall thickness of 30 mm. at its deepest part) and panel facing of a marine structure of shoreline in Singapore [4].

The success of ferrocement largely depends upon its durability (meaning the service life under environmental conditions) aspects [5] [6] and problems like corrosion of reinforcing wire/weld mesh will definitely continue to be top priority technical and economic issues in the civil engineering profession [7]. Even though teams from India, Brazil, Japan and France have brought out the theoretical aspects of causes and processes of corrosion and also conducted few experiments using different parameters with a special focus on reinforcement cover [8], there is a larger need to study the durability aspects of ferrocement structures in the current design philosophy/ methodology [9] and important research areas include corrosion [10].

One of the main reasons for corrosion in ferrocement is that the small mortar cover (of 1-2 mm.) to reinforcing mesh allows the liquids or other corrosive agents to easily pass through and reach the wire/weld mesh and attack the reinforcement. The purpose of cover acting as a barrier and preventing the penetration of harmful liquids and gases is lost in the case of ferrocement due to less cover being used [10]. Several other factors such as proportion/ composition of cement mortar, surface porosity, surface finish and aggregate size and mortar compaction [11] which are detrimental to the quality of ferrocement also needs to be investigated.

Ferrocement has been in existence and developing for more than 150 years, but still researchers feel that further studies can still improve the behaviour of the material [4], [8]. There has been research to improve the mechanical properties of concrete/ mortar in all modes of failure or behaviour of fiber reinforced concrete (FRC) elements using different types of fibers made of steel, carbon, glass and polypropylene [12], [13]; and adding either short discrete or continuous long fibers to the cement-based matrix improves the properties of cement mortar [7] .

This literature review survey is a part of a research work on ferrocement construction technology and an attempt to analyze the major quality issues in ferrocement and suggest suitable improvisation techniques.

II. Previous Studies on Ferrocement

1) Properties of Ferrocement

Ferrocement uses one or more layers of continuous/small diameter steel wire/weld mesh netting (metallic or non-metallic) in cementitious matrices as reinforcement with high volume fraction of reinforcement (ranging between 2 & 8%) and the specific surface of reinforcement is considerably higher for ferrocement than for RCC [7].

Ferrocement has unique properties such as high tensile strength and stiffness; and it has better impact and punching shear resistance than reinforced concrete due to 2-D mesh reinforcing system [7] and undergo large deformations before cracking or high deflections before collapse [7], [13], [14]. Khan [15] studied the impact performance of ferrocement slab system; the performance of ferrocement slabs were checked subjecting them to low velocity projectile impact and the results indicate that increasing the no. of layers of wire mesh led to larger area of load transfer and hence more crack formation; the number of cracks on the impact surface reduced with an increase in the number of layers of wire mesh. Hago [16] conducted experiments on ferrocement roof slab panels and found that the ferrocement slabs had the best behaviour with high load carrying capacity; and it was also found that the width and spacing between the cracks were less; and all slabs showed good ductility represented by large deflections. The studies of Mansure [17] confirm that all ferrocement slabs failed first in punching without total separation; both cracking load and punching shear load increased with an increase in width of square loaded area, mortar strength, volume fraction of reinforcement, and depth of slab, but decreased as the effective span length is increased.

Ferrocement has excellent leakage characteristics for applications in water tanks due to its very small crack widths; moreover, should pressure increase, ferrocement stretches to allow higher leakage and acts as a safety valve, thus, it does not fail [7]. In order to protect reinforcement from corrosion in ferrocement, the maximum crack-width should not exceed 0.05 mm. for corrosive environment and for water retaining structures and 0.10 mm. for other structures [7], [9].

Cracking occurs before or after the hardening of ferrocement; some common types of damage in ferrocement are delaminations, spalls, scaling and local fractures; and the causes of damage are constructional movement of the formworks, settlement shrinkage that cause cracks around reinforcements and fine aggregates, setting shrinkage, internal heat of hydration, temperature stresses, differences in thermal properties of aggregates, and external temperature variations; another major source of cracking is the chemical reaction in ferrocement constituents such as corrosion, carbonation, and reaction of foreign bodies and reactive aggregates [18].

2) Corrosion-related Studies

Ferrocement has small diameter and closely spaced reinforcing wire/weld mesh and smaller cover to reinforcement [7]. Initially, there is initiation of corrosion in the mesh, and this further propogates resulting in reduction of wire diameter and consequently leading to less strength capacity of ferrocement elements [7]. Corrosion in ferrocement elements must be not only delayed but also eliminated [7]. An increase in corrosion resistance of reinforcing mesh and mortar will lead to an increase in durability of ferrocement [19]. The corrosion protection of reinforcement in ferrocement is usually achieved through the use of galvanized wire mesh, increased cover, or with the use of dense mortar achieved by additives such as flyash, silica fumes, and blast furnace slag [20], [21]. Even if galvanized mesh reinforcement is used to prevent corrosion, the protective zinc coating on reinforcement can have certain adverse effects from gas bubble generation giving way to galvanized corrosion; addition of 100-300 ppm. of chromium trioxide to the mixing water of matrix will prevent liberation of hydrogen during hydration process [7].

Use of admixtures prevent the penetration of chlorides into mortar and improve the corrosion resistance performance of ferrocement and durability [22]. Chemical admixtures should be used in ferrocement for the purpose of water reduction for improving impermeability, air entrainment and to suppress reaction between galvanized reinforcement and cement [23]. The corrosion resistance of the metallic wire meshes is improved using corrosion inhibitors [5] in ferrocement like Calcium Nitrite and Tannic Acid. At a 1% dose, both the inhibitors, when applied in a slurry coated form, were found to be sufficiently effective in controlling the corrosion [24], [25]. Corrosion resistance is also achieved by use of dense mortar achieved by additives like silica fume, blast furnace slag and pulverised flyash [20] – [23]. The corrosion rate of the reinforcements coated with polymer-modified pastes is smaller than that of uncoated reinforcement; and corrosion-inhibiting property of ferrocement is also improved by use of Polymer-Styrene Butadiene Rubber (SBR); Ethylene Vinyl Acetate (EVA) modified paste coatings on reinforcements [26]. Painting of external surfaces of ferrocement structures provides better protection to the reinforcement against corrosion effect as compared to unpainted surfaces [23].

Mansure [17] employed an electrochemical-based accelerated corrosion technique to study the corrosion durability of ferrocement. Variables considered include cover thickness; composition of the matrix in terms of water-cement ratio (w/c), sand-cement ratio (s/c), and contents of mineral and chemical admixtures; and use of stainless steel wire mesh. Test results indicate that the addition of mineral admixtures, application of a suitable surface coating, and the use of deeper cover provide excellent protection against reinforcement corrosion. Employment of stainless steel as reinforcement and the use of so-called corrosion inhibitor or a low w/c in the matrix also slows down the corrosion process, but is not as effective as others.

3) Using Fibers in Ferrocement

In ferrocement design, the limitation of crackwidth is a criterion to protect reinforcement from corrosion [27]. Fibers when added to ferrocement improve cracking behavior [28]. Fiber reinforcements are increasingly being used for the reinforcement of cementitious matrix to enhance the tensile strength, toughness, energy absorption capacity and to reduce the cracking sensitivity of the matrix; cement-based composites exhibit the general characteristics of brittle matrix composites; that is, the failure of the matrix precedes the fiber failure, thus allowing the fibers to bridge the propogating crack [29], [30]. The strengthening mechanism of fibers involves transfer of stress from matrix to the fiber by interfacial shear or by interlock between the fibers and the matrix [31]. If steel fibers are added to ferrocement, it has proved to be an effective reinforcing material as well as enhancing the properties of the cement matrix considerably, retarding crack growth and permitting the use of much heavier gauge wire mesh [28], [32]. But the disadvantage of using steel fibers in practical construction is that they are corrosive and protrude, which is hazardous [33], [34]. Since metallic fibers are susceptible for corrosion and organic or natural fibers have inherent drawbacks, especially in cement based systems, researchers have investigated new synthetic fibers (for example, polypropylene flat fibers), which are non-corrosive, and less in weight [7]. The advantages of using polypropylene fibers are alkali resistance, high melting point and low cost of raw material, while, the disadvantages are poor fire resistance, sensitivity to sunlight and oxygen, low modulus of elasticity (in the range of 1-8 GPa) and poor bond with matrix [35].

The Ferrocement Model Code [36] and ACI [10], [31] permits use of non-metallic materials and discontinuous fibers. Incorporation of synthetic fibers like polypropylene fibers in polymer mesh reinforced ferrocement panels have contributed significantly in improving the cracking behavior under flexure; cracked specimen does not separate into various pieces and there is reduction in crack width. Haddad [37] studied the role of fibers in delaying initiation of corrosion cracks; and reducing the rate of corrosion in cement concrete. It was found that both fiber materials used in this study, namely, polypropylene and nylon helped in delaying the initiation of cracking as well as delaying the inducement of steel corrosion and improved the bond strength to a large extent; and fibers played a more significant role as embedded length increased. Eldebs [38] have investigated Portland cement mortar reinforced with polypropylene wires for thin-walled concrete units and found that the polypropylene wires can be used as reinforcement to avoid fragile rupture. Use of non-corrosive synthetic fibers (like polypropylene-Recron 3S) ensure durability against corrosion [39]. Sanjaun [40] investigated the effect of crack control in mortar containing polypropylene fibers on the corrosion of steel in a cementitious matrix. It is concluded that the same matrix composition the ones with fibers seemed to crack less initially and give a better lower corrosion rate; it is also observed that fiber reinforced specimens have ability for self-healing of cracks under the corrosive environment but in plain mortar there is a tendency to increase the crack-width.

Even synthetic fibers are used in RCC structures to enhance several material properties, among which are cracking and micro-cracking, impact resistance, resistance to fatigue, and improved strength in shear, tension, flexure and compression, and improve the qualities of ductility and energy absorption capacity [7] [10] [32]. Banthia [41] found that the polyolefin fibers are generally effective in reducing the amount and size of the shrinkage cracking and the crack widths were either reduced or completely eliminated at some volume fraction of fiber. Khan [15] proved that slabs with Kuralon Poly-vinyl Alcohol (PVA) fibers showed better energy absorption characteristics.

4) Hybrid Ferrocement Composites

Hybrid ferrocement composite means material made of at least two different components-- meshes of different materials (like carbon, PVA) or fibers of different materials or varying properties (such as length, diameter, modulus, strength) or a combination of both meshes and fibers [7]. Dawood [42] brought out that the incorporation of two or more fibers may bridge the cracks effectively. Besides, the hybrid fibers have the ability to arrest cracks at both the micro and macro level. At micro level, fibers inhibit the initation of cracks, and at macro-level, fibers provide effective bridging and in imparting sources of toughness and ductility; the combination of discontinuous fibers and meshes leads to significantly improved flexural behaviour, in terms of strength, toughness, increased shear resistance, and cracking; superplasticizers and other additives are recommended to ensure proper fiber dispersion and matrix penetration of the mesh system [7]. One of the first proponents of the use of a hybrid ferrocement composite was Douglas Alexander of New Zealand and he combined high strength steel wires and steel meshes (as primary reinforcement) with discontinuous steel fibers premixed in the mortar matrix (as secondary reinforcement), to impart ferrocement composites with a combination of high strength and superior cracking and impact characteristics [43], [44].

From the experiments of Desayi [28], it was observed that the inclusion of fibers has reduced the total no. of cracks in ferrocement specimens for all percentages of sand replacement used in their study; and also found that the first crack strength increases with increasing no. of wire mesh layers in the specimen for all percentages of sand replacement and all fibre contents used.

Guerrero [45] investigated the bending behaviour of hybrid ferrocement composites reinforced with PVA meshes and PVA fibers. The conclusions were that good flexural behaviour was obtained in ferrocement plates using non-metallic meshes such as PVA meshes. The combination of discontinuous PVA fibers and meshes improved significantly the flexural strength of ferrocement plates, especially when the number of mesh layers was small and the ductility was improved by up to 40% in comparison to identifical specimens without fibers.

Cyr [46] tested extruded hybrid fiber reinforced cementitious composites. Low modulus fibers with a weak fiber – matrix bond, such as polypropylene, were combined with high-strength, high-modulus fibers, such as glass or polyvinyl alcohol (PVA) to produce composites, which are both strong and tough. The performance of this composite is further enhanced by the addition of PVA fibers, which produce a strain-hardening response. The addition of more inert fibers such as polypropylene fibers to a glass fiber composite, improved durability.

Wang [47] conducted experiments to find out the bending response of hybrid ferrocement plates with meshes and fibers. 3 types of meshes--two expanded steel meshes and one Kevlar FRP (fiber reinforced plastic) mesh, combined with two types of synthetic fibers, namely Spectra and Poly Vinyl Alcohol (PVA) fibers, were experimentally investigated. From the results, it was concluded that expanded steel mesh can be effectively used as reinforcement for ferrocement; good ductility and modulus of rupture (MOR) were achieved increasing the volume fraction of reinforcement leads to an increase in MOR and a decrease in average crack spacing and width; moreover, the presence of fibers improves the shear capacity of the matrix; the addition of fibers to the matrix can be very effective in preventing the spalling of the mortar cover at ultimate load; hybrid composites with 2 layers of Kevlar mesh and Spectra fibers also had similar results; and the addition of fiber to ferrocement plates with only two layers of mesh increases their toughness indices from about two to four times.

In the experimental study of Jagannathan [39], synthetic fibers (polypropylene-RECRON 3S marketed by Reliance Industries, India) have been used that is non-corrosive in nature. This study concluded that incorporation of polypropylene fibers in polymer mesh reinforced ferrocement panels have contributed significantly in improving the cracking behaviour under flexure.

5) Quality Improvisation in Ferrocement

Based on literature survey, the following are some of the methods to improve quality of ferrocement elements:

Specific type of cement, based on environmental factors can be selected and used [48]; good quality of cement which is fresh and free from lumps, and stored in dry conditions should be used; ACI recommends use of appropriate type of cement for each application, for example, ASTM recommends Type II or Type V cements for marine exposure conditions [10], [32].

High quality and well-graded sand which is clean, inert, free of organic matter and deleterious substances and relatively free from silt and clay; 100% passing through 2.36 (no.8) sieve are recommended [49].

In order to tackle/ overcome the problem of corrosion in ferrocement elements, non-metallic mesh reinforcement may be used [50]. Reinforcing Wire/ Mesh should be clean and free from deleterious materials—dust, paint, oil. To improve the durability in ferrocement, dense and well compacted matrix with low-porosity and low-permeability is to be used [51]. In order that the cement mortar should achieve a high compressive strength, proper sand-cement ratio of 1.5-2.5 and water-cement ratio of 0.35-0.45 by weight as recommended by ACI [10], [32]. Proper admixtures are used in ferrocement for the purpose of water reduction, improve permeability and reduce air entrainment and to suppress reaction between galvanized reinforcement and cement matrices [5], [20] – [23], [26]; plasticizers are helpful in producing optimium workability and to minimize voids [52].

• Water used for construction purposes should not contain any substance that is harmful to the process of hydration of cement and which affects the durability of ferrocement [52]. Good water quality which is fresh, clean and potable; pH=>7; free from silt, oil, sugar, chloride and acidic material; and accurate weighing of water before mixing with cement mortar to control w/c ratio are recommended; and water should necessarily be tested for suitability in construction [49].

• Proper curing should be done to maximise hydration and minimize entrapped air; and curing should take place slowly in order to prevent cracks which would weaken the ferrocement product [53]. Moist or wet curing is essential for ferrocement; the use of fogging devices under a moisture-retaining enclosure is desirable; and curing should start within a reasonable time after application of the finishing layer [10], [32].

III. Recommendations of this Study

Based on earlier research works [1] – [53] reviewed for this study, the following improvements in ferrocement are recommended by the present authors:

A. To overcome the problem of corrosion and to ensure long-term performance, it is advisable to select and use reinforcing mesh that is either not susceptible to corrosion or which has a protective coating.

B. High quality of materials should be used in ferrocement and proper mortar composition is to be ensured. Protective coating to reinforcement against corrosion, adding corrosion-inhibitors while casting ferrocement elements, and special painting on external surfaces of ferrocement structures enhance leakage protection and durability, specifically in marine or water retaining structures. Good plastering / casting methods and adequate matrix compaction should be followed in order to improve permeability and bond between the cement matrix and the reinforcing mesh; also, instead of providing very thin cover of 1-2 mm., the cover thickness can be increased based on the construction needs. Water fit for construction purposes should be used for casting ferrocement slabs and adequate curing will enhance the corrosion durability of ferrocement.

C. Since corrosive liquids easily pass through thin cover and reach mesh reinforcement, a thick cover resulting in a wider crack-spacing and consequently a wider crack width can be worked out without increasing the thickness of ferrocement elements beyond 25 mm. For this purpose, new reinforcing materials in ferrocement with proper sand-cement and water-cement ratios should be researched upon and results brought out.

D. The present study has observed numerous advantages in using fibers as dispersed type of reinforcement in cementitious matrix such as its tensile strength, toughness and ductility and for crack reduction. Adding discontinuous short fiber to cementitious matrix could bring significant improvement in ductility and shear capacity as well as moderate increase in tensile strength.

E. Synthetic fibers, especially polymeric fibers such as nylon, polyethylene, polypropylene have become more attractive in recent years for use as reinforcement in cement systems and many researches have established that they do not experience corrosion under the action of hydrating cement media. When a synthetic fibre is incorporated in the ferrocement matrix, appropriate mortar plasticisers/ chemical admixtures is to be added in order to improve workability, impermeability, bond strength, crack resistance, appearance and productivity.

F. Stainless steel meshes as reinforcement is helpful in preventing corrosion to ferrocement elements but it is quite expensive. Instead, use of traditional galvanized steel may be combined with other cheaper and more effective means of corrosion protection for enhanced durability. Fiber reinforced plastic (FRP) meshes is also a promising alternative to steel meshes. However, if experimental research is conducted on fiber reinforced polymeric or plastic meshes, it will bring additional alternatives and impetus to ferrocement construction.

G. Based on extensive literature survey by the present authors on fibers and meshes, it is recommended that further research may be conducted on ferrocement using either new and innovative materials like poly-vinyl chloride (PVC) coated galvanized iron (G.I.) weld mesh, PVA meshes or fibers as reinforcement. Even a Ferrocement Hybrid Composite System can be developed, using a combination of meshes and fibers, that is using meshes (such as PVC coated G.I. weld-mesh) as primary reinforcement and synthetic fibers (like PVA, Polypropylene, Polyethylene and Polyolefin) as secondary reinforcement in ferrocement slab elements and tested for flexure and impact/ toughness; and the corrosion resistance of such hybrid ferrocement elements be studied.

IV. CONCLUSION

Durability is of utmost importance for ferrocement and would perhaps yield the highest payoff. This review evaluated selected papers that have researched on ferrocement and come to a conclusion that there have been very limited studies on corrosion and which has examined the quality issues of ferrocement. Also, studies should be undertaken in order to suggest durable and long-term anti-corrosion techniques to prevent penetration of water and salts that could lead to the corrosion of reinforcing wire mesh.

Due to restricted thickness of ferrocement elements, the number of weld mesh layers cannot be increased beyond a certain limit. This major limitation in use of reinforcing mesh layers affects the strength of ferrocement as a result of which this material cannot be employed where high impact or high load are expected [35]. Therefore, further research should be carried out in line with the recommendations of ACI [10], [32] to characterize new materials and improve the overall performance of ferrocement. New reinforcing mesh systems and matrix designs/ assemblies should be specifically developed for ferrocement applications; and it is very likely that such innovative developments in the mesh system will render ferrocement competitive in all applications where thin elements are used. There is also a need to determine and specify an optimum range of properties for the mesh, such as wire spacing, wire diameter, and the stress-strain characteristics of the mesh system. In addition to having a durable material suitable for numerous structural applications, ferrocement could be a material of choice for the enormous repair and rehabilitation industry offering cost-effective solutions to many problems. This study concludes that if experimental research is conducted on new reinforcing synthetic fibers and weld meshes separately or combining these two materials as a hybrid system in ferrocement slab elements and technical parameters (such as the load carrying capacity, punching shear, toughness and impact and corrosion resistance) studied, it would certainly benefit the construction industry to a great extent.

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