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FERROCEMENT AND POSSIBILITIES OF ITS
APPLICATION IN TURKEY

by

Nedim ÖZDEMİR

B.S. in C.E., Boğaziçi University, 1982

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Submitted to the Institute for Graduate Studies in
Science and Engineering in partial fulfillment of

the requirements for the degree of

Master of Science

in

Civil Engineering

Boğaziçi University

1985

ACKNOWLEDGEMENT

I am deeply indebted to my thesis supervisor Prof. Dr. Ferruh Kocataşkın who helped me throughout my study with advice, guidance and encouragement. It has been only through his fine cooperation and support that the investigations reported in this thesis were developed and realized.

It is my duty to express also appreciation for the permission of use of their laboratory facilities by the Technical University of Istanbul.

I would also like to thank the laboratory technician Mr. Mehmet Yazır for his generous help in the experimental works.

Warm thanks are expressed to Miss. Ayşe Üzen for typing the thesis.

FERROCEMENT AND POSSIBILITIES OF ITS APPLICATION IN TURKEY

Reports on Ferrocement indicate that this composite is gaining increased interest especially in developing countries. It is believed that there could be demand for it also in Turkey. Therefore a preliminary study was made to determine the possible ranges of quality and approximate cost using local reinforcing mesh material in ferrocement and reported in this thesis.

First a literature survey was made about covering its history, development, composition, production techniques and areas of application.

Secondly small size ferrocement specimens were prepared using local wire mesh materials (square woven mesh, chicken wire and expanded metal). These specimens were subjected to simple beam bending tests, charpy impact tests, and tensile strenght tests. Some specimens were also tested after heating to 800 C temperature to determine its after-fire properties. The effect of reinforcement parameters on machanical properties such as flexural rigidity, stress at first crack, ultimate strength in bending-impact and tensile strength have been evaluated. Results were in favor of square woven mesh in the longitudinal direction with four layers. They indicated an upper limit to the volume percentage. They showed that

a composite with considerably improved strength, ductility, toughness, and fire resistance could be obtained.

Thirdly full size ferrocement samples having a length of 100 cm, a width of 50 cm and a high of 2 cm, reinforced with four layers of square woven mesh in the longitudinal direction were prepared for studying their suitability to be used as a roofing material.

They were loaded in flexure on a free span of 80 cm, under four equal concentrated forces spaced at 16 cm from each other. Measurements of deflection, curvature, tensile and compressive strains, observation of crack number, crack width, and crack spacing, observation of creep deflections, and ultimate moment were made and their results were evaluated.

Finally all results were evaluated and some conclusions were reached.

Favorable results were obtained indicating the suitability of this type of ferrocement for roofing purposes under 2 types of loading. First is the dead load and snow. The second is the dead load and a concentrated force of 100 kg at center.

FERROSEMENT VE ONUN TÜRKİYEDE UYGULAMA OLANAKLARI

Ferrosement ile ilgili raporlar genel olarak bu malzemenin bil-
hassa gelişmekte olan ülkelerde gittikçe ilgi kazandığını göstermektedir.
Bu malzemenin Türkiye'de ilgi göreceğine inanılmaktadır. Bu incelemede
yerel donatı malzemeleri kullanarak onun uygun kullanma alanları belir-
lenmeye çalışılmıştır.

İlk önce bu konu ile ilgili, onun tarihçesi, gelişimi, bileşim-
leri, üretim teknikleri ve uygulama alanları hakkında bilgi sahibi olmak
için gerekli dökümanlar araştırılmıştır. Bundan sonra Karetel, sıva teli
ve kümes teli gibi yerel donatı malzemeleri kullanılarak küçük ferro-
sement numuneleri hazırlanmış ve basit giriş eğilme deneyleri, çarpma
deneyleri ve çekme deneyleri bu numuneler üzerinde yapılmıştır. Bazı nu-
muneler 800 °C ye kadar ısıtılmış ondan sonra teste tabi tutulmuş ve bu
malzemenin ateşe karşı dayanımı araştırılmaya çalışılmıştır. Donatı mal-
zemelerinin etkileri; eğilme rijitliği ilk çatlaktaki gerilmeler, maksimum
eğilme mukavemeti, çarpma ve çekme mukavemeti gibi özellikler değerklen-
dirilmiştir. Bu değerlendirmeler sonucunda boyuna doğrultuda 4 kat kare
tel kullanılarak hazırlanan ferrosement numunelerinin en olumlu sonuçları
verdiği gözlenmiştir. Bundan sonra boyuna doğrultuda 4 kat kare tel kulla-

nılarak daha büyük (bir metre boyunda, elli santimetre eninde ve iki santimetre yüksekliğinde) ferrosement nümuneler hazırlanarak bunların çatı levhası olarak kullanabilme imkanları araştırılmıştır. Mesnet noktaları arasındaki 80 cm.lik bölgede, birbirinden 16 cm uzaklıkta, 4 noktada eşit yükleme yapılmıştır. Deformasyon, dönme, çekme ve basınç birim uzamaları, çatlakların oluşumu ve genişlikleri, çatlak aralıkları ve sünme deformasyonları incelenerek artan yük altında değerleri okunmuş ve sonuçlar değerlendirilmiştir.

En son olarak bazı değerlendirme ve sonuçlara ulaşılmıştır. Bu çeşit ferrosement nümunelerinin çatı amaçlarına uygunluğunu gösteren sonuçlar, yapılan 2 yükleme durumu içinde olumludur. Bu yükleme durumlarından birincisi malzeme kendi ağırlığı ve kar yükü altındadır. İkincisinde ise kendi ağırlığı ve orta noktada 100 kg. ağırlık altındadır.

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LIST OF SYMBOLS

- A Cross-Section area of the ferrocement sample.
- B_1 Width of the small ferrocement specimen at casting.
- B_2 Width of the small ferrocement specimen after cutting.
- b Width of the test sample.
- d Wire diameter.
- E_{creep} Modulus of elasticity of ferrocement in the creep region.
- E_{el} Modulus of elasticity of ferrocement in the elastic region.
- $E I_{cr}$ Flexural rigidity of ferrocement at first crack.
- $E I_{cr1}$ Flexural rigidity of the ferrocement samples at first crack for curing at 18°C .
- $E I_{cr2}$ Flexural rigidity of the ferrocement samples at first crack, after heating at 800°C .
- $E I_u$ Flexural rigidity of ferrocement samples at ultimate load.
- $E I_{u1}$ Flexural rigidity of ferrocement samples at ultimate load, after curing at 18°C .

- $E I_{u2}$ Flexural rigidity of ferrocement samples at ultimate load after heating at 800 °C.
- $E I_{\theta}$ Flexural rigidity of the plain mortar.
- $E I_{yi}$ Flexural rigidity of ferrocement samples at a yield point.
- h Depth of test sample .
- L_1 Length of specimen at casting .
- L_2 Length of specimen after cutting .
- L Free span length of the test sample.
- S_f Specific surface of the reinforcing wire mesh in the ferrocement.
- W Failure energy of the ferrocement.
- U_g Charpy-impact strength of the ferrocement.
- U_{cr} Flexural energy of the ferrocement at first crack.
- U_{cr1} Flexural energy of the ferrocement at first crack after curing at 18°.
- U_{cr2} Flexural energy of the ferrocement at first crack, after heating at 800 °C.
- U_u Flexural energy of the ferrocement at ultimate load .
- U_{u1} Flexural energy of the ferrocement at ultimate load, after curing at 18 °C.
- U_{u2} Flexural energy of the ferrocement at ultimate load, after heating at 800 °C.

- U_0 Flexural energy of the plain mortar matrix.
- V_f Volume concentration of reinforcing wire mesh in the composite.
- w Crack width.
- θ Curvature.
- δ Midspan deflection of the simple beam specimen.
- η Creep ratio..
- E_{creep} Modulus of elasticity of ferrocement in the creep region.
- E_{el} Modulus of elasticity of ferrocement in the elastic region.
- σ_{cr} Flexural stress in the ferrocement at first crack.
- σ_{cr1} Flexural stress in the ferrocement at first crack, after curing at 18 °C.
- σ_{cr2} Flexural stress in the ferrocement at first crack, after heating at 800 °C.
- σ_u Flexural stress in the ferrocement at ultimate load.
- σ_{u1} Flexural stress in the ferrocement at ultimate load after curing at 18 °C.
- σ_{u2} Flexural stress in the ferrocement at ultimate load, after heating at 800 °C.
- σ_o Flexural strength of the plain mortar matrix.
- t_b Effective cover of outermost bar
- f_s steel stress

I. INTRODUCTION

A increasing number of publications dealing with the wire mesh reinforced cement mortar composite appeared in recent years and reported on the definition, history, development, composition, production techniques and areas of application of this so called "Ferrocement" material system. 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 like sandwich panels, construction of roofs, shells, silos, pipes, small water tanks and boats.

Although ferrocement construction has been developed during the last years in the world, the state of the application of this new construction material is still in infancy. For continuing application and comparison with other materials, engineering design properties of ferrocement are necessary. A review of investigations in the world indicate that most of the application are in developing countries where labor is inexpensive.

In spite of growing popularity of this material in other developing countries, In Turkey, a developing country with serious housing problems, earlier attempts were made only for producing ferrocement boats,

but application in building construction has not started yet. If ferrocement is better understood as an engineering material, wider use of this material may be possible in Turkey. The scope of this investigation is to determine some favorable properties of ferrocement made with the local reinforcement.

II. LITERATURE SURVEY

II.1 GENERAL KNOWLEDGE

A increasing number of publication dealing with the wire mesh reinforced cement mortar composite appeared in recent years and reported on the definition, history, development, composition, production techniques, physical and mechanical properties and Areas of application of this so called "Ferrocement" materials system.

II.1.1 Definition of Ferrocement

Ferrocement is a type of reinforced composite in which the matrix mortar and the reinforcement consists of layers of wire mesh. The layers of wire mesh are embedded in a portland cement mortar. Although ferrocement is a form of reinforced concrete, it is better to consider it as a composite material. Hence the basic concepts underlying the behavior and mechanics of composite materials should be applicable to ferrocement (1)*. The production of ferrocement can be divided into four phases.¹

- a - Fabrication the skeletal framing system,
- b- Application of the mesh to skeletal framing,
- c- Clastering of the mortar on to the mesh,
- d. Curing.

Experience has shown that the quality of mortar and its application to

* The numbers shown in paranthesis indicate reference numbers listed in References

the mesh are the critical phases. Since no formwork is required as in conventional reinforced concrete, ferrocement is especially suitable for structures with curved surfaces, such as shells, and free-form shapes.^(1,7)

In some instances, its use as a permanent form to a reinforced concrete structure can be economically justified. Although application of ferrocement is more efficient on such curved structures, in normal applications it is more economical to built 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 geodesic domes, wind tunnels, roof shells, tanks, sandwich panels, silos, swimming pools, boats.^(1,4,5,9)

It is believed that the development of new mesh reinforcing system and more efficient production techniques will make ferrocement competitive in a wide range of applications requiring thin structural elements. For such development and comparison with other materials, studies of engineering design properties of ferrocement are necessary.

II.1.2 History of Ferrocement

The concept of ferrocement was introduced in the nineteenth century by Lambot. He made a concrete rowing boat in which the reinforcement was in the form of a network of wires and interlaced thin rods.^(1,9) It was one of the first applications of ferrocement. But subsequent development differed from Lambot's concept. Instead of the mesh, larger rods (which are now called reinforcing bars) were used. Thus the concept of ferrocement was almost forgotten for nearly 100 years. In the early 1940 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.^(1,9) After the second world war, Nervi demonstrated the utility of ferrocement as a boat building material. After Nervi, the interest began to expand in the world, scientific and technical committees turned to the materials science of ferrocement, as a fertile field of investigation. A number of technical papers began to appear in the literature and speculation about the use of ferrocement as a structural material began to rise.

II.1.3 Composition of Ferrocement

Ferrocement consists of a portland cement mortar matrix, wire mesh reinforcement, admixtures and coatings.

The Mortar Matrix

The mortar matrix used in ferrocement consists of hydrolic cement and inert filler materials. Portland cement is generally used, sometimes blended with a pozzolan.⁽¹⁾ The filler material is usually a well-graded sand capable of passing a number 8 sieve.⁽¹⁾ However, depending upon the characteristic of the reinforcing material (mesh opening, distribution) a mortar containing some small size gravel may also be used. The physical properties and microstructure of the resulting mortar depend on the chemical composition of the cement, the nature of sand, the water-cement ratio and the curing conditions of the finished products⁽¹⁾.

It appears that composite action between the matrix and the reinforcement is more pronounced in ferrocement than in ordinary reinforced concrete.

Sometimes randomly distributed fibers may also be used in cement mortar, but they are not considered as a reinforcement. They favorably control the cracking and the capacity of the matrix to resist tensile loads.⁽¹⁾

When fiber-reinforced mortar is used as the matrix, the mesh openings and spacings are usually much larger than for conventional ferrocement.

The Reinforcement

Reinforcement for ferrocement is in the form of layers of continuous mesh. It is fabricated from an assembly of continuous single strand filaments. Specific mesh types include woven and welded mesh. In woven cloth mesh filaments are interwoven, and their intersections are not rigidly connected. Welded mesh has a rectangular pattern and is formed by perpendicular intersecting wires welded together at their intersections. There is a wide variety in mesh dimensions as well as in the amounts, sizes, and properties of the materials used. Properties of the resulting ferrocement product can be affected by filament size or gage, strength, ductility, manufacture and treatment.

Admixtures

Reinforcement may be galvanized or not galvanized. If it is galvanized, then the ferrocement may require chemical additives to reduce the reaction between the matrix and the galvanized reinforcement. Chromium trioxide added to the mix water has been reported to be useful in this

regard.⁽¹⁾ No special precautions need be taken when using nongalvanized reinforcing materials.

Matrix Mix Proportions

The desirable mix proportions of the mortar for ferrocement are :

Cement-sand ratio by weight : 1:1,5 ~ 1:2,5

Water-cement ratio by weight : 0.35-0.5

The maximum size of sand particles depend on the mesh opening.

Coatings

Most of the surface coatings and impregnation treatments available for conventional reinforced concrete can also be applied to ferrocement. These include polymer impregnation, epoxy impregnation etc.⁽¹⁾

II.1.4 Fabrication Procedures

Determination of the most appropriate fabrication technique depends on the desired application and on the availability, skill and cost of labor. There are two methods, to impregnate the mesh in cement mortar.⁽¹⁾ The first one is to force the portland cement mortar into a preexisting skeletal framework of layered continuous mesh, and the second is to force layers of continuous mesh into a bed of mortar. In the first case, a number of different techniques are being used. Among these, the hand plastering of no slump mortar either from one side against a mold, or from both sides, is mostly used. During this procedure, care must be taken to assure full penetration of mortar.

Hand vibrators may be adapted to induce higher mobility to the mortar. Chemical and mineral admixtures also can be used to serve this function.⁽¹⁾ In the procedure of casting against a mold, molds may be made of wood, plywood, fiberglass, ferrocement etc. In the procedure of plastering from both sides, a semirigid skeletal framework of mesh may be formed by wire tying several layers of mesh together. As an alternative to hand plastering and compaction, mortar may be applied by shotcreting. It is necessary to assure full penetration. In the method of forcing the mesh into the plastic mortar, there are two primary fabrication procedures, hand plastering and shotcreting. In either case, an initial layer of mortar is applied to the mold 1-3 mm. thick and this layer is permitted to achieve some initial set. The functional purpose of the initial mortar layer is to assure proper cover and to prevent further penetration of the mesh system which is to be applied.

The methods of fabrication discussed, are labor-intensive in varying degrees and the quality of the resulting products depends greatly on the skill of the hand labor used. Several high technology procedures have been suggested for fabrication. These include packer head machine devices, spin casting for pipe fabrication, and spray suction or vacuum dewatering for the production of thin panel and sheet product.⁽¹⁾

II.2. PHYSICAL AND MECHANICAL PROPERTIES

The subdivision and distribution of the reinforcement is fundamental in understanding many of the properties of ferrocement. Throughout this section parameters associated with the orientation, the total amount the effective area of steel in a particular direction of ferrocement are introduced.⁽¹⁾

In this section we will examine also the properties of ferrocement, such as mechanical properties under static and dynamic loading.

II.2.1. Ultimate Tensile Strength

In tension, the load-carrying capability is essentially independent of specimen thickness, because the matrix cracks well before failure and do not contribute directly to composite strength.⁽¹⁾ For this reason, strength and amount of reinforcement must be defined differently than for flexure and compression. Tensile strength of ferrocement corresponds quite closely to the tensile load capacity of the reinforcing elements^(1,3,10) (FIGURE 2.1). Orientation of the reinforcement has a marked effect on absolute strength and on the relative efficiency of the various reinforcing systems.^(1,10) When welded mesh is oriented at 45° to the applied load, ultimate strength for this orientation is 50-60 percent of that for the parallel orientation (FIGURE 2.2). When expanded metal is used with the longer axis of the diamond shaped openings perpendicular to the applied stress, ultimate strength for this orientation is 15-35 percent of that for the normal orientation (FIGURE 2.2).

The relative effectiveness of different reinforcing systems can be conveniently compared in terms of an efficiency ratio, the ratio of actual ultimate load to predicted ultimate load.⁽¹⁰⁾ The average efficiency ratio for specimens reinforced with welded mesh is 1.13 and for specimens reinforced with expanded metal is 1.19⁽¹⁰⁾. The effect of orientation on efficiency ratio is important. When welded mesh is oriented at 45 deg to the applied load, efficiency ratio drops to 65 percent of that for the

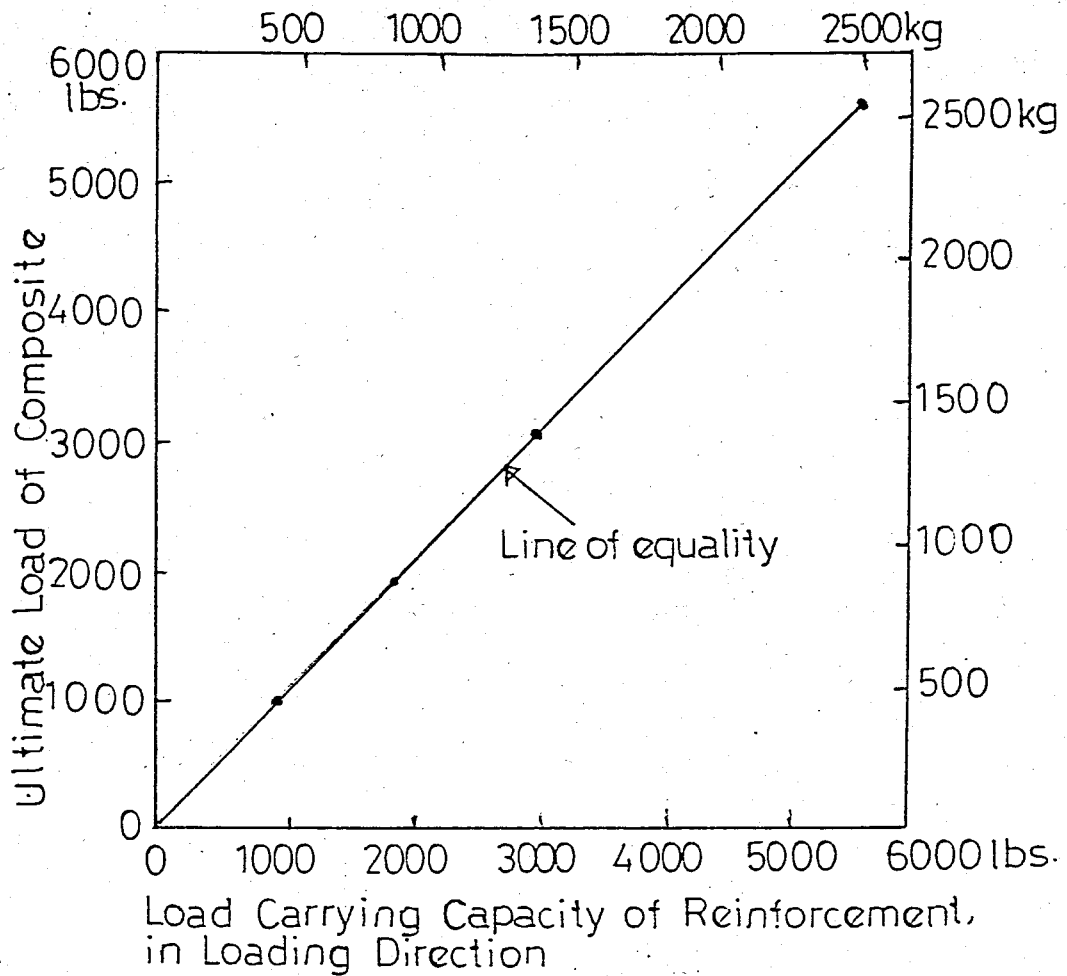


Figure 2.1 Ultimate load of composite versus ultimate capacity of reinforcement (3)

parallel orientation (FIGURE 2.3). When expanded metal is oriented with the longer axis of the diamond-shaped openings perpendicular to the applied stress, efficiency ratio drops to 51 percent of that for parallel orientation (FIGURE 2.3).

In general, the optimal choice of reinforcement for ferrocement strength in tension depends on whether the loading is essentially uniaxial or significantly biaxial.⁽¹⁾ FIGURE 2.2 and figure 2.3 shows that expanded

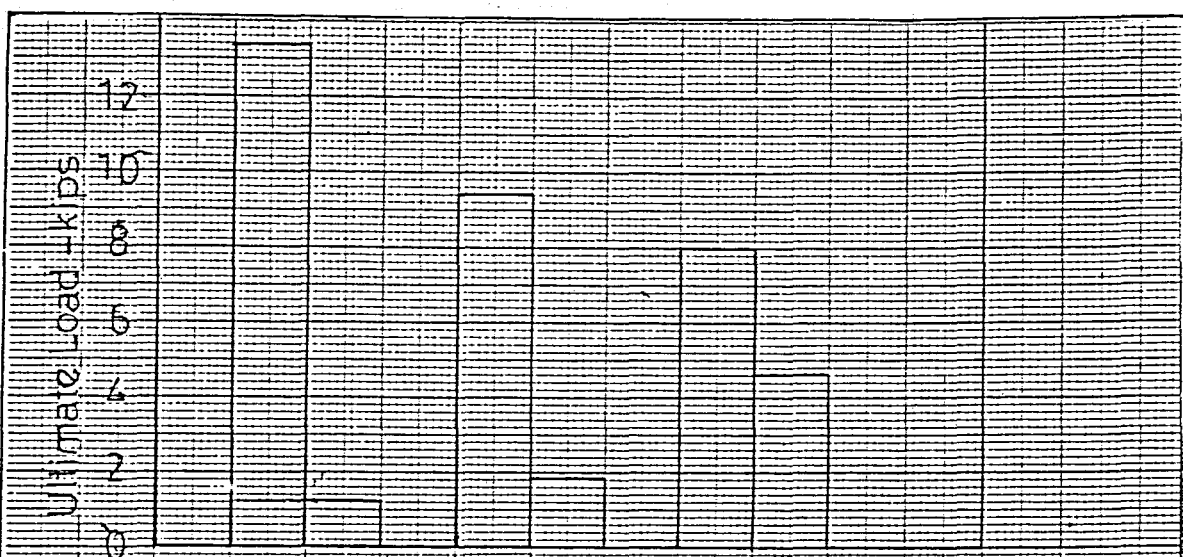


Figure 2-2 Influence of Orientation of Reinforcement on Tensile Strength for Two Types of Expanded Metal and Welded Mesh (10)

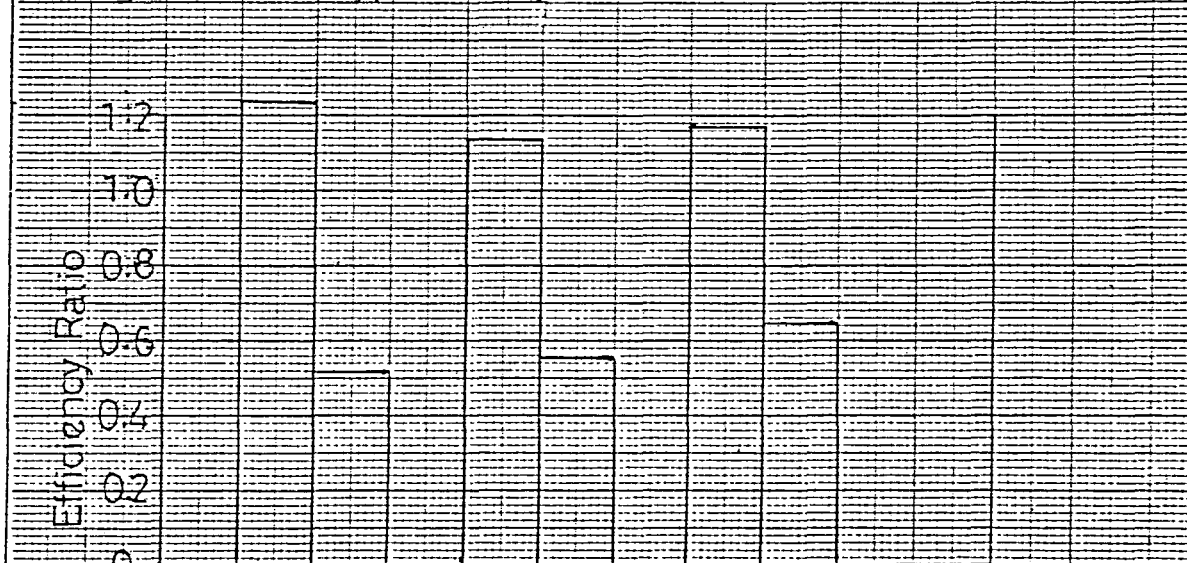
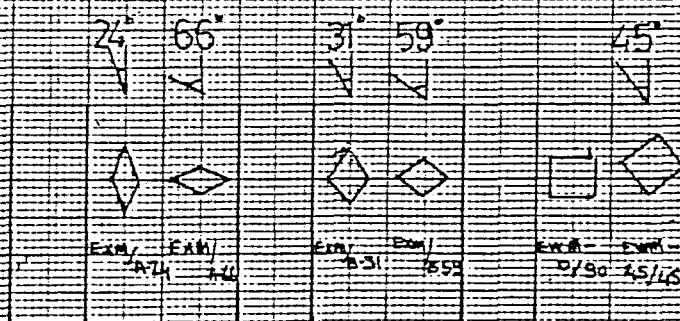


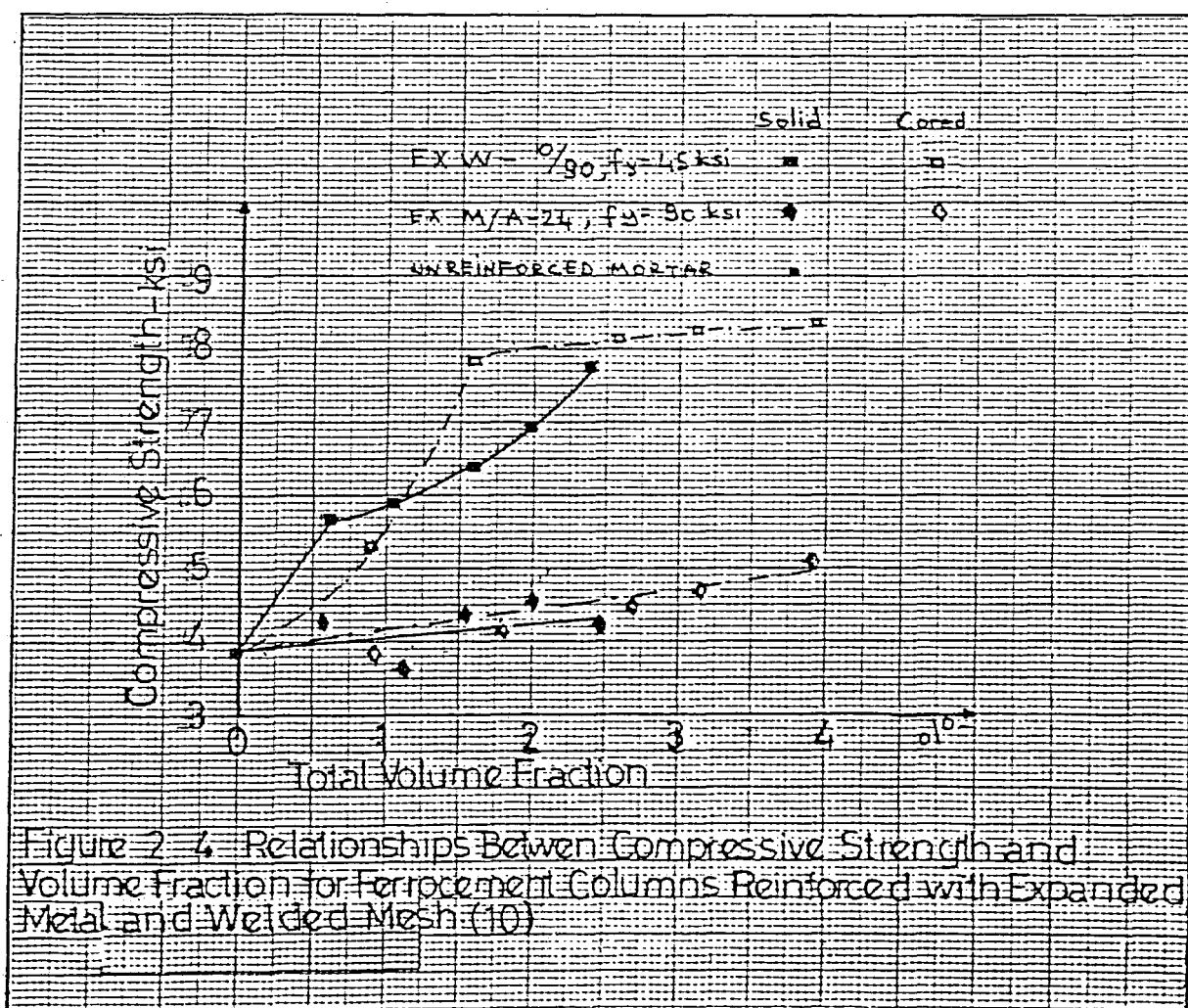
Figure 2-3 Influence of Orientation on Efficiency of Expanded Metal and Welded Mesh Reinforcement in Tension. (10)



metal in its normal orientation is more suitable for uniaxial loading. Because a higher proportion of the total steel is effective in the direction of applied stress.^(1,10) For biaxial loading, square mesh is more effective. Because the steel is equally distributed in the two perpendicular direction.

II.2.2 Ultimate Compressive Strength.

Unlike tension, the matrix contributes directly to compressive strength in proportion to its cross-sectional area. Strength and amount of reinforcement must also be defined. Matrix strength governed primarily by its water-cement ratio, is a major factor as for conventionally



reinforced concrete.⁽¹⁾ But the type, orientation and arrangement of reinforcement is also important.

Comparison of strengths of the solid and cored columns reinforced with welded mesh or expanded metal show that the welded mesh is much superior to the expanded metal.⁽¹⁰⁾ (FIGURE 2.4). Comparison of strength on the basis of the effective percentage area of the longitudinal steel, a parameter that takes into account both the geometry of the reinforcement and the area of load-bearing material, welded mesh is again superior.⁽¹⁰⁾ Infact, for the same number of layers, the effective percentages of longitudinal steel are almost equal for the two types of reinforcement. The difference in performance must be related to their contrasting geometry and the consequential difference in the amount of lateral reinforcement. Certainly the relatively small amount of lateral reinforcement is at least partly responsible for the poor performance of the expanded scissors action in the lateral direction which renders the reinforcement ineffective as the restraint required to exploit the triaxial strength of the mortar within. (FIGURE 2.4). This view is supported by the sudden an substantial increase in poisson's ratio at 60 % - 70 % of ultimate load in columns reinforced with expanded metal (FIGURE 2.5.a), a feature not observed with welded mesh⁽¹⁰⁾ (FIGURE 2.5.b).

According to the results obtained with expanded metal reinforcement, orientation is much less important in compression than in tension.⁽¹⁰⁾

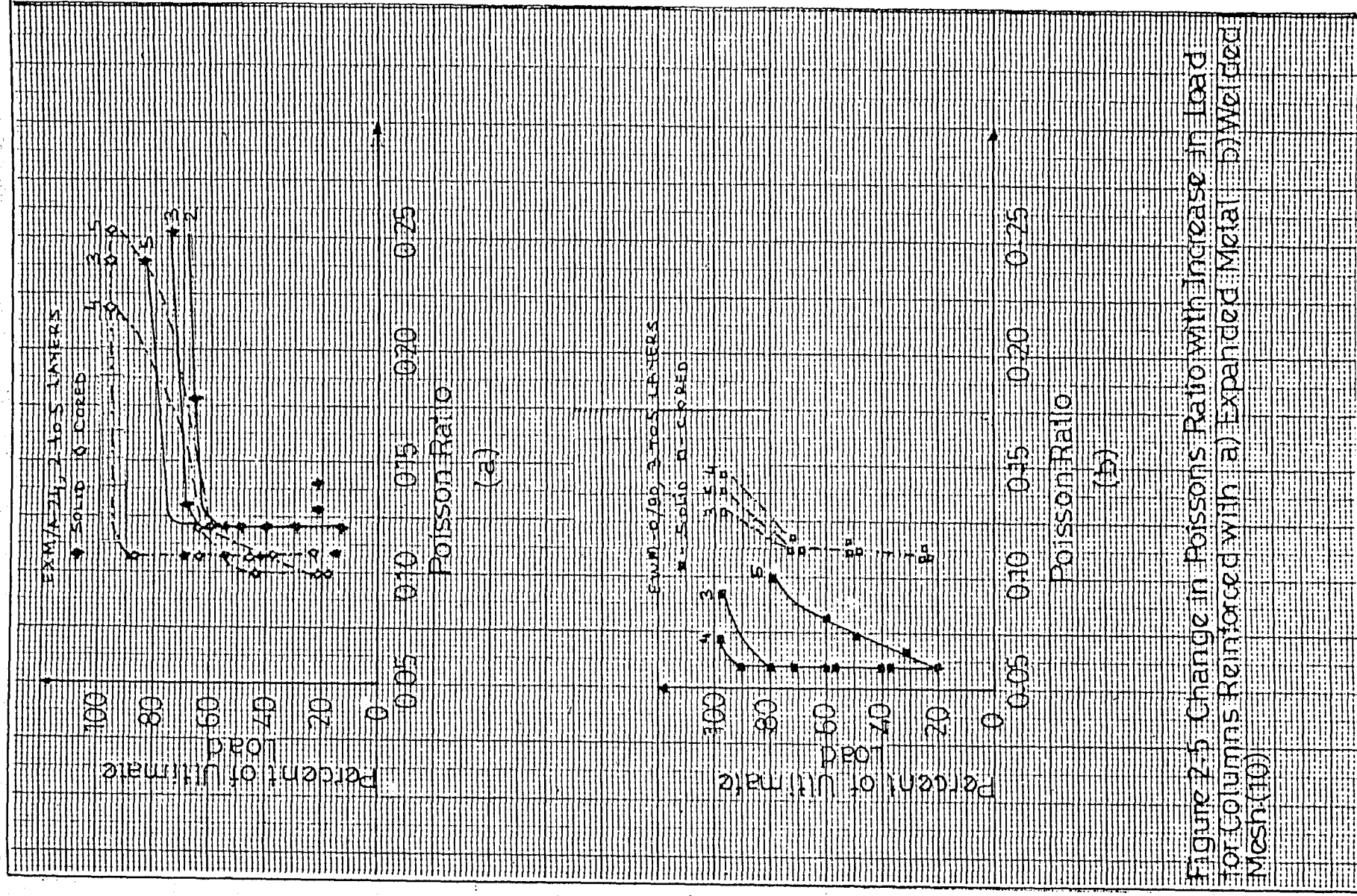


Figure 2-5 Change in Poisson's Ratio with Increase in Load for Columns Reinforced with a) Expanded Metal b) Welded Mesh (10)

II.2.3 Ultimate Flexural Strength and Ultimate Moment

Ultimate strength in flexure naturally reflects the combined influence of factors governing tensile and compressive strengths, and amount, type, orientation and intrinsic geometry of the reinforcing layers.⁽¹⁾ Effective cross sectional area and the position of the reinforcing layers with respect to the neutral axis are very important factors for ferrocement specimens. Several investigators have used the principles of conventional ultimate strength analysis for reinforced concrete to compute the strength of ferrocement.⁽⁵⁾ The term efficiency ratio for ultimate flexural strength is expressed as the ratio between the actual ultimate moment determined by test and the ultimate moment computed by the ultimate strength method.⁽¹⁾ Amount, type and orientation of reinforcement are additional important factors for ferrocement. Orientation has a marked effect on the strength of systems.^(1,4,9) Although orientation has a little effect in the woven mesh, it is most important for the square mesh and expanded metal.^(1,9) For any given effective cross-sectional area of steel, expanded metal and welded mesh used in their primary orientations perform significantly better than woven mesh or standard bars.^(4,9) Decreasing the cross section of the steel elements and consequently increasing the surface area appears desirable for reinforcement liable to bond failure. This is probably less important when bond failure is not a problem.⁽⁹⁾

Ultimate moment is calculated essentially on the basis of methods used for conventional reinforced concrete. According to this method of design, ultimate strength of a reinforced concrete beam depends on the dimensions of the beam, the compressive strength of concrete, the amount, location and yield strength of steel reinforcement. This method of

calculating ultimate moment is outlined below (FIGURE 2.6) :

a. It is assumed that ultimate moment is reached, when mortar in the compression zone fails. The strain in the top compression mortar fiber at the ultimate load is taken $\epsilon_{cm} = 0.005$.

b. Strains are assumed to be linearly distributed.

c. The stress distribution in the mortar from neutral axis to the strain of 0.005 is assumed to be similar to an uniaxial stress-strain curve obtained from a mortar sample with compressive strength of 4125 psi (289 kgf/cm²). The total force in the compression zone of the mortar ($C = \alpha f_c' b a$) and its moment about the neutral axis [$C (a - \beta a)$], is calculated from this stress-strain curve.

d. For an assumed value of the depth of the neutral axis a , the strain in any layer of mesh located of a distance d_i from the top is given by

$$\frac{\epsilon_{cu}}{a} = \frac{\epsilon_{si}}{d_i - a}$$

e. For a value of the strain in a layer of mesh, the stress f_{si} is calculated as ;

$$\text{if } \epsilon_{si} < \frac{f_y}{E} \rightarrow f_{si} = E \epsilon_{si}$$

$$\text{if } \epsilon_{si} > \frac{f_y}{E} \rightarrow f_{si} = f_y$$

with f_y = the yield strength of mesh

f. For an assumed value "a" of the depth of the neutral axis, an equilibrium check is made. Equilibrium of the forces is satisfied if

$\alpha f_c' b a + \sum A_s f_{sj} \text{ (compression)} = \sum A_s f_{sj} \text{ (Tension)}$ (A value of $\alpha = 0.70$ obtained from the evaluation of the uniaxial stress-strain curves of mortars, will be used.)

g. The value of "a" is revised until equilibrium is satisfied.

h. Finally the ultimate moment for the correct value of a, is calculated from;

$$M_u = \alpha f_c' b a (a - \beta a) + \sum_{i=1}^n A_s f_{si} y_i$$

with

n : number of mesh layers

$$y_i = d_i - a$$

(A value of $\beta = 0.40$, obtained from the evaluation of uniaxial stress-strain curves of mortar will be used). The calculated values are close to the experimental ultimate moments. The ratios of experimental to calculated ultimate moments are shown in figure 2.6 as a function of the volume of reinforcement.

II.2.4 Load-Elongation Behavior in Tension

For square mesh reinforcement the load elongation behavior of uncracked ferrocement in tension has been characterised to be linear.^(3.1)

The mortar and the lateral reinforcement continue to play an active role after first cracking.⁽³⁾ In the final stage, the matrix ceases to play

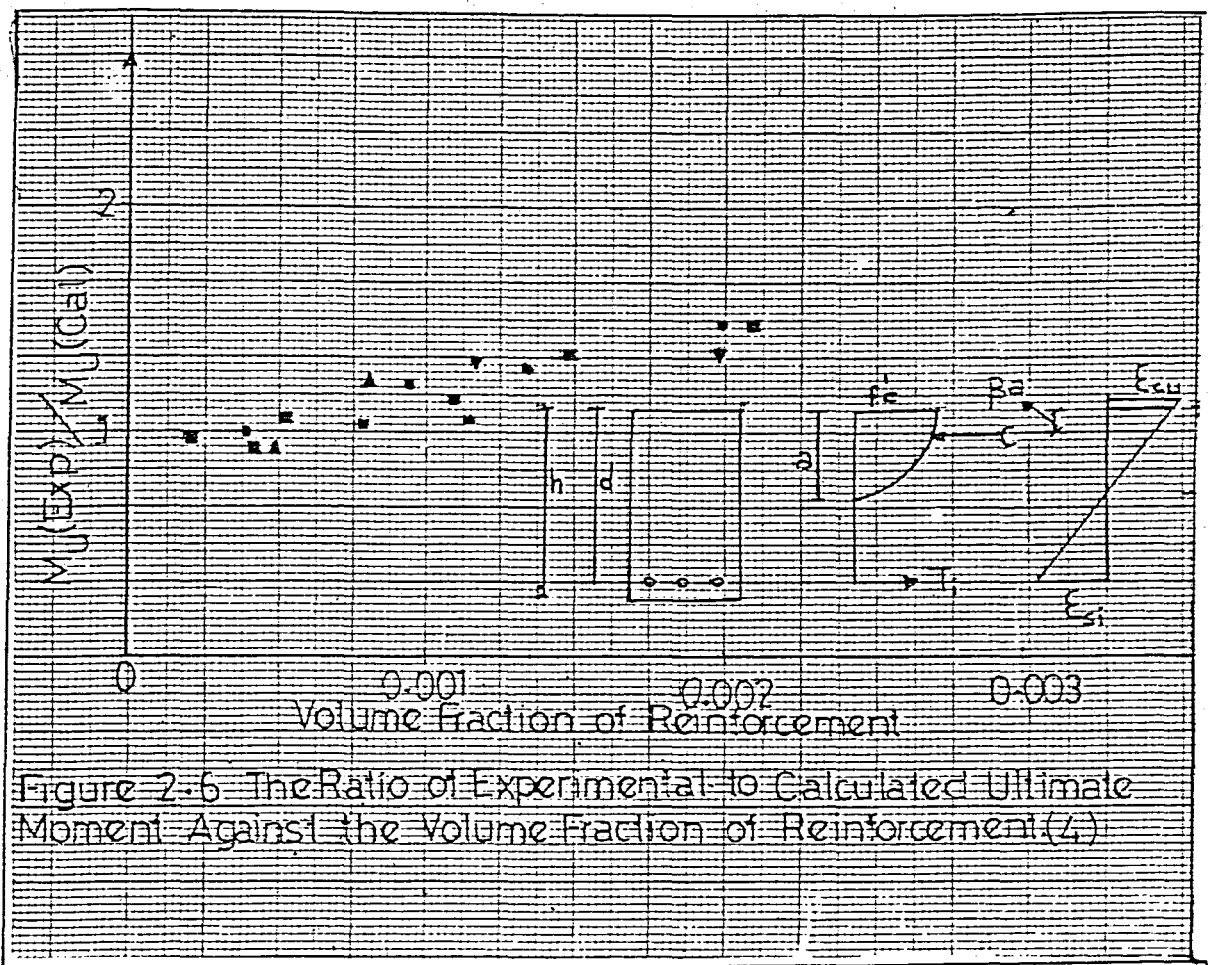


Figure 2-6 The Ratio of Experimental to Calculated Ultimate Moment Against the Volume Fraction of Reinforcement (4)

a role.⁽¹⁾ Failure corresponds to the yielding of the reinforcement. Increases in the number of meshes increases the elongation at ultimate load.⁽³⁾ In general the elongation at ultimate load of ferrocement specimens for the highest number of meshes used approaches that of the mesh alone.⁽³⁾ Toughness and elongation at ultimate load are directly related as toughness can be measured as the area under the load-elongation curve. Toughness provided by a single layer of mesh increases with increasing number of layers of mesh, and approaches that of the mesh alone.⁽³⁾ The type of mesh and orientation is very important to determine the elongation. Elongations are different for

expanded or welded mesh.^(1,10) The composite stiffness for a given type of reinforcement increases as the effective longitudinal area of steel increases.⁽¹⁰⁾

II.2.5 Load - Deformation Behavior in Compression

When the reinforcement is in one plane 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.⁽¹⁾ The initial elastic modulus can be predicted quite accurately and conservatively on the basis of the volumetric influence of two material components acting together. Values of the elastic modulus are slightly higher for specimens reinforced with welded mesh than expanded metal.⁽¹⁾ This reflects the more effective triaxial restraint of the matrix by the welded mesh which is also apparent in the change of the ferrocement poisson's ratios with increasing load. From initial values of 0.06-0.07 and 0.11-0.13 for the welded mesh and expanded metal respectively, the ratio increases only gradually to less than 0.10 just before failure of the mesh-reinforced specimens, while it increases sharply to more than 0.20 at 60-80 percent of ultimate for specimens reinforced with expanded metal.^(1,10) (see Figs 2.5 a and 2.5 b).

II.2.6 Load-Deformation in Flexure

The three-stage behavior identified for direct tension is also applicable to Ferrocement in flexure.⁽¹⁾ The ultimate strength design procedure outlined in 2.3.1 provides one method of calculation of the

compression zone of the mortar. A second, but more complicated method is given by the use of fourier series, to define the stress-strain functions of both mortar and reinforcement, and thereby to compute the moment-curvature relationships^(1,4) from :

$$\sigma = \sum_{m=1}^m A_m \sin \left[\frac{(2m-1)\pi \epsilon}{L} \right]$$

where

σ = stress

ϵ = strain

A_m = The constants of the series

m = The number of terms in the series

L = A constant.

The values of the constants may be determined, in conformity with test results, and the obtained relationships may be used in ultimate moment predictions.

II.2.7 First Crack Strength Under Static Load

One of the parameters which is useful for design of ferrocement is the first crack. The occurrence of first crack is defined as a having a certain width. It can be defined in various ways and therefore can mean different things to different people. It is noted that microcracks are inherent in the mortar matrix even before it is loaded. Some studies say that first cracking is defined as the first deviation from linearity of the load-elongation function in tension (900-1500 microstrain)⁽¹⁾

Another study says that its width is between 0.0001 - 0.0003 in.⁽³⁾

Specimens with higher volume of the same type of mesh reinforcement show higher stresses at first crack.⁽³⁾ For the same volume fraction of reinforcement, the smaller the dimension of the mesh, the higher the stress at first crack against the specific surface of reinforcement S_L .⁽³⁾ This means that for the same volume of reinforcement, different first crack moments can be obtained. Similarly, there is no relationship between the wire spacing and the moment of first cracking.⁽⁵⁾ Better correlation is found between moment at first crack and specific surface of the reinforcement (S_{LT}). If specific surface increases, moment at first crack increases linearly from this correlation, one can formulate⁽⁵⁾:

$$M_{1st} = 400 S_{LT} + M_m$$

M_{1st} = Moment at first crack

M_m = Ultimate moment for mortar (without any reinforcement)

From the values of the moment, the stress in extreme tensile fiber of mortar (f_{1st}) is calculated.

$$f_{1st} = 1600 S_{LT} + f_m$$

f_m = The modulus of rupture of plain mortar

But at a certain value of the specific surface of reinforcement, the stress at first cracking seems to approach a constant value.

II.2.8 Crack Development

Crack development is considered in terms of average crack spacing and the average and maximum width of cracks.⁽¹⁾ Crack width is a critical parameter, and its prediction is necessary to formulate rational design methods. After the occurrence of the first crack, the number of cracks keep increasing with increasing load, but a decreasing rate.⁽³⁾ It is observed that, the higher the volume of steel, the larger the number of cracks, the smaller the average crack spacing. Specific surface of reinforcement is the most important parameter for crack spacing.⁽⁵⁾ The average crack spacing decreases with increasing specific surface for both tension and flexure. Since the average crack spacing appears to be closely related to the specific surface of the reinforcement, the crack width should also depend on the specific surface. To formulate an analytic equation relating crack width with the stress and specific surface of the reinforcement, stresses in the extreme tensile layer of mesh are calculated from the bending moment by using cracked elastic analysis. The elastic analysis is assumed to be valid either until the steel stress reached the corresponding yield strength or the maximum mortar strain in compression obtained a value of 0.003.⁽⁵⁾ A similar equation between crack width and steel stress for conventionally reinforced concrete is

$$w_b = 0.076 \sqrt[3]{\frac{A}{t_b}} R f_s \quad (\text{Gergely-Lutz equation})^{(4.5)}$$

It can be shown that the maximum crack width for ferrocement can be predicted knowing the maximum steel-stress and the specific surface of the mesh reinforcement.⁽⁵⁾ (FIGURE 2.7)

$$w_b = \frac{3.5 \times 10^{-9} f_s}{S_{LT}^{1/3}}$$

The Gergely-Lutz equation indicates that ferrocement is a special case of reinforced concrete, where the larger specific surface of reinforcement yields smaller crack widths for the same stress in the steel.⁽³⁾ In order to predict average crack width as a function of the steel strain in the outermost layer,

$$w_{cal} = \epsilon_s SR$$

formulation gives useful upper bound values to the experimental results.⁽⁴⁾

S = The spacing of the transverse wires

R = Ratio of distances to the neutral axis from the extreme tension fiber and from the centroid of steel

ϵ_s = Tensile strain in the extreme layer of steel.

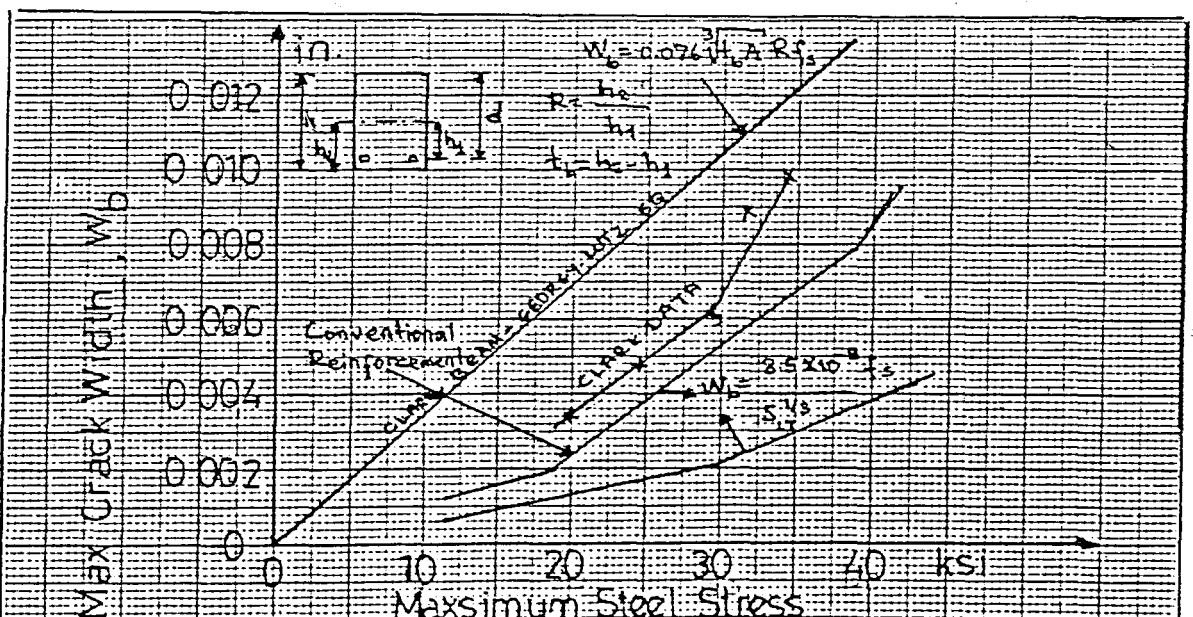


Figure 2-7 The Relationships Between Max. Crack Width and Max. Steel Stress for Ferrocement and Reinforced Concrete (2)

II.2.9 Leakage

In applications involving storage of liquids, the development of cracking directly governs leakage. It has been shown experimentally that in tanks subjected to water pressure the factors which reduce average crack width generally reduce leakage. Leakage was qualitatively observed with the naked eye, when the lime coated exterior surface of the ferrocement tanks along a crack darkened in color as it becomes wet.⁽²⁾ Quantitatively leakage was defined as the loss of water per unit wall area per hr of loading under a specified internal pressure, and following observations were made:⁽²⁾

- a. Ferrocement tanks did not leak before cracking even during long terms of loading.
- b. The stresses at the onset of leakage increased with the specific surface and the volume fraction of mesh reinforcement.
- c. Leakage increased with an increase in steel stress, and a decrease in wall thickness.

II.2.10 Shrinkage and creep

The shrinkage potential of the mortar matrix (unrestrained by reinforcement) is governed largely by its water content, the sand gradation and the presence of admixtures such as pozzolan, lime, water-reducing and air entraining agents etc.⁽¹⁾ The selection of low-workability placement techniques such as guniting or shotcreting, the choice, of a sand without excessive fines, and the use of admixtures can reflect an

Steel has a definite endurance limit. At stress levels below this limit, it has an infinite or at least very long fatigue life.⁽¹⁾ Mortar does not have the definite endurance limit, it will eventually fail under repeated loading.

The fatigue behavior of ferrocement in flexure is almost identical to the behavior of segments of the reinforcing steel in tension.⁽¹⁾ If this is a case, the choice of reinforcement for optimal performance under fatigue loading will be different for static loading.

Relationships between applied stress and number of cycles of failure gives us comparable data to study fatigue behaviour.⁽⁸⁾

The failure of ferrocement flexural specimens in fatigue can be described by the equation.⁽⁸⁾

$$S_r = 93.3 - 19.5 \log N_f$$

S_r = The stress range in the extreme layer of mesh, in kips/in^2

N_f = The fatigue life in kilocycles.

The measured crack widths and deflections under cyclic loading can be represented by an exponential relationship

$$Y = A e^{Br}$$

Y = The crack width or deflection

r = The ratio of number of cycles at which Y is measured the number cycles to failure

A = The static deflection at the maximum load for the first cycle

B = The fatigue contribution to the deflection has to be evaluated from the experimental data.

The increase in deflection during fatigue loading can be related to the fatigue life of the specimen, N_f . The following empirical relation has been developed from deflection results for all specimens.⁽⁸⁾

$$B = 0.329 + 0.1925 \times 10^{-2} N_f - 0.275 \times 10^{-3} N_f^2 < 0.667$$

N_f is in kilocycles

For predicting average crack widths, some procedure may be used with :

A = The average crack width under static max.load, and

$$B = 0.816 + 0.445 \times 10^{-2} N_f - 0.495 \times 10^{-5} N_f^2 < 1.670$$

Since there are no other experimental data available for crack widths of ferrocement, this equation can not be independently checked.

The value of A can be predicted by using

$$W_{avg} = \epsilon_r SR$$

from the results of static tests on ferrocement beams.

II.2.14 Impact Resistance

There is little quantitative or comparative data associated with

measurement of impact resistance. The fundamental governing parameters are not established. The available information is insufficient to indicate what constitutes an optimal reinforcing system from the point of view of impact resistance. The factors such as the type, geometry, and specific surface of the reinforcement are probably of primary importance.

11.3 METHODS OF DESIGN

Any design for ferrocement structures should depend on the type of the application, and should be based on experimental results. Accurate analysis is also necessary to guarantee safe performance. It is believed that the following guidelines for ferrocement made with plain mortar and square meshes is satisfactory. These guidelines have been derived from the analysis of numerous test data, and some recommendation were made by practicing engineers, and specifications used for building ferrocement boats gave information.

Two important reinforcing parameters are V_f (Volume fraction of reinforcement per unit volume of composite) and S_R (specific surface of the reinforcement).

Some properties of ferrocement are the same as for reinforced concrete. But the effective modulus of the reinforcing system of ferrocement is different. Because the modulus of a mesh may not be the same with the elastic modulus of the filament. For welded mesh E_R may be taken equal to the elastic modulus of the steel wires.⁽¹⁾

$E_R = E_s = 29 \times 10^6$ psi (203×10^3 M Pa). For other meshes, E_R may be determined from tensile tests on the ferrocement. For woven mesh E_R may vary from 15 to 25×10^6 psi (105 to 175 M Pa).⁽¹⁾

II.3.1 Allowable Tensile Stress in Reinforcement

The allowable tensile strength in the steel reinforcement may be generally taken as $0.60 F_y$ which is the yield strength measured at 0.0035 strain.⁽¹⁾

II.3.2 Allowable Compressive Stress in Mortar

Allowable compressive stress in the mortar may be taken as $0.45 f'_c$ which is the specified compressive strength of the mortar measured from tests on 3 x 6 in (76 x 152 mm) cylinders.

II.3.3 Volume Fraction and Specific Surface

The total volume fraction of reinforcement in both directions shall not be less than 1.8 percent.

The total specific surface of reinforcement in both directions shall not be less than $2 \text{ in}^2 / \text{in}^3$ ($0.08 \text{ mm}^2 / \text{mm}^3$).⁽¹⁾

About twice these values are recommended for water retaining structures. In computing the specific surface of reinforcement any skeletal steel may be disregarded but it should be considered in computing V_f .

It is recommended that for a given ferrocement composite, mesh opening (S) must be greater than ferrocement composite thickness (t) (without skeletal reinforcement). Furthermore,

If N is the number of layers then $N > 4t$ is in inches

$N > 0.16 t$ is in mm

If skeletal reinforcement is used (skeletal reinforcement not occupy more than 50 percent of ferrocement material)

$N > 4 t^1$ is in inches

$N > 0.16 t^1$ is in mm.

t^1 = thickness of ferrocement material (skeletal reinforcement is included).

II.3.4 Cover of Reinforcement

Average net cover of the reinforcement is about 1/12 in. (2mm).⁽¹⁾

A smaller value can be used, but reinforcement must then be galvanized, the surface protected by an appropriate coating, or the crack width must be limited.⁽¹⁾ It is also recommended that for thicknesses greater than 1/2 in (12 mm), the net cover shall neither exceed $\frac{1}{5}$ of the thickness t , nor 3/16 in. (5 mm).⁽¹⁾

II.3.5 Crack Width Limitation

The maximum value of crack width must be less than 0.004 in. (0.10 mm) for noncorrosive environments, and 0.002 in (0.05 mm) for corrosive environments.⁽¹⁾

II.3.6 Prediction of Crack Widths and Spacing

The maximum crack width for square mesh reinforcement only in flexural members, can be estimated using the equation

$$W_{\max} = \epsilon_s SR = \frac{f_s}{E_R} SR$$

Observed experimental data on cracking of ferrocement specimens, reinforced with different amounts of square meshes with spacings of $\frac{1}{2}$ in (12 mm) and $\frac{1}{4}$ in (6 mm) gave the following maximum crack width formula in flexure.⁽¹⁾

$$W_{\max} = (0.324 f_s - 4.36) \frac{23,000}{E_R} 10^{-4}$$

$W_{\max}$ is a function of f_s , and $W_{\max}$ is in inch, f_s and E_R are in ksi.

$$W_{\max} = (1.194 f_s - 111) \frac{15.85}{E_R} \quad \begin{array}{l} W_{\max} \text{ is in mm} \\ f_s, E_R \text{ is in M Pa} \end{array}$$

In order to predict maximum crack width in tensile ferrocement members the following conservative procedure can be followed assuming the stress in the steel to be less than the yield strength and in any case less than 60 ksi. (414 M Pa).⁽¹⁾

$$\text{for } f_s > 20 S_{RL} \quad W_{\max} = 10 [6.9 + (f_s - 20 S_{RL})] \frac{29,000}{E_R}$$

$$\text{for } f_s < 20 \text{ SRL} \quad w_{\max} = \frac{20}{E_R}$$

f_s and E_R are in ksi, $w_{\max}$ is in inches. If the metric system is used

$$\text{for } f_s > 345 \text{ SRL} \quad w_{\max} = \frac{20}{E_R} + 175 + 3.69(f_s - 345 \text{ SRL})$$

$$\text{for } f_s \leq 345 \text{ SRL} \quad w_{\max} = \frac{35,000}{E_R}$$

f_s and E_R are in MPa, and $w_{\max}$ in mm.

II.3.7 Stress Range

For ferrocement structures to sustain a minimum life of two million cycles, the stress-range in the steel must be limited to $f_{sr} = 30$ ksi ((207 M Pa); for one million cycles $f_{sr} = 36$ ksi (348 M Pa), and for 100000 cycles $f_{sr} = 55$ ksi. (380 M Pa).⁽¹⁾

II.3.8 Durability

In order to improve the long-term durability and corrosion resistance of ferrocement, the following recommendations are made.⁽¹⁾

1. For use in moist freeze-thaw conditions, the mortar should contain about 9 percent entrained air. The requirement applies to ferrocement boats which could be operated in freezing ocean conditions.

2. If concrete surface coatings are used to provide corrosion

protection, their effectiveness over time should be proven by tests simulating service conditions.

3. If admixtures are used in ferrocement, their effects on the corrosion resistance of the material should be assessed.

4. Until test result suggest otherwise, ferrocement structures subjected to corrosive environments should use galvanized meshes, and should be painted.

II.4. APPLICATIONS OF FERROCEMENT

Ferrocement has been used to construct boats, silos roofs, tanks etc, but boat construction has been more extensive than the other applications

II.4.1 Ferrocement Boats

Ferrocement boats have been built in almost every country of the world. The famous Italian architect Nervi developed the ferrocement boat. Infact, in 1848 rowing boats were made by Lambot in France. But subsequent development differed from Lambot's concept. Now-a days, ferrocement boats are produced on a large scale. The boats built in China appear to combine all the favorable characteristic of ferrocement construction. Ferrocement boat construction has been found attractive for many industrially developing countries Because⁽¹⁾

- a. Its basic raw materials are available.
- b. It can be fabricated into almost any shape.
- c. It is more durable and more economical than wood or steel.

d. The skills for ferrocement construction can be easily acquired.

e. Ferrocement construction is less capital-intensive, and more labor-intensive.

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. But there is clear evidence that we have to know some of the troubles with ferrocement boats, in order to utilize them satisfactorily. They are:

a. Mortar application and penetration seems to be the greatest problem in ferrocement boat construction.⁽¹⁾

b. The lack of resistance to impact and punching appears to be the most common cause of damage to ferrocement vessels

c. Paint failures seem to be frequent and no single paint formula appears to give consistently long-term satisfactory result.

II.4.2 Ferrocement Silos

Storage facilities for grain are lacking in most developing countries. It has been reported for instance that up to 25 percent of rice is lost to birds, insects etc in Thailand.⁽¹⁾ Ferrocement silos to store up to 30 tons of grain are suitable and economical for developing countries. Ferrocement is watertight and it can also be made airtight.⁽¹⁾ In an airtight ferrocement, micro-organisms can not survive, and not damage the stored products. The Applied Scientific Research Corporation of Thailand has developed economical airtight ferrocement silos that can hold up to 10 tons of grain, other food, cement or up to 5000 gal. of drinking water.⁽¹⁾ Small

capacity ferrocement bins (up to 3000kg) have been developed, analysed, and tested in India.⁽¹⁾ A cost estimate of ferrocement bins showed them to be less expensive than steel, reinforced concrete, or aluminum bins.

II.4.3 Ferrocement Roofs

In industrially developing countries, there is need for an economical material to built roofs of single family dwellings. It is possible to build walls and floors with local materials, but on roofs local materials can not be economical, durable, and resistant to fire, insects flood and earthquake. Many developing countries import galvanized iron sheet, and use asbestos cement sheets. These two roofing materials may cost as much as 60 percent of the total cost of a house. Ferrocement appears to be an economical alternative material for roofing. Ferrocement roofs made in Mexico were dome shaped with a span of 3-6 m (10-20 ft). Larger ferrocement roofs have been constructed in Italy with spans of 17 m (56 ft) and a thickness of 30 mm (1 in).

Corrugated ferrocement sheets have been developed, and tested by the Building Research Institute in Sri Lanka. This material is widely used as a roofing, is less expensive, and requires less capital investment. The Load carrying capacities, weights, dimensions of these ferrocement sheets were designed to be similar to those of asbestos cement sheets. Furthermore the ferrocement sheets were more ductile than the asbestos cement sheets.

II.4.4 Ferrocement Tanks

Ferrocement is also being explored in developing countries for water tanks. Ferrocement tanks are an attractive alternate material for the storage of water in the industrially developed and developing countries also. Small ferrocement tanks are less expensive than steel or fiberglass tanks.⁽¹⁾

A feasibility study was conducted to determine if there are any advantages of using ferrocement than steel or fiberglass for the construction of these tanks. Its results showed that ⁽¹⁾

a. Ferrocement is an economically feasible material for the construction of water storage tanks for storing energy collected by a solar system.

b. Flexibility of shape, possibility of hot storage, relative lack of maintenance, ductile mode of failure are important advantages of ferrocement over other materials

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

It may be summed up, that there will be many advantageous uses of ferrocement, depending on the type of application and economical consideration.

III. EXPERIMENTAL WORK

In this section, an experimental study is reported which was made to determine the possible ranges of quality, using local reinforcing mesh materials in ferrocement. For this purpose square woven mesh, expanded metal, and chicken wire were used in laboratory specimens. First of all, the mesh materials were examined, and tests were made on the mortar in order to determine the matrix properties. Secondly small ferrocement specimens were prepared and subjected to flexure, impact, and tensile tests. Some specimens were also tested after heating to 800°C temperature. The effects of reinforcement parameters and of heating on mechanical properties such as flexural rigidity, stress at first crack, and ultimate strength have been evaluated. Optimal results were obtained in 20 mm thick specimens with four layers of square mesh wire. Finally full-size ferrocement samples with lengths of 100 cm, widths of 50 cm and a thickness of 2 cm reinforced with 4 layers of square mesh. They were loaded in flexure on a free span of 80 cm, under four equal concentrated forces spaced at 16 cm from each other and from the supports, simulating evenly distributed loading. Measurements of deflection, curvature, tensile and compressive strains, observation of crack number and crack spacing, observation of creep deflection, and measurement of cracking and ultimate moments were made and their results were

evaluated as will be reported in the following parts of this section.

III.1 MATERIALS

III.1.1 Mortar Mix

The mortar mix consisted of sand, water, and cement.

a. sand : Constant and optimal grading is needed in order to secure strength workability, uniformity, and good surface finish of the mortar. Two types of 0-4 mm sand were used. One is a fine sand which was used as 40 percent, and the other a coarse sand which was used as 60 percent, to obtain a grading conforming to a Fuller-parabola of 4 mm maximum size. Gradings are shown in Appendix A..

b. Water : Tap water was used

c. cement: Type I portland cement was used

d. Mix proportions by weight were selected as; cement: water: sand-
1:0.45:2

For one liter of mortar mix, following amounts were used;

635 gr cement

1270 gr sand combined

285 gr Water

Unit weight of the fresh mortar mix was 2.155 kg/lt.

Flow of the fresh mortar was measured to be 120 %.

The calculations for the composition of the fresh mortar are shown in Appendix B..

III. 1. 2 Reinforcing Materials

a. The MeshTypes

Three types of locally available reinforcing mesh materials were used in the tests

- Square woven mesh (lightly galvanized)
- Expanded Metal (Not galvanized)
- Chicken wire (lightly galvanized)

Measured properties of the mesh materials are indicated in Table 3-1, and their appearances are shown in Figure 3.1.

b. Mesh parameters

The most important mesh parameters for ferrocement being volume concentration and specific surface, these values were calculated for one layer in a 20 mm thick ferrocement sample, and were shown in Table 3.1. The method of calculation for these values is given in Appendix C.

III.2 TEST METHODS

III.2.1 Properties of the Mortar Matrix

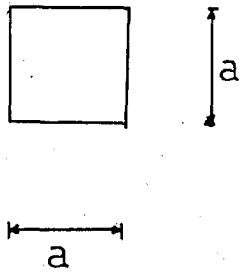
Three different series of test were performed on the mortar

1- a. Flexural strength of mortar, after 28 days of moistcuring, determined on 4x4x16 cm. prisms ranged between 7.3-8.37 MN/m².

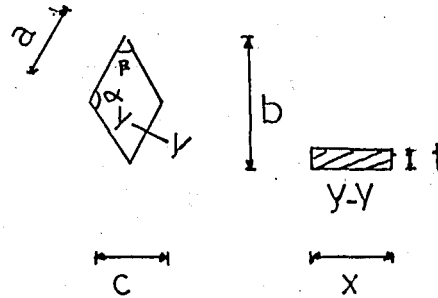
b. Compressive strength determined on broken pieces of these prisms ranged between 44.28-50.65 MN/m².

TABLE 3.1 The Dimensional Properties of Wire Mesh Used.

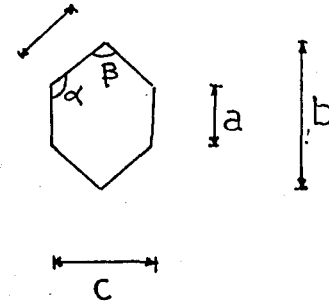
Type	Edge Length	Wire Diameter	Cross Section		Mesh Sizes		Angles		One Layer in 20cm Composite				Treatment
	a mm	d mm	x mm	t mm	b mm	c mm	α °	β °	W_w kg/m ²	V_w cm ³ /m ²	S_f mm ⁻¹	V_f (%)	
Square Mesh	8.0	0.71	—	—	8.0	8.0	90.	90.	0.597	75.5	0.028	0.49	Lightly Galvanized
Expanded Metal	11.0	—	0.70	0.20	18.5	11.0	114	60	0.268	33.9	0.019	0.15	Not Galvanized
Chicken Wire	16.5	0.55	—	—	42.5	22.0	142	78	0.273	34.6	0.009	0.12	Lightly Galvanized



a) Square Woven Mesh



b) Expanded Metal

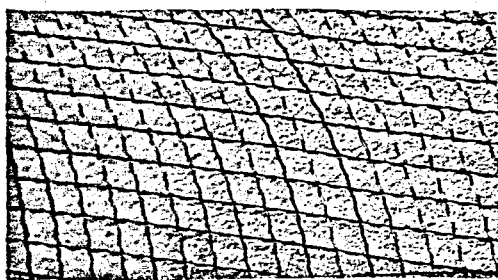


c) Chicken Wire

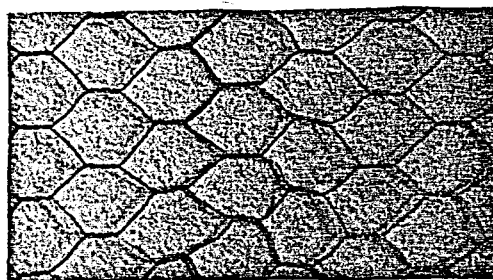
2. Compressive strength of the mortar, after 28 days of moist-curing determined of 7x7x7 cm cubes, ranged between 40.76-45.76 MN/m^2 .

3. Compressive strength of the mortar after 28 days of moist-curing determined on the cylindrical samples having a radius of 10 cm and a height of 20 cm ranged between 38.80-42.18 MN/m^2 .

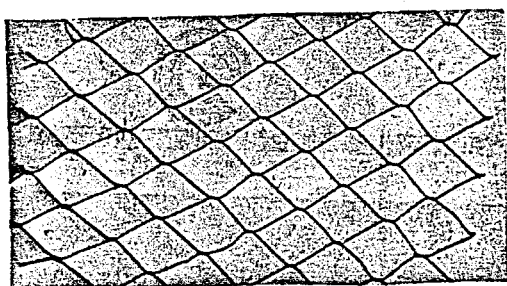
The calculation methods of these values were shown in the Appendix D.



a) Square Wire



b) Chicken Wire



c) Expanded Metal

Figure 31 The Appearance of Mesh Materials

Test Series	At Casting		After Cutting		Test Details			
	L ₁	B ₁	L ₂	B ₂	L	b	h	Type of Tests
1	500	500	500	100	400	100		FLEXURE
	500	500	250	50	200	50		
	1000	500	—	—	800	500		
2	200	70	—	—	200	70		TENSION
3	500	500	250	50	200	50		CHARPY-IMPACT
4	500	500	250	50	200	50		Flexure After Heating 800°C

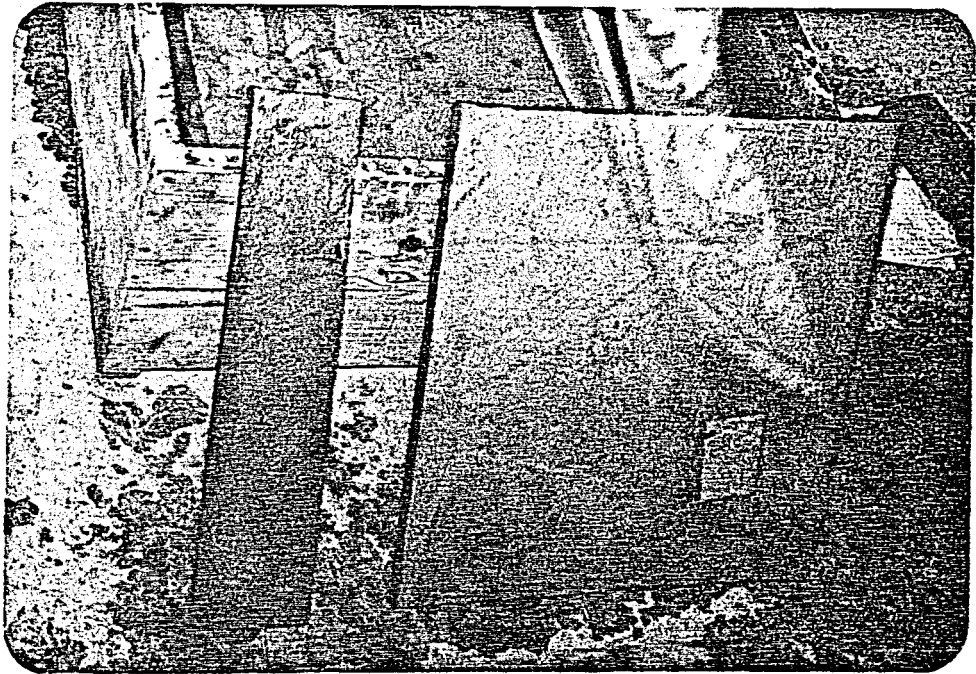


FIGURE 3.2 The appearance of the ferrocement samples; on the right a 50 x 50 cm ferrocement sample at casting, and on the left a 10 x 50 cm ferrocement sample after cutting.

III.2.2 The Definition of Some Properties of Ferrocement

A Constant sample thickness of 20 mm was used in all simple beam flexure tests and charpy-impact tests. Special moulds were used for the preparation of these samples. They had a length of 50 cm, a width of 50 cm, and a thickness of 2 cm. Sizes of the samples, at casting and after cutting into specimens of smaller dimensions for various tests are shown in Table 3.2 together with some of the test details. Finally full size ferrocement samples, with a length of 100 cm, a width of 50 cm, and a thickness of 2 cm were prepared to represent a roofing material, reinforced with 4 layers of square woven mesh, and flexure tests were performed on them. All samples were moistcured for three weeks, stored in laboratory condition, and tested at the age of 28 days. A minimum of two or more samples were used for each test. Some companion samples were heated in an electrical furnace during six hours up to 800°C and held about one hour at this temperature, and then cooled to room temperature, and were tested.

Three types of mesh were used

- a. Square woven mesh in the longitudinal, and in the 45° inclined directions
- b. Expanded metal in the longitudinal, and lateral directions
- c. Chicken wire mesh in the longitudinal, and lateral directions

The number of the mesh layers were varied from two to four for each type of mesh and their appearances are shown in Figure 3.2.

III.2.3 Testing of the Ferrocement Samples

a) Charpy Impact Test

The tests were performed in a charpy-impact testing machine according to the DIN 50115 german standards, which was modified for the small energy capacity with a small size hammer. The samples were tested at a constant impact level of the striker. Failure energies, U were measured, and impact strength, U_g were calculated using :

$$U_g = \frac{U}{A}$$

U = Failure energies
 U_g = Charpy-impact strength

For all samples U and U_g values calculated in Appendix E, and final values were shown in Table 3.3. Impact strength- volume concentration diagram were drawn and shown in Figure 4.1.

b) Tensile Test

The reinforcement used in these test series were square woven mesh and expanded metal. Special dog bone shape moulds were used for these tests. During the tests, tensile stresses and elongations were measured, δ - ϵ graphs were drawn. E , σ_{cr} , ϵ_{cr} , σ_u , ϵ_u values were determined from these graphs. For all samples, these values were calculated in Appendix F, and final results were shown in Table 3.4

Table 3.3 Charpy Impact Test Results.

MESH DETAILS					Charpy Impact Strength	
Type	Orientation.	Number	V_f %	S_f mm^{-1}	U_g $\frac{\text{Nxm}}{\text{m}^2}$	$\frac{U_g}{U_{g_0}}$
None	—	—	—	—	2412	1.00
SQUARE MESH	Longitudinal	2	0.99	0.056	10270	4.258
		4	1.98	0.112	19760	8.192
	45 Inclined	2	0.99	0.056	15050	6.240
		4	1.98	0.112	20550	8.520
EXPANDED METAL	Longitudinal	2	0.30	0.039	2870	1.190
		4	0.60	0.078	4450	1.850
	Lateral	2	0.30	0.039	2820	1.169
		4	0.60	0.078	4450	1.708
CHICKEN WIRE	Longitudinal	2	0.24	0.018	6360	2.636
		4	0.48	0.036	9320	3.864
	Lateral	2	0.24	0.018	6780	2.810
		4	0.48	0.036	9080	3.764

TABLE 3.4 Tensile Test Results of Ferrocement Samples.

Mesh Detail					Based on Reinforcement			Based on the Composite Section					
Type	Orientation	Number	V _f %	S _f mm ⁻¹	σ_{wcr} MN/m ²	E _w MN/m ²	σ_{wu} MN/m ²	σ_{cr} MN/m ²	E _c MN/m ²	σ_{cu} MN/m ²	$\frac{\sigma_{cr}}{\sigma_{co}}$	$\frac{\sigma_{cu}}{\sigma_{cuo}}$	$\frac{E_c}{E_o}$
None	—	—	—	—	—	—	—	0.729	135.4	0.76	1.00	1.00	1.00
Square Wire	Longitudinal	2	0.99	0.056	328.7	37336.4	436.1	1.806	205.4	2.395	2.47	3.13	1.51
		4	1.98	0.112	203.8	20461.5	457.2	2.239	224.7	5.017	3.07	6.57	1.66
	45° Inclined	2	0.99	0.056	230.9	45857.5	316.6	1.076	213.6	1.476	1.48	1.93	1.58
		4	1.98	0.112	89.4	25548.2	300.3	0.833	238.	2.793	1.14	3.66	1.76
Expanded Metal	Longitudinal	2	0.30	0.039	1348.2	184685.8	2443.	0.833	134.8	1.51	1.97	1.98	0.99
		4	0.60	0.078	1009.	142415.4	1502.	1.25	175.9	1.857	1.71	2.43	1.29
	Lateral	2	0.30	0.039	312.4	57530.4	749.9	0.52	96.	1.25	0.71	1.63	0.709
		4	0.60	0.078	374.9	41863.2	473.9	1.285	139.4	1.58	1.76	2.07	1.02

c) Flexure Test

Flexure test were performed in three different groups.

First simple beam flexure tests were performed on the smaller ferrocement samples at 18 °C curing temperature. They had lengths of 25-50 cm, widths of 5-10 cm, a height of 2 cm. A flexure testing machine was used for these tests as shown in Figure 3.3. The scope of these tests was to compare and determine the favorable mesh type for ferrocement roof application. For all specimens, load-deflection values were determined, and load-deflection graphs were plotted, but are not shown in this thesis. Only necessary values for final calculation were reported. Flexural rigidities, flexural strengths, and flexural energies were calculated for the samples at first crack and at ultimate load and are shown in appendix G. Flexural rigidities and flexural strength for the composite were calculated using the following beam formulas:

$$E I = \frac{P L^3}{48. \delta}$$

$$\sigma = 1.5 \times \frac{P L}{b h^2}$$

Flexural energies were calculated using the area under the load-deflection curves of the samples up to the first crack and ultimate load.

Final result obtained were shown in Table 3.5

Secondly simple beam flexure tests were performed on the smaller ferrocement samples heated up to 800°C. The sizes of the samples were the same as that of the first group samples. These specimens were heated in an electrical furnace in six hours up to 800° C and held about one hour at this temperature

ature. The specimens were after this. Load-deflection graphs were drawn, but are not shown here. Only final values were taken for calculations. Flexural rigidities, flexural strengths, and flexural energies calculated are shown in Appendix G. Similar calculation methods which were used in the first section, have been used also here. Final results were shown in Table 3.6, and appearance of the specimen after heating to 800°C are in figure 3.4. Ferrocement samples with expanded metal were broken in to pieces, but ferrocement samples with square woven mesh and with expanded metal cracked after heating up to 800°C Temperature.

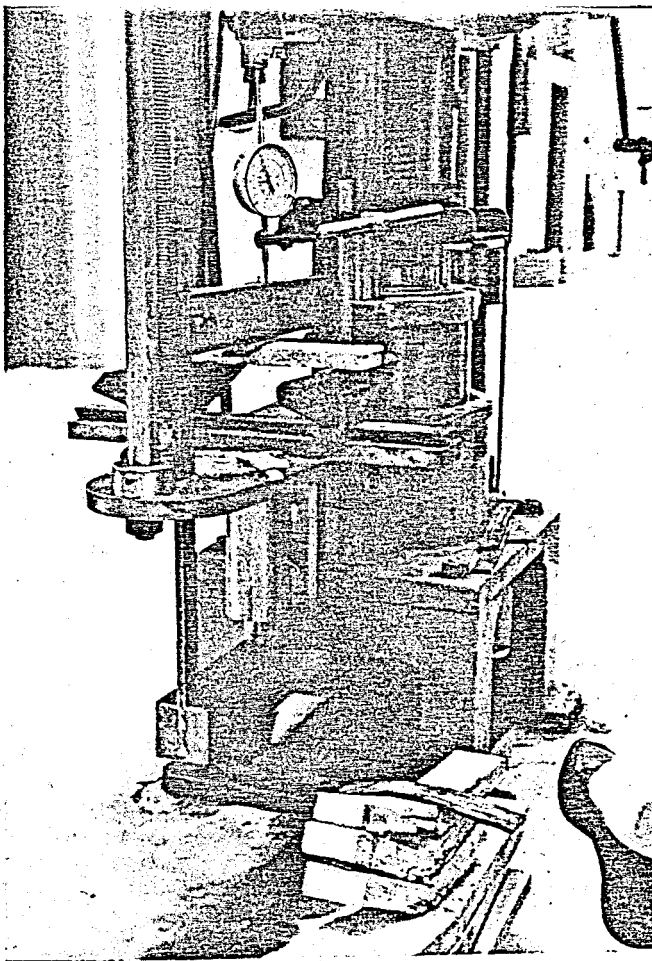


Figure 3.3 Testing machine used for simple beam flexura tests on small samples.

Third flexural test were performed on full size ferrocement samples under four equal concentrated forces spaced at 16 cm. from each other and from the supports, simulating evenly distributed loading. The scope of these test series was to determine the suitability of ferrocement to be used as a roofing material. Four layers square woven mesh in the longitudinal direction which gave the optimum performance in the previous tests on small samples were used throughout these tests.

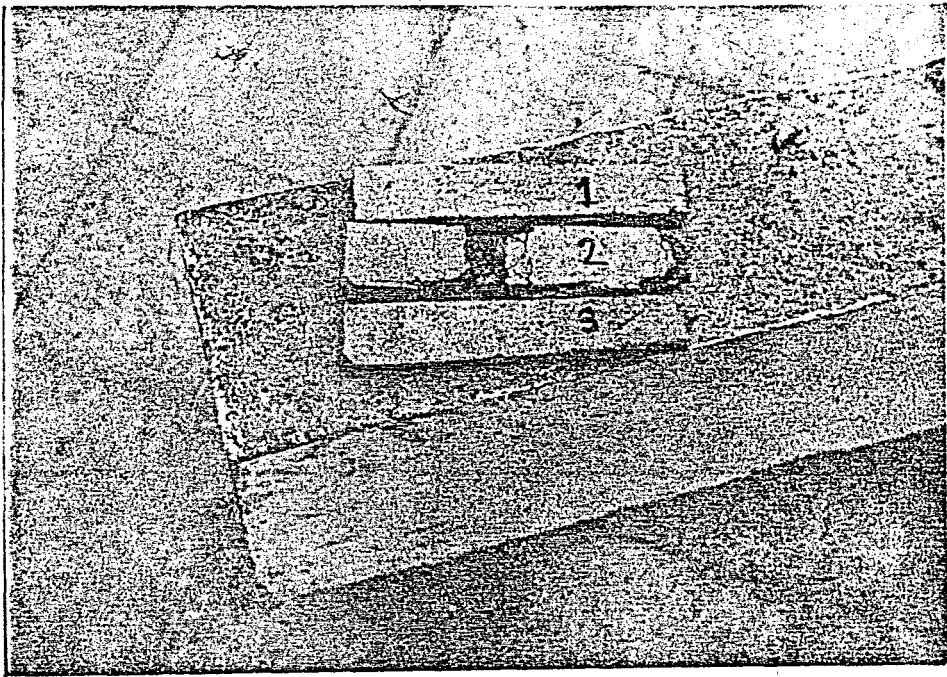


Figure 3 .4. The appearance of the ferrocement samples after heating to 800°C temperature.

- 1) Square wire in the longitudinal direction (Cracked)
- 2) Chicken wire in the lateral direction (broken in to pieces)
- 3) Expanded metal in the lateral direction.(cracked)

Stress, strain, deflection, curvature, and crack development values were measured under load, and were shown in appendix H. Final results were shown in Tables 3.7. Moment-curvature, moment-deflection, moment-strains, moment-crack width, moment-crack spacing, and Moments ratio-rigidity diagrams were drawn and shown in Figs 4.9 - 4.14. Flexural rigidity of ferrocement samples was calculated from deflection or curvature as follows

$$EI \text{ (Nxmm}^2\text{)} = \frac{4.06 \times 10^6 \cdot G \text{ (N)}}{\frac{\delta}{2} \text{ (mm)}}, \text{ and } EI \text{ (Nxmm}^2\text{)} = \frac{120 \cdot G \text{ (N)}}{\frac{\nabla \theta}{\nabla x} \text{ (}\frac{1}{\text{mm}}\text{)}}$$

In addition to this the creep behaviour of ferrocement as a function of loading duration was observed under 200.60 N, and 402.55 N constant total loads during 20 days. Deflection, strains, curvature values were determined under these constant loads. These values were shown in appendix H. Final results are in Table 3.8. Deflection-time, and curvature-time diagrams were drawn and shown in Figures 4.15, 4.16.

TABLE 3.5 Simple Beam Flexure Test Results of Ferrocement Samples at 18°C Curing Temperature.

Mesh Detail					Properties at First Crack					Properties at Ultimate Load				
Type	Orientation	Number	V _f %	S _f	$\frac{EI_{cr}}{EI_o}$	σ_{cr} MN/m ²	$\frac{\sigma_{cr}}{\sigma_o}$	U _{cr} N X m	$\frac{U_{cr}}{U_o}$	$\frac{EI_u}{EI_o}$	σ_u MN/m ²	$\frac{\sigma_u}{\sigma_o}$	U _u N X m	$\frac{U_u}{U_o}$
None	—	0	0	0	1.00	4.79	1.00	0.087	1.00	1.00	4.79	1.00	0.087	1.00
Square Mesh	Longitudinal	2	0.99	0.056	1.34	5.32	1.11	0.189	2.16	0.175	10.72	2.23	9.11	104.7
		4	1.98	0.112	1.7	5.63	1.173	0.177	2.23	0.212	13.74	2.86	12.44	143
	45° Inclined	2	0.99	0.056	1.26	4.9	1.017	0.117	1.34	0.152	5.39	1.12	2.09	23.9
		4	1.98	0.112	1.534	5.59	1.16	0.270	3.1	0.206	8.99	1.87	4.09	46.9
Expanded Metal	Longitudinal	2	0.30	0.039	1.2	7.58	1.58	0.169	1.94	0.610	7.58	1.58	0.169	1.94
		4	0.60	0.078	1.03	6.99	1.46	0.210	2.41	0.49	7.51	1.56	0.64	7.36
	Lateral	2	0.30	0.039	1.01	6.42	1.34	0.132	1.52	0.56	6.82	1.42	0.58	6.67
		4	0.60	0.078	0.905	5.63	1.17	0.172	1.98	0.432	5.74	1.19	0.432	4.96
Chicken Wire	Longitudinal	2	0.24	0.018	1.2	5.29	1.10	0.108	1.24	0.510	5.44	1.13	0.396	4.55
		4	0.48	0.036	1.156	5.5	1.15	0.161	1.85	0.255	5.84	1.22	1.96	22.5
	Lateral	2	0.24	0.018	1.5	5.22	1.09	0.159	1.83	0.409	5.42	1.13	1.09	12.52
		4	0.48	0.036	1.075	5.51	1.15	0.157	1.80	0.282	5.51	1.15	1.57	18.

TABLE 3.6 Simple Beam Flexure Test Results of Ferrocement Samples After Heating up to 800°C Temperature.

Mesh Detail					Properties at First Crack						Properties at Ultimate Load					
Type	Orien tation	Number	V_f %	S_f mm ⁻¹	EI_{cr2} Nxm ²	$\frac{EI_{cr2}}{EI_{cr1}}$	σ_{cr2} MN/m ²	$\frac{\sigma_{cr2}}{\sigma_{cr1}}$	U_{cr2} Nxm	$\frac{U_{cr2}}{U_{cr1}}$	EI_{u2} Nxm ²	$\frac{EI_{u2}}{EI_{u1}}$	σ_{u2} MN/m ²	$\frac{\sigma_{u2}}{\sigma_{u1}}$	U_{u2} Nxm	$\frac{U_{u2}}{U_{u1}}$
None*	—	0*	0	0	—	—	—	—	—	—	—	—	—	—	—	—
Square Mesh	Longitu dinal	2	0.99	0.056	39.4	0.41	1.72	0.32	0.24	1.25	7.96	0.35	6.57	0.61	2.32	0.25
		4	1.98	0.112	55.2	0.39	3.17	0.56	0.14	0.79	11.4	0.69	6.74	0.49	4.19	0.34
	45° Inclined	2	0.99	0.056	19.0	0.21	1.89	0.39	0.074	0.63	4.67	0.30	2.19	0.40	0.71	0.34
		4	1.98	0.112	36.1	0.29	1.69	0.30	0.038	0.14	6.10	0.18	3.00	0.33	1.11	0.27
Expan ded Metal	Longitu dinal	2	0.30	0.039	74.0	0.88	0.91	0.12	0.002	0.011	2.08	0.02	1.13	0.15	0.18	0.71
		4	0.60	0.078	83.3	0.85	1.23	0.18	0.004	0.017	3.70	0.14	1.85	0.25	0.35	0.55
	Lateral	2	0.30	0.039	28.3	0.38	2.04	0.32	0.04	0.29	6.85	0.17	3.54	0.52	0.83	0.14
		4	0.60	0.078	18.9	0.25	3.04	0.54	0.10	0.60	3.41	0.13	4.23	0.61	2.27	0.53
Chick en Wire	Longitu dinal	2	0.24	0.018	73.2	0.86	0.72	0.14	0.02	0.22	1.68	0.05	0.98	0.18	0.31	0.78
		4	0.48	0.036	34.3	0.45	2.66	0.48	0.09	0.53	8.18	0.26	3.59	0.61	0.92	0.47
	Lateral	2*	0.24	0.018	—	—	—	—	—	—	—	—	—	—	—	—
		4	0.48	0.036	30.3	0.47	0.81	0.15	0.004	0.03	0.67	0.01	0.81	0.15	0.39	0.25

* Specimens completely destroyed after heating to 800° temperature and could not be tested.

TABLE 3.7 Flexural Test Results of Full Size Ferrocement Samples.

Sample Number	Total Load $G=4P$ N	$M_{max}=0.12G$ Nxm	Mid span Deflection $\delta_{1/2}$ mm	Tensile Strain ϵ_{bottom} $\times 10^{-3}$	Compressive Strain ϵ_{top} $\times 10^{-3}$	Mid span Curvature $\Delta\theta=2\theta_2$ $\times 10^{-4} (rad)$ $\Delta x=160mm$	$\frac{\Delta\theta}{\Delta x} \times 10^{-4}$ 1/mm	Crack Width mm	The Number of Cracks	Average Crack Spacing mm
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
	164.10	19.70	0.31	0.040	-0.020	16.20	0.101			
	550.10	66.00	0.66	0.080	-0.055	39.44	0.246			
	1030.0	123.61	1.50	0.200	-0.175	71.34	0.446			
	1610.0	193.20	2.82	0.495	-0.345	412.00	2.575			
	1910.0	229.00	7.89	3.245	-1.200	699.84	4.374			
	2310.0	277.00	15.80	4.580	-2.005	816.00	5.102			
	2550.0	306.00	19.94	6.830	-2.505					
	2850.0	342.00	26.05	9.155	-3.210					
	4430.0	531.00						0.46*	9.00*	17.70*
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
	170.0	20.40	0.38	0.070	-0.025	14.13	0.088			
	690.0	82.80	1.35	0.235	-0.125	34.90	0.218			
	1150.0	138.00	2.48	0.520	-0.280	70.20	0.438			
	1590.0	190.80	7.69	2.710	-0.900	290.32	1.815	0.040	4	40.0
	2070.0	248.40	17.24	6.550	-1.965	605.00	3.780	0.140	6	26.6
	2570.0	308.40	26.76	9.930	-2.960	914.00	5.710	0.220	9	17.7
	3040.0	364.80	39.69	15.040	-4.575			0.300	10	16.0
	3340.0	400.08			-5.464					
	4070.0	488.00						1.260*	10*	16.0*

* Observed after unloading

TABLE 3.8 The Creep Results of Full Size Ferrocement Samples

Sample Number	Load $G=4P$ N	$M_{\max}$ Nxm	Mid-span Deflection $\delta_{\frac{1}{2}}$ mm	Tensile Strain ϵ_{bottom} $\times 10^{-3}$	Compressive Strain ϵ_{top} $\times 10^{-3}$	Midspan Curvature $\Delta\theta = 2\theta_2$ $\times 10^{-4}$ rad. $\Delta x = 160\text{mm}$	$\frac{\Delta\theta}{\Delta x}$ $\frac{1}{\text{mm}}$	Time t hour
1	0	0	0	0	0	0	0	0.00
	200.60	24.072	0.25	0.190	-0.180	5.58	0.034	0.00
			0.41	0.230	-0.250	7.32	0.045	46.50
			0.48	0.275	-0.285	7.975	0.049	71.85
			0.53	0.245	-0.310	8.290	0.051	95.0
			0.62	0.230	-0.360	9.890	0.061	167.0
			0.65	0.200	-0.410	10.450	0.065	214.0
			0.68	0.180	-0.430	10.860	0.067	262.0
			0.70	0.165	-0.470	11.34	0.070	310.0
			0.72	0.160	-0.490	11.83	0.073	405.0
2	0	0	0	0	0	0	0.0	0.0
	402.55	48.306	0.53	0.32	-0.31	10.80	0.067	0.0
			0.85	0.38	-0.385	13.92	0.087	71.0
			0.95	0.41	-0.415	14.88	0.093	117.0
			1.015	0.36	-0.450	15.26	0.095	142.0
			1.06	0.36	-0.490	16.48	0.103	166.0
			1.13	0.35	-0.525	17.58	0.109	238.0
			1.16	0.325	-0.550	19.02	0.115	285.0
			1.185	0.300	-0.580	19.65	0.122	333.0
			1.225	0.280	-0.620	20.31	0.126	405.0

IV. EVALUATION OF THE TEST RESULTS

In this chapter, the results, reported in chapter III will be evaluated. Evaluation of the results will be in two steps.

In the first step, comparisons will be made between the results of different types in order to determine the favorable mesh type. Small size ferrocement samples will be used for this purpose.

In the second step, properties of full-size ferrocement samples with four layers of square woven mesh in the longitudinal direction as the favorable mesh type, will be evaluated for the purpose of using ferrocement as roofing material.

IV.1 DETERMINATION OF THE FAVORABLE MESH TYPE

Results of charpy impact tests, tension tests, ~~flexure~~ tests and high temperature tests will be used in this evaluation.

IV.1.1 Evaluation of The Charpy Impact Test Results

The results of charpy impact test summarized in Table 3.3 were plotted in figure 4.1 as functions of mesh type, mesh parameter volume

concentration and orientation of reinforcement.

Charpy impact strength of ferrocement varies depending on the mesh type. It can be seen that square woven mesh gives the highest values, and expanded metal gives the smallest values for the same volume concentration.

Volume concentration is the second important parameter. Charpy impact strengths of ferrocement samples increase with increasing reinforcement concentration. But these increments differ, depending on the mesh types. For an optimum volume concentration of 2 % of the reinforcing mesh, impact strength may reach a value of approximately 8 times that of the plain mortar for square woven mesh in the longitudinal and in the 45° inclined directions. The values for square woven mesh in the 45° inclined direction are largest approximately 3 times that of the expanded metal values, and 1,2 times that of the chicken wire values at the reinforcement concentration of 0.5 %.

Orientation seems not to be very important for the charpy impact strengths of all mesh types. Values obtained for the same mesh type in different directions are approximately equal to each other for the same volume concentration except the square woven mesh. Square woven mesh in the 45° inclined direction is largest about 1.5 times that of the square woven mesh in the longitudinal direction at a volume concentration of 1 %. This can be explained due to the higher absorbed energy in the square mesh at 45° inclination because of larger deflections.

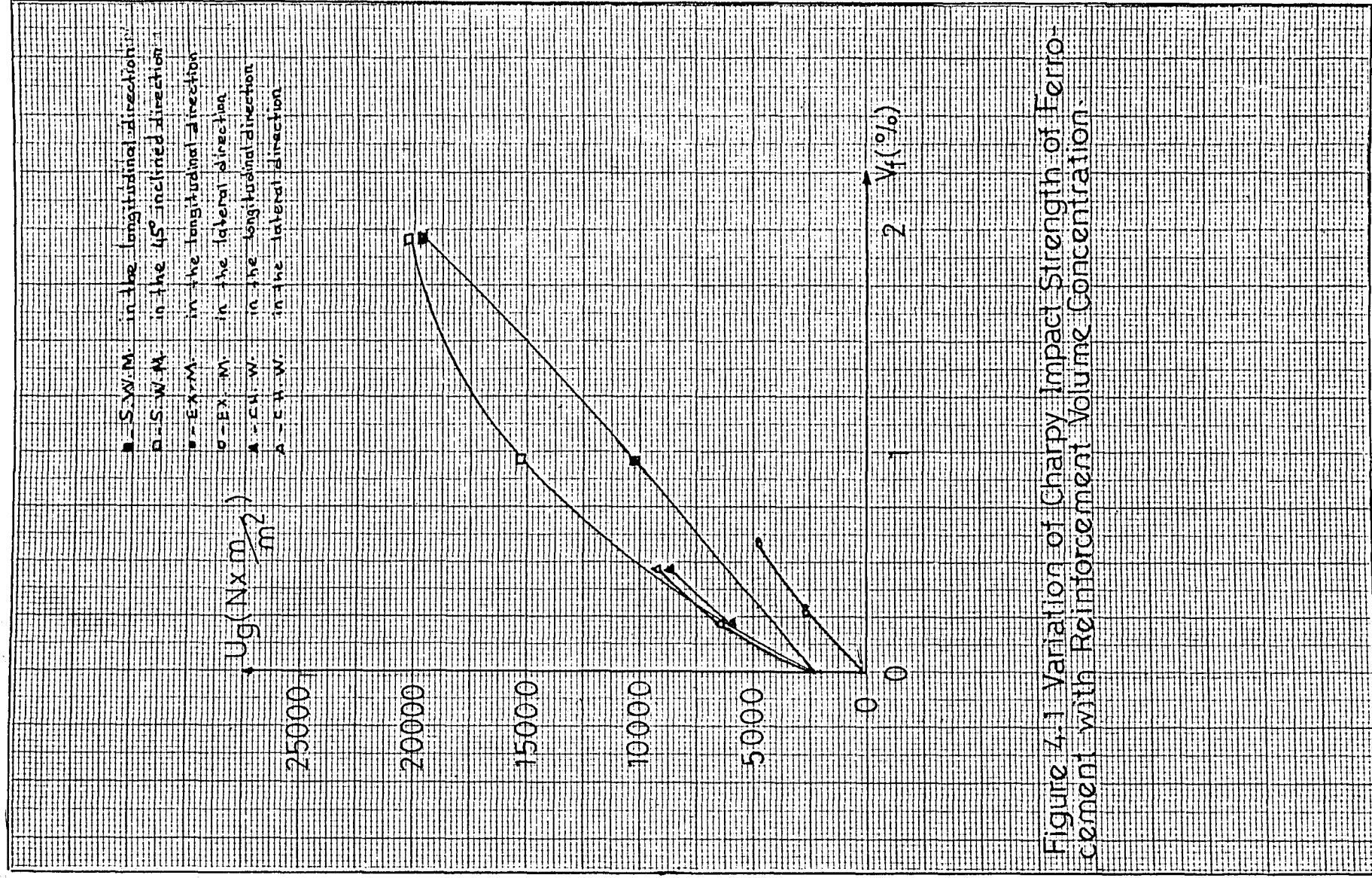


Figure 4.1 Variation of Charpy Impact Strength of Ferrocement with Reinforcement Volume Concentration.

IV.1.2 Evaluation of Direct Tensile Tests of Ferrocement Samples

The results of tensile tests on ferrocement summarized in Table 3.4 were plotted in Figure 4.2 as function of the mesh parameter "Volume concentration"

Tensile properties of ferrocement samples depend on the type, concentration, and orientation of the reinforcement.

The type is the most important parameter. It is seen that expanded metal and square woven mesh have different tensile stress values of the same volume concentration at first crack, and ultimate load. Tensile value of square woven mesh is the largest approximately 3 times that of the plain mortar at first crack and 6.5 times that of the plain mortar at ultimate load for a volume concentration of 2 %.

The variation of the cracking tensile stresses seen in Figure 4.2 a, differ depending on the volume concentration. Although the tensile strength of square woven mesh in the longitudinal direction increase with increasing reinforcement concentration until reaching a maximum at reinforcement concentration of 2 %, square woven mesh in the 45° inclined direction reaches a maximum at a reinforcement concentration of 1 %, and after this point begins to decrease. The variation of the tensile stress of expanded metal in the longitudinal direction has also a similar character, but in the lateral direction it seems to have an opposite character. The ultimate tensile strengths of both mesh types, increase with increasing volume concentration. The increase for square woven mesh is more rapidly than for expanded metal.

Orientation is also important parameter for tensile properties

of ferrocement samples. It is seen that the tensile stresses for the same mesh types in different orientations are not the same. The tensile stresses at first crack and at ultimate load for square woven mesh in the longitudinal direction are approximately 3 times, and 1.85 times higher than its tensile stresses in the 45° inclined direction respectively. These variations for different orientations of two mesh types may be seen in Fig. 4.2 b.

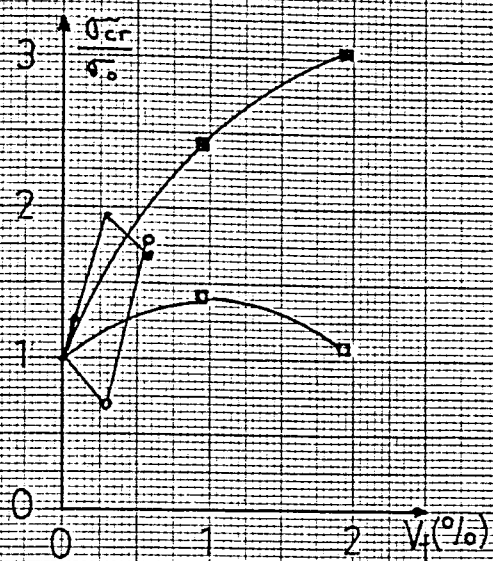
Modulus of elasticity of ferrocement samples are different for both types of meshes. Modulus of elasticity of square woven mesh is the largest approximately 1.75 times that of the plain mortar at a volume concentration of 2 %. The modulus of elasticity of square woven mesh increase with increasing the volume concentration, but modulus of elasticity of expanded metal decrease with increasing volume concentration until reaching a volume concentration of 0.3 % and after this value, it begins to increase. Modulus of elasticity of square woven mesh in the 45° inclined direction is highest approximately 1.06 times that of the square woven mesh in the longitudinal direction at a volume concentration of 2 %.

IV1.3 Evaluation of the flexural properties of ferrocement

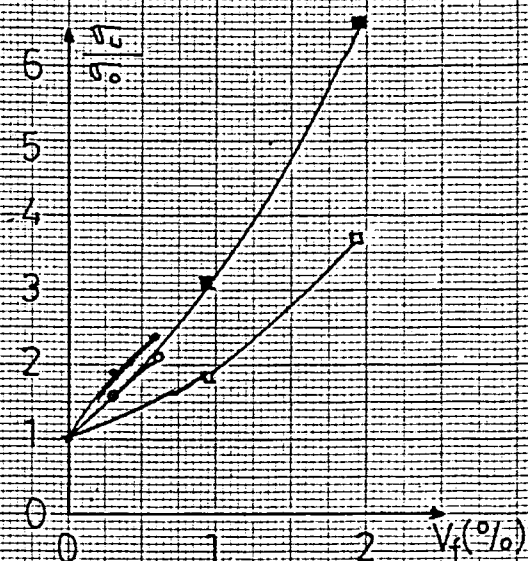
Test results reported in Table 3.5 were plotted in Figures 4.3 through Figure 4.5 as functions of the mesh parameter " volume concentration" (V_f %).

a. Evaluation of the flexural Strengths of Ferrocement

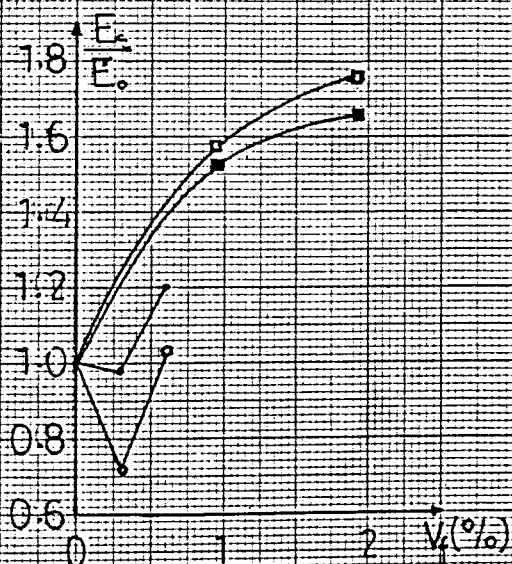
Flexural strengths of the ferrocement samples vary depending on the type, volume concentration, and orientation of the reinforcement.



a) Strength at First Crack



b) Strength at Ultimate Load



c) Modulus of Elasticity

- SW.M. in the longitudinal direction
- SW.M. in the 45° inclined direction
- PL.M. in the longitudinal direction
- EX.M. in the lateral direction

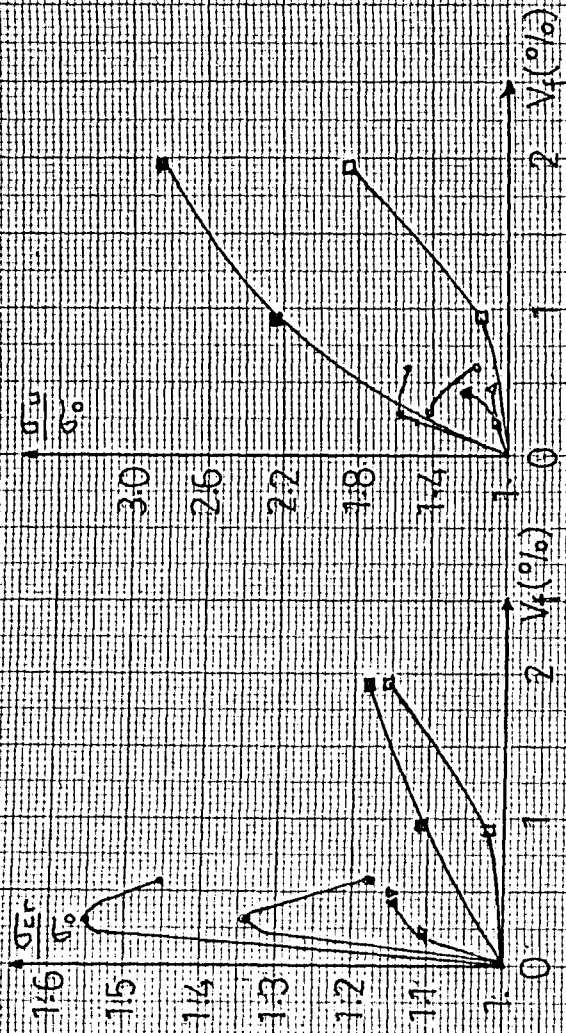
Figure 4.2 Variation of Effective Tensile Properties of Ferrocement Sample with Volume Concentration

The variation of the cracking strengths shown in Figure 4.3 a indicate that expanded metal gave the highest results among the three mesh types, but Figure 4.3b shows that the values for square woven mesh are largest, approximately 3 times that of the expanded metal values, and 1.3 times that of the chicken wire values at the ultimate load.

The strengths of all mesh types increase with increasing reinforcement concentration, but the values of expanded metal begin to decrease after reaching a maximum at a volume concentration of 0.3 % at first crack and at ultimate load. Previous experimental works shows of the square woven mesh appear to decrease after reaching a maximum point at about 2 % volume concentration.

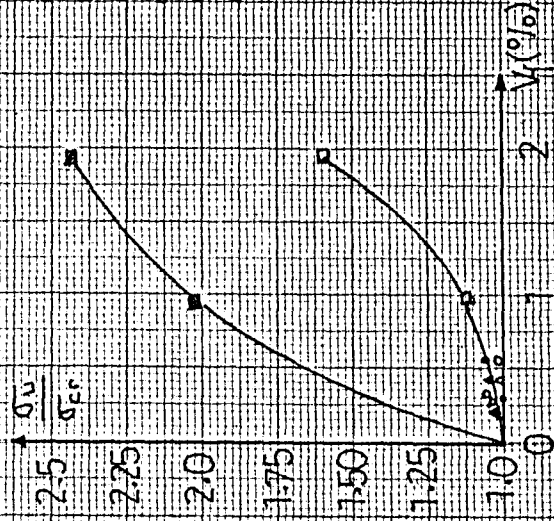
Orientation is the third important parameter. Figure 4.3 shows that the strengths of the same mesh type vary for different orientations of the reinforcement. For example, the strength of square woven mesh in the longitudinal direction is 1.5 times larger than its strength in the 45 inclined direction. The differences due to orientation are shown in Figures 4.3a,b, and c.

Ratios of flexural stresses at cracking and at ultimate load were plotted in Fig. 4.3 c as a function of V_f . These results indicate that with the exception of the square woven mesh in the longitudinal direction, all other mesh types of direction gave the same $\frac{\sigma_u}{\sigma_{cr}}$ ratios for the same volume concentration and that the values of square woven mesh in the longitudinal direction are about 2 times larger than for the others.



a) At First Crack

b) At Ultimate Load



c) Ratio of Strengths

- $\sigma_{u,cr}$ in the longitudinal direction
- $\sigma_{u,cr}$ in the 45° inclined direction
- $\sigma_{u,cr}$ in the longitudinal direction
- ◇ $\sigma_{u,cr}$ in the lateral direction
- ▲ $\sigma_{u,cr}$ in the longitudinal direction
- ▼ $\sigma_{u,cr}$ in the lateral direction

Figure 4-3 Variation of Relative Flexural Strength of Ferrocement with Reinforcement Volume Concentration.

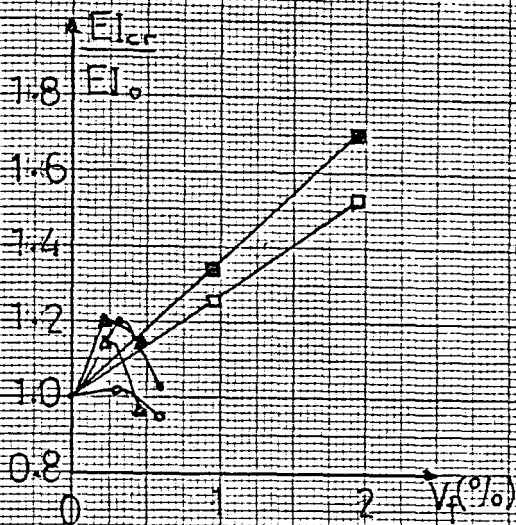
b. Evaluation of the flexural rigidities of ferrocement

The variation of the flexural rigidities seen in Figure 4.4. indicate that the rigidities were effected by type, orientation, and volume concentration.

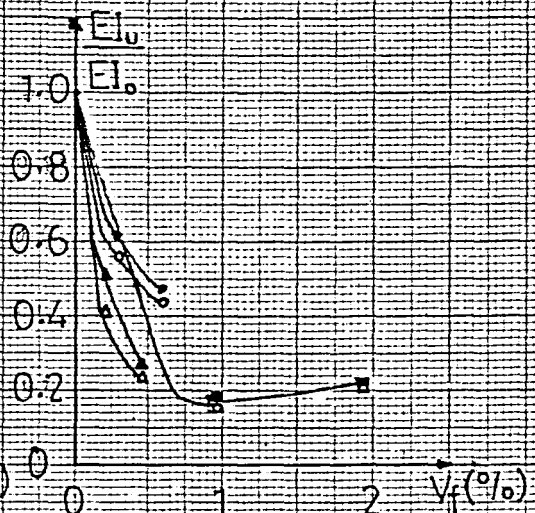
Square woven mesh gives the largest values at first crack and reaches a value of approximately 1.5-1.7 times that of the plain mortar, but on the other hand expanded metal gives the largest values at ultimate load, and its value reaches approximately 0.45-0.60 times that of the plain mortar.

The rigidities of all mesh types depend also on the volume concentration. The values of square woven mesh in both directions increase with increasing reinforcement concentration, and reach a maximum at a volume concentration of 2 % for the first crack, but the values of the other types, the first increase up to certain volume concentrations after which they begin to decrease as seen in Figure 4.3a. After cracking the rigidities of all mesh types fall to much smaller levels than that of the plain mortar, and at ultimate load, their values seem to decrease with increasing reinforcement concentration. The rigidity of the cracked ferrocement with square woven mesh is the smallest approximately one fifth of that of the plain mortar.

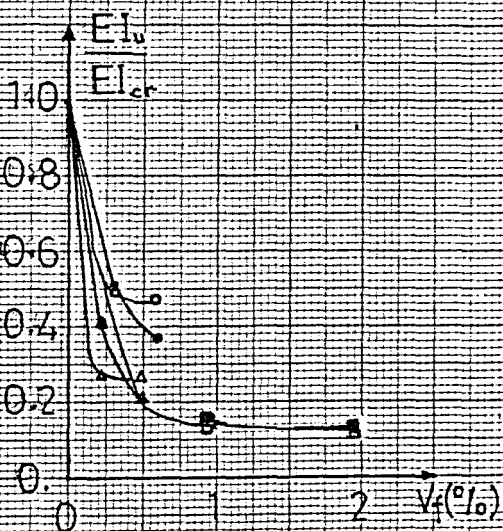
Figure 4.4 shows that orientation seems to be important for the rigidities at first crack, but seems to loose its importance for the rigidities at the ultimate load. The rigidity of square woven mesh in the longitudinal direction is largest, 1.1 times that of its rigidity in the 45° inclined direction at first crack, but the rigidities of the two



a) At First Crack



b) At Ultimate Load



c) Ratio of Rigidities

Figure 4.4 Variation of Relative Rigidities with Reinforcement Volume Concentration

directions become equal to each other at ultimate load. The variations of the rigidities of the various mesh types in different orientations are shown in Figure 4.4.

Figure 4.4c shows that the largest loss of rigidities for the square woven mesh after first cracking. The value at ultimate load decreases to about 12 % of its first crack value for a volume concentration of 2 %.

c. The variation of relative flexural energies of ferrocement

Figure 4.5 showing the comparison of the areas under the load-deflection curves indicates that expanded metal in the longitudinal direction takes the largest flexural energy at first crack for the same volume concentration, but square woven mesh in the longitudinal direction has the highest energy of 140 times that of the plain mortar at a volume concentration of 2 %, and approximately 2.5 times that of the other types at a volume concentration of 0.3 % at ultimate load. Figure 4.5c shows that the values of the flexural energy for the square woven mesh in the longitudinal direction at ultimate load are approximately 70 times larger than those of its values at first crack, but this ratio for the other types is very small, indicating that the other mesh types do not absorb much energy after first cracking.

The flexural energies of all types at first crack, and at ultimate load increase with increasing reinforcement concentration.

Flexural energies are effected by orientation. The flexural energy of the square woven mesh in the longitudinal direction being approximately 3.1 times greater than its energy in the 45° inclined direction at ultimate

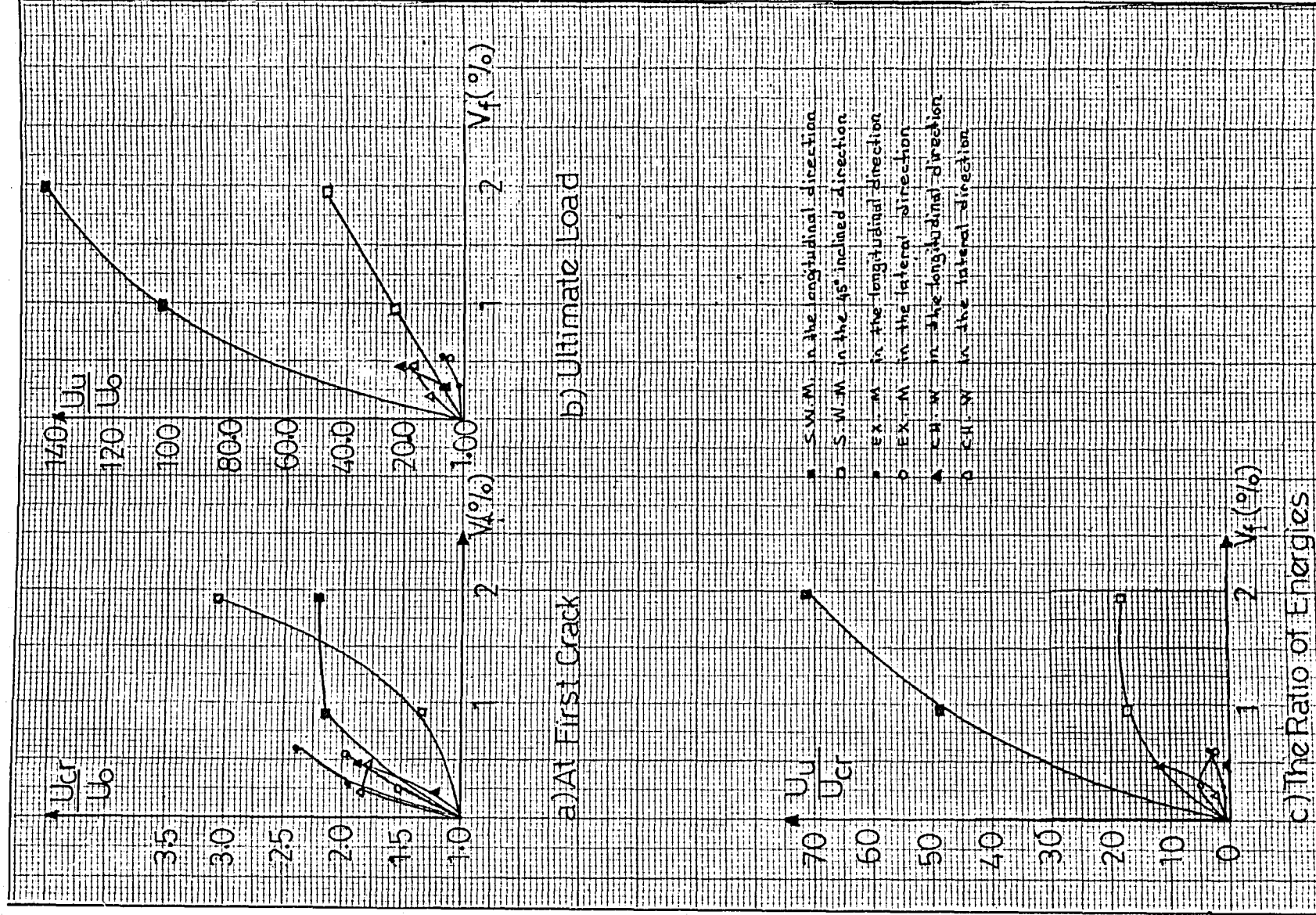


Figure 4.5 Variation of Relative Flexural Energies of Ferrocement with Volume Concentration

load for a volume concentration of 2 %. Variations of flexural energies of all mesh types depending on orientation can be seen from figures 4.5 a,b,c.

IV.1.4 Evaluation of the Effect of Heating to 800 on Flexural Properties of Ferrocement

The variation of these results were not uniform, because the tests were made on small numbers of ferrocement samples. The results for few samples can not give very definite results. Therefore the evaluation of these test results were made in terms of general trends.

Results of heating to 800 C on flexural strengths shown as bands shaded in Figure 4.6 indicate that the strengths seemed to increase proportionally with increasing reinforcement volume concentration, and their values are reduced to small fractions of their original values before heating to 800 C. They show averages of 15 %, and 30 % of that of their original values at both first crack and ultimate load for volume concentrations of 0.5% and 1.0 % respectively. Their values at first crack and ultimate load are approximately 50 % of the original values for a volume concentration of 2 %.

Results of this heating on flexural rigidity shown in figure 4.7 indicate that the rigidities at first crack drop to about 30 % of their original values. The lowered rigidities at ultimate load seemd to increase proportionally with increasing reinforcement volume concentration. They seem to have average values of 15 % that of originals values, for a volume concentration of 0.5. Their values at ultimate load are approximately 70 % of the original values for a volume concentration of 2 %.

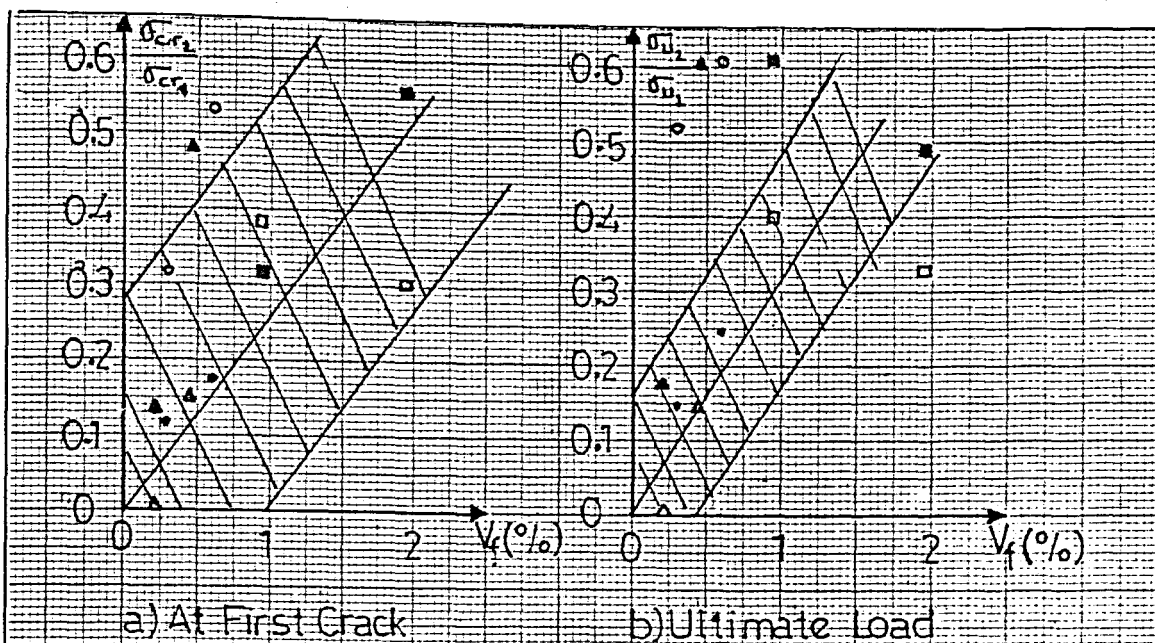


Figure 4.6 Relative Effect of Heating at 800°C on Flexural Strength of Ferrocement.

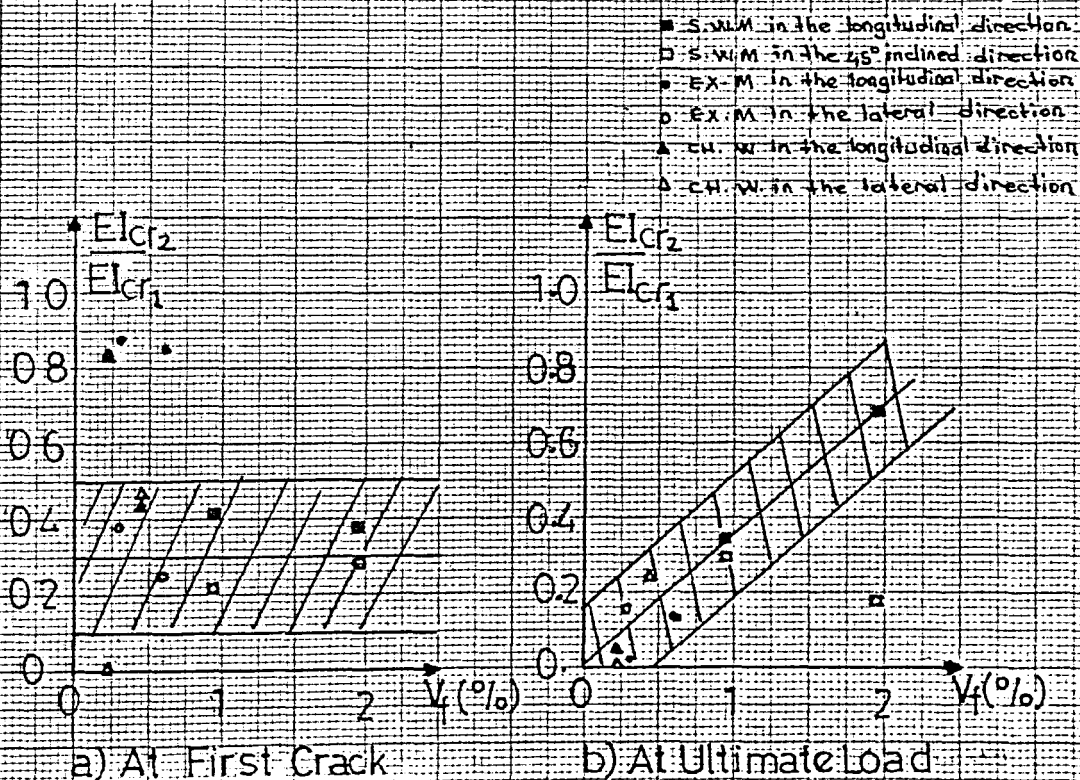


Figure 4.7 Relative Effect of Heating at 800°C on Flexural Rigidity of Ferrocement

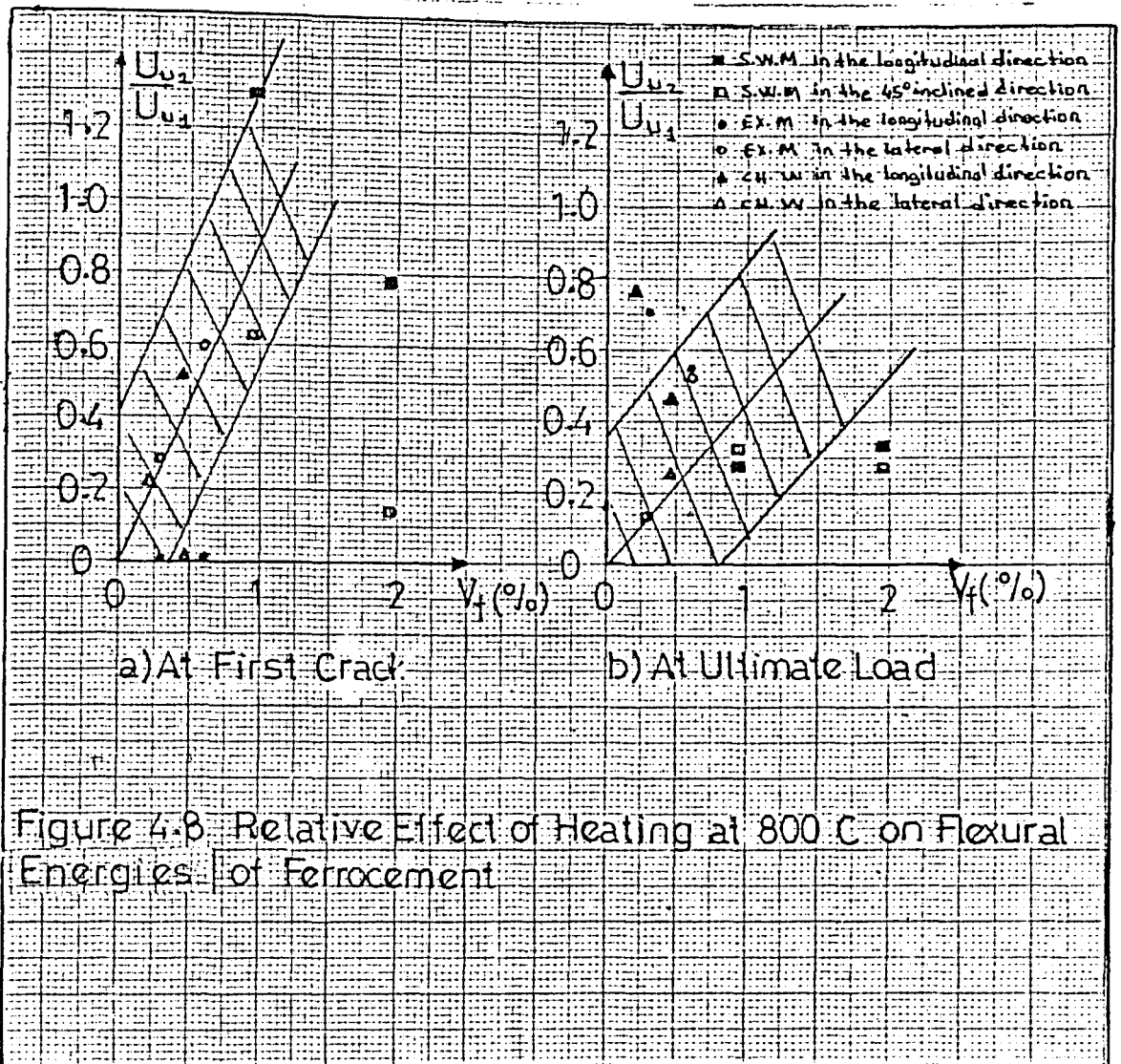


Figure 4-8 Relative Effect of Heating at 800 C on Flexural Energies of Ferrocement

Results of this heating on flexural energy shown in figure 4.8 indicate that the energies seem to increase proportionally with increasing reinforcement volume concentration, and their values drop to small fractions at their original values. They seem to have averages of 30 % that of their original value at first crack and at ultimate load for a volume concentration of 0.5 % respectively.

IV.2 EVALUATION OF FLEXURAL PROPERTIES OF FULL-SIZE FERROCEMENT

As seen in Figure 4.9 the moment deflection diagram of ferrocement samples under increasing load went through three stages:

In first stage, the displacements under increasing load increased linearly until the first crack. The first crack occurred at an average cracking moment of 160 Nxm. The cracking deflection was 2.25 mm and this value was 0.3 % of the free span of the sample, which was 800 mm. The deflections increased also linear in the second stage after the first crack, but at a much faster rate. This was due to the reduction of flexural rigidity. The deflection increased linearly until reaching a moment of 380 Nxm at the beginning of the yielding of the mesh. The deflection at yield point was 34 mm, and this value was 4.25 % of the free span of the ferrocement samples. The deflections also increased after yield point until reaching a moment value of 510 Nxm in the third stage deflections at this moment value could not be determined.

The moment-curvature relation shown in figure 4.10 indicates very similar character. First crack point occurs at a moment of 160 Nxm and yield point occurs at 380 Nxm as before. Unit curvature is $0.8^{-4} \frac{1}{\text{mm}}$ at

the first crack, and 9.6×10^{-4} 1/mm. at a yield point.

Figure 4.11 shows that, after the occurrence of the first crack at a moment of 160 Nxm, the crack width began to increase linearly with increasing moment, until reaching the yield point at a moment of 380 Nxm. The observable smallest crack width near the first cracking being determined as 0.04 mm. at a moment of 190 Nxm and 0.32 mm at the yield point moment of 380 Nxm. After the yielding this crack width increased to the ultimate moment of 510 Nxm, and after unloading the remaining crack width of ferrocement sample was 1.26 mm.

The variation of the average crack spacing of the ferrocement sample at its mid-span section of 16 cm. versus moment shown in Figure 4.12 indicates that after the occurrence of the first crack, average crack spacing was 40 mm, and that it decreased with increasing moment, and reached an end value of 16 cm. at the yield point moment of Nxm. After this value, it was constant. This means that the number of cracks remained after this point and the cracks started to expand excessively.

Extreme fiber strain-moment relationships shown in Figure 4.13 were a further check for the accuracy of the cracking and yield point moments determined from the previous figures.

Figure 4.14 shows the variation the rigidities of ferrocement with moments ratio. The rigidities of the ferrocement samples in the uncracked stage were 2430×10^6 N x mm² until reaching the cracking moment. But in second stage, after the sample cracked its rigidity suddenly reduced, and dropped to a value of 200×10^6 Nxmm². Flexural rigidities were determined from both curvature-moment, and deflection-moment diagrams.

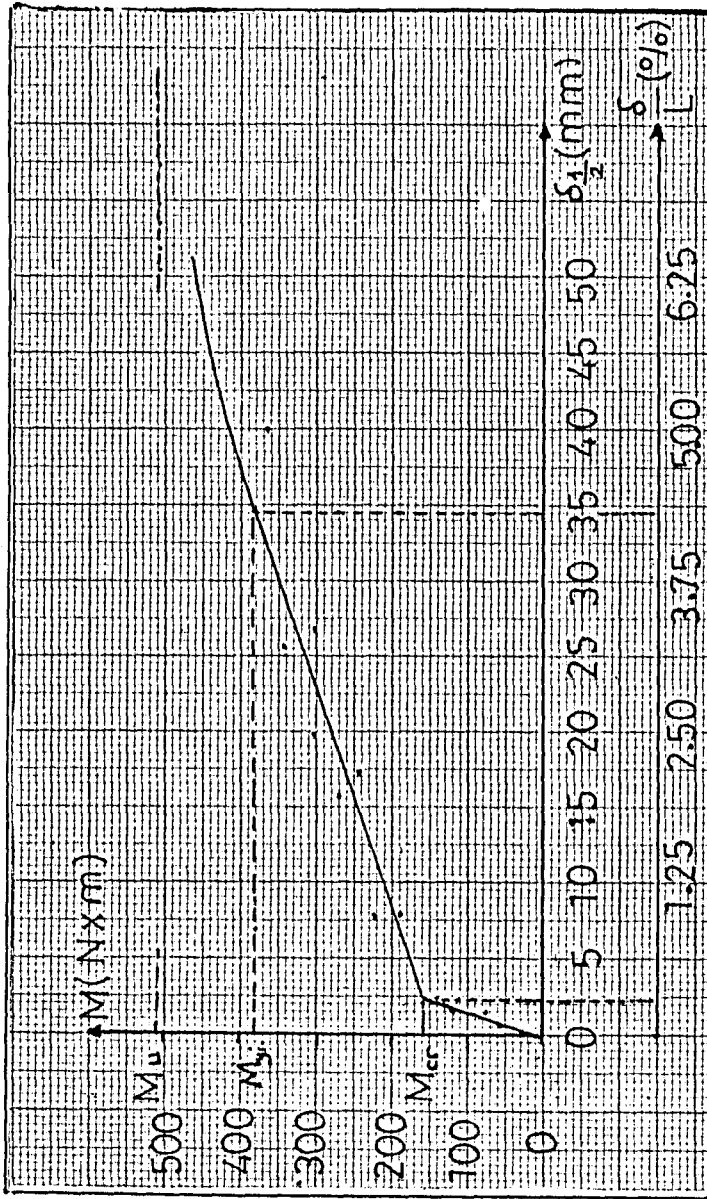


Figure 4-9 Deflection-Moment Relationship of Full Size Ferrocement Samples.

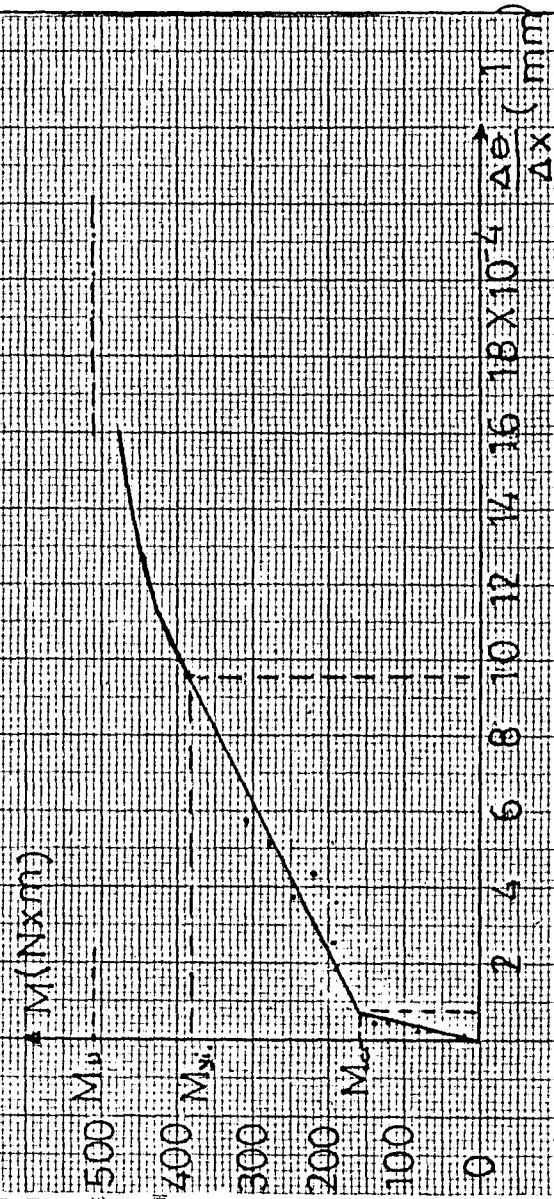


Figure 4-10 Curvature Moment Relationship of Full Size Ferrocement Samples.

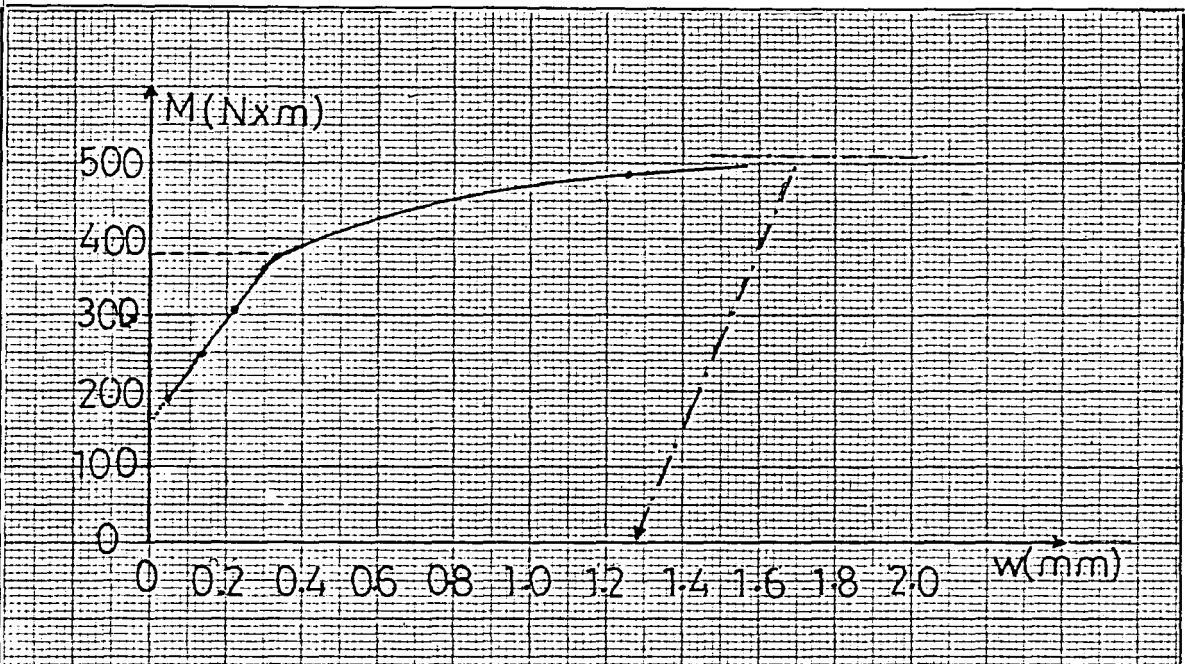


Figure 4.11 Crack Width-Moment Relationship of Full Size Ferrocement Samples.

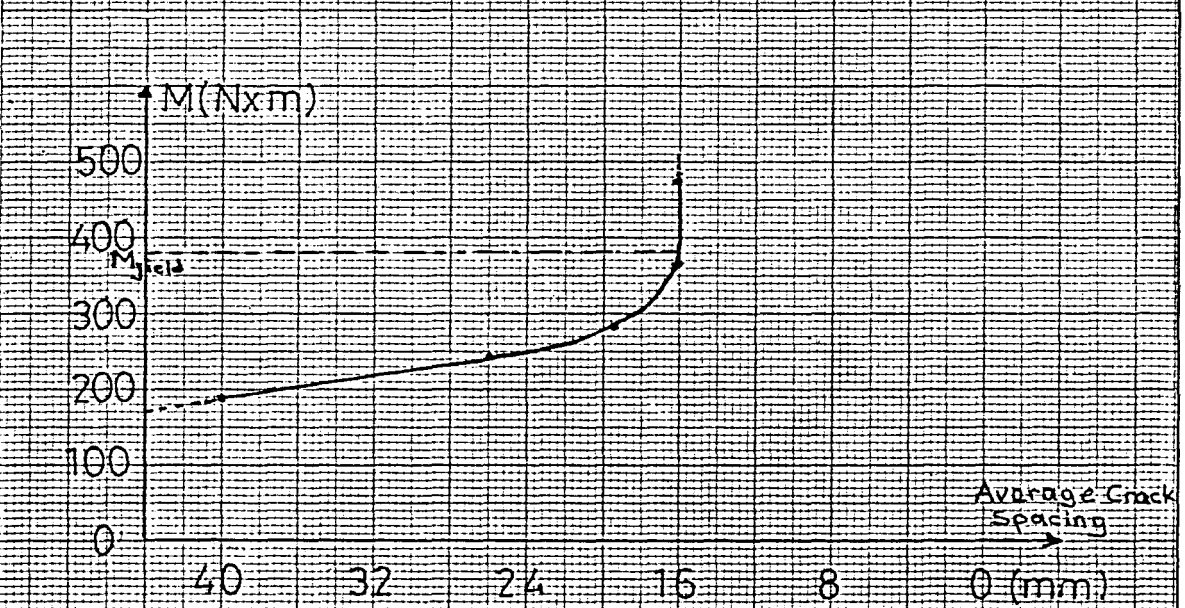


Figure 4.12 Average Crack Spacing-Moment Relationship of Full Size Ferrocement Samples.

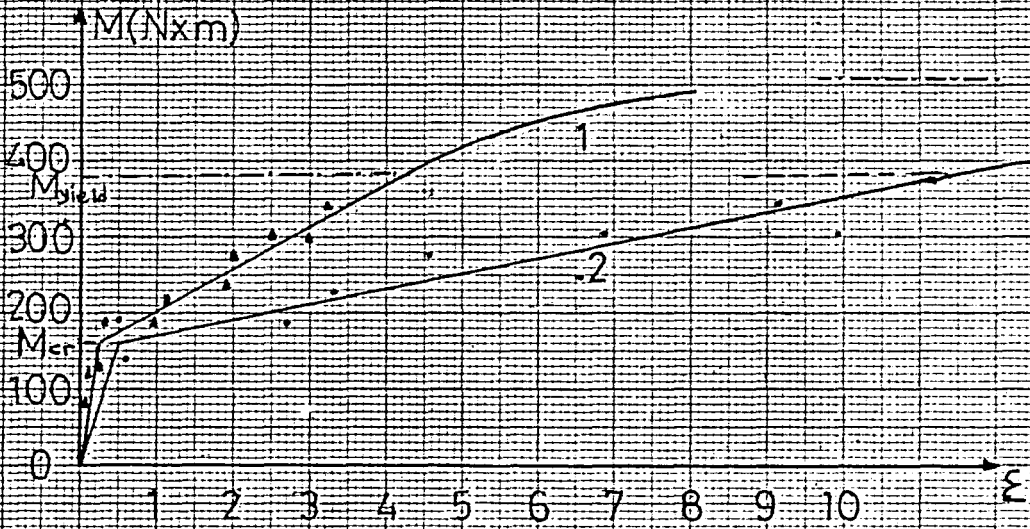


Figure 4-13 Strain Moment Relationship of Full Size Ferrocement Samples; 1-At Bottom, 2-At the Top

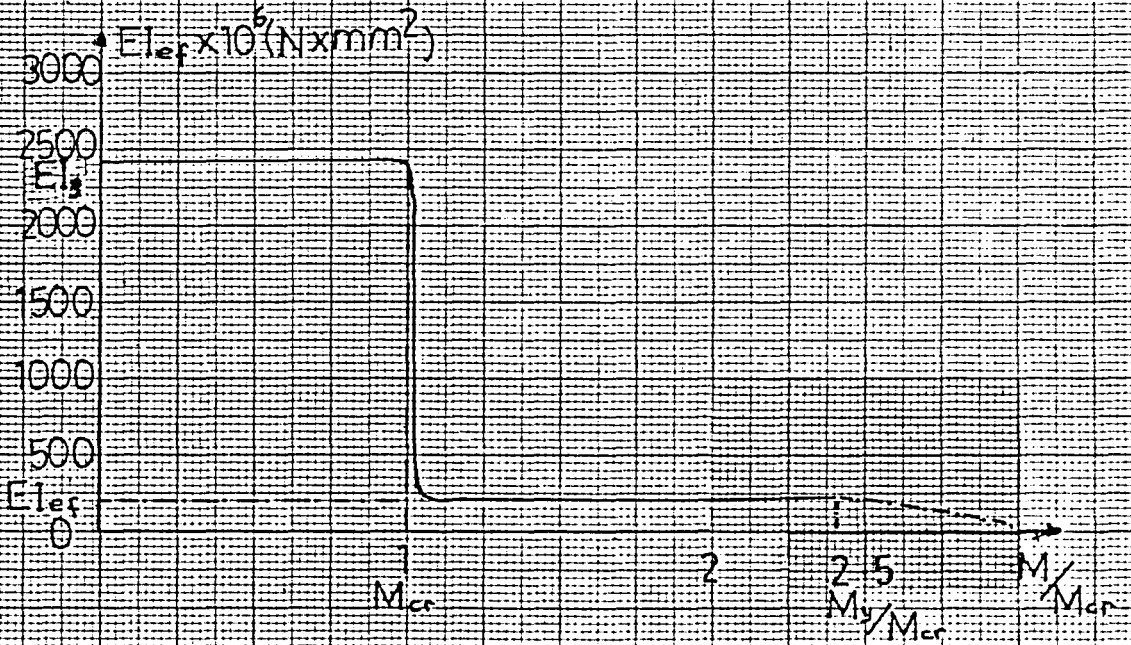


Figure 4-14 Rigidity-Moment Ratio Relationship of Full Size Ferrocement Samples

The values obtained from both methods were near to each other (Formulas were shown in chapter III). This was a check for the accuracy of the results.

IV.2.1 Creep Behaviour of Full-sile Ferrocement Samples

Figures 4.15 and 4.16 show that long time deflections, and curvatures of ferrocement samples under constant load depend on time. Elastic deflections of ferrocement samples under the loads of 402.55 N, and 200.6 N were 0.53 mm. and 0.25 mm. respectively. Elastic unit curvatures under these loads were 0.041×10^{-4} 1/mm. and 0.034×10^{-4} 1/mm. respectively. These deformations increase with time. This deformation on with time is called creep. As it is seen in figure the rate is very rapid when the load is first applied, and decreases exponentially with time. After a long time the deformation will cease. Approximately 17 days, after first loading the creep deflections of the ferrocement samples were 0.695 mm. and 0.45 mm. and creep unit curvatures were 0.66×10^{-4} 1/mm., and 0.38×10^{-4} 1/mm. under constant loads of 402.55 N, and 200.6 N. respectively. It is seen that creep deformation tend to become larger than the original elastic deformations at the ends of 17 days.

The following three element mathematical model was applied for predicting the final creep values of the ferrocement samples :

$$\frac{I \delta}{4.06 \times 10^6} = \frac{G}{E_{el}} + \frac{G}{E_{creep}} (1 - e^{-t/T})$$

The constants E_{el} , E_{cr} and T were determined with the help of the experi-

mental curves shown in Fig. 4.15. Final creep values were calculated by taking $t = \infty$ in this model form :

$$\frac{I \delta_{final}}{4.06 \times 10^6} = \frac{G}{E_{el}} + \frac{G}{E_{creep}}$$

$$E_{el} = 9770 \text{ N/mm}^2 = 9770 \times 10^6 \text{ N/m}^2$$

$$E_{creep} = 4981 \text{ N/mm}^2 = 4981 \text{ N/m}^2$$

δ_{final} values for our ferrocement under the load of 200.60 N and 400.55 N.

$$I = \frac{b h^3}{12} = \frac{0.5 \times (0.02)^3}{12} = 0.33 \times 10^6 \text{ m}^4$$

for $G = 200.60 \text{ N}$

$$\frac{0.33 \times \delta_{final}}{4.06} = \frac{200.60}{9770} + \frac{200.60}{4981}$$

$$0.081 \delta_{final} = 0.0205 + 0.0403$$

$$\delta_{final} = 0.75 \text{ mm.}$$

for $G = 400.55 \text{ N}$

$$\frac{0.33 \times \delta_{final}}{4.06} = \frac{400.55}{9770} + \frac{400.55}{4981}$$

$$0.081 \delta_{final} = 0.0410 + 0.0804$$

$$\delta_{\text{final}} = 1.50 \text{ mm.}$$

We can find the creep ratio using the final deflection at $t = \infty$

$$\delta_{\text{final}} = \frac{G}{E_{e1}} + \frac{G}{E_{\text{creep}}} = \delta_{e1} (1+\eta)$$

$$\eta = \text{creep ratio} = \frac{E_{e1}}{E_{\text{creep}}} = \frac{9770}{4981} = 1.96 \cong 2 \text{ times}$$

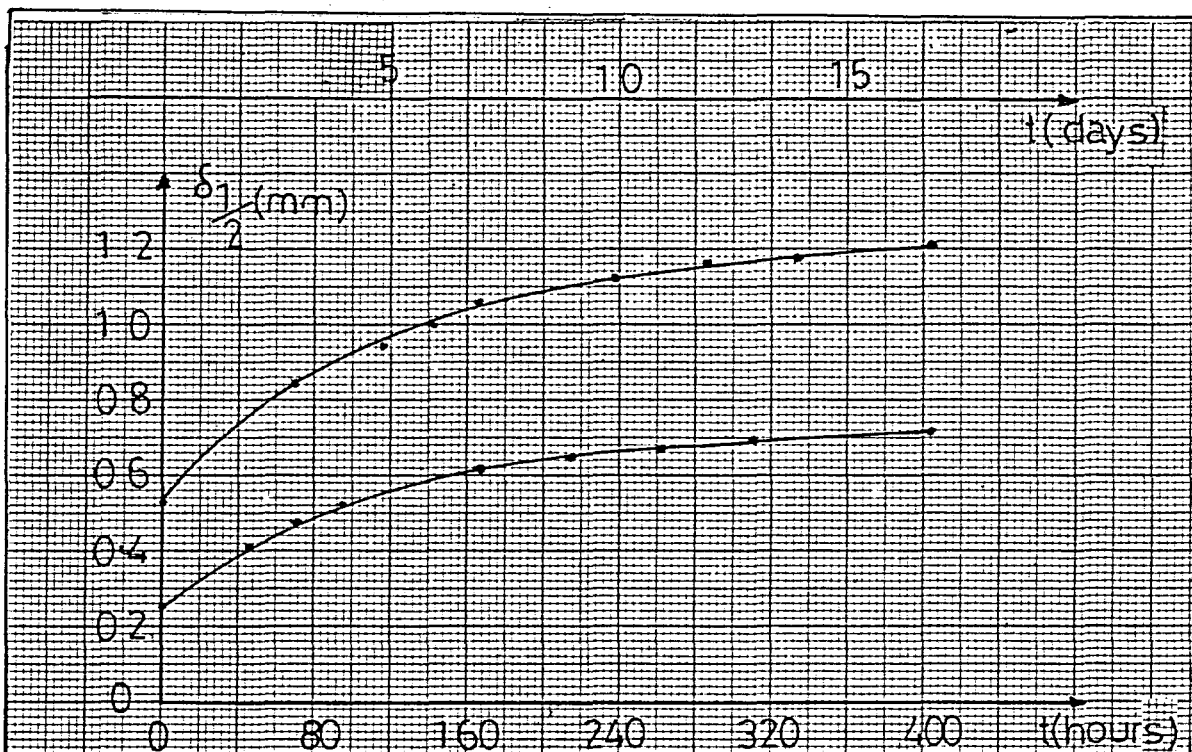


Figure 4.15 Time-Deflection Relationships of Ferrocement Samples for Creep Behaviour Under Loads of 1) 400.55 N, 2) 200.6 N.

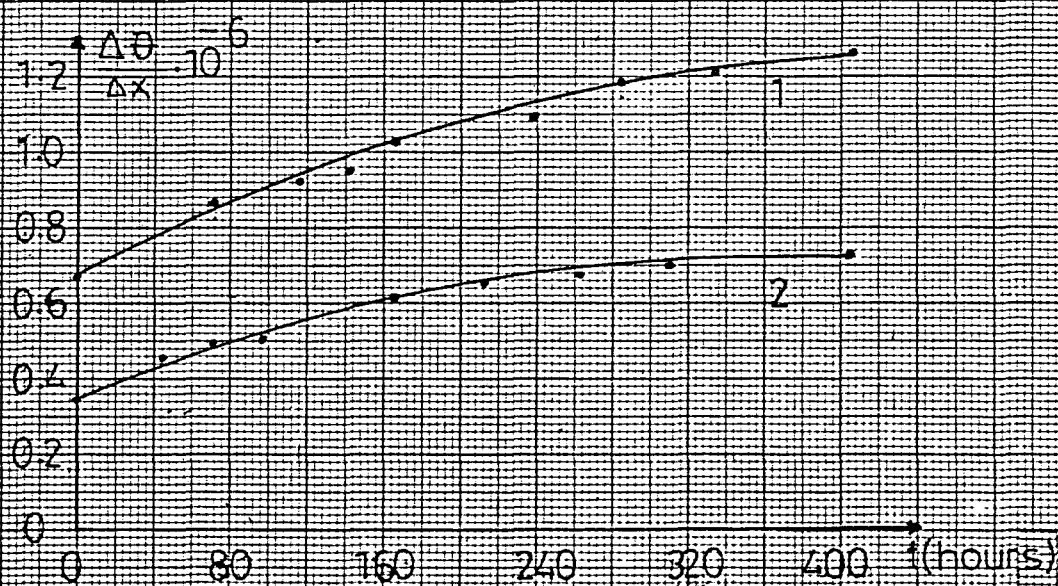


Figure 4.16 Time-Curvature Relationship of Ferrocement for Creep Behaviour Under Loads of 1) 400.55 N, 2) 200.60 N.

V. CONCLUSIONS AND RECOMMENDATIONS

In this section the results shown in the third chapter, and evaluations expressed in the fourth section, will be used to reach the following general conclusions.

V.1 THE CONCLUSIONS REACHED FROM THE SMALL FERROCEMENT SAMPLES

a. Square woven mesh gives the highest charpy-impact Strengths in both the longitudinal and the 45° inclined directions. Its charpy impact strengths are nearly 20000 Nxm/m^2 at an optimum reinforcement volume concentration of 2 %. Its value is nearly 8 times higher than that of the plain mortar.

b. Square woven mesh in the longitudinal direction gives also the highest value for tensile stresses, and its tensile strength reaches a value of 5.017 MN/m^2 at an optimum reinforcement volume concentration of 2 %, and this is 6.5 times greater than the tensile strength of the plain mortar.

c. Although expanded metal has the highest flexural stress at first crack, it breaks suddenly after first cracking, and does not

develop high ultimate strength. Square woven mesh in the longitudinal direction on the other hand may be loaded approximately 3 times more after first cracking, and it reaches an ultimate flexural strength of 13.74 MN/m^2 at an optimum volume concentration of 2 %.

d. Square woven mesh also absorbs the highest energy of 1244 Nxm at a volume concentration of 2 %, and this value is approximately 143 times higher than that of plain mortar

e. After the heating of ferrocement samples to 800°C , the strength of square woven mesh is 50 percent of its original strength at a volume concentration of 2 %, and its flexural rigidity is approximately 70 percent of its original flexural rigidity at a volume concentration of 2 %.

f. In contrast to these advantages, its rigidity is low at first crack and at ultimate load is lowered to 20 % of the plain mortar.

As a final result we may say that in spite of its certain disadvantages, square woven mesh in the longitudinal direction, and at the optimum reinforcement volume concentration of 2 % gives us the most favorable results. Therefore this type of reinforcement has been selected and used in the second part of the investigation.

V.2. CONCLUSIONS OF FULL SIZE FERROCEMENT SAMPLES TO BE USED AS ROOFING

$$I = \text{Moment of inertia} = \frac{b h^3}{12}$$

$$I = \frac{1.00 \times (0.02)^3}{12} = 0.67 \times 10^{-6} \text{ m}^4$$

$$W = \text{section modulus} = \frac{b h^2}{6}$$

$$W = \frac{1.00 \times (0.02)^2}{6} = 67 \times 10^{-6} \text{ m}^3$$

Ferrocement roofing will be under the following effects;

a. Dead load + snow load

Dead load = 48.6 kg/m (weight of the ferrocement of $1 \times 1 \times 0.02 \text{ m}^3$)

Snow load = 75 kg/m

Dead load + snow load = $q = 123.6 \text{ kg/m} = 1236 \text{ N/m}$

$L = 0.8 \text{ m}$ (free span)

$$M_{\max} = \frac{q l^2}{8} = \frac{1236 \times (0.8)^2}{8} = 98.88 \text{ Nxm}$$

$$\sigma_{\max} = \frac{M_{\max}}{W} = \frac{98.88}{67 \times 10^{-6}} = 1.475 \times 10^6 \text{ N/m}^2 = 1.475 \text{ N/mm}^2$$

Under this type of loading the deflection of ferrocement samples are the elastic deflection and creep deflection with time. For uniform loading, the model in chapter IV. can be transformed as following

$$\frac{384 I \cdot \delta_{\max}}{5 \times 10^4} = \frac{q}{E_{el}} + \frac{q}{E_{\text{creep}}} (1 - e^{-t/T_{cr}})$$

From the creep test in paragraph IV.2.1 the following values were obtained for the modulus of elasticity of the ferrocement sample :

$$E_{el} = 9770 \text{ N/mm}^2 = 9770 \times 10^6 \text{ N/m}^2, \text{ and creep ratio, } n = 2,$$

from the flexural loading tests in paragraph IV.2 values obtained following the creep test some what smaller values were obtained for the same properties of the samples : $E_{e1} = 7363 \times 10^6 \text{ N/m}^2$ This indicates some loss of rigidity due to the first loading.

for $t = 0$

$$\frac{384 I \cdot \delta}{5 l^4} = \frac{q}{E_{e1}}$$

$$\delta_{e1} = \frac{5}{384} \cdot \frac{q l^4}{E I} = \frac{5}{384} \times \frac{1236 \times (0.8)^4}{7363 \times 0.67} = 0.00133 \text{ m.}$$

$$\delta_{\text{elastic}} = 1.33 \text{ mm.}$$

$$\text{creep ratio} = 2 \quad t = \infty$$

$$\delta_{\text{creep}} = 1.33 \times 2 = 2.66 \text{ mm}$$

$$\delta_{\text{max}} = 4 \text{ mm.}$$

b. Dead load + 100 kg concentrated force in the center

$$g = 48.6 \text{ kg/m} = 486 \text{ N/m}$$

$$P = 100 \text{ kg} = 1000 \text{ N}$$

$$M_{\text{max}} = \frac{q l^2}{8} + \frac{P l}{4} = \frac{486 \times (0.8)^2}{8} + \frac{1000 \times 0.8}{4}$$

$$M_{\text{max}} = 238.88 \text{ Nxm}$$

$$\sigma_{\text{max}} = \frac{M_{\text{max}}}{W} = \frac{238.88}{67 \times 10^{-6}} = 3.56 \times 10^6 \text{ N/m}^2 = 3.56 \text{ N/mm}^2$$

After these calculations, it can be examined, whether the ferrocement samples may be used as a roofing material.

1. First cracking occurs at a moment of 160 Nxm, and it reaches a yield point at a moment of 380 Nxm. Its ultimate moment is 508 Nxm. The composite stresses at these moment values are :

$$M_{cr} = 160 \text{ Nxm} \quad \sigma_{cr} = \frac{M_{cr}}{W} = \frac{160}{67 \times 10^{-6}} = 2.38 \times 10^6 \text{ N/m}^2$$

$$M_{yield} = 380 \text{ Nxm} \quad \sigma_{yield} = \frac{M_{yield}}{W} = \frac{380}{67 \times 10^{-6}} = 5.67 \times 10^6 \text{ N/m}^2$$

for loading with dead load, and snow

$$\sigma_{cr} = 2.38 \text{ N/mm}^2 > \sigma_{max} = 1.475 \text{ N/mm}^2$$

$$F.S = \frac{2.38}{1.475} = 1.61 \text{ (for cracking)}$$

$$\sigma_{yield} = 5.67 \text{ N/mm}^2 > \sigma_{max} = 1.475 \text{ N/mm}^2$$

$$F.S \equiv \frac{5.67}{1.475} = 3.84 \text{ (for yielding)}$$

These values show that, ferrocement samples gave favorable results for this type loading.

For loading with dead load, and a concentrated force of 100 kg.

$$\sigma_{cr} = 2.38 \text{ N/mm}^2 < \sigma_{max} = 3.56 \text{ N/mm}^2$$

$$F.S = \frac{2.38}{3.56} = 0.67 \text{ (for cracking)}$$

$$\sigma_{\text{yield}} = 5.67 \text{ N/mm}^2 > \sigma_{\text{max}} = 3.56 \text{ N/mm}^2$$

$$F.S = \frac{5.67}{3.56} = 1.6 \text{ (for yielding)}$$

These values show that ferrocement samples will be sensitive, but still safe for this type of loading. They can be loaded with a concentrated force of 100 kg. but some cracks may occur.

2. The deflections were found to be 2.25 mm. at first crack, and 34 mm. at the yield point, in the flexure tests. The deflection is 1.33 mm. at first, but reaches 4 mm. after final creep under dead load, and snow. This value being 0.5 % of the free span, is still within allowable limit.

3. For dead load, and snow, the composite stress is smaller than the cracking stress. Therefore ferrocement will not crack. But in the second type of loading, some cracks may occur. As it is seen fig.IV.11, the crack width will be approximately 0.11 mm. for this moment value of 238.8 Nxm, which crack width is within the permissible limits for interior and exterior structural elements in reinforced concrete.

After obtaining these favorable results indicating the suitability of this type of ferrocement for roofing purposes we can make a feasibility analysis considering its cost:

with the market prices in Istanbul in January 1985

1 kg Portland cement = 16 TL

1 kg Sand = 2,5 TL

1 m² Square woven mesh = 500 TL

The volume of 1 m^2 cement mortar with a thickness of 0.02 m is 0.02 m^3 .

For 1 liter mortar matrix : $0,635 \text{ kg}$ cement, $1,270 \text{ kg}$ sand

For 0.02 m^3 ferrocement roofing

$0.635 \times 20 = 12,7 \text{ kg}$ cement

$1.270 \times 20 = 25,4 \text{ kg}$ sand

4 layers of square woven mesh

$12.7 \times 16 = 203.2 \text{ TL/m}^2$ The price of cement

$25.4 \times 2.5 = 63.5 \text{ TL/m}^2$ The price of sand

$4 \times 500 = 2000 \text{ TL}$ The price of reinforcement

2267 TL The material price of 1 m^2 ferrocement

$2267 \text{ TL} + \text{workmanship} \approx 2500 \text{ TL}$

The price of 1 m^2 ferrocement roofing is approximately 2500 TL .

The price of 1 m^2 asbestos cement roofing is approximately 1500 TL .

It is seen that ferrocement roofing is more expensive than asbestos cement roofing. Although its price is cheaper than ferrocement roofing, some physical and mechanical properties of asbestos cement must be evaluated for an accurate comparison.

VI. RECOMMENDATIONS FOR FUTURE STUDIES

Following points should be investigated in this field, in order to complete our knowledge on the flexural structural behaviour of ferrocement:

- Possibility of using admixtures in the production of ferrocement to increase its mechanical and physical properties.

- Examination of the reactions between the cement base matrix and galvanized reinforcement. Possibility of using some chemical additives like chromium trioxide to prevent corrosion.

- Investigations on the improvement of production techniques, since mesh layers must be thoroughly impregnated in the mortar matrix, uniform distribution of these in the matrix must be insured, which seems to be one of the greatest difficulties in production.

- Investigations on how to obtain a uniform surface in the fabricated ferrocement roofing.

- The experimental results show squattering results for different ferrocement samples due to statictical dispersion. The range of this dispersion must be investigated with large number of tests on samples of the same character and size, results must be evaluated and the average values and

confidence limits must be determined.

- Investigation of the effects of changes in the conditions like temperature, moisture on the properties of ferrocement.

- Investigation of the properties of ferrocement for other mesh types produced in Turkey.

It is advisable to make a more detailed feasibility analysis considering the full cost of ferrocement roofs, and comparing this with other roofing systems.

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APPENDIX A

Sand grading values are shown in Table A. The percentage of fine sand and coarse sand for combined sand is found by using fuller parabola.

At 1 mm. sieve size, their percentages as follows

$$X^1 \times 0.96 + (1-X^1) \times 20 = 0.50 \text{ (Figure A)}$$

$X = 0.40$ Amount of Fine sand

40 % Fine sand

60 % coarse sand

Combined sand grading with 40 % fine sand, and 60 % coarse sand is approximately similar to Fuller parabola (Figure A). These ratios were suitable for our experimental work.

TABLE A Sand Grading Values

Sieve No (mm)	Percent Passing				
	Fine Agg(A)	Course(B)	0.40 A	0.60B	Mix Agg.
0.25	44.0	6.0	17.6	3.6	21.2
0.50	80.0	13.0	32.0	7.8	39.8
1.00	96.0	20.0	38.4	12.0	50.4
2.00	98.0	54.0	39.2	32.4	71.6
4.00	100.0	100.0	40.0	60.0	100.0

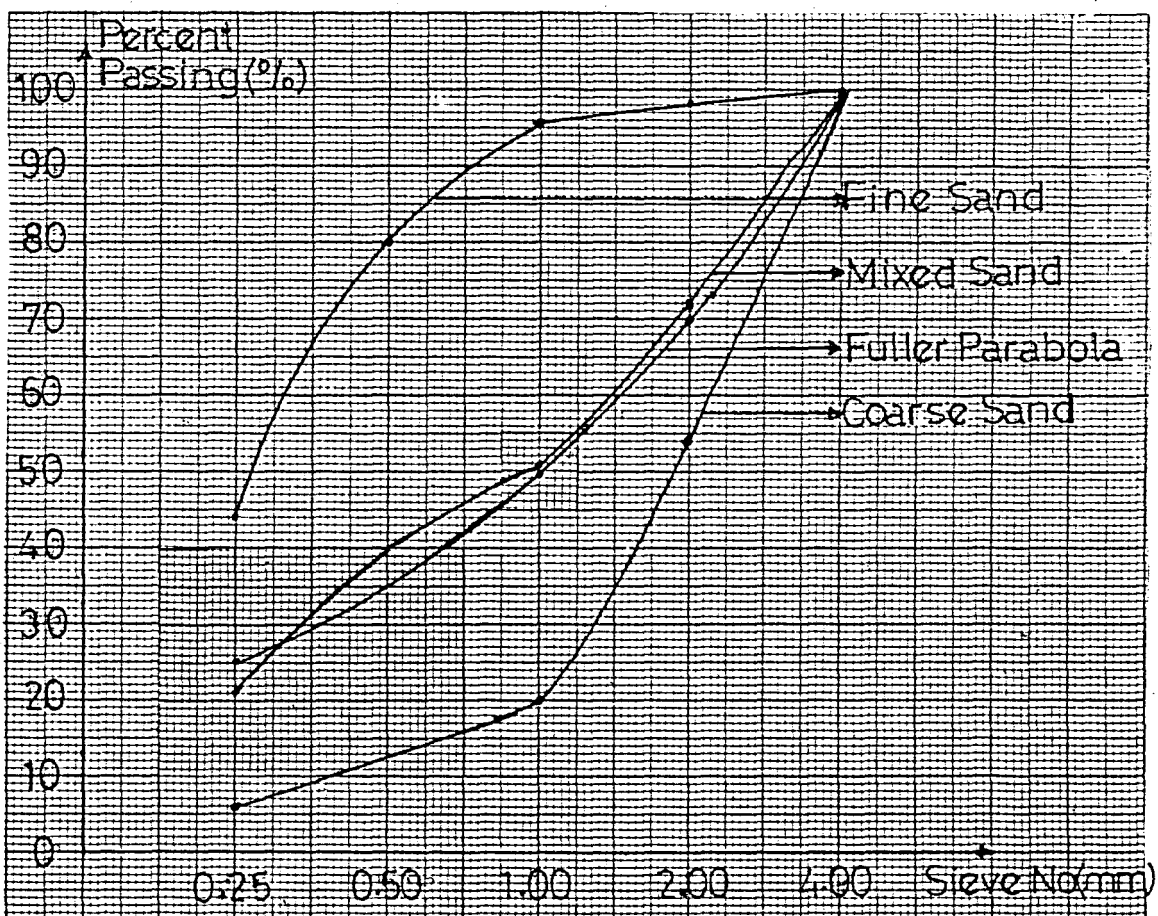


Figure.A Sand Grading

APPENDIX B

Mortar Mix

$\delta_a = 3.1 \text{ kg/lt}$ (Unit weight of cement)

$\delta_a = 2.5 \text{ kg/lt}$ (Unit weight of Aggregate)

W_C = The Weight of Cement

W_a = The Weight of Aggregate

W_w = The Weight of Water

Cement - Sand ratio is 0.5 (by weight)

Water - Cement ratio is 0.45(by weight)

$$\frac{W_C}{\delta_C} + \frac{W_a}{\delta_a} + \frac{W_w}{\delta_w} + 0.01 = 1 \text{ lt.}$$

$$W_a = 2W_C$$

$$W_w = 0.45 W_C$$

$$\frac{W_C}{3.1} + \frac{2W_C}{2.5} + \frac{0.45 W_C}{1} + 0.01 = 1 \text{ t.}$$

$$W_C = 0.635 \text{ kg.}$$

$$W_a = 2W_C = 1.270 \text{ kg}$$

$$W_w = 0.45 W_C = 0.285 \text{ kg.}$$

Unit Weight of Matrix mix

Tare weight = $W_t = 1.180$ kg.

Tare + mortar mix = $W_t + W_m = 5.490$ kg.

$W_m = 5.490 - 1.180 = 4.310$ kg.

$V_t = \text{Tare volume} = 2$ lt

$$\gamma = \frac{W_m}{V_m} = \frac{4.310}{2} = 2.155 \text{ kg/lt}$$

APPENDIX C

MESH PARAMETERS

V_f = Volume Concentration

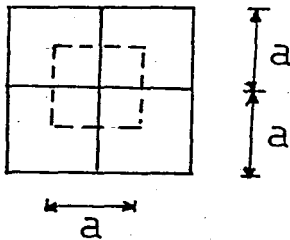
S_f = Specific surface

V = Volume of composite

S = Surface area of mesh wire

V_c = Volume of mesh wire

t = The height of composite

Square woven mesh

$$S = 2 \times a \times \pi \times d$$

$$S = 2 \times 8 \times 3.14 \times 0.71 = 35.67 \text{ mm}^2$$

$$V = a^2 \times t$$

$$V = 8^2 \times 20 = 1280 \text{ mm}^3$$

$$S_f = \frac{S}{V} = \frac{35.67}{1280} = 0.028 \text{ mm}^{-1} \text{ for one layer}$$

0.056 mm⁻¹ for two layers

0.112 mm⁻¹ for four layers

$$V_C = \frac{\pi d^2}{4} \times 2a$$

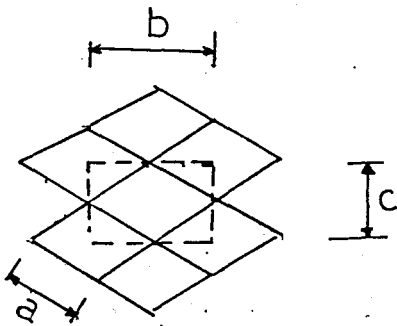
$$V_C = \frac{3.14 \times 0.71^2}{4} \times 16 = 6.33 \text{ mm}^3$$

$$V_f = \frac{6.33}{1280} \times 100 = 0.49 \text{ for one layer}$$

0.98 for two layers

1.96 for four layers

Expanded Metal



$$S = 8 at + 8 ax = 8 \times 11 \times 0.2 + 8 \times 11 \times 0.7$$

$$S = 79.2 \text{ mm}^2$$

$$V = b \times c \times t = 18.5 \times 11 \times 20 = 4070 \text{ mm}^3$$

$$V_C = 4a \times t = 4 \times 11 \times 0.7 \times 0.2 = 6.16 \text{ mm}^3$$

$$S_f = \frac{S}{V} = \frac{79.2}{4070} = 0.0194 \text{ mm}^{-1} \text{ for one layer}$$

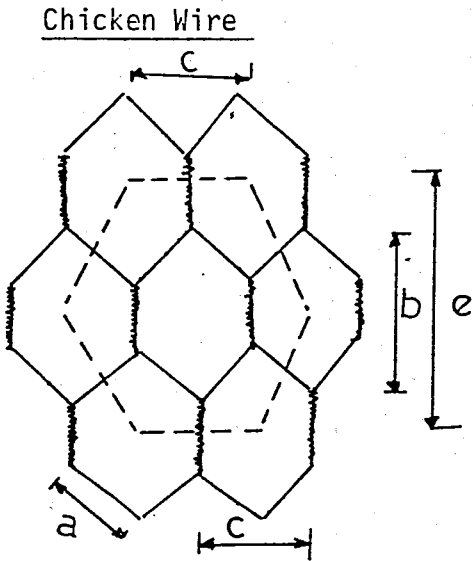
0.0388 mm⁻¹ for two layers

0.0776 mm⁻¹ for four layers

$$V_f = \frac{V_c}{V} = \frac{6.16}{4070} \times 100 = 0.15 \text{ for one layer}$$

$$0.30 \text{ for two layers}$$

$$0.60 \text{ for four layers}$$



$$S = 12 \pi d a = 12 \times 3.14 \times 16.5 \times 0.55 = 341.95 \text{ mm}^2 \quad S = 341.95 \text{ mm}^2$$

$$V = e \times c \times 20 + e \times \frac{c}{2} \times 2 \times 20$$

$$V = 59 \times 22 \times 20 + 59 \times 11 \times 2 \times 20 = 38940 \quad V = 38940 \text{ mm}^3$$

$$V_c = \frac{\pi d^2}{4} \times 12a = \frac{3.14 \times 0.55^2}{4} \times 12 \times 16.5 \quad V_c = 47.01 \text{ mm}^3$$

$$S_f = \frac{S}{V} = \frac{341.95}{38940} = 0.009 \text{ for one layer}$$

$$0.018 \text{ for two layers}$$

$$0.036 \text{ for our layers}$$

$$V_f = \frac{V_c}{V} = \frac{47.01}{38940} \times 100 = 0.12 \text{ for one layer}$$

$$0.24 \text{ for two layers}$$

$$0.48 \text{ for four layers}$$

APPENDIX D

Flexural strength values of the mortar after 28 days moistcuring determined on $4 \times 4 \times 16 \text{ cm}^3$ prisms.

Sample Number	1	2	3	4	5	6	Average
$\sigma (\text{MN}/\text{m}^2)$	7.30	8.30	7.82	7.50	8.37	7.77	7.84

Compressive strength values on broken pieces of $4 \times 4 \times 16 \text{ cm}^3$ prisms.

Sample Number	1	2	3	4	5	6	Average
$\sigma (\text{MN}/\text{m}^2)$	44.28	49.38	48.78	50.61	49.69	48.52	48.52

Compressive strength values $7 \times 7 \times 7 \text{ cm}^3$ cube samples

Sample Number	1	2	3	Average
$\sigma (\text{MN}/\text{m}^2)$	40.56	45.76	41.40	42.64

Compressive strength values of 10 20 cm cylindrical samples

Sample Number	1	2	3	Average
$\sigma (\text{MN}/\text{m}^2)$	38.80	41.71	42.26	40.88

APPENDIX E

CHARPY IMPACT TESTS

Charpy impact test values are shown in Table E.1, E2 and E3, and their calculation method is as follows.

Failure energies are found by using the following formula^{*)}

$$U = \frac{1}{2} (h-h^1)$$

and impact strength, U_g are calculated by using the following formula

$$U_g = \frac{U}{A}$$

A = Cross section of sample.

U = Failure energies

U_g = Charpy-impact strength

*) The difference $(h-h^1)$ was divided by 2, because the scale on the charpy impact machine was prepared for a hammer with a weight of twice the one used in the tests of ferrocement samples.

TABLE E.1 Charpy Impact Test Values of Ferrocement Samples with Square Woven Mesh, and Unreinforced Samples.

Mesh Detail				Dimensions of Sample			Charpy Impact Test Values			
Type	Orientation	Sample Number	Mesh Number	b cm	h cm	A cm ²	50 Nxm max Energy			
							h ₀ Nxm	h' ₀ Nxm	U Nxm	U _g Nxm/m ²
Non	—	1	—	4.8	1.7	8.16	248.5	252.0	1.75	2144.
		2	—	4.75	1.9	9.03	248.5	253.0	2.25	2491.
		3	—	4.55	1.9	8.65	248.5	253.0	2.25	2601.
		Average								2412.
SQUARE MESH	Longitudinal	1	2	4.1	2.0	8.2	248.5	271.7	11.6	14140.
		2	2	4.1	2.05	8.4	248.5	265.0	8.25	9820.
		3	2	4.9	2.0	9.8	248.5	262.0	6.72	6860.
		Average								10270.
		1	4	4.4	2.3	10.12	248.5	282.0	16.75	16550.
		2	4	4.0	2.3	9.2	248.5	289.0	20.25	22010.
		3	4	4.3	2.3	9.89	248.5	289.5	20.50	20720.
		Average								19760.
	45° Inclined	1	2	4.7	2.4	8.69	248.5	278.5	15.00	17260.
		2	2	4.25	2.6	8.61	248.5	273.0	12.25	14220.
		3	2	4.4	1.9	11.5	248.5	280.0	15.75	14220.
		Average								15050.
		1	4	4.7	2.4	11.28	248.5	298.0	24.75	21940.
		2	4	4.25	2.6	11.05	248.5	294.0	22.75	20580.
		3	4	4.6	2.5	11.50	248.5	292.5	22.00	19130.
		Average								20550.

TABLE E.2 Charpy Impact Test Values of Ferrocement Samples with Expanded Metal.

Mesh Detail				Dimension of Sample			Charpy Impact Test Values			
Type	Orientation	Sample Number	Mesh Number	b cm	h cm	A cm ²	50 Nxm max Energy			
							h _o Nxm	h _i Nxm	U Nxm	U _g Nxm ²
EXPANDED METAL	Longitudinal	1	2	5.15	1.97	8.22	248.5	253.5	2.50	3040
		2	2	4.15	1.79	7.07	248.5	252.7	2.10	2970
		3	2	5.05	1.95	8.12	248.5	252.5	2.00	2460
		Average								2820
		1	4	4.5	1.85	7.57	248.5	255.3	3.40	4490
		2	4	4.9	1.75	8.63	248.5	255.5	3.50	4050
		3	4	4.75	1.85	8.53	248.5	255.0	3.25	3810
		Average								4120
	Lateral	1	2	5.0	1.65	10.0	248.5	253.5	2.50	2500
		2	2	4.35	1.63	7.43	248.5	253.5	2.50	3360
		3	2	4.20	1.92	8.12	248.5	253.0	2.25	2770
		Average								2870
		1	4	4.4	1.72	8.38	248.5	255.1	3.30	3930
		2	4	5.07	1.70	8.59	248.5	257.2	4.35	5060
		3	4	4.80	1.77	8.82	248.5	256.2	3.85	4360
										4450

TABLE E-3 Charpy Impact Test Values of Ferrocement Samples with Chicken Wire.

Mesh Detail				Dimension of Sample			Charpy Impact Test Values			
Type	Orientation	Sample Number	Mesh Number	b cm	h cm	A cm ²	50 Nxm max Energy			
							h Nxm	h Nxm	U Nxm	U _g Nxm/m ²
CHICKEN WIRE	Lateral	1	2	4.5	2.12	9.56	248.5	262.0	6.75	7060
		2	2	4.6	2.05	8.97	248.5	262.0	6.75	7520
		3	2	4.55	2.0	9.10	248.5	259.0	5.25	5760
		Average								6780
		1	4	4.55	2.05	9.33	248.5	267.0	9.25	9910
		2	4	4.4	1.95	8.62	248.5	263.0	7.25	8410
		3	4	4.2	2.17	8.68	248.5	264.0	7.75	8920
		Average								9080
	Longitudinal	1	2	4.7	2.2	10.38	248.5	263.8	7.65	7390
		2	2	4.5	2.48	11.16	248.5	260.0	5.75	5150
		3	2	4.6	2.3	10.67	248.5	262.5	7.00	6560
		Average								6360
		1	4	4.7	2.05	9.64	248.5	265.0	8.25	8560
		2	4	4.5	1.9	8.36	248.5	262.5	7.00	8370
		3	4	4.3	1.9	8.38	248.5	267.0	9.25	11030
		Average								9320

APPENDIX F

TENSILE TESTS

The Cross Section of Wire MeshesSquare Wire

$$A_{wi} = \frac{\pi d^2}{4} \times n \text{ (for normal direction } n=10)$$

$$A_{wi} = \frac{\pi d^2}{4} \times n \times \cos \alpha \text{ (for } 45^\circ \text{ inclined } n=12)$$

$$A_{wn} = \frac{3.14 \times 0.71^2}{4} \times 10 = 3.95 \text{ mm}^2 \rightarrow \text{for one layer}$$

$$A_{wi} = \frac{3.14 \times 0.71^2}{4} \times 12 \times \cos \alpha = 3.355 \text{ mm}^2 \text{ for one layer}$$

$$d = 0.71 \text{ mm (Table 3.1)}$$

Expanded Metal

$$\alpha = 60^\circ \quad x = 0.7 \text{ mm} \quad t = 0.2 \text{ mm (Table 3.1) For lateral direction}$$

$$\alpha = 114^\circ \quad x = 0.7 \text{ mm} \quad t = 0.2 \text{ mm (Table 3.1) For longitudinal direction}$$

$$A_{wLA} = x \cdot t \cdot \cos \frac{\alpha}{2} \quad n=10 \text{ (for Lateral direction)}$$

$$A_{wLA} = 0.7 \times 0.2 \times 10 \times \cos 30^\circ$$

$$A_{wLA} = 1.2 \text{ mm}^2$$

$n = 6$ (For longitudinal direction)

$$A_{wLO} = 0.7 \times 0.2 \times 6 \times \cos 57^\circ$$

$$A_{wLO} = 0.445 \text{ mm}^2$$

The Calculation of Tensile Stress Values

All calculations for tensile stress are not shown here, but the results of them are in the Tables F.2, F.3. Let's give an example showing tensile properties of ferrocement sample, and its calculation method. Its load deflection graph is shown in Figure F.1.

Example

Expanded metal with 2 layers in the lateral direction is taken as an example. From the reading values shown in Table F.1, P- ϵ diagram is drawn. P_{cr} , and ϵ_{cr} values are determined. E_w , E_c , $\frac{P_{cr}}{A_w}$, $\frac{P_{cr}}{A_c}$ values depending on composite or wire mesh found. These values are shown in Table F.2 and F.3

Sample calculations for the modulus of Elasticity are,

$$P_{cr} = 100 \text{ kg} \quad \epsilon = 0.0075$$

$$A_w = 2.4 \text{ mm}^2$$

$$\frac{P_{cr}}{A_w} = \frac{100}{2.4} = 4166 \text{ kg/cm}^2 = 146.6 \text{ MN/m}^2 \text{ (based on Reinforcement alone)}$$

$$\frac{P_{cr}}{A_c} = \frac{100}{14.4} = 6.96 \text{ kg/cm}^2 = 0.696 \text{ MN/m}^2 \text{ (based on the composite section)}$$

$$E_w = \frac{\nabla \sigma_{cr}}{\nabla \epsilon} = \frac{416.6}{0.075} = 55546.6 \text{ MN/m}^2 \text{ (based on reinforcement alone)}$$

$$E_c = \frac{\nabla \sigma_{cr}}{\nabla \epsilon} = \frac{0.696}{0.0075} = 92.8 \text{ MN/m}^2 \text{ (based on the composite section)}$$

TABLE F.1 Reading Values of Ferrocement with 2 Layers of Expanded Metal in Lateral Direction.

P (kg)	$\frac{P}{A_w}$ (kg/cm ²)	$\frac{P}{A_c}$ (kg/cm ²)	R _o (mm)	R R _o (mm)	ϵ ($\frac{R R_o}{200}$)
0	0	0	6 00	0	0
30 0	1250 0	2 08	6 20	0 23	0.00115
50 0	2083 0	3 47	6 35	0 35	0.00175
80 0	3333 0	5 55	6 58	0 58	0.0029
100 0	4166 0	6 94	6 75	0 75	0.00375
120 0	5000	8 33	7 01	1 01	0.00505
140 0	5833	9 72	7 26	1 26	0.0063
160 0	6666	11 11	7 45	1 45	0.00725
170.0	—	—	—	—	—

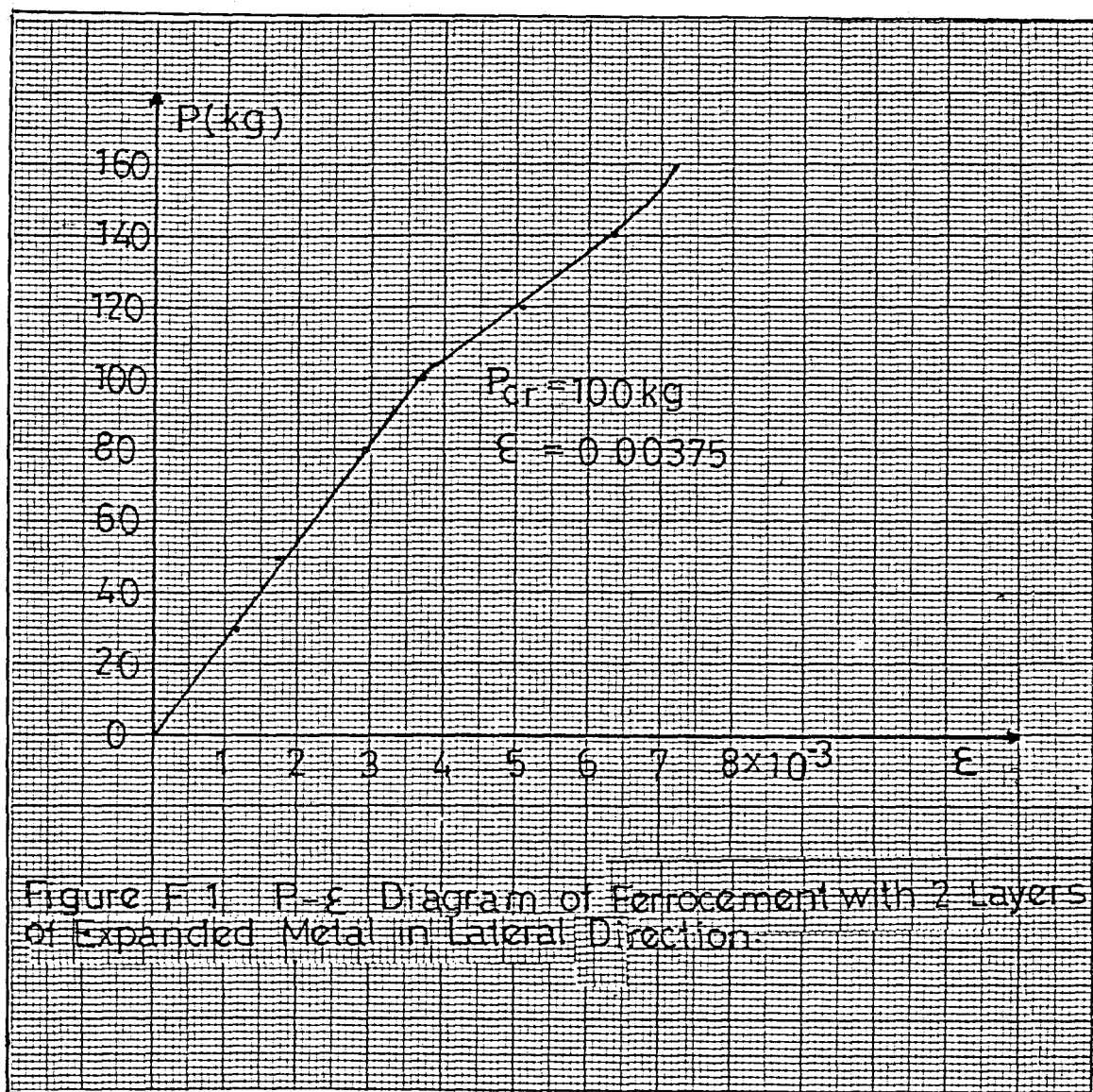


TABLE F 2 Tension Test Values of Ferrocement Samples with Square Woven Mesh and Unreinforced Samples.

Type	Orientation	P N	Mesh Number	P _{cr} N	$\epsilon_{cr} \times \frac{10^{-2}}{2}$	P _{cr} N	Based on Reinforcement Alone.				Based on the Composite Section.			
							A _w cm ²	$\frac{P_{cr}}{A_w}$ MN/m ²	E _w MN/m ²	$\frac{P_u}{A_w}$ MN/m ²	A _c cm ²	$\frac{P_{cr}}{A_c}$ MN/m ²	E _c MN/m ²	$\frac{P_u}{A_c}$ MN/m ²
None	—	1	—	1000	0.58	1110	—	—	—	—	14.4	0.764	151.2	0.764
		2	—	1110	0.505	1110	—	—	—	—	14.4	0.694	119.7	0.764
												0.729	135.4	0.764
SQUARE MESH	Longitudinal	1	2	2400	0.77	3800	0.0791	302.4	39272.7	480.4	14.4	1.67	216.5	2.64
		2	2	2800	1.00	3100	0.0791	354.0	35440.	391.9	14.4	1.94	194.4	2.15
								328.7	37336.4	436.1		1.806	205.4	2.395
		1	4	3450	1.125	7300	0.158	218.0	19377.7	462.0	14.4	2.395	212.8	5.07
		2	4	3000	0.88	7150	0.158	189.6	21545.4	452.5	14.4	2.083	236.7	4.965
								203.8	20461.5	457.2		2.239	224.7	5.017
	45° Inclined	1	2	1700	0.525	2250	0.0671	253.3	48247.4	335.3	14.4	1.18	224.7	1.56
		2	2	1400	0.48	2000	0.0671	208.6	43467.4	298.0	14.4	0.972	202.5	1.39
								230.9	45857.5	316.6		1.076	213.6	1.475
		1	4	1200	0.35	3950	0.134	89.4	25548.2	294.7	14.4	0.833	238.	2.74
		2	4	1200	0.35	4100	0.134	89.4	25548.2	303.3	14.4	0.833	238.	2.79
								89.4	25548.2	298.5		0.833	238.	2.765

TABLE F.3 Tension Test Values of Ferrocement Samples with Expanded Metal.

Type	Orientation	Sample Number	Mesh Number	P_{cr} N	ϵ_{cr} $\times 10^{-2}$	P_u N	Based on Reinforcement Alone.				Based on the Composite Section.			
							A_w cm^2	$\frac{P_{cr}}{A_w}$ MN/m^2	E_w MN/m^2	$\frac{P_u}{A_w}$ MN/m^2	A_c cm^2	$\frac{P_u}{A_c}$ MN/m^2	E_c MN/m^2	$\frac{P_u}{A_c}$ MN/m^2
EXPANDED METAL	Longitudinal	1	2	1000	0.67	2300	0.0089	1123.5	167700.	2584.	14.4	0.694	145.	1.597
		2	2	1400	0.78	2050	0.0089	1573.0	201671.	2303.	14.4	0.972	124.6	1.423
		Average						1348.0	184686.	2443.7		0.833	139.4	1.510
		1	4	2000	0.71	2600	0.0178	1123.5	158239.	1460.6	14.4	1.39	156.4	1.81
		2	4	1600	0.71	2750	0.0178	898.8	126592.	1544.9	14.4	1.11	195.4	1.91
		Average						1011.0	142415.	1502.7		1.25	175.9	1.85
	Lateral	1	2	1500	0.35	1900	0.024	208.3	59514.	791.6	14.4	0.347	99.2	1.319
		1	2	1000	0.75	1700	0.024	416.6	55546.	708.3	14.4	0.696	92.8	1.18
		Average						312.4	57530.	750.		0.52	96.	1.25
		1	4	1700	0.87	2400	0.048	354.1	407011.	500.	14.4	1.18	135.	1.67
		2	4	1900	0.92	2150	0.048	395.8	43025.	447.9	14.4	1.32	143.4	1.49
		Average						374.9	41863.	473.9		1.285	139.4	1.58

APPENDIX G

Simple Beam Flexure Test of Ferrocement Samples

There are approximately 100 samples subjected to simple beam flexure tests. Therefore all calculations of test results are not shown here, but all results are shown in the Tables G.2 - G.11. Tables G.2- G.8 contain normal samples at 18°C. Tables G.9 - G.11 contain samples heated to 800°C Temperature. There is only one example of calculation method of flexure test results of ferrocement sample having a length of 40 cm, a width of 9.95 cm, and a height of 2.05 cm, with 2 layer square woven mesh in the normal direction (TABLE G.3 2ⁿ row)

Reading values of a ferrocement sample for flexure test is in the Table G.1, and load-deflection diagram of these values is in Figure G. The load and deflection values at first crack shown in Figure G are determined, rigidity, strength, and flexural energy of ferrocement are calculated by using the following methods.

$$P_{cr} = 30 \text{ kg} \quad (\text{Figure G})$$

$$\delta_{cr} = 1.17 \text{ mm}$$

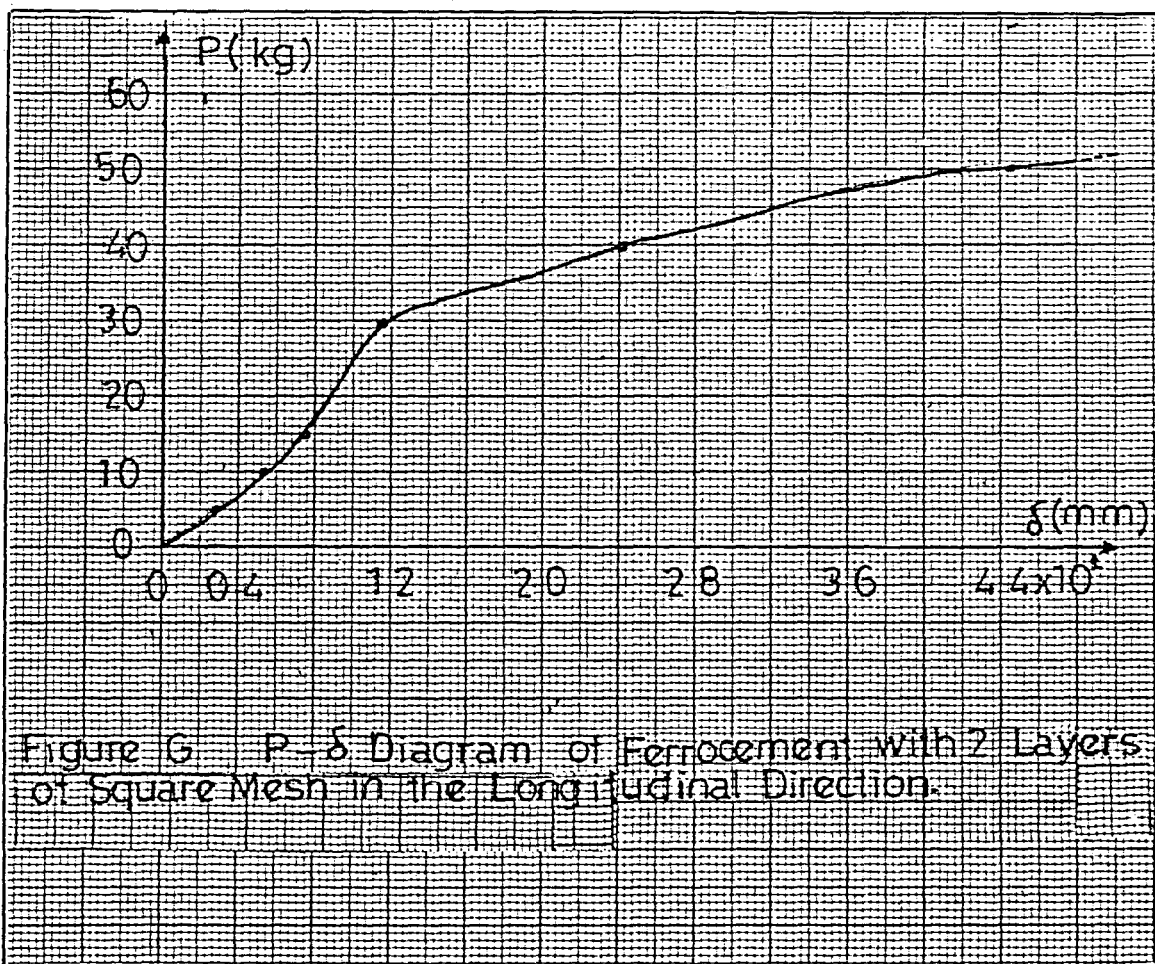
$$P_u = 66 \text{ kg} \quad (\text{Table G.1})$$

$$\delta_u = 13.40 \text{ mm}$$

$$\sigma_{cr} = 1.5 \times \frac{P_{cr} \cdot L}{bh^2} \quad E I_{cr} = \frac{P_{cr} \cdot L^3}{48 \delta_{cr}}$$

TABLE G.1 Reading Values of Ferrocement with 2 Layers Square Woven Mesh in the Longitudinal Direction.

NO.	P	δ	NO.	P	δ	NO.	P	δ
1	2	0	7	30	1.17	13	60	7.65
2	5	0.28	8	35	1.80	14	65	11.50
3	10	0.55	9	40	2.40	15	66	13.40
4	15	0.76	10	45	3.25	16	46	14.60
5	20	0.89	11	50	4.55	17	38	18.25
6	25	1.00	12	55	5.55	18	27	21.30



$$L = 40 \text{ cm.}$$

$$b = 9.95 \text{ cm}$$

$$h = 2.05 \text{ cm}$$

$$c_{cr} = 1.5 \times \frac{30 \times 40}{9.95 \times (2.05)^2} = 43.9 \text{ kg/cm}^2 = 4.39 \text{ N/m}^2$$

$$E I_{cr} = \frac{30 \times 40^3}{48 \times 0.117} = 341880 \text{ kg cm}^2 = 341.8 \text{ N m}^2$$

$$U_{cr} = \frac{1}{2} \times 30 \times 0.117 = 1.75 \text{ kg cm} = 0.175 \text{ Nm (The area under } \delta_{cr}-P_{cr} \text{ curve)}$$

$$u = 1.5 \frac{P_u \cdot L}{b h^2}$$

$$u = 1.5 \frac{66 \times 40}{9.95 \times (2.05)} = 90.7 \text{ kg/cm}^2 = 9.07 \text{ N/m}^2$$

$$E I_u = \frac{P_u \cdot L}{48 \delta_u}$$

$$E I_u = \frac{66 \times 40^3}{48 \times 1.34} = 65670 \text{ kg cm}^2 = 65.67 \text{ N m}^2$$

$$U_u = U_{cr} + \frac{P_c + P_u}{2} \times (\delta_u - \delta_{cr}) \quad (\text{The Area under } \delta_u, P_u \text{ curve})$$

$$U_u = 1.75 + \frac{30 + 66}{2} (1.34 - 0.117) = 60.45 \text{ kg cm} = 6.04 \text{ N m.}$$

These values of our example were shown in Table G.3 and row 2

All values shown in the Tables G.2 - G.11 are calculated like this.

TABLE G.2 Specimens Without any Mesh Reinforcement Tested at 18° Curing Temperature.

Number of Sample	P_{cr} N	δ_{cr} cm	L mm	bh^2 mm ³	σ_{cr} MN/m ²	U_{cr} Nxm	EI_{cr_0} Nxm ²	EI_{cr_0} Average Nxm ²	σ_u MN/m ²	U_u Nxm	EI_{u_0} Nxm ²	EI_{u_0} Ave. Nxm ²
1	280	0.055	400	3250	5.168	0.077	678	533	5.168	0.077	678	533
2	200	0.065	400	3595	3.340	0.065	410		3.340	0.065	410	
3	300	0.080	200	1592	5.65	0.120	62.5	69.5	5.65	0.120	62.5	69.5
4	280	0.061	200	1668	5.034	0.085	76.5		5.034	0.085	76.5	
Average					4.80	0.087			4.80	0.087		

TABLE G.3 Simple Beam Flexure Test Values of Ferrocement Samples with Square Woven Mesh in the Longitudinal Direction.

Sample Number	Mesh Number	R_r N	δ_{cr} mm	L mm	bh^2 cm^2	σ_{cr} MN/m^2	U_{cr} Nxm	$EI_{c_{r0}}$ Nxm^2	$EI_{c_{r1}}$ Nxm^2	$\frac{EI_{c_{r1}}}{EI_{c_{r0}}}$	P_u N	δ_u mm	σ_u MN/m^2	U_u Nxm	EI_{u_0} Nxm^2	EI_{u_1} Nxm^2	$\frac{EI_{u_1}}{EI_{u_0}}$
1	2	350	0.123	400	42.3	4.96	0.21	533	379	0.71	580	3.4	8.22	15.44	533	22.74	0.042
2	2	300	0.117	400	43.6	4.39	0.175	533	341	0.64	660	1.34	9.07	6.04	533	65.7	0.123
3	2	350	0.096	400	41.81	4.30	0.168	533	486	0.912	660	2.70	9.47	13.32	533	32.6	0.061
4	2	420	0.075	200	19.75	6.37	0.158	69.5	93.33	1.34	830	1.12	12.6	6.69	69.5	12.35	0.180
5	2	510	0.085	200	23.15	6.60	0.225	69.5	100	1.43	1110	0.565	14.2	4.10	69.5	32.45	0.47
Average						5.32	0.188			1.00			10.72	9.11			0.175
1	4	400	0.098	400	52.64	4.56	0.196	533	544	1.02	1140	1.57	12.99	11.53	533	96.81	0.181
2	4	400	0.065	400	44.37	5.41	0.130	533	820	1.54	900	1.22	12.17	7.63	533	93.36	0.184
3	4	400	0.052	400	47.4	5.07	0.104	533	1025	1.92	1000	1.135	12.66	7.68	533	117.5	0.220
4	4	580	0.065	200	30.2	5.75	0.188	69.5	148	2.13	1340	0.98	13.29	8.97	69.5	22.79	0.327
5	4	650	0.082	200	26.45	7.37	0.266	69.5	132	1.9	1550	2.46	17.58	26.42	69.5	10.5	0.151
Average						5.63	0.177			1.7			13.74	12.44			0.212

TABLE G.4 Simple Beam Flexure Test Values of Ferrocement Samples with Square Woven Mesh in the 45° Inclined Direction.

Sample Number	Mesh Number	P_{cr} N	δ_{cr} mm	L mm	bh^2 cm	σ_{cr} MN/m ²	U_{cr} Nxm	EI_{cr0} Nxm ²	EI_{cr1} Nxm ²	$\frac{EI_{cr1}}{EI_{cr0}}$	P_u N	δ_u mm	σ_u MN/m ²	U_u Nxm	EI_{u0} Nx ² m	EI_{u1} Nx ² m	$\frac{EI_{u1}}{EI_{u0}}$
1	2	250	0.053	400	36.8	4.09	0.067	533	629.	1.19	260	0.56	4.24	1.36	533.	61.9	0.116
2	2	280	0.053	400	39.6	4.24	0.070	533	704.	1.32	320	0.78	4.85	2.25	533.	54.7	0.102
3	2	260	0.057	400	35.4	4.41	0.074	533	609.	1.14	300	0.74	5.01	1.99	533.	54.05	0.101
4	2	400	0.062	200	21.2	5.66	0.124	69.5	107.5	1.55	460	0.74	6.52	3.03	69.5	10.36	0.149
5	2	480	0.104	200	24.	6.02	0.25	69.5	76.9	1.106	500	0.41	6.36	1.75	69.5	20.3	0.29
Average						4.89	0.117			1.259			5.39	2.09			0.152
1	4	600	0.11	400	65.6	5.49	0.330	533.	727.	1.36	950	0.700	8.61	4.9	533.	180.9	0.339
2	4	550	0.093	400	60.0	5.5	0.255	533.	788.	1.48	900	0.40	9.5	2.48	533.	300.	0.562
3	4	400	0.095	400	55.3	4.55	0.190	533.	561.	1.05	650	0.94	7.05	4.62	533.	92.2	0.172
4	4	650	0.098	200	32.4	6.25	0.318	69.5	110.5	1.59	1050	0.690	9.62	2.80	69.5	25.3	0.364
5	4	650	0.08	200	31.87	6.12	0.260	69.5	135.4	1.95	1000	0.400	9.9	5.59	69.5	41.66	0.600
Average						5.58	0.27			1.534			8.99	4.09			0.407

TABLE G.5 Simple Beam Flexure Test Values of Ferrocement Samples with Chicken Wire in the Lateral Direction.

Sample Number	Mesh Number	P_{cr} N	δ_{cr} mm	L mm	bh^2 cm^3	σ_{cr} $\frac{MN}{m^2}$	U_{cr} Nxm	EI_{c_0} Nxm^2	EI_{c_1} Nxm^2	$\frac{EI_{c_1}}{EI_{c_0}}$	P_u N	δ_u mm	σ_u $\frac{MN}{m^2}$	U_u Nxm	EI_{u_0} Nxm^2	EI_{u_1} Nxm^2	$\frac{EI_{u_1}}{EI_{u_0}}$
1	2	400	0.08	400	34.0	4.72	0.160	533.	667	1.25	410	0.34	4.84	1.21	533.	160.8	0.30
2	2	400	0.06	400	37.3	4.94	0.120	533	888	1.67	440	0.27	5.20	1.00	533.	217.3	0.41
3	2	350	0.05	400	35.0	4.91	0.088	533	933	1.75	380	0.21	533	0.67	533	241.2	0.45
4	2	460	0.096	200	25.4	5.43	0.220	69.5	79.9	1.14	460	0.21	5.43	0.744	69.5	36.5	0.525
5	2	540	0.076	200	26.5	6.11	0.205	69.5	118	1.70	560	0.37	6.31	1.82	69.5	25.2	0.36
Average						5.22	0.159			1.5			5.42	1.09			0.409
1	4	310	0.09	400	36.5	5.1	0.139	533	4.59	0.861	310	0.09	5.1	0.139	533	459	0.861
2	4	380	0.061	400	36.8	6.36	0.116	533	830	1.56	380	0.061	6.36	0.116	533	830	1.56
3	4	330	0.067	200	20.7	4.75	0.110	69.5	82	1.18	330	0.067	4.75	0.110	69.5	82.	1.18
4	4	390	0.134	200	20.	5.85	0.261	69.5	48.5	0.70	390	0.134	5.85	0.268	69.5	48.5	0.70
Average						5.51	0.157			1.075			5.51	0.157			1.075

TABLE G 6 Simple Beam Flexure Test Values of Ferrocement Samples with Chicken Wire in the Longitudinal Direction.

Sample Number	Mesh Number	P_c N	δ_{cr} mm	L mm	bh^2 cm^3	σ_{cr} $\frac{MN}{m^2}$	U_{cr} Nxm	$E I_{c_0}$ Nxm^2	$E I_{cr_1}$ Nxm^2	$\frac{E I_{cr_1}}{E I_{c_0}}$	P_u N	δ_u mm	σ_u $\frac{MN}{m^2}$	U_u Nxm	$E I_u$ Nxm^2	$E I_u$ Nxm^2	$\frac{E I_u}{E I_{c_0}}$
1	2	240	0.06	400	36.8	4.08	0.072	533	533	1.00	240	0.155	4.08	0.235	533	206	0.387
2	2	350	0.065	400	38.4	5.47	0.113	533	717	1.35	350	0.145	5.47	0.393	533	321	0.600
3	2	420	0.080	200	16.96	7.43	0.168	69.5	87.5	1.26	420	0.160	7.43	0.504	69.5	43.7	0.620
4	2	280	0.056	200	20.01	4.18	0.078	69.5	83.3	1.20	320	0.180	4.77	0.450	69.5	29.6	0.430
Average						5.29	0.108			1.20			5.44	0.396			0.510
1	4	400	0.07	400	43.45	5.52	0.140	533	761	1.42	420	0.65	5.80	2.51	69.5	86.15	0.16
2	4	300	0.07	400	40.6	4.44	0.105	533	571.4	1.07	320	0.94	4.73	2.8	533	68.72	0.1292
3	4	300	0.07	400	35.4	5.09	0.105	533	571.4	1.07	340	0.66	5.77	1.93	533	45.39	0.085
4	4	360	0.09	200	24.7	5.43	0.196	69.5	66.7	0.96	370	0.14	5.58	0.38	69.5	44.	0.630
5	4	520	0.10	200	20.2	7.03	0.26	69.5	86.7	1.25	540	0.47	7.3	2.2	69.5	19.5	0.275
Average						5.50	0.161			1.154			5.84	1.96			0.255

TABLE G.7 Simple Beam Flexure Test Values of Ferrocement Samples with Expanded Metal in the Lateral Direction.

Sample Number	Mesh Number	P_{cr} N	δ_{cr} mm	L mm	bh cm ²	σ_{cr} MN/m ²	U_{cr} Nxm	EI_{cr_0} Nxcm ²	EI_{cr_1} Nxcm ²	$\frac{EI_{cr_1}}{EI_{cr_0}}$	P_u N	δ_u mm	σ_u MN/m ²	U_u Nxcm	EI_{u_0} Nxcm ²	EI_{u_1} Nxcm ²	$\frac{EI_{u_1}}{EI_{u_0}}$
1	2	350	0.073	400	39.2	5.36	0.127	533.	639.3	1.20	380	0.303	5.82	0.96	533.	167.2	0.313
2	2	350	0.086	400	41.9	5.02	0.150	533.	542.7	1.02	400	0.130	5.73	0.31	533.	410.	0.769
3	2	340	0.09	200	14.3	6.72	0.153	69.5	62.9	0.905	340	0.09	7.14	0.153	69.5	62.9	0.905
4	2	320	0.061	200	11.9	8.57	0.097	69.5	87.43	1.26	340	0.310	8.57	0.91	69.5	18.27	0.263
Average						6.42	0.132			1.096			6.82	0.583			0.560
1	4	350	0.177	400	39.56	5.30	0.309	533.	263.	0.49	350	0.177	5.3	0.309	533.	269.	0.490
2	4	320	0.072	200	17.5	5.49	0.115	69.5	74.1	1.065	340	0.25	5.83	0.702	69.5	22.66	0.38
3	4	300	0.062	200	15.74	6.10	0.093	69.5	80.6	1.16	320	0.180	6.09	0.458	69.5	29.62	0.426
Average						5.63	0.172			0.905			5.74	0.489			0.432

TABLE G.8 Simple Beam Flexure Test Values of Ferrocement Samples with Expanded Metal in the Longitudinal Direction.

Sample Number	Mesh Number	P_{cr} N	δ_{cr} mm	L mm	bh^2 cm^3	σ_{cr} $\frac{MN}{m^2}$	U_{cr} Nxm	EI_{cr0} Nxm^2	EI_{cr1} Nxm^2	$\frac{EI_{cr1}}{EI_{cr0}}$	P_u N	δ_u mm	σ_u $\frac{MN}{m^2}$	U_u Nxm	EI_{u0} Nxm^2	EI_{u1} Nxm^2	$\frac{EI_{u1}}{EI_{u0}}$
1	2	400	0.087	400	37.3	5.95	0.174	533.	613.	1.15	400	0.087	5.95	0.174	533.	613.	1.15
2	2	430	0.076	400	30.47	7.88	0.163	533.	754.	1.41	430	0.076	7.88	0.163	533.	754.	1.41
3	2	370	0.09	400	35.6	7.24	0.166	533.	548.	1.03	370	0.09	7.24	0.166	533	548.	1.03
4	2	420	0.071	200	16.01	7.49	0.149	69.5	98.6	1.42	420	0.071	7.49	0.149	69.5	98.6	1.42
5	2	400	0.096	200	13.48	9.34	0.192	69.5	69.4	0.99	400	0.096	9.34	0.192	69.5	69.4	0.99
Average						7.58	0.169			1.20			7.58	0.169			1.20
1	4	400	0.115	400	38.4	6.25	0.230	533.	464.	0.87	400	0.115	6.25	0.230	533.	463.8	0.87
2	4	400	0.221	400	33.6	7.15	0.442	533.	241.	0.45	480	0.330	8.58	0.920	533.	194.	0.36
3	4	340	0.058	200	13.36	7.63	0.096	69.5	97.7	1.40	360	0.264	8.08	0.817	69.5	22.7	0.32
4	4	340	0.057	200	14.71	6.94	0.096	69.5	97.7	1.40	350	0.20	7.14	0.589	69.5	29.0	0.419
Average						6.99	0.210			1.03			7.51	0.64			0.490

TABLE G.9 Simple Beam Flexure Test Values of Ferrocement Samples with Square Woven Mesh After Heating up to 800°C Temperature.

Type	Orientation	Sample Number	Mesh Number	P_{cr} N	δ_{cr} mm	L mm	bh^2 cm^3	σ_{cr} $\frac{MN}{m^2}$	U_{cr} Nxm	EI_{cr} Nxm^2	P_u N	δ_u mm	σ_u $\frac{MN}{m^2}$	U_u Nxm	EI_{u2} Nxm^2
None	—	1	—	—	—	200	14.25	—	—	—	—	—	—	—	—
		2	—	—	—	200	14.51	—	—	—	—	—	—	—	—
		Average						—	—	—			—	—	—
SQUARE WIRE	Longitudinal	1	2	120	0.064	200	16.8	2.14	0.037	31.25	420	0.900	7.50	2.29	7.78
		2	2	100	0.035	200	23.37	1.30	0.018	47.61	440	0.900	5.65	2.35	8.15
		Average						1.72	0.024	39.40			6.57	2.32	7.96
		1	4	300	0.109	200	28.1	3.20	0.163	45.87	560	0.900	5.97	3.56	10.37
		2	4	300	0.080	200	28.8	3.13	0.120	62.50	720	1.00	7.50	4.81	12.50
		Average						3.165	0.141	55.2			6.74	4.19	11.44
	45° Inclined	1	2	100	0.105	200	17.2	1.74	0.052	15.9	120	0.600	2.09	0.60	3.33
				160	0.120	200	23.7	2.03	0.096	22.22	180	0.500	2.27	0.81	6.00
		Average						1.89	0.074	19.00			2.18	0.70	4.67
		1	4	140	0.065	200	22.2	1.89	0.045	35.90	260	0.540	3.51	0.99	8.04
		2	4	120	0.051	200	20.0	1.49	0.030	36.36	200	0.800	2.48	1.23	4.17
		Average						1.69	0.037	36.13			3.00	1.11	6.10

TABLE G.10 Simple Beam Flexure Test Values of Ferrocement Samples with Chicken Wire After Heating up to 800°C Temperature.

Type	Orien tation	Sample Number	Mesh Number	P _{cr} N	δ _{cr} mm	L mm	bh ² cm ³	σ _{cr} MN/m ²	U _{cr} Nxm	EI _{cr2} Nxcm ²	P _u N	δ _u mm	σ _u MN/m ²	U _u Nxm	EI _{u2} Nxcm ²
CHICKEN WIRE	Lateral	1	2	—	—	200	15.05	—	—	—	—	—	—	—	—
		2	2	—	—	200	14.75	—	—	—	—	—	—	—	—
		Average						—	—	—			—	—	—
		1	4	40	0.022	200	14.75	0.81	0.004	30.3	40	1.00	0.81	0.395	0.67
		2	4	—	—	200	13.15	—	—	—	—	—	—	—	—
		Average						0.81	0.004	30.3			0.81	0.395	0.67
	Longitudinal	1	2	40	0.061	200	15.9	0.76	0.012	10.93	50	0.34	0.94	0.137	2.45
		2	4	40	0.180	200	17.87	0.67	0.036	3.70	60	1.10	1.01	0.490	0.90
		Average						0.72	0.024	7.32			0.98	0.310	1.68
		1	4	160	0.093	200	18.05	2.66	0.074	28.67	250	0.700	4.155	1.01	5.95
		2	4	220	0.092	200	24.80	2.66	0.101	39.85	250	0.400	3.024	0.82	10.41
		Average						2.66	0.086	34.26			3.59	0.92	8.18

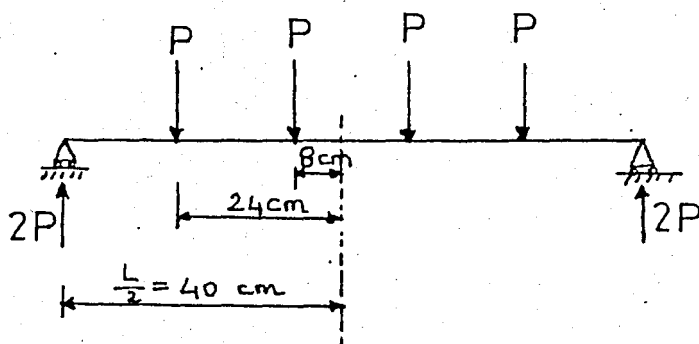
TABLE G.11 Simple Beam Flexure Test Values of Ferrocement Samples with Expanded Metal After Heating up to 800°C Temperature.

Type	Orientation	Sample Number	Mesh Number	P_{cr} N	δ_{cr} mm	L mm	bh^2 cm^3	σ_{cr} $\frac{MN}{m^2}$	U_{cr} Nxm	EI_{cr2} Nxm^2	P_u N	δ_u mm	σ_u $\frac{MN}{m^2}$	U_u Nxm	EI_{u2} Nxm^2
EXPANDED METAL	Lateral	1	2	40	0.009	200.	13.2	0.91	0.0018	74.0	50.	0.400	1.13	0.177	2.08
		2	2	—	—	200.	14.3	—	—	—	—	—	—	—	—
		Average						0.91	0.0018	74.0			1.13	0.177	2.08
		1	4	60	0.012	200.	14.58	1.23	0.0036	83.3	90.	0.400	1.85	0.350	3.70
		2	4	—	—	200.	13.90	—	—	—	—	—	—	—	—
		Average						1.23	0.0036	83.3			1.85	0.350	3.70
	Longitudinal	1	2	70	0.050	200.	16.42	1.278	0.018	23.3	130.	1.14	2.38	1.10	1.90
		2	2	110	0.055	200.	13.93	2.81	0.060	33.3	220.	0.31	4.70	0.56	11.80
		Average						2.04	0.039	28.3			3.54	0.83	6.85
		1	4	120	0.09	200.	14.25	2.53	0.054	22.0	210.	1.44	4.42	2.28	2.43
		2	4	170	0.180	200.	14.41	3.54	0.153	15.74	290.	1.10	6.04	2.27	4.39
		Average						3.035	0.103	18.90			5.23	2.275	3.41

APPENDIX H

For full-size ferrocement samples, deflection at the mid point, curvature, strain, cracking properties at the mid-span of 16 cm of ferrocement samples are determined, and their values are shown in Tables H.1 and H.2. Their creep properties are examined and obtained values are shown in Tables H.3 and H.4.

The maximum moment values are calculated.



$$M_{\max} = 2P \times 40 - P \times 24 - P \times 8 = 48 P$$

$$G = 4P$$

$$M_{\max} = 12 G \text{ (Nxcm)}.$$

TABLE H.1 Flexural Test Values of the Full Size Ferrocement Sample No.1.

Ring Reading	P (N)	Deflection Reading $R_{\delta \frac{1}{2}}$ (mm)	Deflection Values $\delta \frac{1}{2}$ (mm)	Curvature Reading R_{θ_2} (grad)	Curvature Values θ_2 (grad)	Compressive Strain Reading $R_{\epsilon_{top}}$ $\times 10^{-3}$	Compressive Strain Values ϵ_{top} $\times 10^{-3}$	Tensile strain Reading $R_{\epsilon_{bottom}}$ $\times 10^{-3}$	Tensile strain Values ϵ_{bottom} $\times 10^{-3}$	Observed Crack Width (mm)	Number of Cracks	Average Crack Spacing (mm)
—	—	2.66	0.00	0.933	0.00	8.040	0.00	8.620	0.00			
—	164.10	2.97	0.31	0.985	0.0516	8.020	-0.020	8.660	0.040			
—	550.10	3.32	0.66	1.059	0.126	7.985	-0.055	8.700	0.080			
101	1030.0	4.16	1.50	1.160	0.227	7.865	-0.175	8.820	0.200			
223	1610.0	5.48	2.82	2.247	1.314	7.695	-0.345	9.115	0.495			
300	1910.0	10.55	7.89	3.162	2.229	6.840	-1.200	11.865	3.245	First Crack		
374	2310.0	18.46	15.80	3.532	2.598	6.035	-2.005	13.200	4.580			
425	2550.0	22.60	19.94	—	—	5.535	-2.505	15.450	6.830			
485	2850.0	28.71	26.05	—	—	4.770	-3.210	17.755	9.155			
820	4430.0	—	—	—	—	—	—	—	—	0.46	9	17.70

TABLE H2. Flexural Test Values of Full Size Ferrocement Sample No.2.

Ring Reading	P (N)	$R_{1/2}$ (mm)	$\delta_{1/2}$ (mm)	R_{θ_2} (grad)	θ_2 (grad)	$R_{\epsilon_{TOP}}$ $\times 10^{-3}$	ϵ_{TOP} $\times 10^{-3}$	$R_{\epsilon_{BOTTOM}}$ $\times 10^{-3}$	ϵ_{BOTTOM} $\times 10^{-3}$	Observed Crack Width mm	Number of Crack	Average crack spacing mm
—	—	1.11	0.00	0.433	0.00	8.215	0.00	8.480	0.00			
—	170 0	1.49	0.38	0.478	0.045	8.190	-0.025	8.550	0.070			
110	690 0	2.46	1.35	0.544	0.111	8.090	-0.125	8.715	0.235			
207	1150	3.59	2.48	0.657	0.224	7.939	-0.280	9.000	0.520			
300	1590	8.80	7.69	1.358	0.925	7.315	-0.900	11.190	2.710	First Crack 0.04	4	40.0
407	2070	18.40	17.29	2.361	1.927	6.250	-1.965	15.030	6.550	0.14	6	26.6
507	2570	27.87	26.76	3.345	2.911	5.255	2.960	18.410	9.930	0.22	9	17.7
607	3040	40.74	39.63	—	—	3.640	4.575	23.520	15.040	0.30	10	16.0
668	3340	—	—	—	—	2.750	5.465	—	—			
830	4070	—	—	—	—	—	—	—	—	1/26	10	16

TABLE H.3 The Creep Values of Ferrocement Sample Under the Load of 200.6 N.

$G=4P$	$R_{\delta_{\frac{1}{2}}}$	$\delta_{\frac{1}{2}}$	R_{θ_2}	θ_2	$R_{\epsilon_{TOP}}$	ϵ_{TOP}	$R_{\epsilon_{BOT.}}$	ϵ_{BOTTOM}	t
N	mm	mm	grad	grad	$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-3}$	(hour)
0 0	4.00	0.00	0.700	0.00	8.72	0.00	8.41	0.00	0.00
200.60	4.25	0.25	0.7180	0.018	8.54	-0.180	8.60	0.190	0.00
	4.41	0.41	0.7233	0.0233	8.47	-0.250	8.64	0.230	46.50
	4.48	0.48	0.7254	0.0254	8.435	-0.285	8.685	0.275	71.85
	4.53	0.53	0.7260	0.0264	8.41	-0.310	8.655	0.245	95.0
	4.62	0.62	0.7315	0.0315	8.36	-0.360	8.64	0.230	167.0
	4.65	0.65	0.7330	0.0330	8.31	-0.410	8.61	0.200	214.0
	4.68	0.68	0.7346	0.0346	8.29	-0.430	8.59	0.180	262.0
	4.70	0.70	0.7361	0.0361	8.25	-0.470	8.575	0.165	310.0
	4.72	0.72	0.7377	0.0377	8.23	-0.490	8.570	0.160	405.0

TABLE H.4 The Creep Values of Ferrocement Sample Under the Load of 402.55 N.

P	$R_{\delta_{\frac{1}{2}}}$	$\delta_{\frac{1}{2}}$	R_{θ_2}	θ_2	$R_{\epsilon_{Top}}$	ϵ_{Top}	$R_{\epsilon_{Bot.}}$	ϵ_{Bottom}	t
N	mm	mm	grad	grad	$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-3}$	hour
0 00	7.00	0.00	0.1344	0.00	8.580	0.00	8.460	0.00	0.00
402.55	7.53	0.53	0.1688	0.0344	8.265	0.310	8.780	0.32	0.00
	7.85	0.85	0.1787	0.0443	8.195	0.385	8.840	0.38	71.0
	7.95	0.95	0.1818	0.0474	8.165	0.415	8.870	0.41	117.5
	8.015	1.015	0.1830	0.0486	8.130	0.450	8.820	0.36	142.8
	8.06	1.06	0.1869	0.0525	8.090	0.490	8.820	0.36	166.0
	8.13	1.13	0.1904	0.0560	8.055	0.525	8.810	0.35	238.0
	8.16	1.16	0.1950	0.0606	8.030	0.550	8.785	0.325	285.0
	8.185	1.185	0.1970	0.0626	8.000	0.580	8.760	0.300	333.0
	8.225	1.225	0.1991	0.0647	7.960	0.620	8.740	0.280	405.0