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Report on Ferrocement

Reported by ACI Committee 549

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Methi Wecharatana
Robert B. Williamson
Robert C. Zellers
Ronald F. Zollo
Rogerio C. Zubieta

*Members responsible for the revision
†Chairman of the subcommittee on ferrocement

The report and ACI publication SP-61, Ferrocement—Materials and Applications*, provide technical information on the mechanical properties, performance, and applications of ferrocement. The intent of this report is to promote the more effective use of ferrocement as a construction material for terrestrial structures in contrast to marine structures, where it has been so far most widely used.*

Keywords: composite materials; compressive strength; construction materials; crack width and spacing; fatigue (materials); ferrocement; fibers; flexural strength; impact; mechanical properties; reinforced concrete; tension; welded wire fabric.

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CHAPTER 1—INTRODUCTION

1.1—Definition of ferrocement

Ferrocement is a form of reinforced concrete that differs from conventional reinforced or prestressed concrete primarily by the manner in which the reinforcing elements are dispersed and arranged. It consists of closely spaced, multiple layers of mesh or fine rods completely embedded in cement mortar. A composite material is formed that behaves differently from conventional reinforced concrete in strength, deformation, and potential applications, and thus is classified as a separate and distinct material. It can be formed into thin panels or sections, mostly less than 1 in. (25 mm) thick, with only a thin mortar cover over the outermost layers of reinforcement. Unlike conventional concrete, ferrocement reinforcement can be assembled into its final desired shape and the mortar can be plastered directly in place without the use of a form.

The term ferrocement implies the combination of a ferrous reinforcement embedded in a cementitious matrix. Yet there are characteristics of ferrocement that can be achieved with reinforcement other than steel meshes or rods. For instance, the ancient and universal method of building huts by using reeds to reinforce dried mud (wattle and daub) could be considered a forerunner of ferrocement. The use of nonmetallic mesh is being explored at several universities. Such meshes include woven alkali resistant glass, organic woven fabrics such as polypropylene, and organic natural fabrics made with jute, burlap, or bamboo fibers. Therefore, the term ferrocement currently implies the use of other than steel material as reinforcement. The following definition was adopted by the Committee: "*Ferrocement is a type of thin wall reinforced concrete commonly constructed of hydraulic cement mortar reinforced with closely spaced layers of continuous and relatively small size wire mesh. The mesh may be made of metallic or other suitable materials.*"

The preceding definition is relatively broad in scope. It implies that, although ferrocement is a form of reinforced concrete, it is a composite material. Hence the basic concepts underlying the behavior and mechanics of composite materials should be applicable to ferrocement.

1.2—Ferrocement trends

Widespread use of ferrocement in the construction industry has occurred during the last 25 years, but the usage of this new construction material in the U.S. is still in its infancy. The main worldwide applications of ferrocement construction to date have been for silos, tanks, roofs, and mostly boats.

The construction of ferrocement can be divided into four phases:

1. fabricating the steel rods to form a skeletal framing system;
2. tying or fastening rods and mesh to the skeletal framing;
3. plastering; and
4. curing.

Note that relatively low level technical skills are required for Phases 1 and 3, while Phase 2 is very labor-intensive. This is a shortcoming for industrially developed countries but an advantage for countries where unskilled labor is relatively abundant. In developed countries where labor is relatively expensive, shotcreting (as shown in Fig. 1.1), mechanized fabrication of reinforcement cages,[1] or laminating techniques similar to those developed for marine structures can reduce the labor cost.[2,3] Experience has shown that the quality of mortar and its application to the mesh are the most critical phases. Mortar can be applied by hand or by shotcreting. Since formwork is usually not required, in contrast to conventionally reinforced concrete construction, ferrocement is especially suitable for structures with curved surfaces, such as shells and free-form shapes. In some instances, its use as a permanent form for a reinforced concrete structure can be economically justified.[4]

Ferrocement has a very high tensile strength-to-weight ratio and superior cracking behavior in comparison to conventional reinforced concrete. This means that thin ferrocement structures can be made relatively light and watertight. Hence, ferrocement is an attractive material for the construction of boats, barges, prefabricated housing units, and other portable structures. However, even though for these applications ferrocement is more efficient on a weight basis, it is frequently more economical to build with conventionally reinforced concrete. This is especially true in developed countries where, due to higher material cost and the labor-intensive nature of ferrocement, its use is limited to specialized applications such as domes, wind tunnels, roof shells, mobile homes, modular housing parts (Fig. 1.2), tanks, and swimming pools.

While construction with ferrocement may not be cost-effective in many applications, this material competes favorably with fiberglass laminates or steel used in special structures. Two feasibility studies have shown ferrocement costs to be less than those of steel or fiberglass in the construction of wind tunnels[5] or hot water storage tanks.[6] It is believed that the development of new mesh reinforcing systems and more efficient production techniques will make ferrocement competitive in a wide range of applications requiring thin structural elements.

CHAPTER 2—HISTORY

The known use of lime, gypsum, and natural cement mortar goes back as far as 3000 B.C.[7,8] Early applications were generally limited to joining stone blocks, plastering, or coating. It was not until the time of the Romans, however, that natural cement mortar was widely used as a structural material.

In all early developments, concrete was viewed as a material that could be used effectively only in compression. Although the concept of embedding steel or iron rods within fresh concrete in the direction of anticipated tension is associated with the latter half of the 19th century, the construction of a

Fig. 1.1—Mortar being applied to wire mesh by shotcreting to form a shell (Naaman).

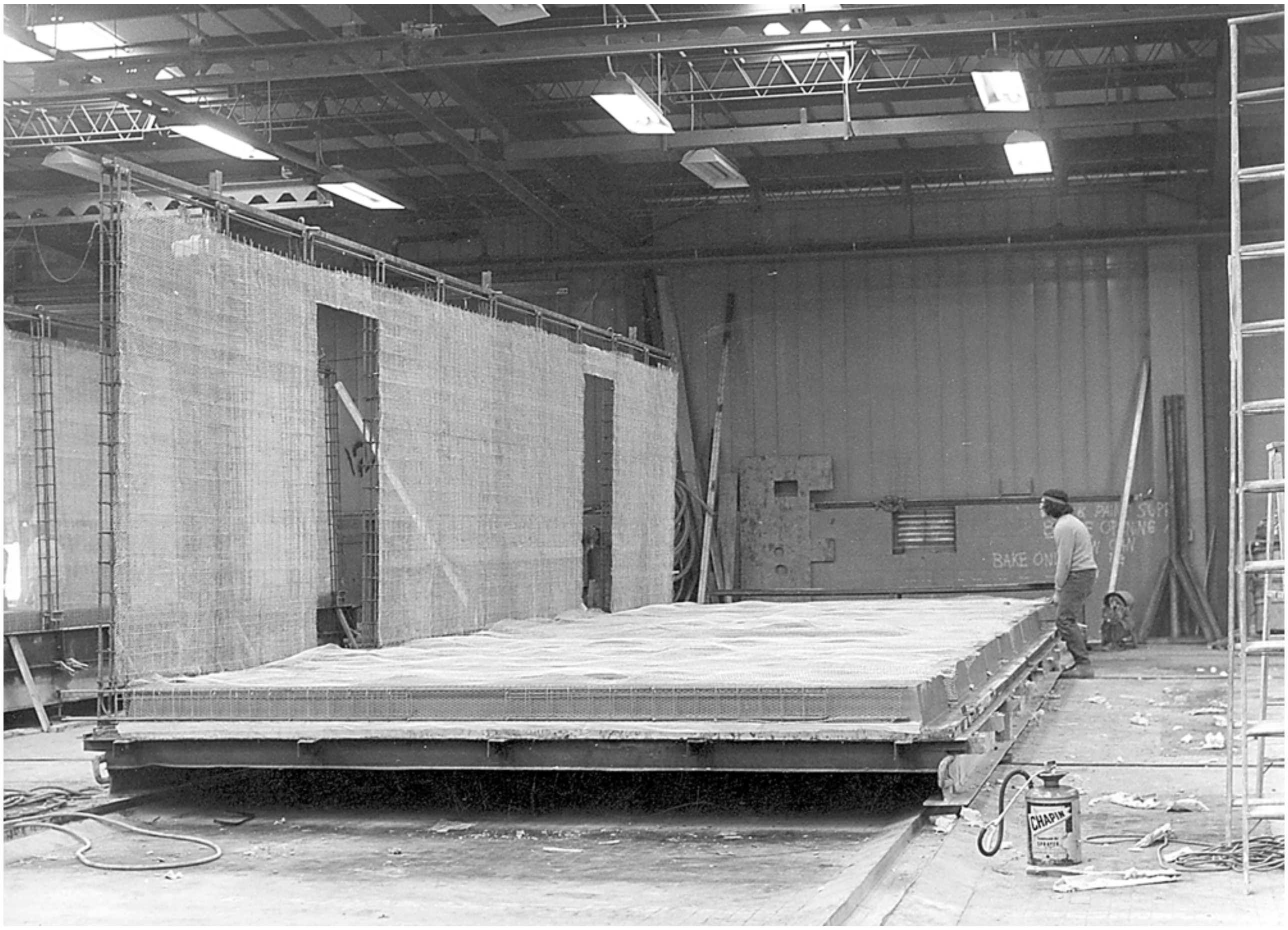


Fig. 1.2—Prefabrication of housing modules.

great gateway to the Acropolis (437 B.C.) required wider spans than were the custom for Greek builders; Mnesicles used iron rods cemented within grooves cut into the tension side of the marble beams. In the 18th century a Frenchman, Soufflot, attempted to increase the strength of masonry construction by burying iron rods in the mortar between the joints. This attempt had limited success because the iron rods rusted and expansive pressures caused by the products of corrosion ruptured the joints.

The concept of embedding reinforcement into wet concrete to form what we now recognize as reinforced concrete almost simultaneously to three persons. Joseph Monier (1823-1906), a French gardener, incorporated a mesh of iron rods into large planting pots in 1849. An Englishman, Wilkinson, made reinforced concrete beams for buildings by putting old mining ropes in the tension side of the beams.[9] And finally, J. L. Lambot made a concrete rowing boat in which the reinforcement was in the form of a network (or basket) of wires and interlaced thin rods.[10,11] In the U.S., during about the same period, Thaddeus Hyatt (1816-1901) undertook extensive tests on reinforced concrete slabs and beams and greatly contributed to rationalizing reinforced concrete theory.[12]

It is, however, the early work of Lambot that is of most interest to us, not only because it was one of the first applications of reinforced concrete, but also because it was a form of ferrocement. His patent on wire-reinforced boats that was issued in 1847 (translated from French in Ref. 13) stated:

"My invention shows a new product which helps to replace timber where it is endangered by wetness, as in wood flooring, water containers, plant pots, etc. The new substance consists of a metal net of wire or sticks which are connected or formed like a flexible woven mat. I give this net a form which looks in the best possible way, similar to the articles, I want to create. Then I put in hydraulic cement or similar bitumen tar or mix, to fill up the joints."

This was the birth of reinforced concrete, but subsequent development differed from Lambot's concept. The technology of the period could not accommodate the time and effort needed to make mesh of thousands of wires. Instead, large rods were used to make what is now called conventional reinforced concrete, and the concept of ferrocement was almost forgotten for 100 years.

Reinforced concrete for boat building reappeared briefly during the First World War, when a shortage of steel plates forced a search for other boat-building materials.[14] However, the conventional use of large-diameter steel rods to reinforce the concrete required thick hulls, making the vessels less practical to operate than lighter wood or steel ships.

In the early 1940s, Pier Luigi Nervi resurrected the original ferrocement concept when he observed that reinforcing concrete with layers of wire mesh produced a material possessing the mechanical characteristics of an approximately homogeneous material and capable of resisting impact.[15,16] Thin slabs of concrete reinforced in this manner proved to be flexible, elastic, and exceptionally strong. After the Second World War, Nervi demonstrated the utility of ferrocement as a boat-building material. His firm built the 165-ton motor sailer *Irene* with a ferrocement hull 1.4 in. (36 mm) thick.[15]

Ferrocement gained wide acceptance in the early 1960s in the United Kingdom, New Zealand, and Australia. In 1965, an American-owned ferrocement yacht built in New Zealand, the 53 ft (16 m) *Awahnee*, circumnavigated the world twice without serious problems, although it encountered several mishaps.[13]

Emphasis on ferrocement as a boat-building material during the 1960s has obscured Nervi's noteworthy applications to buildings. He built a small storehouse of ferrocement in 1947. Later he covered the swimming pool at the Italian Naval Academy with a 50 ft (15 m) diameter dome and then the famous Turin Exhibition Hall—a roof system spanning 300 ft (91 m).[16] In both cases, ferrocement served as permanent forms for the structural system, including the main support ribs.

In spite of the rather unique properties of ferrocement, and the interest created by Nervi's work, use of the material did not expand much beyond its application to boat construction. However, the universal availability of the basic ingredients of ferrocement, steel mesh, and concrete created interest in the potential application of this material in developing countries for everything from roofs to walls of low cost housing to food storage bins and irrigation troughs. In 1972, the National Academy of Sciences, through its Board on Science and Technology for International Development, established the Ad Hoc Panel on the Utilization of Ferrocement in Developing Countries. The report of the Panel greatly stimulated interest in the nonmarine applications of this versatile material.[17-19]

During the late 1960s and early 1970s, the interest of the scientific and technical community turned to the materials science of ferrocement as a fertile field of investigation. Technical papers began to appear in the literature and speculation about the use of ferrocement as a structural material began to rise. An important development was the founding of the International Ferrocement Information Center (IFIC) at the Asian Institute of Technology, Bangkok, Thailand, in October 1976. In collaboration with the New Zealand Ferro Cement Marine Association (NZFCMA), the IFIC publishes a quarterly journal, *The Journal of Ferrocement*. Another periodical, *The International Journal of Cement Composites*, later renamed *Cement and Concrete Composites*, often contains papers related to ferrocement.

ACI Committee 549, Ferrocement and Other Thin Reinforced Products, was organized in 1974 and was given the mission to study and report on the engineering properties, construction practices, and practical applications of ferrocement and to develop guidelines for ferrocement construction.

Ferrocement has great potential for developing and developed countries alike. The low level of technical skills required and the ready availability of materials make it suitable in developing countries for water and food storage structures and housing. In developed countries, the application of advanced technology of building systems and prefabrication makes it attractive for housing and other structural applications. However, considerable research must be conducted if ferrocement is to become an accepted building material, particularly with respect to the present restrictions of many building codes, such as the cover requirements of the reinforcement for fire protection.

This report primarily covers the developments in ferrocement that took place in the countries of the West and of the Third World. The Committee is aware of many developments in research, publication of tests, codification, and construction of ferrocement structures in the former USSR, Poland, China, and other countries. However, most related publications are not referenced here because they have not been translated into English.

CHAPTER 3—COMPOSITION AND CONSTRUCTION

3.1—Introduction

Ferrocement consists of a portland cement mortar matrix, reinforcement, admixtures, and coatings. This chapter deals with the properties of the constituent materials and contains a brief description of the fabrication procedure.

3.2—Matrix

The mortar matrix primarily used in ferrocement consists of hydraulic cement and inert filler material. Portland cement is generally used, sometimes blended with a pozzolan. The filler material is usually a well-graded sand capable of passing a 2.36 mm (No. 8) sieve. However, depending upon the characteristics of the reinforcing material (mesh opening, distribution, etc.), a mortar containing some small-size gravel may be used.

The physical properties and microstructure of mortar depend on the chemical composition of the cement, the nature of the sand, the water-cement ratio, and the curing conditions of the finished product. Since the matrix represents approximately 95 percent of the ferrocement volume, its properties have a great influence on the final properties of the product. There are numerous references describing in detail the effects of various matrix mix proportion parameters on the properties and microstructure of hydraulic cement mortars.[20,21]

The use of portland cement in ferrocement yields a composite in which the matrix is considered to have some tensile strength. It appears that composite action between the matrix and the reinforcement is more pronounced in ferrocement than in ordinary reinforced concrete. The use of fibers will also affect the tensile properties of the resulting matrix.

Addition of short and discrete fibers of different types favorably affects the control of cracking and the capacity of the matrix to resist tensile loads. Therefore, relatively short and slender (l/d = 100) steel fibers may be randomly distributed in hydraulic cement mortars for effective production of ferrocement, the overall effect being to increase tensile strength and improve the shear resistance of these mortars,

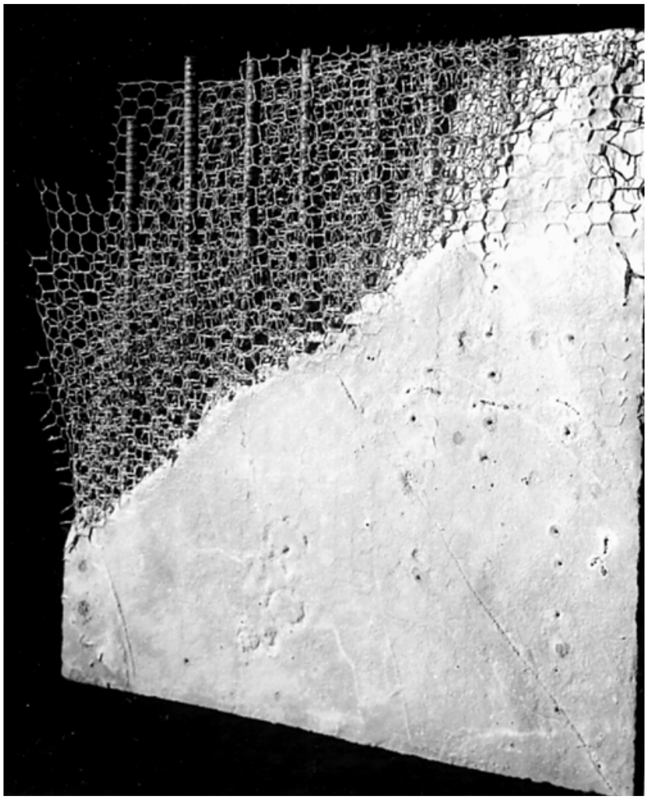


Fig. 3.1—A typical ferrocement section (R. B. Williamson, University of California, Berkeley).

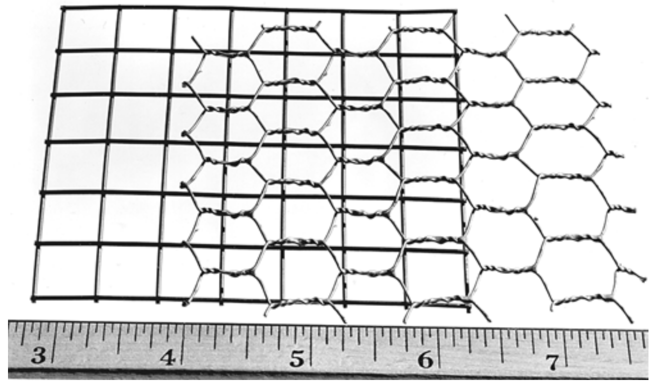


Fig. 3.2—Types of reinforcing mesh commonly used for ferrocement (R. B. Williamson, University of California, Berkeley).

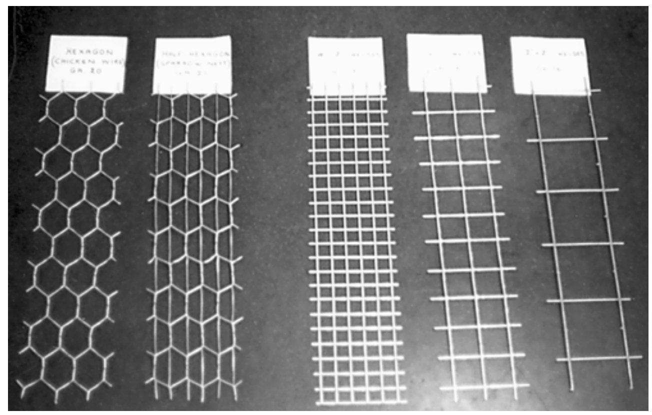


Fig. 3.3—Samples of hexagonal and welded wire mesh.

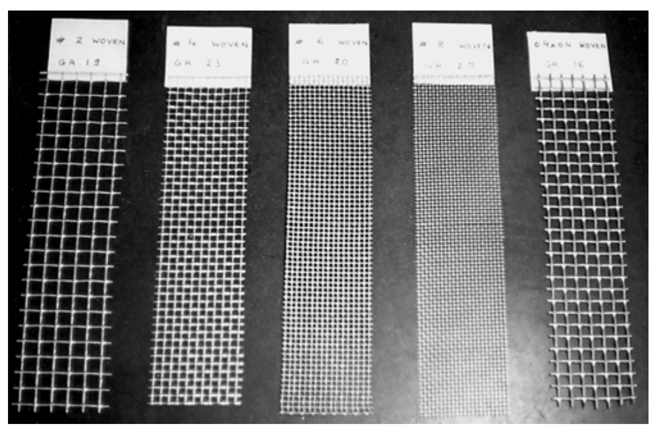


Fig 3.4—Samples of woven wire mesh.

thus influencing the design of the material system and the final properties of the resulting ferrocement product (ACI 544.1R, ACI 544.2R, ACI 544.3R, and ACI 544.4R).[23-25] When fiber-reinforced mortar is used as the matrix, the mesh opening and spacing are usually much larger than for conventional ferrocement.

The water used should be potable and relatively free from organic matter. Water-cement ratios in ferrocement production vary between 0.30 and 0.55, by weight (mass). In general, a workable mix will completely penetrate and surround the mesh reinforcement and will have acceptable amounts of shrinkage and porosity. Water-reducing admixtures may be used to enhance mix plasticity and reduce water.

3.3—Reinforcement

Reinforcement for ferrocement is commonly in the form of layers of continuous mesh fabricated from single strand filaments. Specific mesh types include woven or interlocking mesh (such as chicken wire cloth), woven cloth mesh in which filaments are interwoven and their intersections are not rigidly connected, welded mesh in which a rectangular pattern is formed by perpendicular intersecting wires welded together at their intersections, and specially woven patterns that may include diagonal filament woven through the rectangular mesh pattern. Several examples of woven and welded wire mesh are shown in Fig. 3.1 through 3.4. Two other forms of metal reinforcement are in use: expanded metal lath formed by slitting thin gage sheets and expanding them in a direction perpendicular to the slits; and punched, or otherwise perforated, sheet products. An example of expanded metal lath is shown in Fig. 3.5. Another form of reinforcement consists of continuous filaments that are randomly, or at least irregularly, assembled into a two-dimensional mat form. This particular form of reinforcement has been made with natural organic fibers and glass fibers.[25,26] It is frequently found in developing countries using indigenous materials.[27,28]

There is a wide variety in mesh dimensions as well as in the amounts, sizes, and properties of the materials used. Some mesh filaments are galvanically coated or are impregnated with sizing before, or during, fabrication of the mesh.

Properties of the resulting ferrocement product can be expected to be affected by filament size or gage, strength, ductility, manufacture, and treatment.

3.4—Admixtures

In addition to the numerous admixtures commonly used in the production of both ferrocement and conventional reinforced concrete, ferrocement may require chemical additives to reduce the reaction between the matrix and galvanized reinforcement. Chromium trioxide added to the mix water has been reported to be useful in this regard.[29-32] Recommended solution concentration depends on the water-cement ratio used, but is approximately 300 parts per million by weight of mortar. No special precautions need be taken when using nongalvanized reinforcing materials.

3.5—Matrix mix proportions

The mix proportion ranges of the mortar for ferrocement are:

- Sand-cement ratio by weight, 1.4 to 2.5
- Water-cement ratio by weight, 0.30 to 0.5

The amount of water used should be the minimum consistent with compactibility. This is commonly achieved by using a well-graded, rounded, natural sand having a maximum top size about one-third of the smallest opening in the reinforcing system to ensure proper penetration. A sand passing a 1.16 mm (No. 16) sieve has given satisfactory results in many practical applications.

3.6—Coatings

Many of the surface coatings and impregnation treatments available for use with conventional concrete and reinforced concrete installations can be applied to ferrocement. These include polymer impregnation, and the use of acrylic, latex, and cement-based coatings. They are applied to reduce porosity, control surface deterioration, or provide a surface of a particular functional design.

3.7—Fabrication procedures

The objective of all construction methods is to encapsulate thoroughly the layers of mesh in a plastic portland cement matrix. In the traditional method, the mesh layers are tied by hand to a framework of rods; mortar is forced through this armature, and finished on both sides by conventional plastering techniques. This method is highly labor-intensive and prone to leave voids in the shadows of the mesh and rods. Also, U.S. Navy research on high performance ferrocement hulls showed that rods are an inefficient use of reinforcing because they are not loaded to take advantage of their strength, their spacing allows regions of unreinforced mortar that contribute to weight but not to strength, and they act as stress concentrators. A remarkable increase in strength-to-weight ratio was obtained with mesh only.[32]

The need for rods was eliminated by applying mortar to layers of mesh supported by molds made of wood strips, plywood, fiberglass, rigid foam, ferrocement, concrete, and even compacted earth. Hand-held vibrators aid penetration but care must be used to prevent slump voids and segregation of the matrix materials.

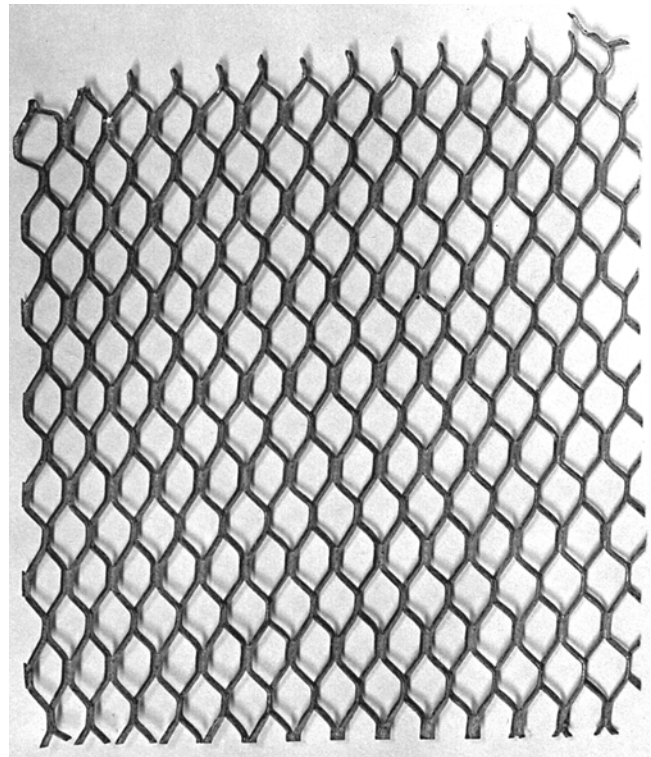


Fig. 3.5—Sample of expanded metal lath.

Laminating techniques similar to those used for fiberglass boat molding were developed in 1963 to eliminate voids, speed production, and reduce labor. In laminating, a 2 to 3 mm-thick layer of mortar is sprayed or applied by hand to a mold and permitted to achieve some initial set. This layer may contain latex or other materials to impart special properties to the surface of the finished product. A second layer of mortar is then applied and, while still soft, strips of mesh are embedded by a roller tool made of closely spaced disks. More layers of mortar and mesh are applied until the desired thickness of ferrocement is obtained.

The laminating process has been used to build marina pontoons, dry-docks, fuel docks, barges, yachts, fishing boats, fuel and water tanks, roofs, canopies, architectural claddings, sewer liners, a skateboard rink, and floating wharves for Loch Ness. As a repair material, laminated ferrocement has been used for watertight, fire-resistant roof overlays, for sheathing a wood barge, and to reinforce the hull of a steel ship, the *Joseph Conrad*, at Mystic Seaport, Connecticut.

Laminated ferrocement has also been applied to floating formwork made of 9 mm (3/8 in.) plywood and oriented strand board (OSB) encased in polyethylene film. This created a corrosion-resistant watertight sheath within which concrete structures were built directly on the water without a dry-dock or shipyard support.[18] Since site acquisition and foundation costs are eliminated, concrete floating structures can now cost less than their counterparts ashore.

The traditional fabrication methods are all labor-intensive to varying degrees, and the quality of resulting products depends greatly on the skill of the hand labor used. Experience has shown, however, that for all of the procedures discussed, the level of skill required can be quickly mastered, and excellent results can be achieved provided proper supervision is maintained. Several high-technology procedures have been suggested. These include packer head machine devices and spin casting for pipe fabrication, and spray suction or vacuum dewatering for the production of thin panel and sheet products.[33] The use of these and other high-technology production procedures, however, must await the time when the ferrocement material and design system become economically and functionally competitive in the developed world.

CHAPTER 4—PHYSICAL AND MECHANICAL PROPERTIES

4.1—Introduction

Many of the properties unique to ferrocement derive from the relatively large amount of two-way reinforcement made up of relatively small elements with a much higher surface area than conventional reinforcement. In the words of Nervi,[15] who first used the term ferrocement, its most notable characteristic is "greater elasticity and resistance to cracking given to the cement mortar by the extreme subdivision and distribution of the reinforcement." The recognition of parameters defining the subdivision and distribution of the reinforcement is fundamental to understanding many of the properties of ferrocement. Two such parameters are the volume fraction and the specific surface of reinforcement. The volume fraction of reinforcement is the volume of reinforcement per unit volume of ferrocement and the specific surface is the bonded surface area of reinforcement per unit volume of ferrocement (see also Sections 5.3 and 5.6). Limiting values of these parameters are often found in the technical literature. Reinforcement concentration should be at least 25 to 31 lb/ft^3 (440 to 500 kg/m^3)[15] (a volume fraction of 5.1 to 6.3 percent), an average spacing between reinforcing elements should be of the order of 0.2 in. (5 mm)[34] to 0.4 in. (10 mm),[35,36] and a specific surface should be at least 5.1 in.^{2}/in.^{3} (0.2 mm^{-1}).[37]

Unfortunately, despite the generality of the definition of ferrocement given in Chapter 1, a lack of appropriate data precludes meaningful comparison of the properties of various forms of ferrocement except those using steel wire reinforcement. The order of discussion of properties in the subsequent paragraphs is as follows: mechanical properties under static loading (ultimate strength, elasticity, and stress-strain behavior), mechanical properties under dynamic loading (fatigue and impact), crack development and its relationship to serviceability, shrinkage and creep, and durability.

4.2—Ultimate strength under static load

Throughout this section, parameters associated with the orientation and the total amount of reinforcement and the effective area of steel in a particular direction are introduced. The orientation is defined as the angle in degrees between the reinforcing elements and the direction of the applied stress, e.g., EXM/A-24 for Type A expanded mesh with all the elements at ± 24 deg to the applied stress, or EWM 0/90 for

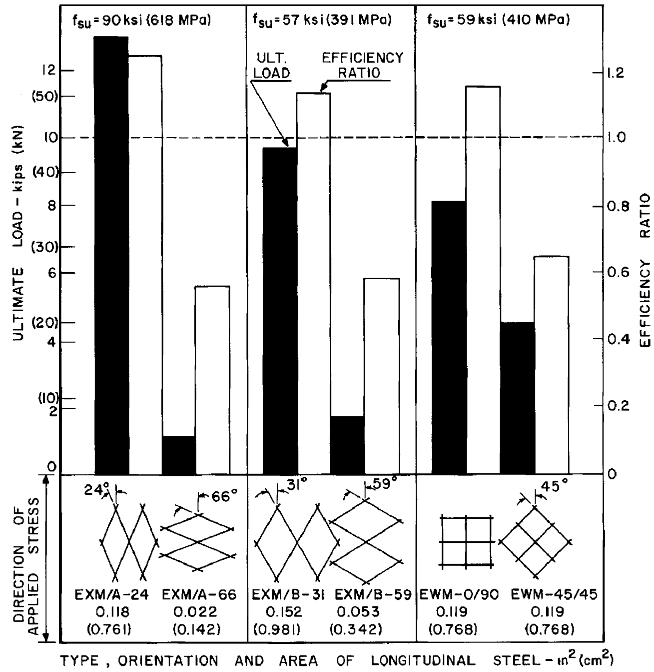


Fig. 4.1—Influence of orientation of reinforcement on the ultimate tensile strength of ferrocement and the efficiency ratio for: Types A (left) and B (center) expanded metal, EXM, and square welded mesh, EWM (right) (Ref. 35).

electro-welded mesh with wires at 0 deg (parallel) and 90 deg (transverse) to the applied stress (Fig. 4.1). The effective area of steel in a particular direction is based on the cross-sectional area of the elements multiplied by the cosine of the angle between the elements and the direction of the applied stress (Fig. 4.1). The total amount of reinforcement is expressed either as a percentage of the volume of ferrocement or as a weight of steel per unit area or volume of ferrocement as appropriate.

4.2.1 *Ultimate tensile strength*—In tension, the load-carrying capability is essentially independent of specimen thickness because the matrix cracks before failure and does not contribute directly to composite strength. Therefore, material performance is often expressed in terms of load rather than in terms of stress. Generally, the tensile strength (load) of ferrocement using expanded metal, welded, or woven mesh in their normal orientations corresponds very closely to the tensile load capacity of the reinforcing elements, that is, the product of ultimate steel strength and cross-sectional area effective in the direction considered.[37-40] The corresponding tensile strength (stress) is equal to the tensile load capacity divided by the cross section of ferrocement. There are notable exceptions occurring when welded mesh is oriented at 45 deg to the applied load, or when expanded metal is used with the longer axis of the diamond-shaped holes perpendicular to the applied stress.[39,40] For example, for 0.5 in. (13 mm) welded mesh (Fig. 4.1—right), ultimate strength for the 45 deg orientation is 50 to 60 percent of that for the normal orientation, while for two types of expanded metal (Fig. 4.1—left and center), strength in a direction perpendicular to the normal orientation is only 15 to 35 percent of that for the normal orientation.[39] Hexagonal mesh (chicken wire) has also been shown to induce anisotropic strength characteristics in tension, with the higher strength observed when the direction of the twisted wires is parallel to the applied stress.[41]

To distinguish strength differences associated solely with orientation from those arising directly from changes in the effective cross-sectional area (number of elements per unit width multiplied by their cross-sectional area multiplied by the cosine of the angle of inclination of the applied stress), it is useful to eliminate the latter by calculating the ratio of actual strength of ferrocement, determined by tests, to the product of the effective area and actual tensile strength of the reinforcement, termed the efficiency ratio. This gives a true indication of the effectiveness of the various reinforcements in different orientations (Fig. 4.1) and shows that the observed strength differences are strongly associated with the orientation of the reinforcing layers, not just with differences in effective cross-sectional area of the reinforcement.

In general, the optimal choice of reinforcement for ferrocement strength in tension depends on whether the loading is essentially uniaxial or significantly biaxial. For example, Fig. 4.1 shows that expanded metal in its normal orientation is more suitable than other reinforcement meshes for uniaxial loading because a higher proportion of the total steel is effective in the direction of applied stress.[39] For biaxial loading, square mesh is more effective because the steel is equally distributed in the two perpendicular directions, although the weakness in the 45 deg direction may govern in this case. However, under biaxial conditions the anisotropy associated with expanded metal or hexagonal mesh can be countered by alternate orientation of successive layers, just as the anisotropy of wood is overcome in the fabrication of plywood.

4.2.2 *Ultimate compressive strength*—In this mode, unlike tension, the matrix contributes directly to ferrocement strength in proportion to its cross-sectional area, so strength and amount of reinforcement are most appropriately defined in terms of stress and volume fraction of reinforcement. Obviously, matrix strength, governed primarily by its water-cement ratio, is a major factor, as for conventionally reinforced concrete. However, the type, orientation, and mode of arrangement of the reinforcement are also important. For example, solid and hollow (identified as cored in Fig. 4.2 because they are formed with the aid of a soft polystyrene core) columns peripherally reinforced with welded mesh are significantly stronger than their counterparts reinforced with expanded metal (Fig. 4.2).[39] This is attributed to the lateral wires in the mesh acting in a manner similar to conventional helical reinforcement by restraining the enclosed matrix, while the expanded metal undergoes a scissors action, visually apparent in the failure mode, that prevents effective triaxial restraint and renders the ferrocement little stronger than the unreinforced matrix. The drastic change of slope in the upper two curves of Fig. 4.2 is attributed to general yielding of the mesh system, as observed by substantial increase in Poisson's ratio (see Section 4.4.2). When mesh reinforcement is arranged parallel to the applied load in one plane only (as opposed to the closed peripheral arrangement), no improvement in strength is observed.[40,42,43]

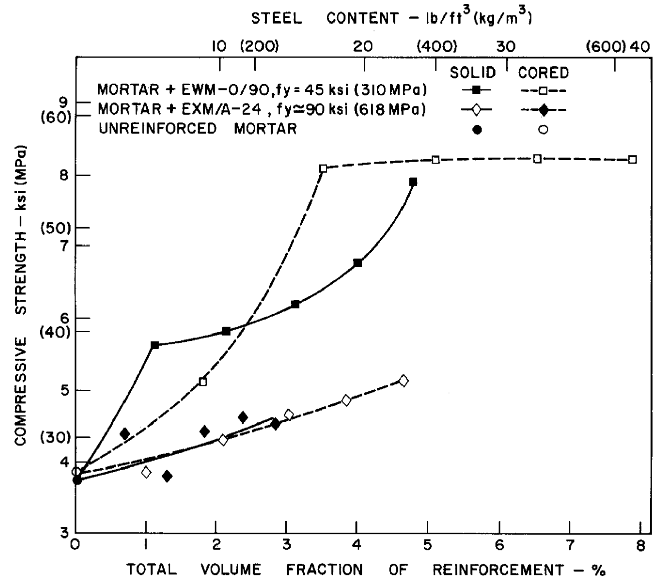


Fig 4.2—Relationships between compressive strength and steel content or volume fraction for ferrocement columns reinforced with expanded metal or welded mesh (Ref. 35).

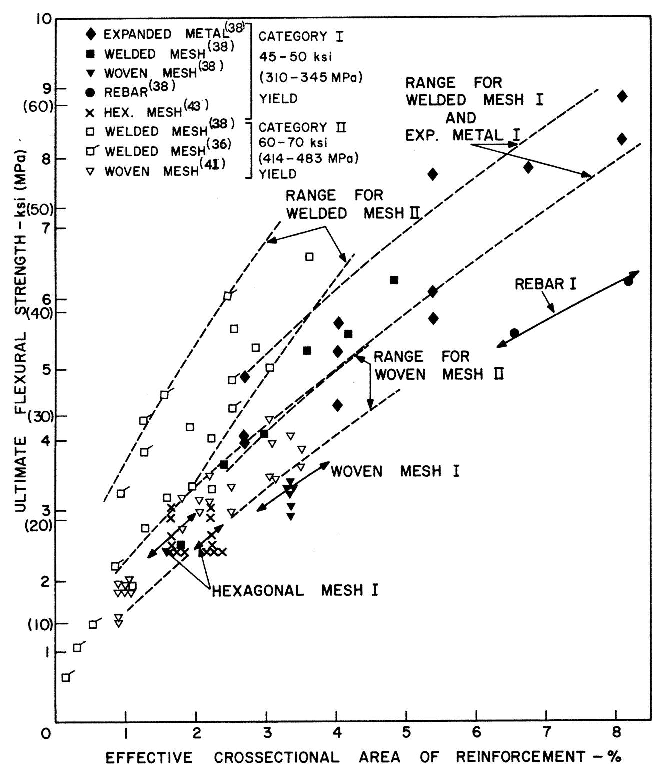


Fig. 4.3—Relationships between ultimate flexural strength of ferrocement and effective cross-sectional area of reinforcement in the direction of applied stress (Ref. 38, 40, 44, 46).

When axial compression is associated with bending, the resulting interaction relationship is similar to that for conventional reinforced concrete as shown in Fig. 4.3.[43] Based on rigid-plastic material behavior, a method is proposed in Ref. 43 to obtain bending moment-axial load interaction curves for ferrocement.

4.2.3 *Ultimate flexural strength*—Ultimate strength in flexure naturally reflects the combined influence of factors governing tensile and compressive strength, that is, the amount, type, orientation, and intrinsic geometry of the reinforcing layers. Several investigators[44-48] have used the principles of conventional ultimate strength analysis for reinforced concrete to compute the strength of ferrocement specimens. Recently, a rigid-plastic analysis has been proposed.[49] It gives a very simple means of estimating the ultimate strength of ferrocement. These methodologies, although satisfactory in many cases, take account only of the effective cross-sectional area and position of the reinforcing layers with respect to the depth. The type of reinforcement and the orientation, spacing, and geometry of the layers are additional important variables unique to ferrocement. In addition to comparing absolute strength, it is useful to establish a general indicator of performance applicable to all data that eliminates the influence of differences in matrix and reinforcement strengths, specimen size, position of the reinforcing layers, etc. This isolates the importance of these variables and highlights the circumstances where a conventional ultimate strength analysis is inadequate. The indicator chosen is the efficiency ratio and is the equivalent of that selected for tensile strength, that is, the ratio of the actual ultimate moment determined by test to the value of the ultimate moment computed by the ultimate strength method. Although the actual computation of the ultimate strength depends to some extent on the strain distribution and mode of failure assumed,[50] the type of stress/strain function chosen for the reinforcement,[44] and the stress block coefficients and ultimate strain selected for the mortar.[45] But efficiency ratios based on any particular method of computation are comparable in a relative sense regardless of the method used.

Before considering the efficiency ratios of various systems, it is instructive to compare the performance of various reinforcing systems in terms of the relationship between actual ultimate flexural strength measured by test and the effective area of reinforcement in the longitudinal direction. A comparison was made with the various reinforcements in their normal orientations (as previously defined for expanded metal, square mesh, hexagonal mesh) at two levels of reinforcement strength (Fig. 4.4). The distribution of the reinforcing layers was assumed uniform throughout the depth of cross section, and skeletal reinforcing bars were not considered. The comparison showed that expanded metal and square welded mesh perform significantly better than woven meshes or conventional bars with end anchorage. (Conventional bar reinforcement was included for comparative purposes only and would not be permitted by the ACI Building Code because it would not meet cover requirements). Also, woven mesh, conventional bars, and hexagonal mesh perform similarly. Clearly, based on effective longitudinal area of reinforcement, expanded metal and square welded mesh in their normal orientations are more effective in flexure than are other types of reinforcement, despite differences in test specimen size, mortar cover, and the specific surface and spacing of the reinforcing layers. The use of the efficiency ratio gives a truer indication of the effectiveness of the various reinforcements. Despite minor differences in the methods of applying ultimate strength analysis to the computation of ultimate moment, the general consensus is that efficiency ratios for expanded metal and welded mesh in their normal orientations are higher than those of woven meshes and are in the range 1.05 to 1.20.[44,46,48,51] Similar efficiency ratios have also been obtained for both simple uniaxial[40,52] and biaxial[53] loading (circular slabs with a central load) using hexagonal mesh laid in alternate layers with skeletal bars between them. The performance of all of these reinforcing systems meets and slightly exceeds expectations based on strength analysis. Some additional strength is apparently imparted by the two-way nature of the reinforcements, as already noted for tensile strength.

There are probably three reasons for the greater flexural effectiveness of square welded mesh and expanded metal over woven mesh. First is the possibility of debonding promoted by premature straightening of the longitudinal wires, which in woven meshes are not initially straight due to the weave. This straightening also reduces the apparent modulus of the mesh system. Second is the resistance to bond failure associated with anchorage of the longitudinal elements by the transverse or oblique elements in welded mesh and expanded metal. Third is the effect of the transverse component of the reinforcement restraining lateral expansion of the matrix in the compression zone due to inherent fixity with the longitudinal reinforcement, thereby strengthening the matrix by creation of a biaxial stress condition. Since all

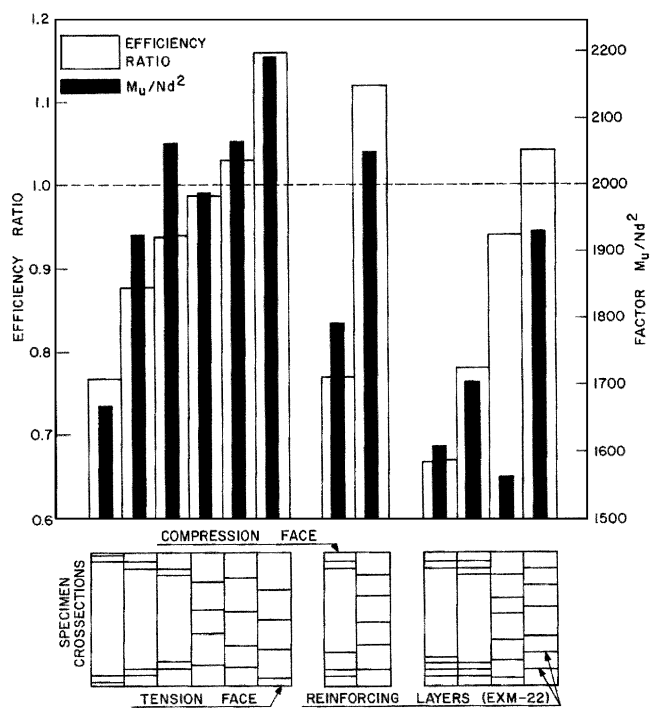


Fig. 4.4—Effect of spacing of the reinforcing layers (4, 5, or 6 layers of expanded metal) on flexural performance and efficiency ratio, where N *is the number of reinforcing layers and* d *is the effective depth (Ref. 40).*

three considerations also apply to some extent to hexagonal mesh, they may influence its performance in a similar manner.

The orientation of the reinforcement is just as important for flexural strength as it is for tensile strength, particularly when strength under biaxial loading is considered. While square meshes offer equal strength in both directions parallel to the wires, strength in the 45 deg orientation is 67 to 80 percent of that parallel to the wires for welded mesh, with rather less difference for woven mesh.[44,48] With expanded metal and hexagonal mesh, an even greater degree of strength anisotropy is possible. For expanded metal, strengths in the transverse direction are particularly low, 11 to 15 percent,[47] 23 percent[53] and 33 percent[3] of the values for the normal orientation, and are somewhat dependent on the nature of the reinforcement. For hexagonal mesh, strengths in the transverse direction average 57 percent of those in the normal orientation.[53] These reductions are greater than expected on the basis simply of decreases in the effective cross-sectional area of the reinforcement. Efficiency ratios for expanded metal in the transverse direction are of the order of 0.5, clearly indicating another case in which performance is well below that expected from ultimate load analysis.

The specific surface of the reinforcement, a parameter that depends on both the diameter of the reinforcing elements and their elemental (as opposed to interlayer) spacing (see Section 5.3), has been shown to influence ultimate strength for relatively large woven meshes up to 6 in. (150 mm) square.[36] However, examination of comparable data for both welded[44] and woven[51] meshes smaller than 1 in. (25 mm) shows no evidence of the influence of specific surface on ultimate strength.[44] Apparently, an increase in specific surface is only beneficial so long as bond failure at the wire-matrix interface is a factor affecting ultimate strength.[46] When bond failure is not a governing factor, e.g., in welded mesh and expanded metal where effective anchorage is provided by the transverse reinforcement, or in very fine meshes of all kinds, specific surface greater than the minimum required to prevent bond failure is of no benefit. In fact, it can even be disadvantageous because of reduction in strength, apparently caused by inability to achieve full penetration of a fine mesh by the mortar matrix.[51]

The spacing of the reinforcing layers in ferrocement is normally fairly uniform throughout the available depth of cross section, except when the skeletal bar reinforcement is present. Nevertheless, the idea that concentrating the layers at the top and bottom faces of a flexure specimen increases the flexural strength because of their greater distance from the neutral axis is not unreasonable.[54] However, such an arrangement may sometimes reduce the absolute strength and efficiency ratio by promoting horizontal shear failure, which normally is not a problem in ferrocement units with uniformly and closely spaced reinforcement and a large span-depth ratio[46] (Fig. 4.5). When expanded metal mesh is used, optimal efficiency ratios and compliance with the expectations of conventional ultimate strength analysis seem to result when the reinforcing layers are spaced uniformly through the effective depth (Fig. 4.5).

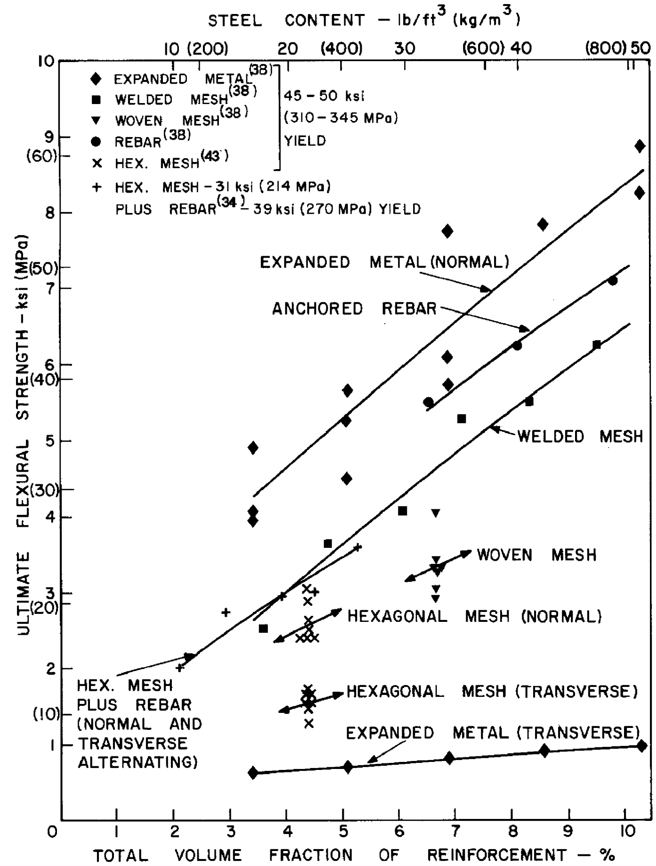


Fig. 4.5—Relationships between ultimate flexural strength of ferrocement and total amount of reinforcement (Ref. 36, 40, 46).

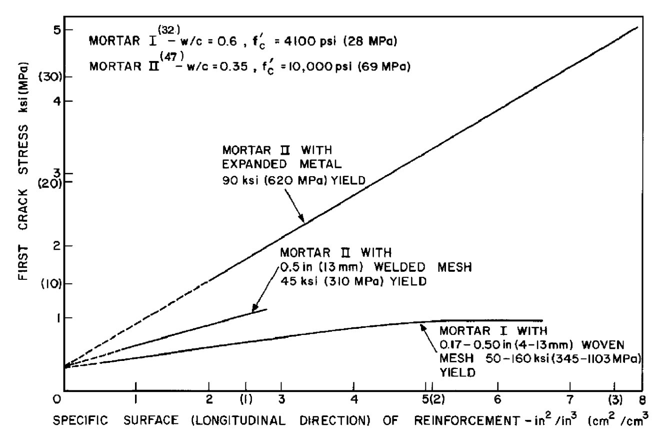


Fig. 4.6—Relationships between fire-crack strength of ferrocement in direct tension and the specific surface of the reinforcement (Ref. 34, 50).

In general, the optimal choice of reinforcement for flexural strength, as already noted for tensile strength, depends on whether the loading is essentially uniaxial or significantly biaxial. For uniaxial loading, the cost-effectiveness of different reinforcements is illustrated by the relationship between flexural strength and steel content or volume fraction (Fig. 4.6). Clearly, expanded metal is the best choice on this basis. Also, it generally costs less per unit weight.[3] Alternating layers of hexagonal mesh with skeletal bars in both directions seems equally effective for the same yield strength[53] (note the lower yield strength in Fig. 4.6 for this system). Under biaxial conditions, welded mesh is probably the best choice, although the inherent weakness on the 45 deg diagonal axial should be taken into account. When expanded metal or hexagonal mesh are employed under these conditions, the orientation of the successive layers should be alternated to counter their anisotropic characteristics.

Another consideration governing the choice of reinforcement is the ability to adopt easily the curvature of the unit to be constructed. Hexagonal mesh is particularly suited to complex doubly-curved sections, square mesh to singly-curved sections, and expanded metal to planar sections.

4.2.4 *Shear strength*—Remarkably few of the many studies of ferrocement have included shear strength evaluation, perhaps because ferrocement is used primarily in thin panels where the span-depth ratio in flexure is large enough that shear is not the governing failure criterion. Parallel longitudinal alignment of the reinforcing layers in ferrocement effectively precludes the inclusion of shear reinforcement equivalent to the bent-up bars or stirrups used in reinforced concrete, so ferrocement is not particularly suited to resisting shear. However, this is not required in most applications. Shear strength has been determined for specimens reinforced with woven mesh and skeletal bars, tested in bending at a shear span/depth ratio of 0.4.[55] While the test values reflect the characteristics of the steel and mortar used, the shear strength remains at a constant fraction of about 32 percent of the equivalent flexural strength for a fairly wide range of steel contents 18 to 35 lb/ft^3 (288 to 480 kg/m^3). Tests conducted in bending on specimens reinforced with welded mesh at span/depth ratios ranging from 1 to 3 indicate that failure in transverse shear is possible for specimens with high volume fraction of reinforcement and low strength of mortar only at a small span-depth ratio.[56] However, in general, shear failure is preceded by the attainment of flexural capacity of ferrocement. In the case of in-plane shear, similar to that existing in the web of an I-beam under transverse loading, the Truss Model Theory has been found to give a good estimate of the ultimate shear strength.[57]

Some ferrocement boat builders have demonstrated qualitatively the toughness of the material in punching shear through accidental and deliberate tests involving collisions with rocks or other boats.[3]

4.3—First crack strength under static load

The term first-crack strength or its equivalent appears frequently in literature on the behavior of ferrocement under tension and flexure, but its use without qualification is unfortunate because it can be defined in various ways and therefore can carry different meanings. In a comprehensive discussion of this problem,[58] it is noted that microcracks are inherent in the mortar matrix even before it is loaded. As the microcracks widen, propagate, and progressively join together under load, they are detected by some means, visual or otherwise, and termed "first cracks." However, in the various Polish and Russian studies[58] "first cracking" is defined by a crack width ranging from 2×10^{-4} in. (0.005 mm)

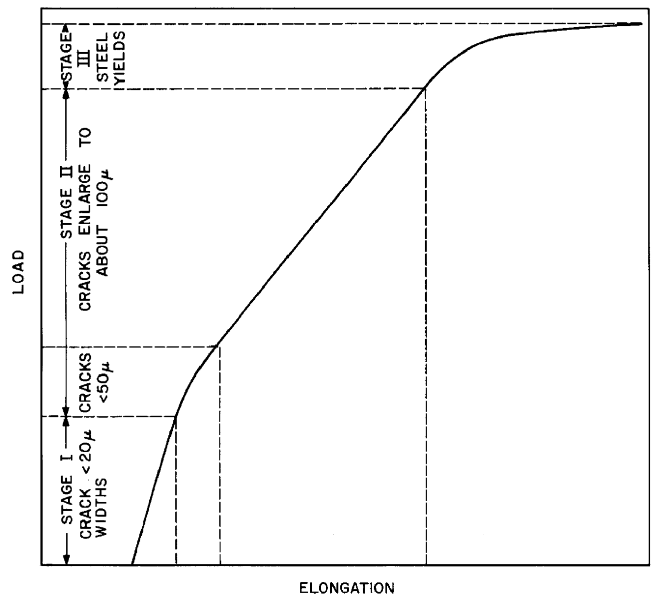


Fig 4.7—Schematic three-stage load-elongation relationship for ferrocement in direct tension (Ref. 40).

to a size visible to the naked eye, 1.2 to 3.3×10^{-3} in. (0.03 to 0.1 mm). Consequently, a cracking strain in these studies ranges from the cracking strain for the unreinforced matrix (100 to 225 microstrain) to values established in other ways and ranging from 800 to 2000 microstrain.[58] In other studies, first cracking is defined as the first deviation from linearity of the load-elongation function in tension (900 to 1500 microstrain)[38] or the corresponding deviation of the load-deflection curve in flexure.[45,52] First cracking is also defined as a crack width under flexural loading of 0.003 in. (0.075 mm)[44] the point at which the matrix at the tension face of flexural specimen reaches a strain equal to the cracking strain of the unreinforced matrix,[51] or simply as the first visible crack.[39,46,53]

Quite obviously, until a generally accepted definition of first-crack is adopted, associating a stress or strength with this condition is fraught with difficulty and misunderstanding. A more useful approach may be, in the future, to relate load or stress to average crack width and arrive at an allowable design stress corresponding to the average crack width considered permissible in service (also see in Section 5.8).

Despite the problem of definition, there is a general agreement[38,59] that, in direct tension at least, resistance to cracking increases with an increase in the amount or degree of subdivision of the reinforcement defined in terms of the specific surface of the longitudinal component of the reinforcement, that is, its surface area per unit volume of ferrocement (Fig. 4.7). The difference between welded and woven mesh is apparently minor. However, the difference between expanded metal and the above types of mesh is very significant and is obviously associated with factors other than specific surface. Specimens reinforced with expanded metal resist visible cracking to about 80 percent of their ultimate strength while cracking in mesh-reinforced specimens starts at a much lower percentage of ultimate strength. The cracking develops gradually to a point where the spacing of the cracks corresponds to the spacing of the transverse wires in the mesh.[59]

In flexure, relationships linking cracking with specific surface are less well defined, and considerable data scatter reflects the possible influence of other variables.[44,49,52,58,60] Specific surface in these cases is defined as the surface area of total reinforcement per unit volume of ferrocement located in the tension zone only. This is perhaps questionable on the grounds that cracking is primarily controlled by the layers in the immediate vicinity of the tension face, the remaining internal layers having less influence. Despite the questionable logic of this definition, the available data for expanded metal and hexagonal or square mesh show that, in general, cracking resistance increases from a lower bound value corresponding to the strength of the mortar matrix to higher values proportional to the specific surface.

The greater effectiveness of expanded metal to inhibit cracking is again notable, with the ratio of first-crack to ultimate load at 80 percent,[60] just as high as for direct tension. Another investigation[3] refers specifically, without giving data, to the ability of panels reinforced with expanded metal to accept strain with less visible cracking than panels containing the same weight of welded or woven mesh. The available data generally suggest that, while specific surface is one factor influencing first-crack strength, other factors related to the geometry of the reinforcement are also important.

In shear, equations have been developed to predict the diagonal cracking strength of ferrocement reinforced with welded mesh.[56,57] However, the equations consider only the effect of the volume fraction of reinforcement. The effects of other important parameters, including the type of reinforcement, on diagonal cracking strength of ferrocement need to be established.

4.4—Elasticity and load-deformation behavior

Following the consideration given to ultimate and cracking strengths, it is appropriate to examine the overall load-deformation behavior of ferrocement under various forms of static loading, in particular its elasticity which historically has been identified as one of its major attributes.

4.4.1 *Load elongation behavior in tension*—For square mesh reinforcements, the load-elongation behavior of ferrocement has been characterized in three stages.[38,40,61] In the initial stage, the matrix and reinforcement act as a continuum having a composite elastic modulus about equal to that predicted from the volumetric law of mixtures of the longitudinal reinforcement and the matrix.[38,59] The second stage, associated with a fully cracked matrix, also can be approximated by a straight line. Its modulus (see Sections 5.3 for the definition of modulus) is somewhat greater than the product of the volume fraction and the modulus of the longitudinal reinforcement.[38,40] This supports the view that the mortar[40] and the lateral reinforcement[39] continue to play an active role after first-cracking, either individually or in combination. In the third stage, the matrix ceases to be effective. Failure corresponds to the yielding of the reinforcement.

While the foregoing is based on the observation of specimens reinforced with square meshes, and may be qualitatively true for other types of reinforcement, the type of reinforcement and its intrinsic geometry are major factors governing the moduli of elasticity (Stages 1 or 2) and overall load-deformation behavior (Fig. 4.8). For example, a more complex analysis taking into account the orientation of the oblique reinforcing elements is necessary to predict the modulus of ferrocement with hexagonal mesh.[40] Also, the overall stiffness and elongation at failure are clearly different for expanded metal and welded mesh (Fig. 4.8), probably reflecting differences in the ductility of the steel and in the stiffness of the reinforcing network itself.

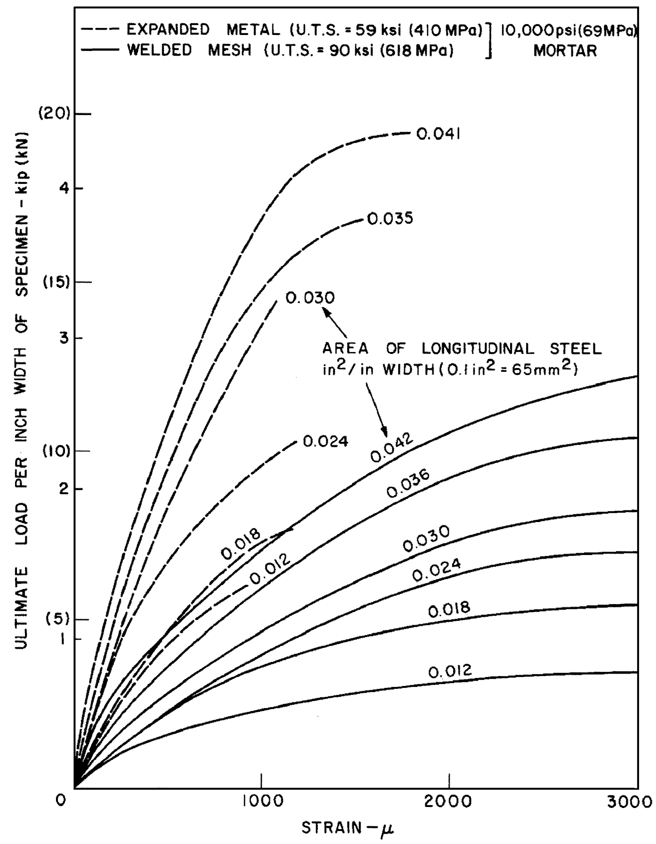


Fig. 4.8—Comparative load-deformation relationships in direct tension for ferrocement with different types of reinforcement (Ref. 35).

4.4.2 *Load-deflection behavior in compression*—When the reinforcement is in one direction only, it has a minimal effect on the load-deformation relationship, and the associated elastic modulus remains virtually the same as that for the mortar matrix.[40] When the reinforcement confines concrete, the load-deformation relationship is curvilinear with the initial tangent modulus increasing gradually with the amount of reinforcement,[42,43,59] but the increase is only marginal. The initial elastic modulus can be predicted accurately and conservatively on the basis of the volumetric influence of the two material components acting together.[62] Values of the elastic modulus are slightly higher for specimens reinforced with welded mesh than for their equivalents with expanded metal. This reflects the more effective biaxial restraint of the matrix by the welded mesh, which is also apparent from the changes in Poisson's ratio of ferrocement with increasing

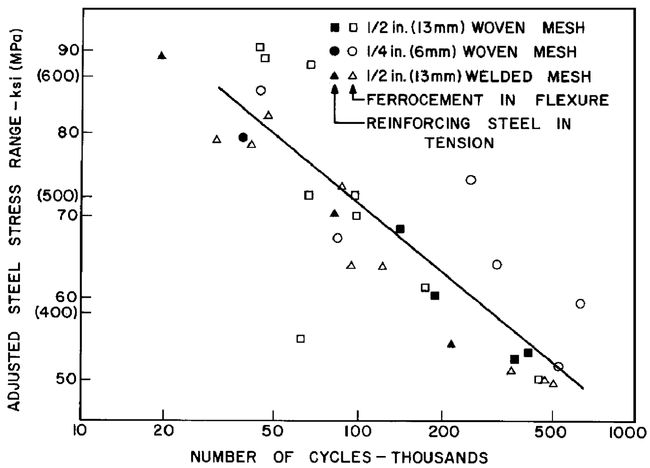


Fig. 4.9—Comparison of the fatigue behavior of ferrocement in flexure with the behavior of wire from the reinforcing meshes in tension, based on stress ranges adjusted in zero mean stress (Ref. 57).

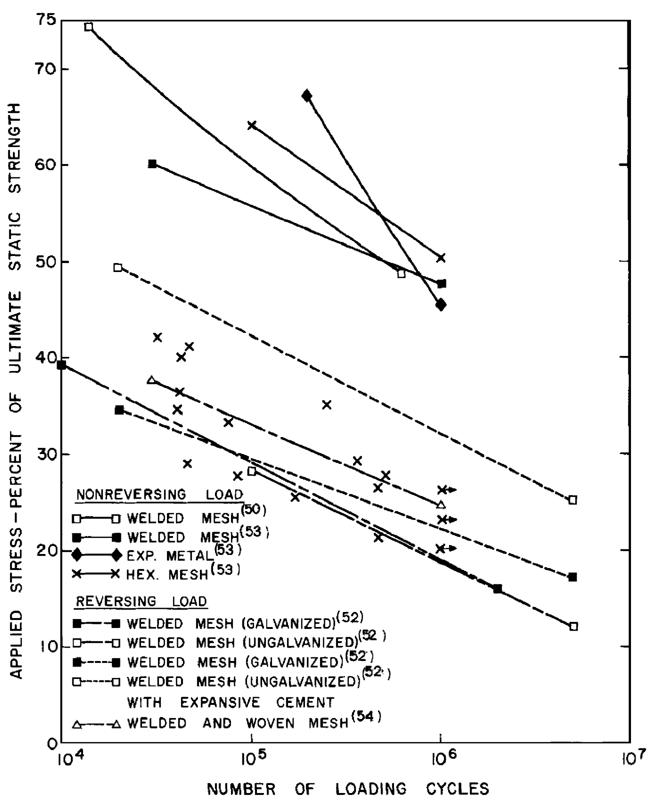


*Fig. 4.10—*S-N *relationships for ferrocement in flexure (Ref. 53, 55-57).*

load. From initial values of Poisson ratios of 0.06 to 0.07 and 0.11 to 0.13 for ferrocement with welded mesh and expanded metal respectively, the ratio increases only gradually to less than 0.10 just before failure of the mesh-reinforced specimens. It increases sharply to more than 0.20 at 60 to 80 percent of ultimate for specimens reinforced with expanded metal.[39]

4.4.3 *Load-deformation behavior for flexure*—The three-stage behavior already identified for direct tension is also

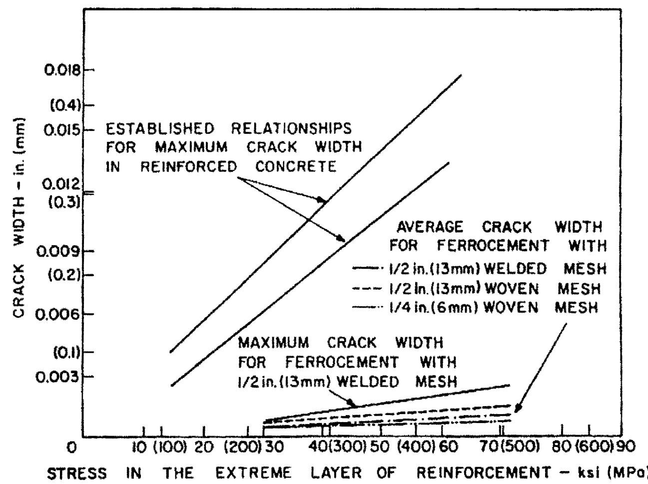


Fig. 4.11—Comparison of crack widths for mesh-reinforced ferrocement and reinforced concrete in flexure (Ref. 45, 72).

applicable to ferrocement in flexure (Fig. 4.11). A method of predicting the moment-curvature relationship, based on the assumption of a second degree stress-strain curve for the mortar in compression and a simple bilinear (elastic/plastic) relationship for the steel in tension, has been proposed.[49] Another proposed method uses Fourier series to define the stress-strain functions of both mortar and reinforcement, and thereby computes the moment-curvature relationships.[45] This approach gives results that agree satisfactorily with the corresponding relationships determined experimentally for the first two stages up to yielding of the reinforcement, but some discrepancies are reported for the third stage between yield and ultimate.

4.5—Strength under fatigue loading

The two constituents of ferrocement, steel and mortar, have quite different fatigue characteristics. Most steels have a definite endurance limit; that is, at stress levels below this limit they have an infinite or at least very long fatigue life. In contrast, a brittle material like mortar does not have a definite endurance limit; that is, it will eventually fail under repeated loading no matter how low the applied stress. Presumably, the fatigue behavior of either material may govern the performance of ferrocement. Only the flexural mode has been studied in published reports.

4.5.1 *Flexural fatigue*—Investigations of the fatigue performance of ferrocement in flexure[63-69] have employed various forms of loading incorporating center-point or third-point applications of nonreversing or fully reversing load at rates of 1 to 39 cycles per second. Six of the seven studies conclude that the fatigue performance of the ferrocement depends directly on the fatigue performance of the steel reinforcement. The remaining one[65] notes specifically that the reinforcement (square welded mesh) did not fail by fatigue, but by tensile fracture, and that failure was caused by inability of the mortar to resist disintegration and spalling. The majority viewpoint, that ferrocement performance is governed primarily by the fatigue behavior of the reinforcement, receives support from a relationship developed using welded and woven mesh reinforcement.[69] This relationship shows that the fatigue behavior of ferrocement in flexure is almost identical to the behavior of segments of the reinforcing steel in tension (Fig. 4.9). If this is the case, the choice of reinforcement for optimal performance under fatigue loading may be influenced by considerations quite different from those previously proposed for static loading. For example, while welded mesh may be better than woven mesh for static loading, woven mesh may be preferable for fatigue loading because it has been shown[70] that the fatigue behavior of welded mesh is influenced by the degree of geometrical stress concentration introduced during welding and by the method for forming the welds. Observations[63,66] confirm, with some exceptions,[65] that failure of the reinforcement occurs predominantly at the welds. In the case of expanded metal, failure occurs predominantly at the nodes or joints.[66] Hexagonal mesh apparently does not exhibit regions of preferential failure,[66] and may offer advantages similar to woven mesh. In general, the fatigue behavior of steel suggests that all factors influencing the nature and quality of the surface finish of the reinforcement. For example, galvanizing may affect performance to some extent.

Since it is customary to examine fatigue behavior in terms of *S-N* (applied stress versus number of cycles of failure) relationships, the available and comparable data are presented in this form[63,65,66,69] (Fig. 4.10). This makes it clear that, of the many variables involved, the nature of the loading is of paramount importance. This reflects the known significance of the stress range in the fatigue behavior of many materials. Other differences, such as the apparently more rapid rate of fatigue using expanded metal or the possible adverse effect of galvanizing (Fig. 4.10), are less defined, and may apply only to the particular data shown.

Most investigators[63,69] have observed a gradual increase in deflection, a decrease in stiffness, and an increase in average crack width[69] with repeated cyclic loads. A more rapid rate of increase in deflection and average crack width precedes failure, and equations predicting the growth of both parameters for ferrocement reinforced with square welded or woven mesh have been developed.[69]

4.6—Impact resistance

Reports attesting to the favorable characteristics of ferrocement in collisions between boats or with rocks are numerous.[3,15] The main attributes seem to be resistance to disintegration, localization of damage, and ease of repair. However, in view of the experimental complexity associated with measurement of impact resistance, little quantitative or comparative data exist. Drop-impact tests on panels[53] indicate that the severity of cracking inflicted varies significantly with the type of reinforcement, but the fundamental governing parameters are not established. Tests using ballistic pendulums to produce the impact, and flow of water through the specimen after testing to assess the damage,[71] show that damage decreases as the strength and specific surface of the mesh reinforcement increase. However, at this time the available information is insufficient to indicate what constitutes an optimal reinforcing system for impact resistance. The factors that influence first-crack strength, such as the type, geometry, and specific surface of the reinforcement, are probably of primary importance.

4.7—Crack development and leakage

Crack development is considered in this section in terms of average crack spacing and the average and maximum width of cracks. For mesh-reinforcing systems, the average crack spacing decreases with increasing specific surface for both tension and flexure.[38,44] However, other factors, such as the geometry of the reinforcement, also influence crack development, as noted in Section 4.3. In flexure, mesh size is also important. The average crack spacing corresponds closely to the transverse wire spacing, and the average crack width reduces as this spacing decreases.[45] The relationship between maximum crack width or average crack width and steel stress in the extreme tensile layer of reinforcement shows that the steel stresses and crack widths in ferrocement are substantially smaller than in conventionally reinforced concrete (Fig. 4.11). For meshes of the same size, crack widths are smaller for the welded type than for the woven variety. Unfortunately, there is no comparable data for expanded metal, which has previously been identified with greater resistance to cracking.

In applications involving storage of liquids (see Chapter 6) the development of cracking directly governs leakage. It has been shown experimentally[72] that in tanks subjected to water pressure the factors that reduce average crack width generally reduce leakage. The limiting average crack width proposed for design from these tests [pressure up to 100 psi (0.69 MPa)] is 0.0015 in. (0.04 mm). However, the authors[69] point out that this may be conservative for lower pressure designs, for example, sanitary engineering structures where the permitted design crack width for conventionally reinforced concrete is 0.004 in. (0.1 mm) (ACI 350R). Polish and Russian research[58] suggests an even lower limit for absolute watertightness in ferrocement of 0.0008 in. (0.02 mm), although the limit associated with the corrosion of reinforcement is somewhat higher: 0.002 to 0.004 in. (0.05 to 0.10 mm).

4.8—Shrinkage and creep

A limited number of publications make reference to quantitative data comparing the shrinkage and creep characteristics of different forms of ferrocement. Nevertheless, there is no reason why principles governing the behavior of conventional reinforced concrete should not generally apply.

The shrinkage potential of the mortar matrix (unrestrained by reinforcement) is governed largely by its water content, which in turn is governed by the workability required for placement, the sand gradation, and the presence of additives such as pozzolan, lime, water-reducing and air-entraining agents, etc. Thus, the selection of low-workability placement techniques such as shotcreting, the choice of a sand without excessive fines, and the use of admixtures can reduce shrinkage of the matrix as circumstances permit. The actual shrinkage of ferrocement also depends on the restraint offered by the reinforcement, which is a function of the volume fraction in the direction considered and probably other factors previously associated with crack development, that is, specific surface, type of reinforcement, and wire spacing in mesh.[73]

Like shrinkage, the creep of ferrocement is a function of the creep potential (unrestrained condition) of the matrix and the restraint offered by the reinforcement.[74] Again, certain parameters, such as a low paste/aggregate volume fraction and a low applied stress/strength ratio, will minimize the creep of the mortar matrix, while creep of the ferrocement may be further influenced by factors such as the volume fraction of the reinforcement in the loading direction.

4.9—Durability

Although the measures required to ensure durability in conventionally reinforced concrete (ACI 201.2R) also apply to ferrocement, three other factors that affect durability are unique to ferrocement. First, the cover is small and consequently it is relatively easy for corrosive liquids to reach the reinforcement. Second, the surface area of the reinforcement is unusually high; so the area of contact over which corrosion reactions can take place, and the resulting rate of corrosion, are potentially high. Third, although steel reinforcement used in ferrocement is generally galvanized to suppress corrosion, the zinc coating can have certain adverse effects from gas bubble generation. All three factors assume varying degrees of importance, depending on the nature of the exposure condition. However, in spite of these unique effects, there is no report in the literature of serious corrosion of steel in ferrocement other than that associated with poor plastering or poor matrix compaction (see Section 6.3). To ensure adequate durability, a fully compacted matrix is necessary. A protective coating may be desirable (see Section 3.6 and ACI 515.1R). The use of pozzolanic materials (e.g., Class F fly ash and ground granulated blast furnace slag) in ferrocement can improve resistance to sulfates and seawater attack in a similar manner as in conventional concrete.

4.9.1 *Deterioration associated with the mortar matrix*—Such deterioration arises as a consequence of contact with chemicals that react with cement paste, as a result of physical disruption induced by freezing, or by surface wear due to abrasion.

Attack by chemicals that react with cement paste is minimized by insuring low permeability in limiting the water-cement ratio to a maximum of 0.5. Paste permeability increases sharply above this value.[75,76] Proper curing to maximize hydration and effective consolidation to minimize entrapped air are also useful.

For the relatively common condition of exposure to sea water or ground water where the sulfate concentration of the water exceeds 150 ppm, additional sulfate resistance may be obtained by limiting the water-cement ratio to 0.45 or less (ACI 211.1) regardless of the type of cement. Otherwise it is recommended that ASTM C 150 Type II or Type V cement be used since their reduced tricalcium aluminate contents make the cement less vulnerable to attack by sodium or potassium sulfates. However, magnesium sulfate, which attacks the tricalcium silicate hydrates present in all portland cement pastes, is potentially more dangerous than either sodium or potassium sulfate. Also, in terms of the rapid rate of deterioration induced, the ineffectiveness of sulfate-resisting cements, ammonium sulfate is particularly worth noting.[77] For sea water exposure, limiting the water-cement ratio seems to be adequate, since samples from various ferrocement panels made from Type I cement with water-cement ratios of 0.35 to 0.45 have performed satisfactorily after 350 cycles of wetting and drying.[53] More severe exposure conditions may require special protective coatings.

Supplementary cementing materials such as fly ash, ground granulated slag, and silica fume are desirable as partial cement replacement in mixtures required to be waterproof or chemically resistant.

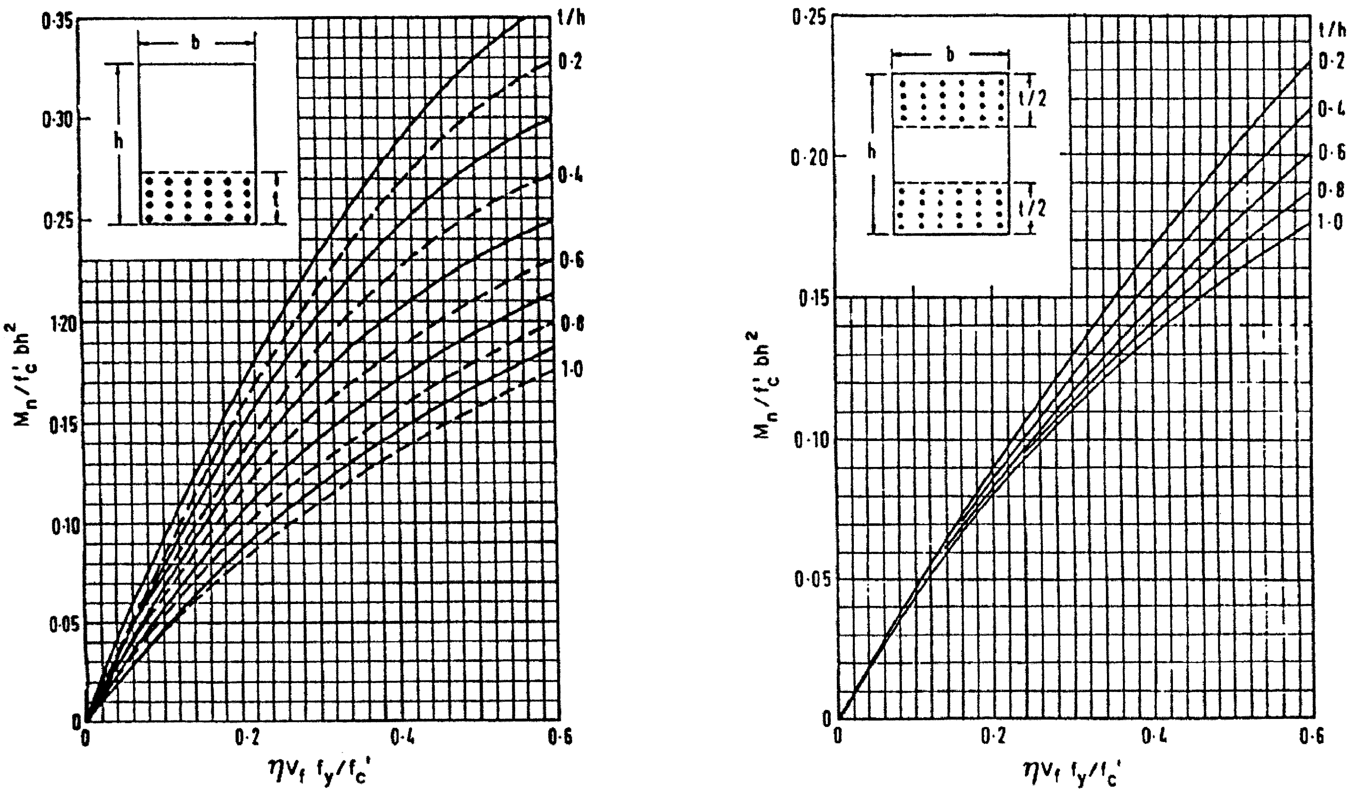
Freeze-thaw deterioration is most effectively prevented by proper air entrainment (about 10 to 13 percent of the mortar volume[78]), a fact that is well established for concrete and applies equally to ferrocement. Maintenance of low water-cement ratio, less than 0.45, is also recommended for freeze-thaw exposure (ACI 211.1). Unlike concrete, the freeze-thaw resistance of ferrocement has received little study.

Resistance to abrasion is governed primarily by the compressive strength of the matrix,[79] which in turn is largely dependent on the water-cement ratio. Once again, the importance of a lower water-cement ratio is apparent. However, the characteristics of the sand may also be significant, a high silica content generally leading to better abrasion resistance. A decrease in aggregate size also has an adverse effect on abrasion resistance, and the amount of material passing the No. 50 sieve should be kept as low as possible.[79]

4.9.2 *Deterioration associated with reinforcement*—Such deterioration can arise whether the matrix is cracked or uncracked.

When the matrix is uncracked, in galvanized forms of reinforcement the zinc coating can be attacked by the alkalies in the fresh cement paste, leading to the formation of calcium zincate and hydrogen. An effective means of inhibiting the formation of hydrogen is to add 100 to 300 ppm of chromium trioxide to the mixing water.[31,32] Once the mortar sets, the hydrogen evolution ceases; the coating of calcium zincate formed apparently provides a protection to the reinforcement and no further attack takes place.[80] A potentially more serious difficulty is the galvanic corrosion that can take place when galvanized steel (mesh) and ordinary steel (skeletal bars) are in contact via the electrolytic solution present in mortar. Zinc is anodic to the steel. The formation of zincate leads to an increase in solid volume which may cause blistering, reduce bond, and weaken the ferrocement structurally.

When the matrix becomes cracked, deterioration occurs more rapidly since access for air and water or corrosive liquids to the steel becomes easier. Galvanizing, when present, combats this problem. Note, however, that galvanizing is a sacrificial system and is beneficial only until the zinc is consumed in the galvanic cell. In its absence the width of cracks and their continuity may affect corrosion resistance. Reference to maximum design crack widths based on service conditions is made in Sections 4.7 and 5.8.



Singly reinforced ferrocement

Symmetrically reinforced ferrocement section

Fig. 5.1—Design charts for ferrocement (Ref. 82).

4.10—Fire resistance

Regardless of whether the matrix is cracked or not, a problem unique to ferrocement is its potentially poor fire resistance because of the inherent thinness of its structural forms and the abnormally low cover to the reinforcement. There is limited information in the literature on fire tests performed on ferrocement.[81]

CHAPTER 5—PERFORMANCE CRITERIA

5.1—Introduction

Any design-related recommendation for ferrocement structures should depend on the type of application and should be based on a rational analysis supported by test results. However, in view of the present state of knowledge of ferrocement, and except for special applications where an accurate analysis may be needed to assure safe performance, the committee believes that the following guidelines for ferrocement made with plain mortar and square meshes will lead to satisfactory performance. These guidelines have been derived from the analysis of numerous test data, from recommendations made by practicing engineers, and from some specifications used for building ferrocement boats (ACI 318, ACI 350R, Ref. 37-39, 41, 45, 46, 49, 53, 56, 63, 64, 72, and 82-89).

5.2—Design methods

To predict the behavior of ferrocement under service load conditions, an elastic analysis similar to that of the working stress design method for reinforced concrete is acceptable, provided that the modulus of the steel mesh system (which may be different from the modulus of the steel wire as described in Section 5.3) is considered. In case of shear, the diagonal cracking strength may be estimated by using the equations proposed in Ref. 56.

The strength of flexural members can be predicted by analyzing ferrocement as a reinforced concrete member using the ACI Building Code (ACI 318). As ferrocement has several layers of mesh reinforcement, an analysis similar to that of beams in pure bending is suggested.[45] Alternatively, a rigid-plastic analysis as proposed in Ref. 49 may be used, and design charts similar to those available for conventional reinforced concrete may be developed. Fig. 5.1 presents two such curves taken from Ref. 82. A simplified non-dimensional expression for ultimate strength design of ferrocement is given in ACI 549.1R. For tensile members, the ultimate load can be approximated by the load-carrying capacity of the mesh reinforcement alone in the direction of loading.[38,39]

5.3—Definitions

Two important reinforcing parameters are commonly used in characterizing ferrocement and are defined as:

V_t = volume fraction of reinforcement. It is the total volume of reinforcement per unit volume of ferrocement. For a ferrocement reinforced with square meshes, V_t is equally divided into V_{tl} and V_{tT} for the longitudinal and transverse directions, respectively

S_r = specific surface of the reinforcement. It is the total bonded area of reinforcement (interface area) per unit volume of composite. For a ferrocement using square meshes, S_r is divided into S_{r1} and S_{rT} in the longitudinal and transverse direction, respectively. The relation between S_r and V_t, when wire meshes are used, is:

$$S_r = \frac{4V_t}{d_b} \tag{5.1}$$

where d_b is the diameter of the wire.

Although the definitions of most of the properties of the components of ferrocement are the same as for reinforced concrete, one property defined here as the effective modulus, E_r, of the reinforcing system, needs some clarification. This is because the modulus of a mesh (steel or other) is not necessarily the same as the elastic modulus of the filament (wire or other) from which it is made. In a woven steel mesh, the weaving imparts to the wires an undulating profile. When tested in tension, the woven mesh made from these wires will stretch more than a similar welded mesh made from straight wires (everything else being the same). Hence, the woven mesh behaves as if it had an elastic modulus smaller than that of the steel wires from which it is made. In addition, when a woven mesh is embedded in a mortar matrix and tends to straighten under tension, the presence of the matrix resists such straightening. To account for the above effects, the term "effective modulus of the reinforcing system" E_r is used. For welded steel meshes, E_r may be taken equal to the elastic modulus of the steel wires; for other meshes, E_r may be determined from tensile tests on the ferrocement.

5.4—Allowable tensile stress

The allowable tensile stress in the steel reinforcement may be generally taken as $0.60f_y$, where f_y is the yield strength measured at 0.0035 strain or obtained by using the procedure described in ACI 549.1R. However, for liquid restaining and sanitary structures it is preferable to limit the tensile stress to 30 ksi (207 MPa) unless crack width measurements on a test model indicate that a higher stress will not impair performance.[85] The above values are appropriate provided the weaving pitch of the mesh system is moderate, approximately 3 in. (75 mm), in order to insure an adequate effective modulus.[85]

5.5—Allowable compressive stress

The allowable compressive stress in ferrocement may be taken as $0.45\ f_c'$ where f_c' is the specified compressive strength of the mortar measured from tests on 3 x 6 in. (76 x 152 mm) cylinders.

5.6—Volume fraction and specific surface of reinforcement

The total volume fraction of reinforcement V_t in each direction should not be less than 1.8 percent. The total specific surface of reinforcement, S_r, in both directions, should not be less than 2 in.^{2}/in.^{3} (0.08 mm^2/mm^3). About twice these values are recommended for water-retaining structures. In computing the specific surface of the reinforcement, any skeletal steel may be disregarded, but it should be considered in computing V_t.

It is tentatively recommended that for a given ferrocement material (without skeletal reinforcement) of thickness h the recommended spacings of transverse wires s should not be larger than h. Furthermore, the number of layers of mesh, n, should preferably be such that:

$$\begin{aligned} &n \geq 4h && \text{where } n \text{ is in inches} \\ &n \geq 0.16h && \text{where } h \text{ is in mm} \end{aligned} \tag{5.2}$$

If skeletal reinforcement is used, it is recommended that the skeletal reinforcement not occupy more than 50 percent of the thickness of the ferrocement material. If h' is the thickness in which the meshes are distributed, the number of layers of mesh should preferably be such that:

$$\begin{aligned} &n \geq 4h' && \text{where } n' \text{ is in inches} \\ &n \geq 0.16h' && \text{where } h' \text{ is in mm} \end{aligned} \tag{5.3}$$

5.7—Cover requirements

The recommended average net cover of the reinforcement is about $^1/_{12}$ in. (2 mm). However, a lesser value can be used provided the reinforcement is galvanized, the surface protected by an appropriate coating, and the crack width limited (see Section 5.8). It is also recommended that for thicknesses greater than 1/2 in. (12 mm), the net cover should not exceed 1/5 of the thickness h or 3/16 in. (5 mm), whichever is smaller, in order to insure proper distribution of the mesh throughout the thickness.

5.8—Crack width limitations

It is recommended that the maximum predicted value of crack width be less than 0.004 in. (0.10 mm) for noncorrosive environment and 0.002 in. (0.05 mm) for corrosive environments or water-retaining structures. The maximum crack width in tension and flexural members for square mesh reinforcement can be predicted by using the approaches described in Ref. 87 and 41, respectively.

5.9—Stress range

For ferrocement structures to sustain a minimum fatigue life of two million cycles, the stress-range in the steel should be limited to f_{sr} = 30 ksi (207 MPa). A value of f_{sr} = 36 ksi (248 MPa) can be used for one million cycles and 55 ksi (380 MPa) for 100,000 cycles.[69,88]

5.10—Durability

1. Ferrocement liable to be subject to freezing and thawing while moist should contain about 10 percent entrained air.
2. Only protective coatings proven by test or past performance should be used.
3. Admixtures should be free from chlorides or other materials found to promote steel corrosion. Common lignosulfo-

nate water-reducing admixtures assist in protection of steel and in reducing permeability of the ferrocement.

4. In designing ferrocement for corrosive environments, consideration should be given to: (a) the use of galvanized reinforcement; (b) steps to minimize water content; (c) use of chemical and mineral admixtures to reduce permeability; and (d) use of proven appropriate coatings.

CHAPTER 6—APPLICATIONS OF FERROCEMENT

6.1—Introduction

The concept of ferrocement, of reinforcing cement mortar by closely spaced layers of fine wire mesh, was originally conceived one and a half centuries ago by Lambot for boat building. The use of this material was subsequently promoted for civil engineering structures by Nervi one century later in the 1940s. Ferrocement material has since been extensively studied and the basic technical information on various aspects of design, construction, and application is now available.

Despite the evidence that ferrocement was an adequate and economical building material, it gained wide acceptance only in the early 1960s.[90-121] There has been widespread use of ferrocement throughout the world in such countries as Canada, United States, Australia, New Zealand, United Kingdom, Mexico, Brazil, the former USSR, Eastern European countries, China, Thailand, India, Indonesia, and in other developing countries.

Ferrocement construction in the early 1970s was labor intensive and particularly suitable for rural applications in developing countries. This does not require heavy plant or machinery and, being a low-level technology, the construction skills can be acquired fairly quickly. Accordingly, considerable research effort has been directed in developing low-cost rural applications compatible with local traditions. In urban areas the potential application of ferrocement must be viewed from a different perspective. To alleviate the acute shortage and high cost of skilled labor, more so in developed countries, mechanized methods must be used to expedite the speed of construction.

Since the ferrocement has very high tensile strength-to-weight ratio and superior cracking behavior, it is ideally suited for thin-walled structures such as boats and water retaining structures. The possible areas of applications of ferrocement and their performance are highlighted in this chapter.

6.2—Boats

Ferrocement boats have been built in almost every country of the world. Some idea of the extent of ferrocement boat construction is given in Ref. 91, which lists boat construction in the countries of the Asian-Pacific region. The People's Republic of China is the only country in which ferrocement boats have been introduced on a large scale. In other countries, ferrocement occupies a fraction of a percent of the total boat-building market.

Ferrocement boat construction has been found attractive for many industrially developing countries because: (a) its basic raw materials are available in most countries; (b) it can be fabricated into almost any shape and traditional design can be reproduced or improved; (c) it is more durable than most woods and more economical than imported steel; (d) ferrocement construction skills can be acquired easily; (e) ferrocement construction is less capital-intensive and more labor-intensive; and (f) except for sophisticated and highly stressed designs such as those in deep-water vessels, a trained supervisor can achieve the requisite amount of quality control using fairly unskilled labor.

Ferrocement is a relatively heavy material compared to wood and fiber-reinforced plastic. Most wooden boats below 33 ft (10 m) length are built with a plank thickness of 1 in. (25 mm). To obtain the same hull weight, ferrocement would have to be only 0.3 in. (8 mm) thick. Although small ferrocement boats have been built of this thickness, the corresponding impact resistance is not sufficient for work boats used in fishing or transport. At its present stage of development, ferrocement has proved most suitable for boats above 33 ft (10 m). Even for this larger size, a ferrocement boat will be heavier than a wooden boat, but this is of little disadvantage at moderate speed (between 6.5 and 10 knots).[53]

The boats built in China appear to combine all the favorable characteristics of ferrocement construction. Ferrocement ships have been built to lengths of 325 ft (99 m). A photograph of a 500-passenger vessel is shown in Fig. 1 of Ref. 18. Thousands of smaller boats are built annually in boat yards all over China, using mass production techniques such as precast ferrocement bulkheads and frames that shape the boat and become an integral part of the final structure.[17] These ferrocement sampans are designed for smooth-water use on rivers and canals, and so do not require as stringent design specifications as deep-water vessels.

6.2.1 *Service evaluation of ferrocement boats*—Ferrocement boats have been in service in large numbers only in the last few years. Many of these boats were not built according to any well-defined specifications. Very few systematic efforts have been made to record failures and maintenance problems. Thus, it is difficult to rationally and unequivocally comment on the performance of ferrocement boats. Nonetheless, attempts have been made to assess the conditions of some existing ferrocement vessels.[90-92] Ferrocement fishing boats built in New Zealand have been surveyed by the New Zealand Marine Department. Results of that survey are reported in Ref. 90. Experience with 300 commercially built craft in more than 20 countries has been analyzed in Ref. 91. Sutherland describes his personal experience with about 80 boats that have been in service up to about 10 years.[92] From these reports, it is evident that ferrocement can be utilized very satisfactorily for boat building. However, the following problem areas are worth noting:

Mortar application and penetration seems to be the greatest problem in ferrocement boat construction. Many defects and failures can be attributed to improper plastering. On several occasions, damage to the hull revealed serious corrosion of steel due to the presence of voids; no corrosion of steel was found in dense mortar.

5. The lack of resistance to impact and punching appears to be the most common cause of damage of ferrocement vessels. Although the repair of the damaged area is not

complicated, the frequency and the nuisance of repairing the damage have been reported to reduce the enthusiasm for ferrocement boats among many fishermen.

6. Paint failures seem to be frequent and no single paint formula appears to give consistently long-term satisfactory results.[92]

6.3—Silos

Farms and villages in most developing countries have inadequate storage facilities for grain. It has been reported that up to 25 percent of rice is lost to birds, fungi, rodents, and insects in Thailand.[93] Ferrocement silos for storing up to 30 tons of grain appear quite suitable and economical for developing countries. Ferrocement offers low permeability and with appropriate sealants can be made airtight. In an airtight ferrocement bin, micro-organisms cannot survive to damage the stored product.[93]

The Applied Scientific Research Corporation of Thailand (Bangkhen, Bangkok-9) has developed a family of economical, airtight ferrocement silos that can hold up to 10 metric tons of grain and other foodstuffs, fertilizer, cement, pesticide, or up to 5000 gal (18.9 m^3) of drinking water. The base of the silo is saucer-shaped and consists of two layers of 2 in. (50 mm) thick, mesh-reinforced concrete with an asphalt seal between the layers. These silos are conical in shape. The curved walls slope inwards to a central entrance hatch at the top which eliminates the need for a roof structure.

In Ethiopia, underground pits are the traditional method of grain storage. It has been found that when the traditional pit is lined with ferrocement and provided with an improved airtight lid, a hermetic storage chamber with desirable resistance to moisture penetration can be achieved.[94]

Small capacity ferrocement bins (up to 3 metric tons) have been developed, analyzed, and tested in India.[95] The units are cylindrical in shape, 3.9 ft (1.20 m) in diameter and are prefabricated in heights of 3 ft (1.0 m). The bins were tested with wheat in a laboratory to ascertain the ability of ferrocement to carry the bin wall load. They were also tested in the field to judge their effectiveness against insects. A cost analysis of ferrocement bins showed them to be less expensive than steel, reinforced concrete, or aluminium bins.

6.4—Tanks

The preceding remarks regarding the need in developing countries for grain storage apply equally to the storage of drinking water. Thus, the use of ferrocement is also being explored in developing countries for water tanks.[96,97] Funded by the International Development Research Centre of Canada, two prototype cylindrical water tanks for the collection of rainwater (Fig. 6.1) were designed, constructed, and tested for use in the rural areas of the Philippines.[98] Several hundred ferrocement tanks, which have been in use for the past several years, have been built on a self-help basis in many provinces in the Philippines. In Bangladesh, an elevated ferrocement water tank of 12,500 gal (46 m^3) capacity was successfully constructed in 1989.[99] It incorporates some unique design features, compatible with the local conditions, that not only simplified the construction process but also resulted in substantial economy.

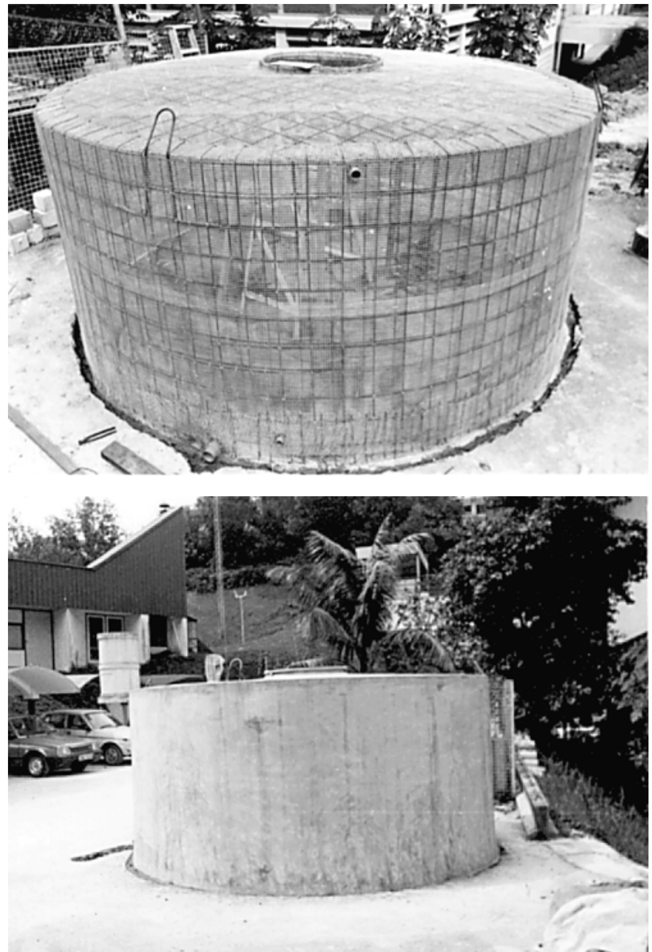


Fig. 6.1—Ferrocement tanks for rain water collection (Ref. 98).

Ferrocement tanks are an attractive alternative material for the storage of water in the industrially developed countries as well. Small ferrocement tanks of less than 5000 gal capacity (18.3 m^3) are being factory-built in New Zealand.[100] A recent feasibility study found ferrocement tanks to be less expensive than steel or fiberglass tanks. For the storage of water heated by solar energy, tanks of approximate total capacity of 160,000 gal (605 m^3) were required for a proposed design of a new physical science education center for the Science Museum of Virginia, in Richmond. A feasibility study was conducted to determine if there were any advantages to using ferrocement rather than steel or fiberglass for the construction of these tanks. The results of this feasibility study, including the detailed design, methods of construction, and drawings for the ferrocement tanks are given in the final report submitted by the Science Museum of Virginia to the U. S. Energy, Research and Development Administration.[6,84] The following conclusions are based on the study:

7. Ferrocement is an economically feasible material for the construction of water storage tanks for storing energy collected by a solar system.
8. Flexibility of shape, freedom from corrosion, possibility of hot storage, relative lack of maintenance, and ductile

Fig 6.2—Ferrocement flume (Ref. 100).

mode of failure are important advantages of ferrocement over other materials commonly used for low to medium pressure [up to 50 psi (345 kPa)] storage of fluids.

9. Ferrocement tanks require less energy to produce than steel tanks.

A large rectangular ferrocement flume 115 ft (35 m) long, 6.6 ft (2 m) wide, and 4.3 ft (1.3 m) high has been built in the hydraulic engineering laboratory at the National University of Singapore (Fig. 6.2) to conduct model tests under wave action.[101] The concept of precast ferrocement panel with in-situ joints was used.

6.5—Roofs

In industrially developing countries, there is an urgent need for identifying materials that are economical for building roofs of single family dwellings. It is possible to build walls and floors of a dwelling using local materials. However, past attempts to manufacture (from local materials) roofs which are economical, durable, and resistant to fire, insects, flood, and earthquakes have not been very successful. As a result, many developing countries import galvanized iron sheets or use asbestos cement sheets. These two roofing materials may cost as much as 60 percent of the total cost of a house.[17] Ferrocement appears to be an economical alternative material for roofing.[100] The previously described advantages of ferrocement for boats apply equally well to roofs. Ferrocement roofing materials can be factory mass-produced in prefabricated form, a process best suited to the concentrated demands of the urban area, or it can also be fabricated in situ in villages.

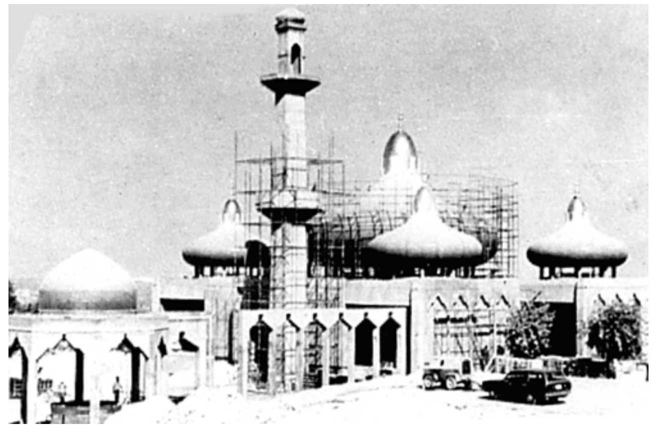


Fig. 6.3—Ferrocement domes (Ref. 109).

Fig. 6.4—Ferrocement secondary roof slabs (Ref. 1).

The success of ferrocement for self-help housing is well documented in Ref. 89 and 102, in which construction of hundreds of ferrocement roofs for poorer areas of Mexico is described. Many of these ferrocement roofs were dome shaped with a span of 10 to 20 ft (3 to 6 m). The domes were shaped by reinforcing rods that were tied to the masonry walls. The construction of the roofs requires no mechanical equipment.

Large ferrocement roofs have been constructed in Italy. A recent design and construction of six ferrocement shells for a roof to shelter animals is described in Ref. 104. The roofs have a span of 56 ft (17 m) and a thickness of 1.2 in. (30 mm). The performance of other geometrical shapes for use as roofs has also been investigated at the National University of Singapore.[105-107] Note that since the stresses produced by dead load are critical in the design of roofs, thin ferrocement shells should be economical for roof structures. The use of ferrocement as roofing for large span structures has been successfully used in many European and South American countries.[108] Domes were constructed in Jordan using 1-in. (25 mm) thick ferrocement with internal ribs[109] (Fig. 6.3).

Corrugated ferrocement sheets have been developed and tested by the Building Research Institute, State Engineering Corporation, Colombo, Sri Lanka. These sheets are developed

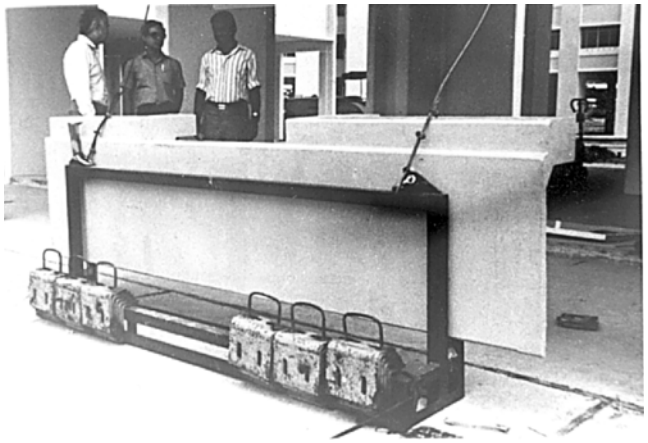


Fig. 6.5—Ferrocement sun shades (Ref. 1)

as a replacement for asbestos cement corrugated sheets which are widely used as a roofing material. It has been reported that ferrocement sheets are less expensive and require less capital investment and foreign exchange. These ferrocement sheets are designed so that their weight, dimensions, and load-carrying capacities are similar to the widely used asbestos cement sheets. In addition, it has been observed that ferrocement sheets are more ductile than asbestos cement sheets.[110] Thus, since the supply of asbestos fibers is limited and since they are carcinogenic, ferrocement may be a very suitable replacement.

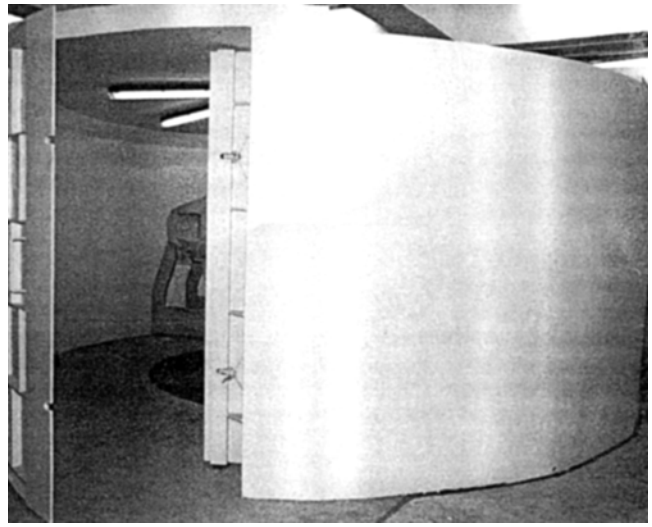


Fig. 6.6—Ferrocement enclosure for centrifuge (Ref. 114).

Ferrocement is also an attractive material for secondary roofing that is necessary to provide heat insulation in high-rise buildings.[1] After a detailed investigation at the National University of Singapore, the building authority is convinced of the improved performance of ferrocement. As a result there has been a large scale replacement of traditional light-weight concrete units by ferrocement slabs (Fig. 6.4).

6.6—Miscellaneous applications

In addition to the applications briefly mentioned here, many other uses of ferrocement as a structural material are being explored throughout the world. These include: sunscreens[111,112] (Fig. 6.5) and sandwich wall panels[113] for highrise buildings, permanent forms for conventional concrete construction,[4] biogas digesters, floor decks, swimming pools, water towers, small deck bridges and culverts,[104,114] ferrocement enclosure for geotechnical centrifuge[115] (Fig. 6.6) and ferrocement overlay for concrete pavement resurfacing.[116] Recently ferrocement has been used in repair works.[117,118]

6.7—Summary

The widespread use of ferrocement has begun only in the past two decades. Although adequate design information and field experience have been acquired for many types of ferrocement structures, the future extent of ferrocement construction will depend mainly on economic considerations.

Whether ferrocement can economically compete with other alternative materials depends on the type of application and the country of application. It is not possible to make any general conclusion regarding the economic viability of ferrocement construction since its cost can vary significantly from country to country. The cost will depend on the method of fabrication (for example shotcrete versus hand plastering) and many other economic parameters.

For industrially developing countries where the cost of materials is relatively higher than the cost of labor, some applications of ferrocement can be cost competitive through mechanized production and proper choice of reinforcement. Another factor frequently held responsible for its slow growth is the lack of design codes and specifications, without which building authorities are reluctant to accept a new material.

CHAPTER 7—RESEARCH NEEDS

7.1—Introduction

The paradox associated with ferrocement is that it is both the oldest and newest form of reinforced concrete and, therefore, research needs comprise those common to conventional reinforced concrete and those peculiar to ferrocement.

7.2—Scope of research needs[119-121]

The most desirable characteristics of ferrocement are related to the distribution and subdivision of the reinforcement throughout the mortar. But at what point in the subdivision is ferrocement just another form of reinforced concrete? There have been attempts to set lower limits on the specific surface or volume fraction of reinforcement that would establish the boundary between ferrocement and reinforced concrete. But such efforts could be misleading since the characteristics of ferrocement are a continuous function of the degree of subdivision of the reinforcement. The issue becomes even more complex when one recognizes that the reinforcement can take the form of reinforcing bars or strands used in combination with mesh of relatively small diameter elements. Moreover, since the definition of an allowable service stress could be related to an allowable crack width which depends on the degree of dispersion of the reinforcement, the dilemma arises of having design stresses related to the manner in which the reinforcement is dispersed. No doubt, allowable stresses will also be related to the type of application (tanks, roof elements, wall panels, etc.) and the type of reinforcement (ductile or high strength).

The above discussion emphasizes the fact that the principal research needs in ferrocement will continue to be in the area of understanding the fundamental mechanism whereby the reinforcement and matrix interact to distribute strains, improve first-crack strength, and control the size and spacing of cracks.

7.3—Specific research needs

Although there is a very extensive range of possible research activities, a few special areas will be mentioned that appear important for the full development of ferrocement. These relate to impact resistance, fatigue strength, corrosion, compressive strength with various types of meshes, and strength under multiaxial loading conditions.

Test data on in-plane shear strength is scant. The in-plane shear is important when ferrocement is used as wall panels or partitions in structures subjected to "racking" or in-plane shear forces due to wind and earthquake loads.

Test data for combined load conditions such as in-plane shear and flexure,[12] tension, and compression are needed. An example is the use of ferrocement for folded plate roof elements in long span lightweight construction where in-plane shear and bending stresses are important.

In ferrocement construction, connections are sometimes unavoidable. So far, one study has reported tests on in-situ connections.[123] Further investigations are needed to study connections between precast elements to broaden the scope of ferrocement application. Research on long term behavior[74,124,125] and durability[125-127] are limited.

Tests on the fire resistance of ferrocement are limited at present. The cover requirements for reinforced concrete to achieve minimum fire ratings cannot be applied to ferrocement. This often hinders its use by architects and engineers who must, when appropriate, secure a related exemption from the building official.

Performance criteria such as those proposed in Chapter 5 for rectangular mesh must be developed for other types of wire mesh reinforcement.

The performance of ferrocement is greatly dependent on the characteristics of the reinforcing mesh. There is 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. New mesh systems and assemblies may be specifically designed for ferrocement applications. It is very likely that new developments in the mesh system will render ferrocement competitive in all applications where thin elements are used.

Durable and long-term effective sealants are needed for ferrocement, especially in marine applications, to prevent penetration of water and salts that could lead to corrosion of the reinforcing mesh.[100] Although several methods, such as laminating techniques, are available to ensure void or cavity-free ferrocement, further work is needed to cover different site and construction requirements. Also needed is the development of suitable methods to detect voids, and economical means of repairing the voids.[120]

With the availability of ACI's "Guide for the Design, Construction and Repair of Ferrocement (549.1R)" and the recent development of a number of efficient and economical fabrication procedures like 'Vibro-pressing' and 'laminating techniques,' the need now is to make designers and contractors aware of ferrocement's potential.

Further investigations are needed to study the composite behavior of ferrocement and reinforced concrete (or other structural materials) type of elements. An example of such an application would be composite bridge decks. In particular, how ferrocement and R/C composite construction would enhance fatigue, flexural as well as first cracking strength.

Studies of connections of ferrocement and non-ferrocement elements (i.e., R/C, metallic plates, etc.) are also needed.

7.4—Summary

The future of ferrocement will depend as much upon design creativity as it will depend upon long and laborious research efforts. It is important to recognize that ferrocement, like other fiber reinforced concrete, enables design for a range of tensile stresses and strains in the composite far beyond the ranges previously permitted. This feature, combined with the absence of a thick cover requirement over the reinforcement, provides great flexibility in designing roofs, walls, liquid containers, and precast architectural forms that could provide factory-finish surfaces for members that are cast in the field.

CHAPTER 8—REFERENCES

8.1—Specified and/or recommended references

The documents of the various standards-producing organizations referred to in this document are listed below with their serial designation. The documents listed were the latest effort at the time this document was written (revised). Since some of these documents are revised frequently, generally in minor detail only, the user of this document should check directly with the sponsoring group if it is desired to refer to the latest revision.

American Association of State Highway and Transportation Officials (AASHTO)

T 259 Resistance of Concrete to Chloride Ion Penetration
T 260 Sampling and Testing for Total Chloride Ion in Concrete and Concrete Raw Materials

American Concrete Institute (ACI)

201.2R Guide to Durable Concrete
211.1 Standard Practice for Selecting Proportions for Normal, Heavy-Weight, and Mass Concrete
318 Building Code Requirements for Structural Concrete
350R Concrete Sanitary Engineering Structures
515.1R A Guide to the Use of Water-Proofing, Dampproofing, Protective, and Decorative Barrier Systems for Concrete
544.1R Report on Fiber Reinforced Concrete
549.1R Guide for the Design, Construction and Repair of Ferrocement

ASTM International

C 150 Standard Specification for Portland Cement
C 666 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C 672 Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals

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This report was submitted to letter ballot of the committee and was approved in accordance with ACI balloting requirements.