Design Guide for Ferrocement

Reported by ACI Committee 549

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This guide provides technical information on physical and mechanical properties, design criteria, and testing of ferrocement. The objectives are to promote the most effective use of ferrocement in terrestrial structures, provide architects and engineers with the necessary tools to specify and use ferrocement, and provide owners or their representatives with a reference document to check the acceptability of a ferrocement alternative in a given application.

Keywords: composite materials; construction materials; ferrocement; fibers; reinforcing materials; structural design; welded wire fabric.

CONTENTS

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CHAPTER 1—GENERAL

1.1—Scope

This guide is based on technical information assembled from current practice, developments, and advances in the field of ferrocement around the world. It represents a practical supplement to ACI 549R. This guide covers physical and mechanical properties, performance and design criteria, and testing.

The objectives of this guide, in conjunction with ACI 549R, are to promote the effective use of ferrocement in structures, provide architects and engineers with the necessary tools to specify and use ferrocement, and provide owners or their representatives with a reference document to check the acceptability of a ferrocement alternative in a given application. This guide is consistent with ACI 318, except for the special characteristics of ferrocement, such as reinforcement cover and limits on deflection.

Ferrocement is a form of reinforced concrete using closely spaced multiple layers of mesh, small-diameter rods completely infiltrated with mortar, or encapsulated in mortar, or both. The most common type of reinforcement is steel mesh. Other materials such as selected organic, natural, or synthetic fibers may be combined with metallic mesh. This guide addresses only the use of steel reinforcement in a hydraulic cement mortar matrix.

Applications of ferrocement are numerous, especially in structures or structural components where self-help or low levels of skills are required. Besides boats and marine structures, ferrocement is also used for housing units, water tanks, grain silos, flat or corrugated roofing sheets, and irrigation channels (ACI 549R).

1.2—Approval for use in design and construction

Use of ferrocement and the procedures covered in this guide may require approval by the authority or governmental agency having jurisdiction over the project.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_c = cross-sectional area of ferrocement composite
A_s = total effective cross-sectional area of reinforcement in the direction considered
A_s = $\sum_{i=1}^{N} A_{si} A_s = \sum_{i=1}^{N} A_{si}$
A_{si} = effective cross-sectional area of reinforcement of mesh layer i in the direction considered
b = width of ferrocement section
c = distance from extreme compression fiber to neutral axis
d'' = clear cover of mortar over first layer of mesh
d_b = diameter or equivalent diameter of reinforcement used
d_i = distance from extreme compression fiber to centroid of reinforcing layer i
E_c = elastic modulus of mortar matrix
E_{cr} = elastic modulus of cracked ferrocement in tension (slope of the stress-strain curve in the cracked elastic state)
E_r = effective modulus of the reinforcing system
E_s = elastic modulus of steel reinforcement
f_c' = specified compressive strength of mortar
f_{si} = stress in reinforcing layer i
f_{su} = strength of mesh reinforcement or reinforcing bars
f_y = yield strength of mesh reinforcement or reinforcing bars
h = thickness of ferrocement section
M_n = nominal moment strength
N = number of layers of mesh; nominal resistance
N_n = nominal tensile strength
n_r = modular ratio of reinforcement
S_r = specific surface of reinforcement
S_{rl} = specific surface of reinforcement in the longitudinal direction
S_{rt} = specific surface of reinforcement in the transverse direction
s = mesh opening or size
V_f = volume fraction of reinforcement
V_{fi} = volume fraction of reinforcement for mesh layer i
V_{fl} = volume fraction of reinforcement in the longitudinal direction
V_{ft} = volume fraction of reinforcement in the transverse direction
β_1 = factor defining depth of rectangular stress block
η = global efficiency factor of embedded reinforcement in resisting tension or tensile bending loads
η_l = value of η when the load or stress is applied along the longitudinal direction of the mesh system or rod reinforcement
η_t = value of η when the load or stress is applied along the transverse direction of the mesh reinforcement system or rod reinforcement
η_θ = value of η when the load or stress is applied along a direction forming an angle θ with the longitudinal direction

ε_{ci} = strain of mesh reinforcement at layer i

ε_{cu} = ultimate compressive strain of mortar (generally assumed to be 0.003)

ε_y = nominal yield strain of mesh reinforcement = f_y/E_r

Σ_o = total surface area of bonded reinforcement per unit length

σ_{cu} = stress in ferrocement composite at ultimate strength in tension

σ_{cy} = stress in ferrocement composite at yielding of the reinforcement

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, ACI Concrete Terminology. Definitions provided here complement that resource.

longitudinal direction—roll direction (longer direction) of the mesh as produced in plant.

skeletal reinforcement—framework of widely spaced tied steel bars that provides shape and support for layers of mesh or fabric attached to either side.

transverse direction—direction of mesh normal to its longitudinal direction; also, width direction of mesh as produced in plant.

CHAPTER 3—PHYSICAL AND MECHANICAL PROPERTIES

3.1—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 (1956), "Ferrocement's 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 (5.3, 5.6). Limiting values of these parameters are found in IFS 10-01. Unfortunately, despite the generality of the definition of ferrocement, 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.

3.2—Reinforcing parameters

Three parameters are commonly used in characterizing the reinforcement in ferrocement applications: the volume fraction, the specific surface of reinforcement, and the effective modulus of the reinforcement.

3.2.1 *Volume fraction of reinforcement,* V_f—V_f is the total volume of reinforcement divided by the volume of composite (reinforcement and matrix). For a composite reinforced with meshes with square openings, and equal size wires in each direction, V_f is equally divided into V_{fl} and V_{ft} for the longitudinal and transverse directions, respectively. For other types of reinforcement, such as expanded metal, V_{fl} and V_{ft} may be unequal. Examples of computation of V_f are shown in Appendix A.

3.2.2 *Specific surface of reinforcement* S_r—S_r is the total bonded area of reinforcement (interface area or area of the steel that comes in contact with the mortar) divided by the volume of composite. S_r is not to be confused with the surface area of reinforcement divided by the volume of reinforcement. For a composite using square meshes and equal size wires in each direction, S_r is divided equally into S_{rl} and S_{rt} in the longitudinal and transverse directions, respectively.

For a ferrocement plate of width b and depth h, the specific surface of reinforcement can be computed from

$$S_r = \frac{\Sigma_o}{bh} \tag{3.2.2}$$

where Σ_o is the total surface area of bonded reinforcement per unit length.

3.2.3 *Relation between* S_r *and* V_f—The relation between S_r and V_f when square-grid wire meshes of equal diameter are used is

$$S_r = \frac{4V_f}{d_b} \tag{3.2.3}$$

where d_b is the diameter of the wire. For other types of reinforcement, such as expanded metal, S_{rl} and S_{rt} may be unequal.

3.2.4 *Effective modulus of the reinforcement*—Although the definitions of most ferrocement properties are the same as for reinforced concrete, one property that may be different is the effective modulus of the reinforcing system, E_r. This is because the elastic 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, weaving imparts an undulating profile to the wires. When tested in tension, the woven mesh made from these wires stretches more than a similar welded mesh made from identical straight wires. Hence, the woven mesh behaves as if it has a lower elastic modulus 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 matrix resists the straightening, leading to a form of tension stiffening. A similar behavior occurs with expanded metal mesh (lath) and hexagonal mesh. To account for the aforementioned effects, the term "effective modulus of the reinforcing system" E_r is used. For welded steel meshes, E_r may