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CONTENTS

Discussion of the technical materials published in this issue is open until **October 1, 1979** for publication in the Journal.

IFIC

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EDITORIAL

This issue being the 8th issue of the new version o the Journal of Ferrocement published by IFIC in cooperation with NZFCMA it can be said that it is now a well established publication. This acceptance on a worldwide basis is underlined by the rapidly increasing number of subscribers, by its selection by ISI for insertion in its publications (Current Contents, Science Citation Index, ASCA) and by the USSR Academy of Sciences for abstracting in its Referativny Zhurnal.

Nevertheless, as already stated in previous editorials many ways for improvement of the Journal of Ferrocement have been identified and the next step for the Editors is to implement such improvements with the cooperation of its readers, Correspondents and Members of the Editorial Board.

Let us recall here that the Journal needs:

a) many more technical notes and news items coming especially from our"amateur"readers.

b) more papers to be submitted for publication in the Journal sent by persons, institutions or firms involved both in fundamentral or in applied research on ferrocement and related materials.

c) more advertisements from firms, not only because of the corresponding financial support provided for the Journal's publication, but also because advertisements are often useful information.

We must also emphasize here that though the fundamental objective of the Journal is to cover all types of information on ferrocement, we believe it must expand its coverage to other types of reinforced cement which might, like ferrocement itself, be of interest to developing countries.

We earnestly hope that with the help of our readers the Journal of Ferrocement will develop rapidly in what we want it to be - a forum for exchanging and disseminating all types of information on ferrocement and related construction materials.

The Editors

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A Possibility to Increase the Mortar Strength of Ferrocement*

T. Yen,+ C.F. Su† and M.F. Chang‡

The mortar of ferrocement, that is generally used in practice, is a mixture of cement and sand; its high strength is mainly based on high cement content and low water-cement ratio. Instead of this traditional concept this paper suggests methods which attempt to improve the properties of the mortar by changes in the aggregates used for the mix. Method 1 replaces the normal sand with a type of high quality rock sand and Method 2 finds a new gradation of sand such that a reduction of cement content and a higher mortar strength is achieved.

INTRODUCTION

Among the methods for increasing the strength of mortar, the most effective is to increase the ratio of cement to sand. Yet such treatment will greatly increase its cost besides leading to a danger of excessive cracking as a result of higher cement content. A mix with a lower water-cement ratio also attains a higher strength but at the cost of a reduction in the workability in the mortar.

Mortar for ferrocement, in general practice uses a cement-sand ratio of about 1/1.75 by weight and a water-cement ratio of 0.35-0.40. However, strengths of such mixes rarely exceed 580 kg/cm^2 [1-3]. Literatures [4] show that most of the ferrocement designers disregard the effects of sand gradations while designing. This contribution of the authors is hence aimed at highlighting the deficiencies which might result as a result of a casual disregard of sand gradation effects on the strength of the mortar. Besides checking on use of better quality sands and finding an ideal gradation of sands, the investigation also extends to determine the influence of some admixtures on rich mortar mixes. Three dispersing agents viz., Plastiment, Pozzolith and Magizon were added to observe the extent of improvement of consistency and strength of the mortar.

MATERIALS USED

Cement

A product of Taiwan Cement Company, Type 1 was used for all the tests.

Aggregates

(i) *Standard Sand:* The sand gradation for casting compressive and tensile test specimens conform to ASTM C109-58 and ASTM C190 respectively.

(ii) *High Quality Sand:* Table 1 gives the physical properties and sieve analysis details of this type of sand titled Aggregate I and Aggregate II that pass through sieve #4 and #60 respectively. This type of sand was obtained from Hwa-Lieu in East Taiwan.

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* Adapted by consent of the author with minor changes from the Proceedings of the International Conference on Materials of Construction for Developing Countries (August 22-24, 1978, AIT, Bangkok).

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(iii) *Normal Sand:* Physical properties and sieve analysis details of this type of sand which comes from West Taiwan are presented in Table 1.

Table 1. Sieve Analysis and Properties of Sand

Aggregate type	Percentage retained						Fineness Modulus FM	Specific Gravity S	Absorption (%)
	#8	#16	#30	#60	#100	pan			
I	7.8	56.5	71.9	78.1	84.8	100	2.21	2.61	0.6
II	-	-	-	19.5	44.9	100		2.60	0.5
Normal Sand	4.1	14.3	46.4	71.0	91.8	100	2.28	2.60	1.8

Admixtures

Three dispersing agents namely Plastiment, Pozzolith and Magizon were used.

MIX DESIGN

Mortar With Standard Sand

Experiments for compressive and tensile strengths follow ASTM C109 and ASTM C190 specifications and as a result the cement-sand ratio used for compression test specimens equals 1/2.75 while that for tension test specimens equals 1/3. Aggregate II was used to replace a part of Standard Sand viz., 5%, 10%, 20%, and 30% by weight. After replacement as stated, the powder content (sand passing through 0.25 mm sieve openings) in the mixed sand for tensile test remains 5%, 10%, 20% and 30% respectively but for compression test the mixed sand has powder content of 38.8%, 32.2%, 40% and 47.5%* respectively.

Mortar With High Quality Sand:

(i) Using Aggregate I, change the cement-sand ratio keeping the mortar consistency constant

let Cement/Aggregate = 1/1.5; 1/2.5; 1/3.5
Cement/Normal Sand = 1/2.5

(ii) Replace Aggregate I partly with Aggregate II keeping the cement-sand ratio and mortar consistency constant.

let Cement/Normal Sand = 1/2.5

and use mix percentage as below:

Aggregate I	=	100%	90%	80%	70%
Aggregate II	=	0%	10%	20%	30%
Powder content	=	22%	29.8%	37.6%	45.4%

* The powder contents of Standard Sand for the compressive test of cement is ca. 25%.

(iii) Using a mixture of 80% Aggregate I with 20% Aggregate II and keeping the mortar consistency constant

let Cement/Natural Sand = 1/1.5; 1/2.5; 1/3.5

(iv) Using the aggregate described in (iii) keep the cement-sand ratio constant and let water/cement ratio = 0.36; 0.375; 0.40; 0.425; 0.45; 0.475

TEST RESULTS AND DISCUSSION

Mortar With Standard Sand

The test results of compressive and tensile strength of mortar, in which the Standard Sand was replaced by different percentages with Aggregate II are presented in Table 2 and Table 3. These results are also sketched as in Fig. 1 and Fig 2. It can be observed from these figures that both of the strengths increase with an increase in the "replacing percentage" of Aggregate II until it is 20%. Beyond this limit any increase in the "replacing percentage" decreases

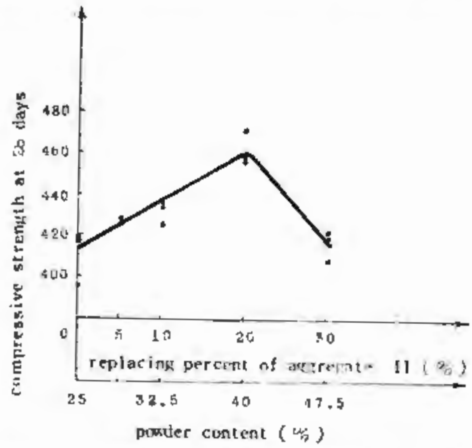

Fig. 1. Influence of powder content in Standard Sand on the compressive strength of mortar.

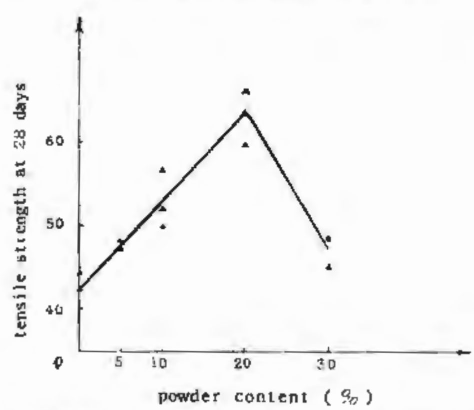

Fig. 2. Influence of powder content in Standard Sand on the tensile strength of mortar.

Table 2. Compressive Strength of Mortar with Standard Sand that is Partly Replaced by Aggregate II

Replacement percentage (%)	Powder content (%)	Water cement ratio	Flow number	Compressive strength at 28 days (Kg/cm²)		Change (%)
0	25	0.484	80.6	417.5 419.5 395.6	410.9	0
5	28.8		80.8	425.5 428.1 425.5	426.4	+3.8
10	32.5		82.6	434.3 425.5 432.5	430.8	+4.8
20	40		68.2	458.0 470.3 457.1	461.9	+12.4
30	47.5		49.1	421.1 418.4 408.8	416.9	+1.5

Table 3. Tensile Strength of Mortar with Standard Sand that is Party Replaced by Aggregate II

Replacement percentage (%)	Powder content (%)	Water cement ratio	Tensile strength at 28 days (Kg/cm²)		Change (%)
0	0	0.416	44.3 42.2 33.1	43.3	0
5	5		47.5 41.8 48.2	45.8	+10.0
10	10		52.0 49.9 56.6	52.8	+21.9
20	20		66.1 63.6 59.8	63.1	+45.7
30	30		48.5 45.0 48.2	47.2	+10.2

the strength. It is hence quite evident that the optimum "replacement percentage" is 20%. In other words maximum strength is attained when the powder content in the sand for compression and tension test are ca. 40% and ca. 20% respectively. This behaviour is in accordance with the reports published by the U.S. National Academy of Science [4].

The rate of increase of strength with increase in "replacement percentage" up to 20% is more for tensile strength as when compared to compressive strength. This can be attributed

Table 4. Relationship Between Compressive Strength of Mortar and Cement-Sand Ratio

Aggregate type	Cement / Aggregate ratio	Flow number	Water cement ratio	Compressive strength at 28 days (Kg/cm²)		Change (%)
I	1/1.5	106	0.42	598.8 606.1 586.0	597.0	+37.5
	1/2.5	101	0.45	503.0 510.5 508.0	507.2	+16.8
	1/3.5	107	0.52	398.5 413.7 419.7	410.6	− 5.5
Normal Sand	1/2.5	97	0.44	442.7 422.6 437.7	434.3	0

Table 5. Relationship Between Tensile Strength of Mortar and Cement-Sand Ratio

Aggregate type	Cement / Aggregate ratio	Flow number	Water cement ratio	Flexural strength (Kg/cm²)		Change (%)
I	1/1.5	125	0.39	107.2 137.0 121.0	121.7	+ 101.5
	1/2.5	111	0.48	87.5 92.0 96.3	91.6	+ 51.7
	1/3.5	124	0.62	75.6 75.6 82.0	77.7	+ 28.6
Normal Sand	1/2.5	122	0.47	60.4 60.3 60.4	60.4	0

to the relationship between the surface area of the aggregate and bond stress. An increased powder content ensures a larger bonding strength and as a result a greater tensile strength [6]. The compressive strength on the other hand has no significant relation to bond stress and the like.

Mortar With High Quality Sand

Mortar is mixed in a 6.5 litre capacity concrete mixer. Cement and sand is drymixed for half a minute before mixing water is added. Compression and bending test specimens conform to ASTM C348-72.

(i) *Aggregate I:* The test results of compressive and flexural strength of mortars that have different proportions of cement with respect to Aggregate I show a proportionate decrease in strength with an increase in aggregate content. However, in comparison with Normal Sand mortar with the same cement-sand ratio of 1/2.5 the improvement of compressive strength is ca.17 % while it is ca.51 % for flexural strength.

(ii) *Mixed Aggregate (I & II):* The test results of Aggregate I partly replaced by Aggregate II, which increases the powder content in the mixed aggregate are presented in Table 6

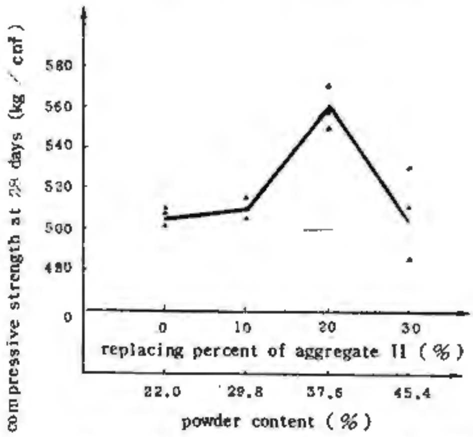

Fig. 3. Influence of powder content in Sand on the compressive strength of mortar.

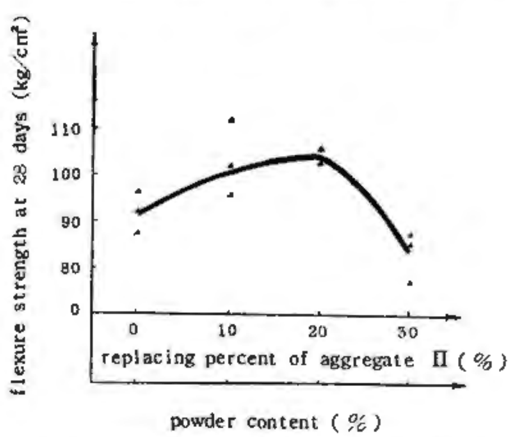

Fig. 4. Influence of powder content in Sand on the flexural strength of mortar.

and Table 7. These are also presented in Fig. 3 and Fig. 4 respectively. From Fig. 3 it can be observed that the maximum compressive strength is attained with the "replacement percentage" is 20% or in other words when the powder content is 37.6% (refer Table 6).

From Fig. 1 and Fig. 3 it can be readily observed that maximum compressive strength is attained when the powder content nears ca.40%. As for the flexural strength of mortar

Table 6. Compressive Strength of Mortar with Aggregate I that is Partly Replaced by Aggregate II

Replacement percentage (%)	Powder content (%)	Flow number	Water cement ratio	Compressive strength at 28 days (Kg/cm^2)		Change (%)
0	22.0	101	0.45	503.0 510.5 508.0	507.2	0
10	29.8	102	0.42	505.7 510.3 515.7	510.7	+ 0.7
20	37.6	105	0.43	557.5 549.5 570.2	559.2	+ 10.3
30	45.4	106	0.44	485.8 531.5 511.7	509.7	+ 0.5

Table 7. Flexural Strength of Mortar with Aggregate I that is Partly Replaced by Aggregate II

Replacement percentage (%)	Powder content (%)	Flow number	Water cement ratio	Flexural strength at 28 days (Kg/cm^2)		Change (%)
0	22	111	0.48	87.5 92.0 96.3	91.6	0
10	29.8	117	0.50	111.7 95.7 101.6	103.0	+ 12.4
20	37.6	115	0.52	102.7 105.2 104.1	104.0	+ 13.5
30	45.4	116	0.54	77.1 85.2 87.8	83.4	– 9.0

presented in Table 7, replacing of Aggregate I by Aggregate II increases the flexural strength until a 20% replacement or until when powder content in sand is ca.40%. This is appreciably higher than 20% determined by using Standard Sand as in Fig. 2 because Standard Sand for tensile test of cement has finer particles* and as a result larger surface area in comparison with Aggregate I.

According to the above test results along with their analysis, a best sand gradation for achieving the maximal strength of mortar should follow the curve presented in Fig. 5 which has been obtained from a sand mixture of 80% Aggregate I and 20% Aggregate II. This mixture henceforth to be called Aggregate III has been used in all further experiments.

As observed from Table 8, the compressive strength of mortar with Aggregate III is proportional to the cement content though there exists a reasonable improvement in strength

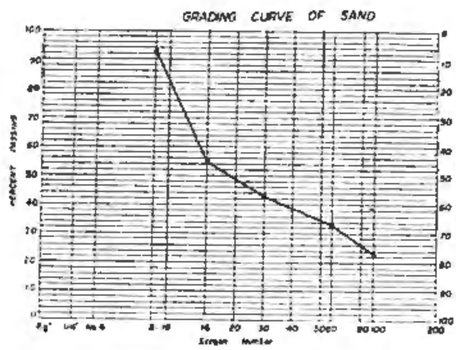

Fig. 5. A suggested ideal curve of sand gradation for ferrocement.

Table 8. Relationship Between Compressive Strength of Mortar and Cement-Sand Ratio

Aggregate type	Cement / Aggregate ratio	Flow number	Water cement ratio	Compressive strength at 28 days (Kg/cm²)		Change (%)
III	1/1.5	71	0.33	617.0 647.0 627.0	630.3	+ 45.1
	1/2.5	83	0.41	528.0 533.0 521.0	527.0	+ 21.3
	1/3.5	85	0.50	438.0 440.0 442.0	440.0	+ 1.3
Normal Sand	1/2.5	97	0.44	442.7 422.6 437.7	434.3	0

* Standard sand for tensile test of cement must pass sieve #20 while it must be retained on sieve #30.

as when compared to mortar with Aggregate I. In other words a cement:Aggregate III mortar of 1:3.5 cement-sand ratio has the comparable strength to that made with cement:Aggregate I mortar of 1:2.

From Tables 4 and 8 a relationship between compressive strength and mix rate can be drawn as presented in Fig. 6. The mortar properties for use in ferrocement as suggested by Huang [1], Sutharatanachaiyaporn [3], National Academy of Science [4] and Raisinghani [7] the cement-sand ratio should be around 1/1.75 and the water-cement ratio in the range 0.35-0.40 for which a compressive strength in the range 460 kg/cm^2-570 kg/cm^2 is attained. Comparing these strength values, from Fig. 6 it can be observed that a cement-sand ratio of 1/2 to 1/3 will be sufficient when using Aggregate III.

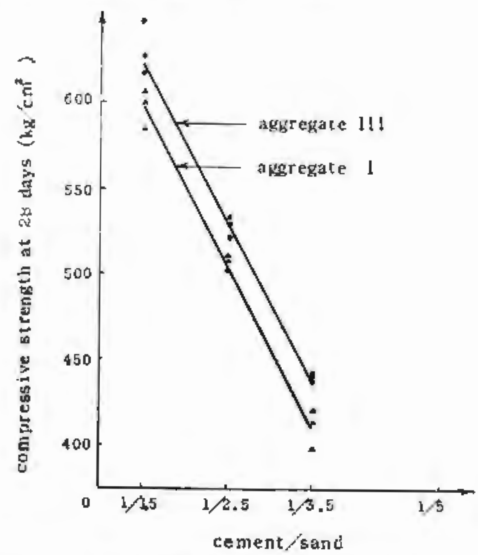

Fig. 6. Relationship between cement-sand ratio and the compressive strength of mortar.

(iii) *Other factors influencing strength*

Using Aggregate III the effect of water-cement ratio on the compressive strength of mortar was studied with a cement-sand ratio of 1/2.5. Test results thus obtained are presented in Table 9. The compressive strength decreases with an increase in the water-cement ratio though the decrease is reasonably small. The consistency of the mortar increases very rapidly with an increase in the water-cement ratio. It seems that a water-cement ratio of 0.4 is ideal. Besides agreeing well with suggestions from the National Academy of Science [4], it possesses adequate cohesive property of being stiff enough to stick onto the steel mesh without falling off while plastering (as suggested by Hurd [8]).

Influence of Admixtures

In order to investigate the influence of admixtures on mortar, three kinds of dispersing agents, Plastiment, Pozzolith and Magizon were added in mortar with low water-cement ratios of 0.325, 0.35 and 0.375. Their consistency represented by flow numbers and compressiv strengths that were measured are presented in Table 10. Comparing Tables 9 and 10, it can

Table 9. Influence of Water-Cement ratio on Compressive Strength of Mortar

Cement / Aggregate III ratio	Water cement ratio	Flow number	Compressive strength at 28 days (Kg/cm^2)	
1/2.5	0.360	0	633 579 605	605.7
	0.375	29.6	574 577 589	580
	0.400	45.8	583 571 581	578.3
	0.425	71.1	563 577 557	565.7
	0.450	82.9	563 553 557	558
	0.475	111.4	547 537 549	544.3

be observed that dispersing agents can improve mortar consistency to a great extent. For example, with a water-cement ratio of 0.375 dispersing agents like Plastiment and Magizon increase the flow numbers from ca.30 to ca.95, without any appreciable change in the corresponding compressive strengths. Hence, dispersing agents in mortars of rich mixes improve workability without reducing its strength. Since the sand gradation suggested in this paper contains high powder content utilizing dispersing agents proves to be of significant use.

CONCLUSIONS

(i) Mortars mixed with high quality sand has a higher strength than with mortars that use Normal Sand. For a cement-sand ratio of 1/2.5 the former is ca.17% higher in strength than the latter.

(ii) For rich mixes the compressive and flexural strengths can be increased by increasing the powder content (particle size less than 0.25 mm) in sand. However, beyond a certain powder content both these strengths decrease with any further increase in the powder content.

(iii) Maximum strengths can be attained with a cement-sand ratio of 1/2.5 when the powder content in sand equals to ca.40% and the sand gradation cruve follows the one presented in Fig. 5. Comparing the strengths to a mortar using Normal Sand with the same

Table 10. Influence of Dispersing Agent on Mortar

Dispersing agent		Water cement ratio	Flow number	Cement / Aggregate III ratio	Compressive strength at 28 days (Kg/cm²)	
Item	Dose(cc/Kg-cement)					
Plastiment	0.35	0.325	71	1/2	673 633 639	648
		0.35	85		637 639 635	637
		0.375	94		631 621 623	625
Pozzolith	0.5	0.325	60	1/2	670 661 677	669
		0.35	89		601 631 603	612
		0.375	127		521 531 511	521
Magizon	0.5	0.325	30	1/2	643 639 620	634
		0.35	71		577 575 601	584
		0.375	96		583 559 599	580

cement-sand ratio, it is observed that the compressive strength and flexural strength increase is ca.21% and ca.72%. Larger increase in flexure is of significant advantage while considering ferrocement structures.

(iv) Use of dispersing agents in mortars improves the workability considerably without any appreciable change in its compressive strength.

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The Design and Construction of Ferrocement Caissons With Corrugated Frictional Base Plates Used in the Breakwater of Hsin-Kang Fishing Harbor*

C.F. Su+, Y.H. Lee‡ and R.H. Chang‡

Due to the unfavorable construction conditions and budget limitation, the caissons of the composite-type breakwater were partly fabricated with ferrocement. The caissons, 10m long, 12m wide and 6.7m high, were composed of sandwiched type side wall of reinforced concrete and ferrocement, ferrocement partition, and reinforced contrete bottom plate protected by ferrocement shell on the bottom surface. Because of workability and high strength of ferrocement, the base plate could be easily corrugated. In this case, the friction coefficient of corrugated plate to rubble increased to 0.8, and the width of the caisson could be considerably reduced. The ferrocement plates were pre-cast on the beach, and then set up on a simple slipway for launching. After launching, the reinforced concrete components was cast to complete the whole caisson. The weight of the caisson at launching was only about one half of the finished caisson, thus it was much easier to launch and simple facilities would be adequate. There was also a saving in the construction time and cost.

INTRODUCTION

The Hsin-Kang Fishing Harbor is located on the eastern coast of Taiwan, facing the Pacific Ocean. The exact position is 120° 22′ 36″E, 23° 5′ 40″N, as shown in Fig. 1. Because the harbor entrance opens to the south, the waves coming from the south and southeast enter the harbor basin and cause the outer portion of the basin to become very rough. Therefore the outer basin, which comprises 60-70% of the area of the total basin, can not be put to full use. Recently, because of fisheries development and consequently increase of fishing boats, improvement of the harbor became quite necessary.

From 1976, the Consultancy began to study the improvement plans with the help of model test to obtain the best layout of the breakwaters. The final conclusion was that both the east and west breakwaters should be turned counter-clockwise by 30 degrees from the head of the existing breakwaters and lengthened by 90m and 12m respectively, as shown in Fig. 2. The caisson-type breakwaters were adopted. Large size caissons should be used for the breakwaters, where the water depths of the breakwaters varied from 5m to 9.5m, to protect them against the wave force of 4.6m in significant wave height and 12 sec. in wave period, which was the wave height at the site of the east breakwater. If the traditional reinforced concrete caissons were used, the width of the caisson should be 15m. To construct such a large caisson, a dry dock or floating dock or slipway would be required. The construction cost of such facility, even one of the simplest construction, would require US$250,000. This was as much as a quarter of the budget estimate for the improvement of the harbor. Furthermore, the harbor is surrounded by hills; its water basin was formed by dredging the land area, when it was constructed in 1929. Therefore the appron of the wharf is lower than its back by about

* Published also in the Proceeding of the International Conference on Materials of Construction for Developing Countries (August 22-24, 1978), AIT, Bangkok.

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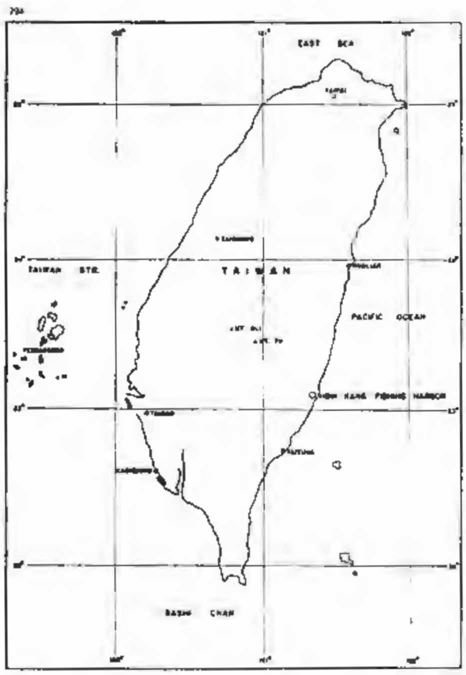

Fig. 1. Positions of Hsin-Kang fishing harbor.

Fig. 2. Layout of Hsin-Kang fishing harbor.

20m. It is difficult to provide space near the harbor to install or build such a facility. Due to the shortage of space and budget, some other ways would be found to solve the problem of construcing large size reinforced concrete caisson.

After detailed studies, the authors found that the use of high strength ferrocement could solve this problem. Ferrocement is mainly used to contruct fishing boat in Taiwan [1]. Recently, it was also applied to housing and other structures. The authors have made preliminary study of the feasibility of fabricating cassions with ferrocement [2]. Now, a further study was made to put this into practice.

The purpose of this paper is to illustrate how to apply the characteristics of ferrocement and simple facilities to fabricate caissons under the unfavorable conditions and budget limitation and how to increase the frictional capacity to decrease the width of caissons and consequently to reduce the construction cost. The experience of fabrication technology of ferrocement caisson would be helpful to the engineers of developing countries.

IMPROVEMENT OF FRICTIONAL CAPACITY

Generally, the stability of composite-type breakwater is mainly controlled by the horizontal sliding of the vertical portion. Thus, if the resistance force can be increased, it is possible to use a more economical cross section. In the past, many engineers were also interested in the problem of how to increase the friction force. For instance, in Japan [3] [4] the engineers used specially shaped base plate of caisson or concrete block stopper or asphalt mat on the top layer of mound foundation or placing concrete block behind the caisson to increase the resistance force against the attack of waves. But these methods are not applicable due to the difficulty of construction in situ or their doubtful effectiveness.

In the present paper, the method used to increase the friction coefficient is by use of caisson base plate of special shape. The size of model plate was 50cm by 80cm, and five kinds of base plates were tested: the base plates with (1) smooth surface, (2) 1cmϕ rough angular stone surface, (3) conoid legs surface (1.2cm high, tip diameter 1.2cm, base diameter 1.6cm and spacing 9.6cm), (4) wavy surface (2.3cm high and 6.5cm long), (5) wavy surface with 10cm × 10cm × 15cm block put behind the caisson. The above plates were placed on model rubble mound foundations consisted of rubble size dimensions (1) below 3/8″ ϕ (2) 3/8″ϕ–1″ϕ (3) 1″ϕ – 3″ϕ rough angular rubbles respectively.

The procedure of the test was that first the sieved rubbles were placed and levelled in a metal pan, then water was poured into the pan until the surface was 1cm higher than that of the rubble mound. The test was carried out by pulling method when the model caisson was placed on the mound. Its sliding distance was measured by the static pressure equipment in the scale of 1/100mm and the force to pull the caisson was determined by the level type equipment. Finally, the friction coefficient was calculated by the weight of caisson and the pulling force.

The results of testing are shown in Table 1. It is obvious that the base plate with wavy surface is the most effective. Fig. 3 shows the relation of friction coefficient μ to the sliding

Table 1. Summary of Test Results of Friction Coefficient

Rubble Size of Mound Foundation		3/8″	3/8″ϕ – 1″ϕ	1″ϕ – 3″ϕ
Friction Coefficient	Smooth Surface	-	0.52	0.61
	Rough Angular Stone Surface	0.64	0.58	0.60
	Conoid Legs Surface	0.70	0.65	0.68
	Wavy Surface	0.45	0.68	0.81
	Wavy Surface with Block	-	0.71	0.89

distance for the base plate with wavy surface. The minimum value of μ occurs at the start of movement of the caisson. Then, the friction coefficient increased with the moving of the caisson until it reached some distance, at which it approached a constant value. On the other hand, it appears that the μ value is larger for coarser rubble. But when the rubble size is larger than 3"ϕ, it is not known whether the friction coefficient still increases with rubble size due to the lack of test data. Furthermore, the similarity for friction coefficient is also not clear. However, from the relation of rubble size to the angle of repose, it is reasonable to consider that the μ value will increase slightly or will approach a constant, when the rubble size is larger than 3"ϕ. Fig. 4 shows the μ values for different rubble size of rubble mound foundation with and without concrete blocks put behind the caisson. In which the maximum value of μ = 0.89 can be achieved.

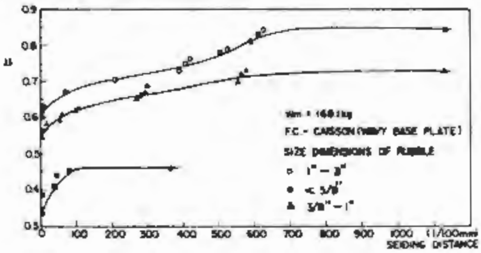

Fig. 3. μ Value versus sliding distance of caisson for rubble of different size.

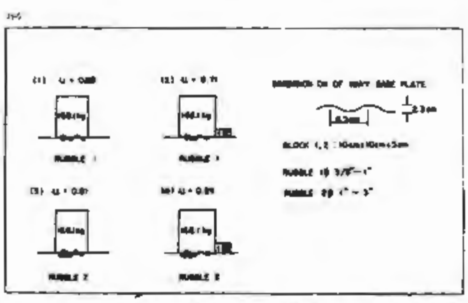

Fig. 4. μ Values of mound foundation of different rubble sizes with and without concrete blocks put behind caisson.

FEATURES OF FERROCEMENT CAISSON

The typical cross section of the breakwater is shown in Fig. 5. The caisson is 10m long, 12m wide and 6.7m high (Fig. 6).

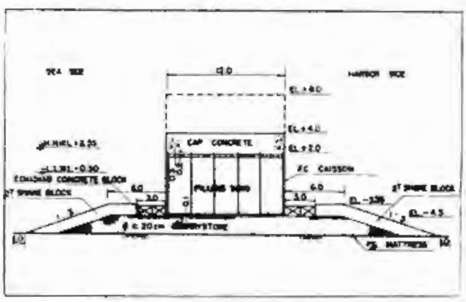

Fig. 5. Typical cross-section of the breakwater.

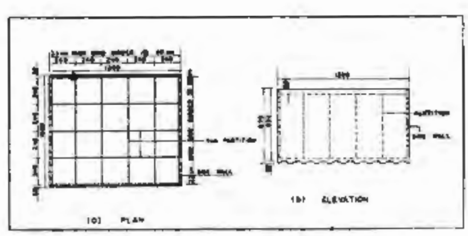

Fig. 6. Ferrocement caisson.

The structure of the caisson mainly consists of three parts: base plate, side wall and partition. The side wall is a sandwiched type, the inner and outer portion are 3.0cm and 3.5cm ferrocement plate respectively, between them a 30cm thick reinforced concrete wall is poured to connect the ferrocement plates after the launching of the caisson. The ferrocement plates were designed to be used as formwork, but their strength still could meet the requirement of the design purpose of the caisson. After launching, the reinforced concrete portion that was poured (210 kg/cm^2) is considered as the real side wall. The partition is a 4cm thick ferrocement plate only. The corrugated base plate is formed by 20cm to 40cm thick reinforced which is prevented from cracking by a 5cm thick ferrocement at the bottom surface. The concrete structure of the caisson is briefly described in the following subsections.

1) *Base Plate:*

According to the results of the mentioned tests of friction capacity, the most effective base plate is that with wavy surface, but it is difficult from the point of view of construction. Therefore the wavy surface was modified to a corrugated shape, as shown in Fig. 7(a). The friction coefficient was conservatively considered as 0.8, and its bottom surface was prevented from cracking at the corners and penetration by ferrocement plate. The 5cm thick ferrocement plate was designed by welding 4-layer, 0.914mm by 3/4□" wire mesh with # 5 @10cm main steel bars and #2 @50cm temperature steel bars, on the steel 3-layers of wire mesh was welded again, and then the mortar was plastered. The connection between ferrocement and reinforced cement portion was by C and D beams, with 60cm span, whose steel bars were also welded with the main steel bars of ferrocement. The portion of reinforced concrete with two ways #4 @ 7cm steel bars was cast after launching, as shown in Fig. 7. Due to the special shape of bottom surface, the friction coefficient can be increased to 0.8 from 0.6 in general case, while the width can be reduced to 12m from 15m.

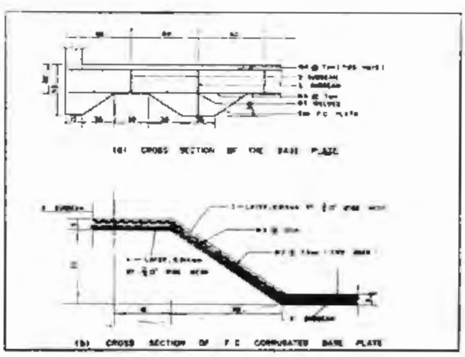

Fig. 7. Base plate.

2) *Partition:*

The 4cm thick partition was formed by # 4 @ 7cm vertical steel bars and # 4 @5cm horizontal steel bars welded to each other as the main steel, on both sides of which a 3-layer, 0.914m by 3/4□" wire mesh was welded respectively, and then the ferrocement mortar was plastered.

3) *Side Wall:*

The 3.5cm thick outer ferrocement plate was formed by #2 @ 5cm vertical bars and #3 @ 7cm horizontal bars, each bar was welded as the main steel, and on the outer and inner sides of the main steel a 4- and 3- layer, 0.914mm by 3/4□" wire mesh was welded respectively. The 3cm thick inner ferrocement plate mortar was plastered on a 3-layer outer wire mesh and a 2-layer inner wire mesh, both of them were welded to the central main steel consisted of #3 @ 6cm horizontal bars and #2 @ 5cm vertical bars. Because the ferrocement plates were too thin, in order to prevent excessive deflection, these two plates were connected by welding vertical and horizontal steel subbeams so that the reinforced concrete could tie the ferrocement as a unit.

4) *Weight of Caisson:*

The first step of the caisson as mentioned above, a part of reinforced concrete was cast at joints before launching, consequently its launching weight was about 220 ton. When the second step was completed, all of the reinforced concrete was cast, the total weight was about 450 ton. Therefore, the weight at launching was just one half of the total weight. If a 15 m wide reinforced concrete was adopted, its weight would be almost up to 600 ton. Thus, using this technology, the weight of caisson at launching can be reduced about by 60%.

FABRICATION OF FERROCEMENT CAISSON

There are two steps in the fabrication of ferrocement caisson. Firstly, the ferrocement plates were pre-cast on the beach, and then set up at the prepared simple slipway to launch. Secondly, reinforced concrete was cast continuously after the ferrocement caisson had floated in the inner basin. The detailed steps are described as follows:

1) *Pre-casting Ferrocement Plates:*

The ferrocement caisson is composed of thirty-one plates. They are two corrugated base plates, eight side walls and twenty-one partitions. Two corrugated base plates, each 10m by 6m, compose the base plate, as shown in Fig. 8. Eight side walls, two walls for every side, compose the four side walls of the caisson. Every side wall has the inner and outer ferrocement shells joined by steel subbeam truss. This reserves the space for the reinforced concrete. The width of the pre-cast partition differs with the size of the compartment. On the construction, the ferrocement plates were constructed on the asphalt pavement, the steel bars were joined by welding and in order to make the thickness of the plate uniform, the vibrator was used to plaster the mortar.

(a) WELDING OF CORRUGAUED BASE PLATE (b) PRE-CASTING ON CORRUGATED BASE PLATE

Fig. 8. Fabrication of the base plate.

2) *Curing of Ferrocement Plates:*

Special curing is not necessary for the ferrocement plates. Their compressive strengths reach 350 kg/cm^2 after seven days.

3) *Materials of Ferrocement Mortar and Its Cylinder Test:*

The cement, sand and water ratio of 1.0:1.6:0.6 was used for the mortar. A mixture of COR-3 rapidard in the ratio of 0.15 was added to increase the workability. The fine aggregate should pass though No.4 U.S. sieve size and be greater than No.100 U.S. sieve size, and silica aggregate produced in Taiwan was used in this construction. The cement used was Type 1 normal Portland cement.

Nine samples, 15cm in diameter and 30cm in height, were carried out for the cylinder test and their compressive strengths are shown as follows:

Sample Number	Age (days)	Compressive Strength (kg/cm^2)
1	7	354.55
2	28	372.66
3	28	397.73
4	28	440.34
5	28	366.50
6	28	504.60
7	28	604.00
8	28	448.00
9	28	521.00

4) *Setting Up of The Ferrocement Caisson:*

After seven days, the pre-cast plates were ready to be set up. The corrugated base plates were first put on the simple slipway, which with slope of one to eight, was constructed by four 50 kg/m railways on the pillow blocks and the rollers across the railways on the top. In addition, two wooden plates were put beneath two launching slipping surface to support the caisson, as shown in Fig. 9. Two caissons could be set up at the same time.

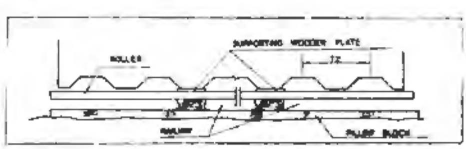

Fig. 9. Supporter of the base plate during setting up of the caisson.

After two base plates had been completely jointed, the welding of the steel bars for the reinforced concrete at the bottom followed. Then, the partitions and the side walls were set up one by one, which were first welded temporarily to adjust the position, as shown in Fig. 10. When those walls were adjusted to the precise position, the steel bars at the joint were welded completely. Particular care was taken at the junctions of two plates by additionally welding the skeletal steel bars through each other and then plastering them with mortar. Besides, the reinforced concrete was pre-cast around the base plate and along two launching slipping surface to avoid accidental cracking during launching Approximately, it took 13 to 14 days to finish the above mentioned procedures.

Fig. 10. Setting up of the ferrocement caisson.

5) *Launching of the Ferrocement Caisson:*

The launching of the ferrocement caissons was carried out during the flood tide. Two 50-ton jacks were used to lift the caisson at the back and helped by one 65-HP bulldozer to move it. At the same time, the caisson, roped with 1.5 inches nilon rope, was pulled by one 35-HP fishing boat, as shown in Fig. 11. After launching, the caisson was towed to the opposite side wharf to cast the reinforced concrete at the bottom and side wall.

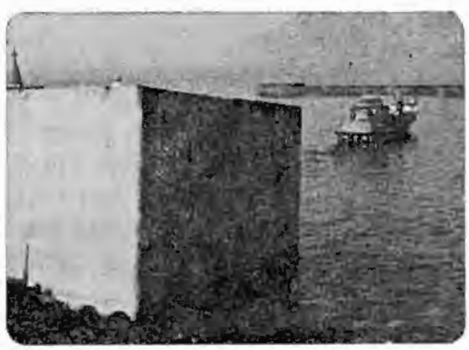

Fig. 11. Launching of the caisson.

PLACING OF THE CAISSON

Until the reinforced concrete reached its required strength the caisson could be floated to the prepared rubble mound foundation to be put in the place. When it was adjusted to the precise position, the caisson was sunk by opening the valves, then filled with rubbles and sand, and capped with concrete.

CONSTRUCTION COST OF FERROCEMENT CAISSON

The total construction cost of one ferrocement caisson, which is 10m long, 12m wide and 6.7m high, is presented in the following page.

Material Cost	US$18,880.00
Construction Cost	11,800.00
Overhead	920.00
Total Cost	US$31,600.00

CONCLUSION

In conclusion, the advantages of ferrocement caisson may be summaried as follows:

1) The weight of the entire caisson at launching can be considerably reduced to about 40% of that of the traditional reinforced concrete caisson. So, only simple facility is needed for launching and launching is much easier too.

2) Since the caisson is pre-fabricated on the beach, the necessary facility is quite simple and construction cost may be quite reduced.

3) In the pre-fabrication, the quality of the ferrocement plates can be better controlled There is a saving in the construction time and the field limitation for construction is less.

4) Because of the workability of the ferrocement, the base plate of the caisson can be corrugated to any special shape to increase the friction coefficient, and consequently to reduce the width of the caisson.

5) The partitions made of ferrocement only, already have enough capability to resist flexural and compressive loads. This can reduce the weight of the caisson.

ACKNOWLEDGEMENT

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Performance Criteria for Ferrocement

Antoine E. Naaman*

The increasing application of ferrocement as a structural material has created the need for specifications related to its usage similarly to those developed for reinforced concrete and steel structures. To satisfy this need some guidelines and requirements related to specific applications of ferrocement, such as boat building, have been already published. The guidelines and criteria presented in this paper are more general in nature and should be applicable to most ferrocement structures; they summarize and update previously published work and present a new expanded section on design requirements and satisfactory performance. Design examples are developed.

INTRODUCTION

The increasing application of ferrocement as a structural material has created the need for specifications related to its usage similarly to those developed for reinforced concrete and steel structures. Such need has been already identified by the ferrocement boat industry as witnessed by some recently published requirements on the construction of ferrocement boats [1-3]. In a recent paper Shah [4] has provided tentative recommendations for the construction of ferrocement water tanks. Similar publications will simplify the construction of ferrocement structures and guarantee their safe performance. Also, they are of great value to professional users and practitioners as they provide a more rational basis for design.

Legally speaking, specifications must come from and be officially approved by various technical organizations and governmental agencies. As to the author's knowledge, a document containing such specifications will not be available in the near future, it seems that some more general guidelines, not necessarily related to a specific application of ferrocement, will represent a valuable first step toward such a goal.

Based on (1) the above mentioned requirements [1-4], (2) an extensive series of tests to investigate the mechanical properties of ferrocement [5-10], (3) a number of tests on ferrocement wall panels [11] (which included corrugated panels and sandwich panels) and ferrocement water tanks [12] where reinforcing parameters, load deformation response, cracking, leakage and cost characteristics were studied, (4) an extensive survey of ferrocement and reinforced concrete related literature where some forms of specifications or recommendations were found and analyzed [13-24], and (5) a survey of the applications of ferrocement in some typical structures [25] where reinforcing parameters and other variables were observed (Table 1), the author is presenting these guidelines and the corresponding design criteria for the construction of ferrocement structural members.

They are divided into four major sections, namely: Materials, Testing, Design, and Construction.

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Table 1. Ferrocement: Current Ranges of Composition and Properties

Wire-Mesh Reinforcement	Wire Diameter:	$0.020 \leq \phi \leq 0.062$ inches ($0.5 \leq \phi \leq 1.5$ mm)
	Type of Mesh:	Chicken wire or square woven or welded wire galvanized mesh; expanded metal
	Size of Mesh Openings:	$1/4 \leq m \leq 1$ inch ($6 \leq m \leq 25$ mm)
	Number of Mesh Layers:	Upto 12 layers per inch of thickness (Upto 5 layers per cm of thickness)
	Fraction Volume of Reinforcement:	Upto 8% in both directions corresponding to upto 40 pounds of steel per cubic foot of concrete (630 Kg/m^3)
	Specific Surface of Reinforcement:	Upto 10 in^2/in^3 in both directions (Upto 4 cm^2/cm^3 in both directions)
Intermediate Skeletal Reinforcement if used	Type:	Wires; wire fabric, rods; strands
	Diameter:	$1/8 \leq d \leq 3/8$ inches ($3 \leq d \leq 10$ mm)
	Grid Size:	$2 \leq G \leq 4$ inches ($5 \leq G \leq 10$ cm)
Typical Mortar Composition	Portland Cement:	Any type depending on application
	Sand-to-Cement Ratio:	$1 \leq S/C \leq 2.5$ by weight
	Water-to-Cement Ratio:	$0.4 \leq W/C \leq 0.6$ by weight
	Recommendations:	Fine sand all passing U.S. sieve No. 8 and having 5% by weight passing No. 100, with a continuous grading curve in-between
Composite Properties	Thickness:	$1/4 \leq t \leq 2$ inches ($6 \leq t \leq 50$ mm)
	Steel Cover:	$1/16 \leq c \leq 3/16$ inch ($1.5 \leq c \leq 5$ mm)
	Ultimate Tensile Strength:	Upto 5,000 psi (3,445 N/cm^2)
	Allowable Tensile Stress:	Upto 1,500 psi (1,033 N/cm^2)
	Modulus of Rupture:	Upto 8,000 psi (5,512 N/cm^2)
	Compressive Strength:	4,000 to 10,000 psi (2,756 to 6,890N/cm^2)

GUIDELINES

Materials

Cement

The cement is to be ordinary portland cement and shall conform to the ASTM standard C-150. ASTM Type I is recommended; other types of portland cements may be used if special properties such as high early strength and sulfate resistance are needed. The cement should be fresh and of uniform consistency. Where there is evidence of lumps or any foreign matter in the material, it should not be used. The cement is to be stored under dry conditions and for as short a duration as possible.

Fine Aggregates (Sand)

Sand shall be obtained from a reliable supplier and shall comply with ASTM standard C-33 for fine aggregates. It should be clean, hard, strong, free of organic impurities (ASTM C-40) and deleterious substances. It should be inert with respect to other materials used and of suitable type with regard to strength, density, shrinkage and durability of the mortar made with it.

Grading of the sand is to be such that a mortar of specified proportions is produced with a uniform distribution of the aggregate, which will have a high density and good workability and which will work into position without segregation and without use of a high water content. The fineness of the sand should be such that 100% of it passes standard sieve No. 8. Table 2 gives some guideline on desirable gradings.

Table 2. Guidelines on Desirable Sand Gradings

Sieve Size U.S. Standard Square Mesh	Percent Passing by Weight
No. 8	100
No. 16	50-85
No. 30	25-60
No. 50	40-30
No. 100	2-10

Water

Water used in the mixing is to be fresh and free from any organic and harmful solutions which will lead to a deterioration in the properties of the mortar. Salt water is not to be used.

Admixtures

Special considerations shall be given to the addition of materials to the concrete for special purposes. Approval may be given by the consulting engineer, when the material is to be added to directly or indirectly reduce the water to cement ratio or according to approved standards, if any.

If admixtures are used they should conform to federal specifications SS-P-570B and ASTM C-260, C-494 or C-618. The use of additive not covered by the above specifications (such as polymer latex modified mortar) shall be based on test data to comply with the specified mortar properties.

Mortar Mix Proportions

The recommended mix proportions for a typical application are: sand-to-cement ratio by weight = 2, and water-to-cement ratio by weight = 0.45 to 0.5. The sand-to-cement ratio may be increased to 2.5 when shotcreting is used to account for the loss of particles caused by the rebound. Other mix proportions than those recommended here (Table 1) and admixtures such as water-reducing agents may be used provided the specified properties such as compressive strength are attained. Attention should be paid to estimating the moisture content of the aggregate in order to provide a reliable control of the water-cement ratio.

Quantities of materials are normally to be determined by weight although the aggregates may be determined by volume, due allowance being made for bulking due to moisture.

The slump of the fresh mortar shall be the lowest possible that will permit thorough compaction and should not exceed 2.5 inches (6 cm); the 28-day compression strength of 3 in. x 6 in. (7.5 x 15 cm) moist cured cylinders should not be less than about 4000 psi (2756 N/cm^2).

Control of the sand fineness modulus (ASTM C-33 or C-330), water-to-cement and aggregate-to-cement ratios should be carefully maintained to provide uniform properties throughout the structure. The general requirements for constituent materials and mortar quality shall also be guided by Chapters 3 to 6 of the ACI 318-77 building code requirements for reinforced concrete.

Paint Coating

For ferrocement water retaining structures paint is recommended on both surfaces. Any good quality epoxy paint such as, for example, Sikaguard HI-BILD 664/9 or equivalent is acceptable. The paint should be stable and durable for up to a specified temperature and pressure as well as chemically inert for the type of local water used.

Steel Reinforcement

The reinforcement should be clean and free from all loose mill scale, dust and loose rust, and coatings such as paint oil or anything that might reduce bond.

a) Wire mesh. Several types of mesh reinforcement can be used: galvanized chicken wire mesh, woven or welded square galvanized meshes, or expanded metal sheets. Square type meshes are recommended if isotropic properties of the ferrocement material and/or if accurate apriori prediction of these properties are desired. Woven or welded square galvanized wire mesh shall conform to ASTM standard A-185 with a wire diameter of not more than 1/16 in. (1.5 mm) and a yield strength at 0.2% offset strain, in excess of 65,000 psi (448 MN/m^2).

b) Welded wire fabric. The welded fabric which can be used in combination with wire mesh shall comply with ASTM standards A-496 and A-497. The minimum yield strength of the wire shall be (according to ASTM A-82) 65,000 psi (448 MN/m^2) for the smooth wire and 70,000 psi (483 MN/m^2) for the deformed wire. The wire diameter shall preferably be less than 3/8 in. (10 mm) when used in ferrocement.

c) Rods, wires, strands. If used, reinforcing rods shall be as specified by ASTM A-615 and ASTM A-616 for grade 60. If prestressing wires or strands are used, they shall comply with ASTM A-421 and ASTM A-416. Preferably all shall have diameters smaller than 3/8 in. (10 mm) when used in the ferrocement wall.

Testing

This section applies essentially to large or unusual ferrocement structures where little previous experience exists. Such typical structures include water retaining or carrying structures and large water tanks of more than 10,000 gallons (40000. liters) capacity.

Preliminary Tests

The preliminary tests should include:

a) The compressive strength of the mortar (based on cubes or cylinders) in order to determine suitable mix proportions, and in accordance, for example, with ASTM standard C-496-66.

b) The stress-strain curves in tension of the different types of steel reinforcement used, especially the wire mesh in order to determine strength and modulus of the reinforcing system and predict crack widths.

c) The bending properties of ferrocement plates which are representative of the proposed design (ASTM C-78-64). These tests should reflect predicted strength and cracking behavior; they should show: (1) that failure is by rupture of the steel reinforcement (for better ductility), (2) that the modulus of rupture assuming a homogeneous elastic section should be in excess of a certain specified value, and (3) that the maximum crack width should be less than or equal to a specified value.

Quality Control and Delivery Tests

During and after the construction, the following tests should be performed in order to assure quality and uniformity of the ferrocement material and serviceability of the structure:

a) Specific weight of fresh mortar (ASTM C-138).
b) Amount of entrained air (ASTM C-260).
c) Compressive strength of mortar specimens cured in place of 1, 7 and 28 days, and moist cured for 28 days.
d) Split cylinder tests (ASTM C-496-62T) and flexural strength (ASTM C-293) on 28-day moist cured mortar specimens.
e) Tensile tests on samples of wire mesh reinforcement in order to determine their stress-strain characteristics.
f) Flexural tests at 28 days on ferrocement plates fabricated at the same time as the structure and cured on site, using a method identical to that for the structure.
g) For water retaining structures pulse velocity tests at several locations on the surface of the structure (after the curing period but before filling with water) to ascertain that no voids are present inside the wall and that the finished mortar is compact and homogeneous. Where the consulting engineer suspects any voids in the shell, he may request suitable cores to be drilled out for examination.
h) After completion, the structure is to be closely inspected for surface defects and care should be taken to patch these defects with epoxy filler cement or similar approved filler. Water retaining structures shall be filled with water, before being painted, in order to detect any leaking pinholes in the surface; these must be closed using an epoxy based adhesive or equivalent. The surface will then be presumed watertight and subsequently will be painted under dry conditions.

Design

Ferrocement is a thin highly reinforced shell of mortar in which the steel reinforcement is distributed throughout the section so that the material under stress acts approximately as a "homogeneous" material. Any design related recommendation for ferrocement structures should depend on the type of application and should be based on a rational analysis supported by test results. However, in view of the present state of knowledge of ferrocement and except for special applications where an accurate analysis may be necessary to guarantee safe performance, the following guidelines for ferrocement made with plain mortar and square steel meshes should lead to a satisfactory performance. Engineering judgement must be exercised if other types of meshes are used.

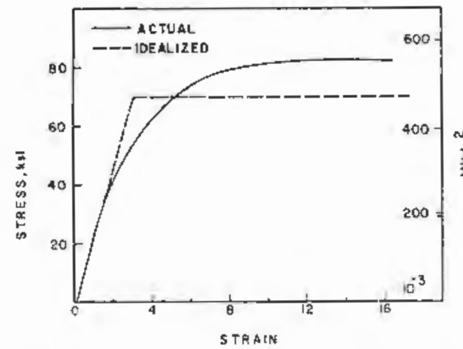

Fig 1. Typical idealzation of the mesh stress strain curve

a) The total volume fraction of reinforcement V_f, in both directions, shall not be less than 1.8%. The total specific surface of reinforcement S_R, in both directions, shall not be less than 2 in^2/in^3 (0.8 cm^2/cm^3). About twice these values are generally recommended (and more for water retaining structures). In computing the specific surface of reinforcement the skeletal steel may be disregarded while it may be considered in computing V_f.

Table 3. Reinforcing Parameters for Ferrocement

Minimum V_f (approx.)*	1.8%
Minimum S_R (approx.)*	2 in.^{2}/in.^{3} (0.8 cm^2/cm^3)
Mesh opening	$s \leq t$
Number of mesh layers	$N \geq 4.0\ t$ (t in in.) $N \leq 1.6\ t$ (t in cm)
Cover $C_{avg.}$ (approx.)	2 mm ($t \leq \frac{1}{2}$ in.) $\leq t/5$ ($t \geq \frac{1}{2}$ in.) $\leq 3/16$ in. (5 mm)

*It is recommended to double the above values for water retaining structures.

b) The recommended average net cover of the reinforcement is about 1/12 in. (2 mm). However, a lesser value can be used provided the reinforcement is galvanized, the surface protected by painting and the crack width limited to a low value. It is also recommended that for thicknesses larger than 1/2 in. (12 mm) the net cover shall not exceed 1/5 the thickness t nor 3/16 in. (5 mm), in order to insure proper distribution of the mesh throughout the thickness.

c) For a given ferrocement material (without skeletal reinforcement) of thickness t the recommended mesh opening s should not be larger than t. Furthermore, the number of layers oı mesh N should be such that:

$$N \geq 4t.$$

If skeletal reinforcement is used it is recommended that the skeletal reinforcement does not occupy more than 50% of the thickness of the ferrocement material. For this case use $N \geq 4t'$ where t' is the thickness in which meshes are distributed s, t, and t' are in inch units.

In order to predict the behavior of ferrocement under service load conditions, an elastic analysis similar to that of reinforced concrete "Working Stress Design" method is acceptable provided the modulus of the steel mesh system (which may be different from the modulus of the steel wire) is considered. Ultimate load can also be predicted for flexural members by analyzing ferrocement as a reinforced concrete member (or column) using the ACI ultimate strength design method. For tensile members the load at ultimate can be approximated by the load carrying capacity of the mesh reinforcement alone in the direction of loading.

If the working stress design method is used, allowable stresses for the constituent materials and for the composite have to be specified. Suggested values are shown in Table 4 and described below:

Table 4 Allowable Tensile Stresses in the Steel

Non-water retaining structures	$\bar{f}_s = 0.60 f_y$ Ex. for $f_y = 65$ ksi $\bar{f}_s = 39$ ksi
Water retaining structures	$\bar{f}_s = 30$ ksi
Fatigue loading (maximum allowable stress range)	$\bar{f}_{sr} = 30$ ksi (fatigue life of about 2×10^6 cycles)

d) The allowable tensile stress in the steel reinforcement may be generally taken as $0.60 f_y$ where f_y is the yield strength measured at 0.0035 strain; however, for water retaining and sanitary structures it is preferable to limit the tensile stress to 30 ksi (207 MN/m^2) unless crack width measurements on a test model indicate that a higher stress would not impair performance. The above values hold provided the pitch weaving of the mesh system is moderate in order to insure an adequate modulus.

For pure tensile elements in ferrocement, an allowable tensile stress in the composite of up to $\overline{\sigma}_{ft}$ 1000 psi (7 MN/m^2) may be used as a first approximation to determine the required thickness t of the element; then the required area of steel in the loading direction A_{sL} can be determined using cracked section analysis.

e) The allowable compressive stress in the composite may be taken as $0.45 f_c$ where f_c is the specified compressive strength of the mortar measured from tests on 3 × 6 in. (7.5 × 15 cm) cylinders.

f) 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 MN/m^2). A value of $f_{sr} = 36$ ksi (248 MN/m^2) can be used for one million cycles and 55 ksi (380 MN/m^2) for 100,000 cycles.

Although the design of ferrocement structures is often based on stress limitations or strength criteria, the concept of serviceability, i.e., acceptable overall behavior under service load and during service life is becoming prevalent. Serviceability in concrete structures is often related to cracking behavior and crack widths. Little quantitative information, however, exists on cracking in ferrocement. The following limits and prediction equations can be used as a first approximation and until more substantial experimental data become available.

g) It is recommended that the maximum value of crack width be less than 0.004 in. (0.010 mm) for non-corrosive environment and 0.002 in. (0.005 mm) for corrosive environment and/or water retaining structures.

h) The maximum crack width for flexural members can be predicted as a first approximation using the following equation [8]:

$$W_{max} \simeq \varepsilon_s \times S \times \beta = \frac{f_s}{E_R} \times S \times \beta \qquad \ldots\ldots\ldots (1)$$

where

ε_s = strain in the outermost layer of steel
f_s = stress in the outermost layer of steel
S = mesh opening size
β = ratio of distances to the neutral axis from the extreme tensile fiber and from the outermost layer of steel
E_R = modulus of the reinforcing system
[Note: $E_R = E_S \simeq 29 \times 10^6$ psi (203×10^3 MN/m^2) for welded mesh; E_R may vary from 15 to 25×10^6 psi (105 to 175 MN/m^2) 10^3 for woven meshes depending on the pitch of the weaving as observed in various tests]

Note that equation (1) is valid for both the U.S. and metric system. It is an equation based on theoretical considerations and is recommended here mostly because of its simplicity. Regression equations based on experimental data [23] were also developed and can be used instead, to predict average and maximum crack widths in flexure. They are given by:

$$W_{av} = \frac{23000}{E_R} (0.271 f_s - 3.73) 10^{-4} \qquad \ldots\ldots\ldots (2)$$

and

$$W_{max} = \frac{23000}{E_R} (0.324 f_s - 4.36) 10^{-4} \qquad \ldots\ldots\ldots (3)$$

where

W_{av} = average crack width, in.
W_{max} = maximum crack width, in.
f_s = stress in the outermost layer cf steel, ksi

If the metric system is used, equations (2) and (3) become:

$$W_{av} = \frac{15.9}{E_R}(f_s - 95) \qquad \ldots\ldots\ldots (4)$$

and

$$W_{max} = \frac{15.9}{E_R}(1.2 f_s - 111) \qquad \ldots\ldots\ldots (5)$$

where crack width is in mm and steel stress and elastic modulus are in MN/m^2.

i) To predict crack widths in tensile ferrocement members, one can refer to the theoretical equation developed by Huq and Pama [26]. It has the advantage of accounting for many of the parameters found important in the cracking response of ferrocement and can be adapted to estimate flexural cracking [27] as well. A less accurate empirical design procedure has been also developed [23] to predict cracking under tensile loading. It applies when the steel stress f_s is less than the yield strength and in any case less than 60 ksi (414 MN/m^2). It is summarized as follows:

For any $f_s \leq 20\ S_{RL} = f_{sta}$ (stress at crack stabilization)

$$W_{max} = \frac{20}{E_R} \qquad \ldots\ldots\ldots (6)$$

where W_{max} is given in inches, S_{RL} in in.$^{-1}$, f_s in ksi and E_R in ksi.

For $f_s > 20\ S_{RL}$

$$W_{max} = 10^{-4}\left[6.9 + (f_s - 20\ S_{RL})\right]\frac{29000}{E_R} \qquad \ldots\ldots\ldots (7)$$

If the metric system is used equations (6) and (7) would lead to the following:

For any $f_s \leq 345\ S_{RL}$

$$W_{max} = \frac{3500}{E_R} \qquad \ldots\ldots\ldots (8)$$

where f_s is in MN/m^2, S_{RL} in cm^{-1}, W_{max} in mm and E_R in MN/m^2:

for $f_s > 345\ S_{RL}$

$$W_{max} = \frac{20}{E_R}\left[175 + 3.69\ (f_s - 345\ S_{RL})\right] \qquad \ldots\ldots\ldots (9)$$

j) Test results on cyclic loading of ferrocement beams have indicated that the average and maximum crack widths at a given load keep increasing with the number of oading cycles. This may be due to the effects of cyclic creep of mortar and bond deterioration at the mesh mortar interface due to fatigue.

The following relationship was found acceptable to represent crack width data, average or maximum, under fatigue loading up to about 90% of fatigue life:

$$W = Ae^{Br} \qquad \ldots\ldots\ldots (10)$$

where

W = average or maximum crack width

A = value of crack width at maximum load under static test. It could be predicted from equations (1) to (5)

e = base of Naperian logarithms

r = cycle ratio; i.e., number of cycles at which crack width is calculated to the number of cycles to failure N_f

B = a parameter determined from the experimental data and described in (9). A constant value of B = 1.67 is proposed for $N_f \geq 450{,}000$ cycles which is generally the case for most design situations.

In order to use equation [10] the number of cycles to failure N_f is needed. A regression analysis of the data [9] between stress range in the steel and the number of cycles to failure has led to the following relation:

$$f_{sr} = 152.3 - 19.5 \log_{10} N_f \qquad \ldots\ldots\ldots (11)$$

where

f_{sr} = stress range in the outermost layer of steel in ksi

N_f = number of cycles to failure

Thus if f_{sr} is known, N_f can be predicted, or if a certain value of N_f is required by the design the corresponding limit on stress range can be determined.
Using the metric system, equation [11] gives

$$f_{sr} \simeq 1050 - 134.5 \log_{10} N_f \qquad \ldots\ldots\ldots (12)$$

where f_{sr} is in MN/m^2.

Illustrative examples showing the use of the above design criteria are given in Appendix A.

Construction

Fabrication of Reinforcing Cage

The wire mesh and/or mesh fabric or rods are to be placed and shaped to the structure form. Adequate reinforcement are to be placed locally where higher stresses are expected.

The different layers of wire mesh should be carefully and securely tied together and to the central layer of coarser skeletal reinforcement (rods or welded wire fabric, if any) in order to provide an as even thickness as possible and to avoid movement during the placing of the mortar.

Any multiple discontinuities in reinforcement are to be avoided and an adequate overlap is to be provided according to the following recommendations: and overlap of at least 3 in.

(7.5 cm) or six times the mesh size whichever is higher is recommended to assure continuity between the ends of a layer of mesh; where reinforcing rods are joined, the overlap must be in accordance with the recommendations of the ACI 318-77 Building Code, Section 7.

If holes are needed in the shell, they should preferably be cut before plastering. Adequate reinforcement must be placed locally around holes to account for stress concentrations. The locations of holes should preferably be where stresses and pressures are minimal. Additional protective coating such as epoxy sealers must be provided around connections.

Mortar-Plastering

Mixing, handling and compaction of the mortar should be consistent and closely supervised to ensure high quality material. The builder should be guided by established codes of practice such as the ACI 318-77 Building Code, Sections 4 and 5.

The mortar must be thoroughly compacted during placing to ensure the absence of voids around reinforcement and in the corners of any framework.

Under no circumstances should the mortar be compacted simultaneously from both sides of the reinforcement in one operation. Vibrators and hand rodding can be used if necessary to achieve better penetration and distribution.

The mortar should be placed within a reasonably short period of adding the mixing water and with continual agitation during the waiting period. During handling and placing of the mortar care shall be taken to avoid segregation of the mix.

When plastering of the structure is done in more than one operation, care is to be taken to ensure a sound joint; same shall hold for the main joint between the foundation and the tank wall. The use of bonding agents where mortar joints are made will be given special consideration and has to be approved by the consulting engineer. Under no circumstances is any bonding agent which is unstable in water to be used.

Apertures for various fittings should where possible be formed prior to placing the mortar (or may be cut after completion and curing of the hull if it is shown that this last method is equivalent). All apertures should have the bare concrete surface adequately sealed before fixing the skin fittings.

Shotcreting

The application of the shotcrete technique to ferrocement reduces the difficulty of adequate placement of low slump mortar with trowel or hand. The two known methods of shotcreting the "dry" and the "wet" method are both acceptable for application in thin shell structures. In either method the material and process must comply with the ACI Standard 506-66"Recommended Practice for Shotcreting."

Curing

Ferrocement structures are to be properly cured once the mortar has taken its first set (which occurs 3 to 4 hours after mortar application). The set mortar or concrete is to be kept wet for a period dependent on the type of cement used and the ambient condittions. The method of curing should normally be by water spray but other proven methods are acceptable such as steam curing and membrane curing. The temperature of curing must be above 50° F The contractor should be guided by the ACI 318-77 Building Code, Section 5.

Painting

The paint if needed or desired should be applied after completion of curing and after the surfaces have been dried. Manufacturers instructions should be followed.

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APPENDIX A

Illustrative Design Examples

The following variables will be used throughout: compressive strength of mortar f_c'=5000 psi (35 MN/m^2); elastic modulus of the woven reinforcing mesh E_R = 23000 ksi (159,000 MN/m^2); steel stress-strain curve assumed elasto-plastic (Fig. 1) with a yield strength f_y = 70000 psi (483 MN/m^2); allowable compressive stress in ferrocement $\bar{\sigma}_{fc}$ = 0.45 f_c' = 2250 psi (15.5 MN/m^2); modular ratio n = 5.4.

Tensile Element

Design the wall of a ferrocement cylindrical tank subjected, under service load, to a maximum hoop (ring) tension T = 500 lbs/linear in.

Assuming an allowable stress σ_{ft} = 1000 psi for the composite leads to the required thickness:

$$t = \frac{T}{\bar{\sigma}_{ft}} = \frac{500}{1000} = 0.5 \text{ in. (12.5 mm)}$$

The amount of streel A_{sL} per inch wide strip in the loading direction is obtained assuming a cracked section and an allowable tensile stress in the steel $\bar{f}_s$ = 30 ksi (207 MN/m^2). Note that this stress satisfies the recommended limits for water retaining structures and for fatigue loading; thus :

$$A_{SL} = \frac{T}{\bar{f}_s} = \frac{500}{30000} = 0.0167 \text{ in}^2 \text{ (10.6 mm}^2\text{)}$$

Assume the reinforcement consists of woven wire mesh with 0.5 in. (12.5 mm) wire spacing and a wire diameter of 0.042 in. (1.07 mm). The cross-sectional area of one wire equals 0.00138 in^2 (0.89 mm^2); the number of wires needed per inch equals (0.0167/0.00138 $\simeq$ 12 wires). As two wires exist per inch and per layer of mesh, six layers are needed to provide the required value of A_{sL}. It can be checked that the thickness t can just accommodate them.

The total volume fraction of reinforcement in both directions, assuming square mesh, is given numerically by:

$$V_f \simeq \frac{2 \times 0.0167}{t} = 0.0668$$

or 6.68%. The corresponding specific surface of reinforcement is given by:

$$S_R = \frac{4V_f}{\phi} = \frac{4 \times 0.0668}{0.042} = 6.36 \text{ in.}^2/\text{in.}^3 \ (2.5 \text{ cm}^2/\text{cm}^3)$$

Note that the above values satisfy all the recommendations to qualify the composite as ferrocement.

As the predicted value of the steel stress at crack stabilization (20 S_{RL}) is high compared to the service stress, the maximum crack width is given by equation (6):

$$W_{max} = \frac{20}{E_R} \simeq 0.00087 \text{ in. } (0.022 \text{ mm})$$

which is less than the limit of 0.002 in. (0.05 mm) recommended for water retaining structures.

The above design has largely satisfied most limitations. Note, however, that an allowable tensile stress of 1000 psi (7 MN/m^2) in the composite generally leads to a high volume fraction of reinforcement. The reader may want to check that if a stress of 800 psi (5.5 MN/m^2) was used, the following alternative design would have been acceptable: $t = 0.625$ in. (16 mm) and same area A_{sL} of longitudinal reinforcement; the reinforcement consists of a square skeletal steel grid [2 in. (5 cm) wire spacing with wire diameter of 0.125 in. (3.2 mm)] and four layers of the woven wire mesh used previously; the corresponding value of V_f is 5.5% and S_R is 3.99 in.^{2}/in.^{3} (1.57 cm^2/cm^3); assuming the same modulus of elasticity as above leads to a stress at crack stabilization (20 S_{RL}) of 40 ksi (276 MN/m^2) larger than the service stress in the steel; thus the same value of maximum crack width is also obtained from equation (6) and is satisfactory.

Flexural Element

Check the feasibility of using the ferrocement sandwich panel shown in Fig. 2a as a typical element of a one-way simply supported slab. Assume a dead load including weight of 20 lbs/linear ft and a live load of 60 lbs/linear ft; the live load corresponds to 40 lbs/sq. ft or approximately 195 kg/m^2. The span length is 12 ft (3.7 m).

1. Let us first determine the values of midspan moments; the subscript D is used to describe the effect of dead load, L that of live load, S that of service load and U that of ultimate load. Thus:

$$M_D = \frac{w_D \lambda^2}{8} = 4320 \text{ lb in.}$$

$$M_L = \frac{w_L \lambda^2}{8} = 12960 \text{ lb in.}$$

$$M_S = M_D + M_L = 17280 \text{ lb in.}$$

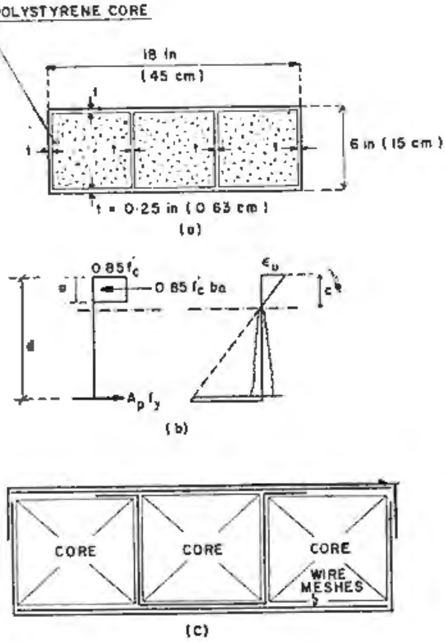

Fig. 2: (a) Typical Section of ferrocement sandwich slab.
(b) Stress and strain diagrams at ultimate.
(c) Layout of reinforcement.

2. *Ultimate Strength Design.* The factorized ultimate moment to be resisted by the ferrocement section is given by:

$$M_U = 1.4\ M_D + 1.7\ M_L = 28080 \text{ lb in.}$$

Using the ultimate strength design approach of the ACI code leads to two equations of equilibrium at ultimate behavior of the section: a force equilibrium equation and a moment equilibrium equation. Thses equations contain two unknowns namely "a" the depth of the compressive stress block and A_s the area of tensile reinforcement. In writing these equations it will be assumed at first that the section acts as a rectangular section at ultimate and that the influence of the reinforcement in the compressive zone is negligible. (These assumptions are confirmed by the results obtained for this example and there will be no need here to revise the design.) The two equations (Fig. 2b) are:

$$A_s f_y = 0.85 f_c'\ ba \qquad \ldots\ldots\ldots (13)$$

$$M_U = \phi A_s f_y \left(d - \frac{a}{2}\right) = \phi\, 0.85 f_c'\ ba\left(d - \frac{a}{2}\right) \qquad \ldots\ldots\ldots (14)$$

Replacing ϕ by 0.9 and M_U by its value in equation (14) leads to a quadratic equation in "a" for which one positive root exists, namely $a \simeq 0.07$ in. (1.78 mm). The corresponding location of the neutral axis is given by $c = a/\beta_1\ 0.07/0.80 \simeq 0.09$ in. (2.23 mm); as "c" is less than the flange thickness the section is acting as a rectangular section as previously assumed; thus equation (13) gives:

$$A_s = \frac{0.85 f_c' \, ba}{f_y} = 0.0765 \text{ in.}^2 \ (49.35 \text{ mm}^2)$$

Using a square wire mesh having a wire spacing of 0.25 in. (6.35 mm) and a wire diameter of 0.025 in. (0.63 mm) leads to the reinforcement shown in Fig. 2c. Note that the tensile steel area provided amounts to 0.0825 in.^{2} (53.22 mm^2) slightly higher than the above required value.

For the above section it can be shown that the applied moment is substantially less than the maximum resisting moment by the concrete and that the shear resistance is largely adequate.

3 *Working Stress Design.* The allowable stress in the steel under full service load must be specified. One may consider first the value $f_s = 0.60 f_y = 42$ ksi (290 MN/m^2) . However, the slab is subjected to fatigue under the repetitive applications of live loads; the stress range in the steel is limited to $\bar{f}_{sr} = 30$ ksi; as the live load is 75% of the service load, the maximum allowable steel stress should be $\bar{f}_s = 30/0.75 = 40$ ksi (276 MN/m^2).

The required area of tensile steel is given by:

$$A_s = \frac{M_s}{\bar{f}_s Jd} \qquad \text{........ (15)}$$

where Jd is the lever arm between the tensile and compressive forces in the section. For the sandwich-type section shown J can be estimated as 0.95. Thus:

$$A_s \simeq \frac{17280}{40000 \times 0.95 \times 5.875} = 0.0774 \text{ in.}^2 \ (49.9 \text{ mm}^2)$$

The above value is not very different from that obtained using the U.S.D. approach and leads for all practical purposes to the same reinforcement shown in Fig. 2c.

4. To estimate the value of maximum crack width under service load, two approaches can be considered for this particular section: one, that the section is acting in flexure and the other that the lower flange is acting as a pure tensile member.

If flexure is considered, the maximum crack width can be estimated from equation (3) assuming $f_s = \bar{f}_s = 40$ ksi:

$$W_{max} = \frac{23000}{E_R} [0.324 f_s - 4.36] 10^{-4} = 0.00086 \text{ in.} \ (0.022 \text{ mm})$$

If pure tension in the lower flange is considered, the value of the specific surface of reinforcement in the flange in the loading direction must be determined. It can be shown that the volume fraction of steel in the loading direction is 1.83% and the corresponding specific surface is 2.93 in.^{2}/in.^{3} (1.15 cm^2/cm^3). Thus the stabilization stress is given by:

$$f_{sta} = 20 \, S_{RL} = 20 \times 2.93 = 58.6 \text{ ksi} \ (404 \text{ MN/m}^2)$$

and as $f_s < f_{sta}$ the maximum crack width can be predicted by:

$$W_{max} = \frac{20}{E_R} = 0.00087 \text{ in.} \ (0.022 \text{ mm})$$

which is surprisingly very close to the value obtained assuming flexure behavior.

Let us estimate the effect of fatigue on crack width. As the stress range in the steel was assumed equal to 30 ksi (207 MN/m^2), the fatigue life of the ferrocement element can be estimated at about 2×10^6 cycles from equation (11). Using equation (10) with $A = 0.00087$ and $B = 1.67$ leads to the following predicted values of maximum crack widths at different cycles:

For	$r = 0.25$ (0.5 million cycles)	gives $W_{max} = 0.00132$ in. (0.034 mm)
	$r = 0.50$ (1 million cycles)	gives $W_{max} = 0.00201$ in. (0.051 mm)
	$r = 0.75$ (1.5 million cycles)	gives $W_{max} = 0.00304$ in. (0.077 mm)
	$r = 0.90$ (1.9 million cycles)	gives $W_{max} = 0.00391$ in. (0.10 mm)

It can be seen that although the maximum crack width under static load was substantially smaller than the recommended limit of 0.004 in. (0.1 mm), the effect of cyclic fatigue loading can significantly reduce the gap between them.

5. The above example dealt with a particular section of ferrocement where the reinforcement was essentially concentrated in the flanges. If a rectangular section was used with several layers of reinforcement across the depth, the reader may want to refer to the work of Huq and Pama [26-27] for a more general and complete analysis. If the ACI code approach is used with U.S.D. or W.S.D., the section (with several layers of reinforcement) may be also analyzed as a column under pure bending and should lead to very realistic results.

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Ferrocement Gas Holder for Biogas Plants*

N.V.Raman,+ V.P. Narayanaswamy†, P.C. Sharma† and H.B. Jayaraman†

The importance of biogas plants for meeting the energy requirements of the rural areas in the developing countries and the ways to reduce their cost are discussed. The merits of ferrocement as a construction material for the gas holder of biogas plants are discussed. The design and the casting procedure for ferrocement gas holder, developed at the Centre are explained in detail. A test procedure for testing gas holder for leakage is given. The details of the side guide system are explained. Cost figures for the ferrocement gas holder are presented and compared with those of steel gas holder.

INTRODUCTION

The recycling of agricultural and biological wastes through biogas plants provides a cheap and renewable source of energy besides rich manure. With the present level of technology biogas can be used for heating, lighting and for running stationary engines. The benefits of biogas have been highlighted by the Economic and Social Commission for Asia and the Pacific [1] More than 20,000 plants based on cow dung have already been installed in the villages of India during the last two decades. However this amounts to only a fraction of the total potential as estimated by the National Committee on Science and Technology, Government of India. The main constraint appears to be the high initial cost of the plant based on present designs, which is therefore beyond the means of the average family in the rural areas of the developing countries. Besides, the gas holder, which accounts for about 40 to 50 per cent of the total cost of the plant, is susceptible to corrosion and therefore needs expensive maintenance. The Structural Engineering Research Centre, Roorkee is developing alternative designs for biogas plants to reduce the initial cost and to increase the life of the gas holder. Designs and fabrication techniques for ferrocement gas holders suitable for family-size biogas plants have been developed by the Centre under the All India Coordinated Project on Biogas. In the present paper the details of the ferrocement gas holder developed at the Centre and suitable for a plant with a capacity of 2 cu.m. of gas per day are discussed.

COMPONENTS OF A BIOGAS PLANT

The typical biogas plant of the conventional design consists of a digester and a gas holder [2]. The digester is a well dug below ground level in which the slurry containing fermentable material (usually cow dung) mixed with the required quantity of water is fed through an inlet pipe every day. The slurry undergoes decomposition under anaerobic conditions releasing gas contianing 50 to 60 per cent methane besides carbon dioxide, hydrogen sulphide and traces of moisture. The digested slurry flows through an outlet pipe into an outlet tank. In larger plants a partition wall is provided in the well diagonally to separate the fresh slurry from the digested slurry.

The gas generated by fermentation is collected in the gas holder which floats on the slurry like a stopper. The gas holder is in the form of a cylinder with a dome-shaped top. The self

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weight of the gas holder exerts a pressure of 7.5 to 15 cm. of water, which is sufficient to operate the gas appliances. It is fabricated from mild steel sheets and is braced with mild steel angles. The vertical movement of the gas holder is ensured by a central guide system consisting of two galvanized iron pipes one sliding over another. The outer pipe is welded to the centre of the dome, projecting on the inside, and the inner pipe is mounted on a framework resting on a ledge supporting the gas holder. The scum formed on the surface of the slurry is broken through an arrangement consisting of radial and vertical arms attached to the inside of the gas holder.

The components of a typical biogas plant developed by the Khadi and Village Industries Commission (KVIC) are shown in Fig. 1.

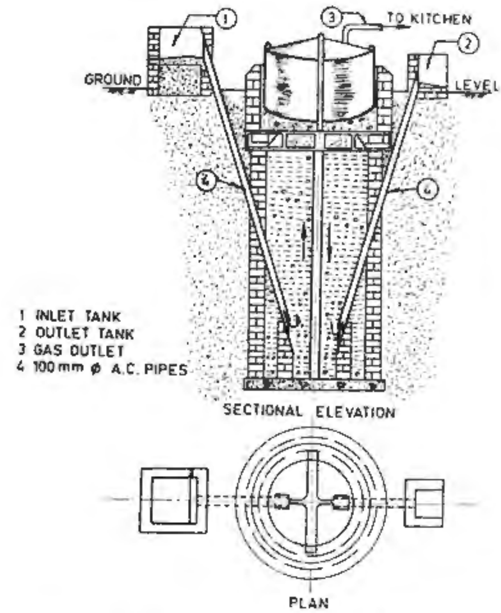

Fig. 1. Typical biogas plant of KVIC design.

Designs for biogas plants have been developed by several other institutions such as Indian Agricultural Research Institute [3], Planning, Research and Action Institute [4] and National Environmental Engineering Research Institute [5]. However most of the plants installed in the country are of the K.V.I.C. design. The distinguishing feature of the design by the Indian Agricultural Research Institute is the provision of a side guide system consisting of three sets of pulleys and counterweights to ensure vertical movement of the gas holder.

OPTIMUM DESIGN OF BIOGAS PLANTS

The cost of the family-size biogas plant designed according to the conventional practice is high. Considerable economy can be achieved by more rational selection of the design parameters such as the volumes of the gas holder and the digester, more efficient utilisation of materials in the various components of the plant, especially in the digester, use of substitute materials such as ferrocement for the gas holder and optimization of the geometrical dimensions of the various components for minimum cost. The above aspects of design have been discussed in detail by the authors elsewhere [6]. In the present paper the details of design and fabrication of ferrocement gas holder for a plant of capacity 2 cu.m. of gas per day will be discussed. Such a plant will meet the requirements of cooking for a family of 4 to 6 persons and will require dung from about 6 adult animals.

USE OF FERROCEMENT FOR GAS HOLDER

Gas holders are at present fabricated from mild steel sheets which are expensive and scarce. Besides, they require frequent painting as they are susceptible to corrosion. Some attempts have been made in the past to use substitute materials such as plywood, polythene with bamboo basket reinforcement, stoneware, ferrocement etc. for the gas holder. Among these materials ferrocement appears to be the most promising from consideratios of economy, safety, ready availability, ease of fabrication and performance. Production of ferrocement gas holders on commercial scale has already been reported [7,8]. However, no systematic scientific investigations on the use of ferrocement for gas holder seem to have been carried out.

Ferrocement is a composite material consisting of layers of thin wire mesh impregnated with rich cement mortar. In other words it is a reinforced mortar, but unlike reinforced concrete it has high resistance to cracking and permeability which is essential for the satisfactory functioning of gas holder. Ferrocement can be cast into sections as thin as 1 cm. and therefore suited for precast products because of the resulting low weight of the components. A semi-mechanised process for casting thin cylindrical units of ferrocement has been developed and patented by the Centre [9]. By using this process very good control of thickness and high degree of compaction are achieved ensuring thereby high impermeability to gas. The process is labour-intensive and does not require power or expensive machinery.

Ferrocement gas holders are much cheaper than mild steel gas holders of the same capacity and can be fabricated in the rural areas using local labour, skilled and unskilled. The technology involved is labour-intensive and calls for only moderate skills and is therefore ideally suited for application in the rural areas of the developing countries. The material has low thermal conductivity and therefore the rate of gas production is fairly uniform in all seasons. It has high resistance to corrosion and therefore needs minimum of maintainance. Ferrocement has high impact strength and hence can withstand the rigours of transport and handling. Any accidental damages caused can be easily repaired.

DETAILS OF FERROCEMENT GAS HOLDER DEVELOPED AT THE CENTRE

The ferrocement gas holder developed at the Centre is suitable for a plant of capacity 2 cu.m. of gas per day and consists of a wall unit and a roof unit, cast seperately and assembled. The wall unit is cast on a horizontal wooden mould lined with galvanised iron sheet. The mould is made in several segments to facilitate easy assembling and demoulding. The mould is mounted on the process stand which enables rotation and stretching of the wire mesh. Mortar is applied over the wire mesh layer by layer so that all voids are filled thoroughly. The details of the process stand and the mould are given in Fig. 2.

The reinforcement for the wall unit consists of two layers of galvanised iron woven wire mesh and one layer of mild steel welded wire fabric in between. The welded wire fabric gives the necessary strength and rigidity to the wall unit while the woven mesh constitutes the skin reinforcement which ensures crack control. The bottom edge of the wall unit is reinforced

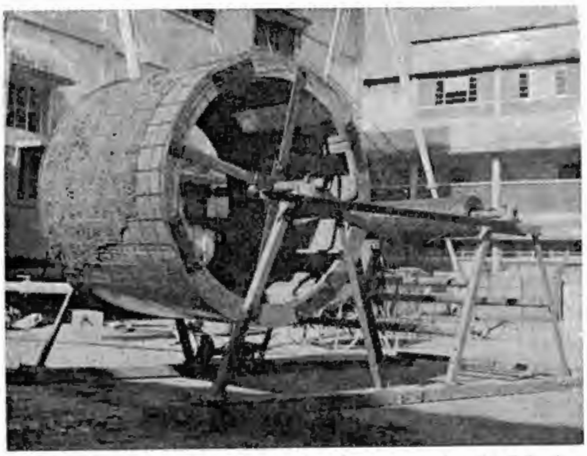

Fig. 2. Process equipment for casting ferrocement cylindrical units.

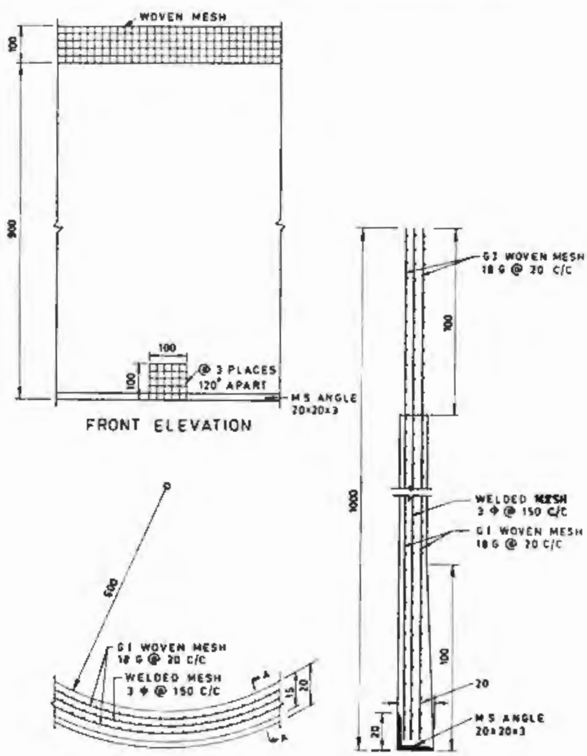

Fig. 3. Reinforcement details for wall unit.

by a ring made of mild steel angle which protects the edge from any damage during handling. Inserts are provided near the top and bottom edges for attaching the scum breaking arrangement. The reinforcement details for the wall unit are given in Fig. 3.

The roof unit of the gas holder is made in the form of a segment of a spherical dome, as this shape is the most efficient for resisting the forces due to self weight and internal pressure.

It is cast on masonry moulds or wooden moulds. The reinforcement for the roof unit consists of two layers of galvanised iron woven wire mesh with mild steel bars in the radial and circumferential direction in between. The mild steel rings may be replaced by rings of galvanised iron wire to keep the thickness of the dome within desired limit. The dome is provided with six fillets equally spaced along the periphery for laterally supporting the wheels of the guides. A socket is placed on the surface of the dome for connecting the gas outlet pipe. The reinforcement arrangement for the roof unit is given in Fig. 4.

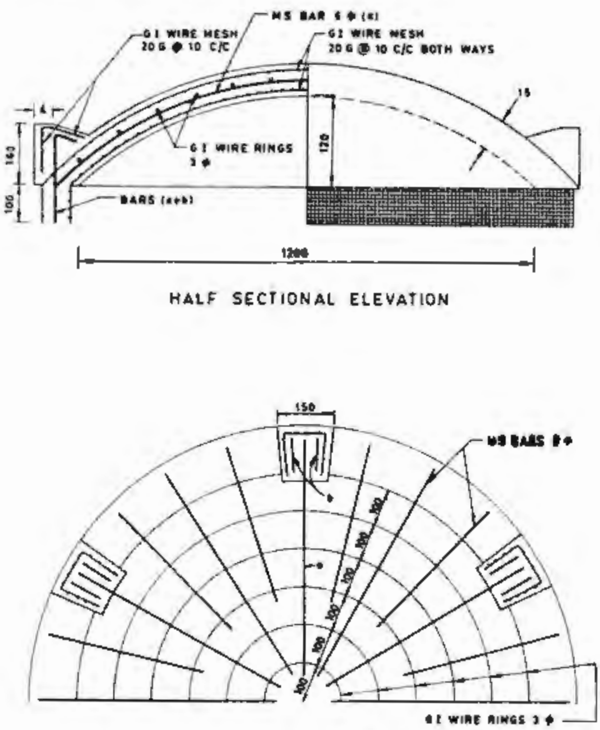

Fig. 4. Reinforcement details for roof unit.

The wall and the roof units are cast side by side and when these have attained sufficient strength (usually after 7 days) the roof unit is supported over a number of props in alignment with the wall unit. Mortar is applied on the junction from the inside as well as from the outside. The curing is continued for another 7 days after which the mortar attains sufficient strength.

The mortar used for the gas holder consists of ordinary portland cement and coarse sand in the proportion of 1:2 with a water/cement ratio of 0.45. The mix has a stiff consistency to facilitate application by hand on a curved surface. Part of the coarse sand may be replaced by fine sand to obtain better grading and finish. Admixtures are added to improve the impermeability. The crushing strength of 5 cm. mortar cubes at 7 days has been found to be between 150 and 200 kg/cm^2.

The scum breaking arrangement is attached to the inserts provided near the top and bottom edges of the wall unit. It consists of three mild steel bars at top and bottom placed radially and connected by vertical bars. The radial bars function in addition as bracings for the gas holder. The scum formed on the surface of the slurry is broken by the vertical bars on rotation of the gas holder once in a few days. The completed gas holder with the scum breaking arrangement is shown in Fig. 5.

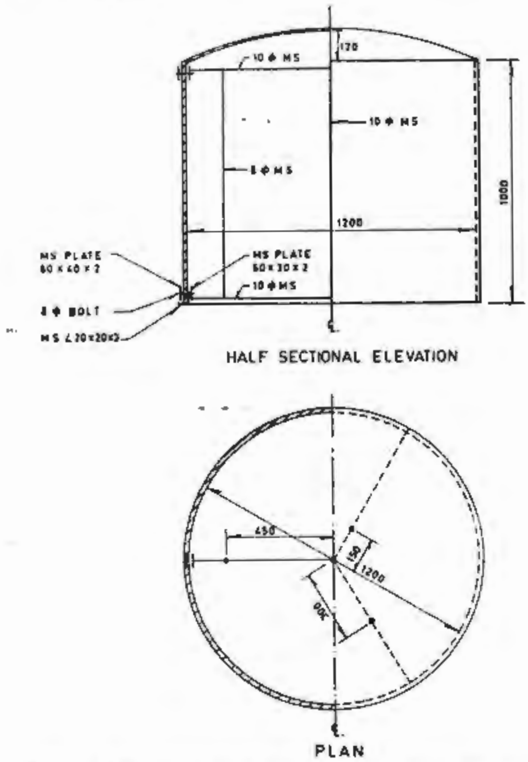

Fig. 5. Gas holder with scum breaking arrangement.

STRESS ANALYSIS FOR GAS HOLDER

A detailed stress analysis of the ferrocement gas holder was carried out using the classical thin shell theory applicable to thin circular cylinders and thin shells of revolution under axi-symmetric loading. The analysis was carried out in the following steps:

(i) Primary system based on membrane theory
(ii) Deformations of the boundaries due to membrane stress resultants
(iii) Correction deformations due to unit edge effects at the boundaries
(iv) Establishing compatibility to compute the magnitude of the edge effects necessary to eliminate the membrane deformations
(v) Finding the final stress resultants in the dome roof and cylindrical wall portion.

Loads taken into account in the analysis were as follows:

(1) Self weight
(ii) Internal gas pressure
(iii) Forces caused by shrinkage and temperature variation

The stresses obtained from the analysis were found to be well within allowable limits for cracking. The details of analysis are being presented elsewhere.

SURFACE COATINGS FOR FERROCEMENT GAS HOLDER

As the cement mortar is porous and is therefore not fully impermeable to gas, it is necessary to apply suitable surface coatings to the inside and outside surfaces of the gas holder to improve its impermeability to gas. In addition these coatings provide protection against corrosion. Trials using bituminous surface coatings have given satisfactory results. A ferrocement gas holder developed at the Centre and coated with bituminous surface coating has been functioning satisfactorily for the last three years (Fig. 6.). Other resin-based coatings are being developed and tried on gas holders of larger sizes. Preliminary results on the performance of these coatings have been found to be satisfactory.

Fig. 6. Biogas plant with ferrocement gas holder.

TESTING FERROCEMENT GAS HOLDER FOR LEAKAGE

A test procedure has been evolved for testing ferrocement gas holder for leakage. In this procedure the gas holder is tested under conditions similar to those in service. The gas holder is placed in a shallow circular tank with the gas outlet at the top open. Scales are fixed on the wall of the gas holder at three equally spaced locations. The gas outlet is kept open and the tank is filled with water until the water level is 10 to 15 cm. above the bottom of the gas holder. The gas outlet is then closed. When the water level in the tank rises further (say by about 15 cm), the gas holder starts floating. Filling with water is continued further until the gas holder is about 20 to 30 cm. above the bottom of the tank. The vertical movement of the gas holder is ensured by a system of wheels acting against the wall surface. In this position soap water is poured on the surface of the gas holder. Points of leakage are indicated by air bubbles appearing on the surface of the gas holder.

If any points of leakage are noticed, then the gas holder is allowed to settle down by opening the gas outlet. The points of leakage are sealed with one layer of surface coating applied at these points. After the coating has dried the above test is repeated until no points of leakage are noticed. The scale readings are then recorded and the gas holder is allowed to remain in this position for 24 hrs. When there is no appreciable change in the mean value of the scale readings over a period of 24 hrs., the performance of the gas holder may be deemed satisfactory.

The test set up for carrying out the test for leakage is shown in Fig. 7.

Fig. 7. Ferrocement gas holder under test for leakage.

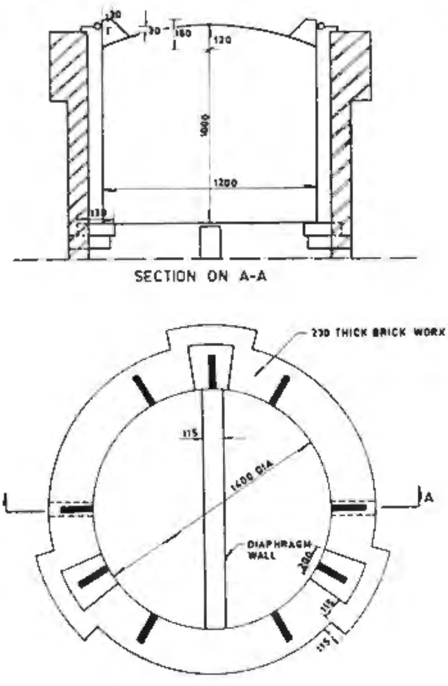

Fig. 8. Side guide system for gas holder.

SIDE GUIDE SYSTEM FOR GAS HOLDER

The steel gas holder of the conventional design is provided with a central guide system to ensure vertical movement. The Centre has developed a side guide system which is much cheaper and functions equally well. In this system the vertical movement of the gas holder is ensured by twelve rubber wheels, six at each level, attached to clamps fixed to the wall of the digester (Fig. 8.). The clamps are located in such a way that whatever is the position of the gas holder, it is in contact with all the wheels. The proposed guide system is very in expensive. The rubber wheels are readily available in the market and the clamps can be easily fabricated in a small workshop. Replacement of the worn out wheels can be done without affecting the functioning of the gas holder.

The amount of tilting of the gas holder in the side guide system is negligible. The annular space around the gas holder can therefore be kept as small as possible thereby reducing the loss of gas into atmosphere to the minimum. The clamps are made adjustable in such a way that by releasing them the gas holder can be rotated as and when required for scum breaking.

ECONOMICS OF FERROCEMENT GAS HOLDER

In this section a comparison between the costs of ferrocement gas holder with the side guide system and steel gas holder with the central guide system is made. The cost figures for the various components of the gas holder are given in Table 1. These figures are based on the rates that were prevailing in 1976. It is seen that the total cost of the ferrocement gas holder is Rs.478 as against Rs.910 for the steel gas holder. This amounts to a saving of as much as 47 percent.

Table 1. Estimate of Cost for Ferrocement Gas Holder.

No.	Item	Cost*(Rs.)
1	Cement mortar	44
2	G.I. Wire mesh	114
3	Welded Wire fabric	16
4	G.I. Wire	4
5	M.S. Bars and structurals	30
6	M.S. Bolts and nuts	3
7	G.I. Socket	3
8	Labour & Fabrication charges	100
9	Charges for moulds	25
10	Painting charges	50
		389
	Overheads @ 10%	39
		428
11	Guide system	50
12	Total	478

* (U.S.$ = Rs 8.50 approx.)

CONCLUSIONS

From the foregoing discussion it is seen that the cost of biogas plants can be reduced considerably and thereby brought within the reach of the average family in the rural areas of the developing countries, by effecting several improvements in design. Among these the replacement of mild steel gas holder by ferrocement gas holder has been found to be the largest source of cost reduction. Further savings are possible by a more rational choice of design parameters for the digester, especially the retention period, and efficient design of the digester wall. The ferrocement gas holder developed at the Centre and suitable for a plant of capacity 2 cu.m. of gas per day has been found to be very economical compared to steel gas holder. the savings in cost being as much as 47 per cent.

Besides being economical ferrocement gas holder has better performance in winter, needs minimum of maintenance and has a longer life. Repairs, if any, are carried out more easily. Ferrocement technology is labour-intensive and makes use of local materials and local labour, skilled and unskilled. The process for making ferrocement cylindrical units, developed at the Centre, is ideally suited for the fabrication of ferrocement gas holders as it does not require expensive machinery or power.

Ferrocement gas holder for a 3 cu.m. plant is now under development at the Centre.

ACKNOWLEDGEMENT

The present paper is based on the work carried out at the Structural Engineering Research Centre, Roorkee for the project "Development of Ferrocement Gas Holder for Biogas Plants" under the All-India Coordinated Project on Biogas, sponsored by the Dept. of Science and Technology, Govt. of India. The development of surface coatings for the gas holders is being carried out in collaboration with the Central Building Research Institute, Roorkee.

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Bibliographic List on Ferrocement: Part VIII

This list includes a partial bibliography on ferrocement and related topics. The AIT Library and Regional Documentation Center has these articles and books. Reprints and reproductions, where copyright laws permit, are available at a nominal cost (see page no. iv). Please quote the serial number of the list at the time of request.

Earlier seven parts of the Bibliographic List have been published in the last seven issues of the Journal of Ferrocement (Vol. 7, Vol. 8 and Vol. 9, No. 1).

Also avilable now is the first volume cf "Ferrocement and its applications—a bibliography" which contains 736 references compiled from the list that have appeared in the previous issue of the Journal of Ferrocement. Unlike in this list, the first volume includes a more detailed classsification of the references. Copies of this IFIC publication can be ordered at a cost of US$2.00 per copy (surface postage inclusive).

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News and Notes

DENMARK

A Building System in Ferrocement

At the Institute of Building Science in the School of Architecture at The Royal Danish Academy of Fine Arts, Denmark, a working group was established in 1971 under the name "The group for practical building experiments". The group conducted experiments with domes, pneumatic constructions, energy saving/ecological installations using minimum of construction skills. The study extended to ferrocement structures too, as a possible solution to the long search.

Working under this group, architect, M. Freddie was entrusted with a project "A building system in ferrocement". The idea behind this project was to design singly-curved ferrocement units which could be used in different combinations to form the walls, foundations, floor and roof of a typical dwelling unit. Special features like a porch, balcony, bay window and external staircase were also incorporated into the dwelling unit. A typical ferrocement unit developed as a consequence of the study is made up of a ferrocement shell of 16 mm thickness. These shells are stabilized by a U-profiled metal strap (see figures below) on which internal linings are also fixed. The space between the metal strap and the ferrocement shell is filled with polystyrene insulation after leaving adequate voids to accommodate installations for pipe work, electrical conduits and air-conditioning ducts. The roof units are strengthened by using foamed polystyrene instead of polystyrene. It is convenient to make the wall units one storey high and the span of roof and floor units equalling 6 m approximately. These units can be assembled with ease to form 1 or 2 storeyed houses. Besides structural aspects, more tress was laid on the aesthetic applications of ferrocement for the construction of single family shelters. As a continuation of this work, another project entiled "Development of building components of ferrocement" was undertaken. This part of the research involved numerous experiments with different mortar mixes, types of reinforcements, varied casting methods using a number of types of moulds. Successful testing were conducted on a prototype of the exact dimensions. In addition to the School of Architecture certain private enterprises showed particular interest in the project

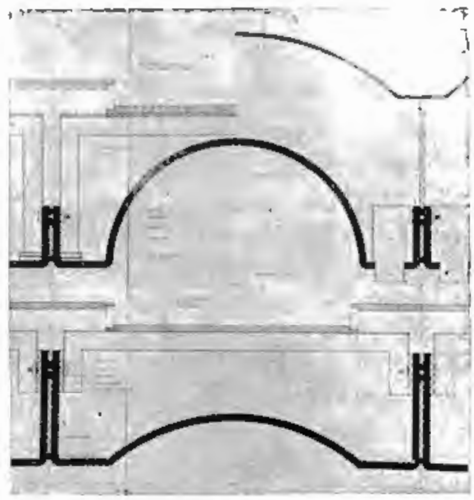

Fig. 1

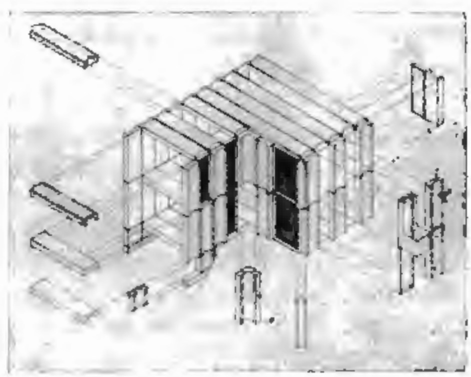

Fig. 2

namely, Alborg Portland Cementfabrick, Nordish Kabel-og Tradifabrikker, Rockwool A/S and H & H Industri A/S-Engineering Division.

IFIC NEWS

Journal of Ferrocement in International Scanning Lists

Since IFIC took over editorial and publication rights of the Journal of Ferrocement in July 1977 from the NZFCMA, the Journal has undergone numerous changes in text, presentation format and overall contents. IFIC's earnest efforts in attempting to upgrade the contents of the Journal in collaboration with the NZFCMA, so that it can cater to a broader spectrum of subscribers has been amply rewarded. Since July 1977 the contents of this quarterly appears regularly in the famed international weekly Current Contents/Engineering, Technology and Applied Sciences, published by the Institute for Scientific Information, U.S.A. Additionally, the Institute of Scientific Information of the Academy of Sciences of the USSR will from January 1979 be abstracting technical papers published in the Journal in their prestigious publication Referativnyi Zhurnal. The scanning of the Journal of Ferrocement in these two popular publications would no doubt be a heartening news to all concerned in promoting the use of ferrocement.

Correspondent for India Appointed

Mr. P.C. Sharma, Scientist, Structural Engineering Research Centre (Roorkee), India has been appointed as a correspondent to the Journal of Ferrocement, effective from January 1, 1979. Besides being responsible for routine task of reporting developments in ferrocement technology and applications from the region, Mr. Sharma, who served IFIC as a Technical Specialist (refer to News and Notes section of January 1979 issue of the Journal) will also serve to promote IFIC activities in India.

INDIA

Indian P.M. Briefed About IFIC and Ferrocement

A Science Exhibition and Scientists's Conference which was held in Wardha late December last year provided an ideal forum for popularising ferrocement as a versatile material suited for use in rural areas. Structural Engineering Research Centre (SERC, Roorkee and Madras) had set up an impressive display of ferrocement products, which also included information about IFIC and its activities. The Indian Prime Minister, Shri Morarji Desai, who visited the exhibition was briefed about the potentials of ferrocement for rural applications Being impressed with the display and activities of organizations like SERC and IFIC, the Prime Minister expressed his desire that the use of this wonder material for rural applications be encouraged through rural development schemes. The material he suggested should be used on a large scale to uplift the rural poor.

A lecture cum slide show was also presented during the occassion by IFIC's correspondent for India, Mr. P.C. Sharma at the "Centre of Science for Villages" and "J.B.C. Research Institute", Wardha. This lecture on ferrocement which also highlighted the role of IFIC in promoting the use of ferrocement was attended by over 100 engineers and scientists (see photographs below).

Fig. 3

Fig. 4

ITALY

Ferrocement Pioneer Passes Away

Pier Luigi Nervi, 87, Italian builder and architect famed for his graceful, dramatic structures of ferrocement and reinforced concrete died of a heart attack in Rome.

Originally trained in Civil Engineering, Prof. Nervi first began experimenting with concrete design when he constructed an all concrete theater in Naples in 1927. He went on to create a strong, light composite of mortar and steel mesh called 'ferrocemento' and, by casting large structural components at construction sites, managed to mould concrete into soaring, titled buttresses and high swooping ceilings. His finest buildings critics agree, are the vast Exhibition Hall in Turin, Rome's sunburst-domed Palezzetto dello Sport and the oystershell shaped, ribbed-concrete Pope Paul VI Audience Hall in the Vatican.

In the U.S. his works include San Francisco Cathedral and New York City's George Washington Bridge Bus Station. Modest and hardworking, Prof. Nervi always considered himself an engineer rather than an architect; yet his work, once described as "poetry in concrete", earned him the 1964 gold medal of the American Institute of Architects. In his demise, the entire community of ferrocement users lose a pioneer in the field of ferrocement technology.

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VITA is a private, non-profit international development organization. Its objective is to support and promote efforts which enable low-income people to meet their own needs through the promotion and implementation of technologies appropriate to local cultural requirements and technical resources. Over 4000 experts in virtually every technical field volunteer their time and expertise to assist with efforts related to this goal. Collaboration with insitutions sharing VITA's commitment is of special interest.

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For turther information write to VITA, 3706 Rhode Island Ave. Mt. Rainier, Maryland 20822, U.S.A.

International Meetings

International Symposium on the Behaviour of Building Systems and Building Components, Vanderbilt University, U.S.A., March 8-9, 1979

This international symposium is expected to serve as a forum for the discussion of such topics as: design of building systems and building components, parameters which affect building performance, behaviour of building components, behaviour of building systems subjected to lateral loads, thermal and wire effects, foundation movement, current research on building components and systems, analysis of structural failures, comparison of various building systems and experience with recent innovations in building systems or building components. For further information contact:

Prof. Fred W. Beaufait,
P.O. Box 1533, Station B,
Vanderbilt University,
Nashville, Tenn. 37235,
U.S.A.

RILEM Symposium on Quality Control of Concrete Structures, Stockholm Sweden, June 17-21, 1979

The aim of the symposium is to exchange and review the current knowledge and experience and to simulate continued development of quality control techniques with reference to concrete and concrete structures. Emphasis will be placed on the evaluation of quality control and its relation to structural safety. The basic principles of quality control in building will be discussed, followed by a detailed examination of the technical aspects of quality control, including the development of testing methods, methods of sampling, the evaluation of quality control criteria and how quality control systems are built up. The symposium is expected to deal with quality control of the finished product, whether this by ready-mixed concrete, prefabricated units or in-situ structures. Due importance will be given to process control and intermediate checks for separation of the responsibilities during the course of production. For further information contact:

RILEM,
c/o Stockholm Convention Buraue,
Strandvägen 7c,
S-11456 Stockholm, Sweden.

World Congress on Shell and Spatial Structures, Madrid, Spain, September 24-28, 1979

Held on the ocassion of the 20th aniversary of the International Association for Shell and Spatial Structures (IASS), the congress is expected to comprise two types of sessions. Main sessions on the following topics: Theoretical studies related to development of shell and spatial structures, non-traditional and outstanding projects and designs carried out in the last decade, new materials for construction of shell and spatial structures besides general reports on the work of some of the IASS working groups, presented by their chairmen. Other sessions dedicated to some of the specific working groups. For further information contact:

Mr. L.M. Ortega,
Laboratrio Central de En sayo de Materiales de Construccion,
Alfonso XII, No. 3,
Madrid-7, Spain.

The International Congress on the Chemistry of Cement, Paris, France, June 30 - July 5, 1980.

The following themes have been selected for the above Congress: Influence of raw materials, fuels and manufacturing processes on clinker structure and properties; hydration of pure Portland cements; structure of slags and hydration of slag cements; structure of pozzolanas and fly-ash-hydration of pozzolanic and fly-ash cements; special cements' cement pastes-rheology; interface reaction between cement and aggregate in concrete mortar. For further information contact:

CERILH,
23, rue de Cronstadt,
75015 Paris, France.

International Conference on Concrete Ships and Floating Structures, Rotterdam, Holland, November 12-14, 1979

A major conference on "Concrete Ships and Floating Structures" will be held at the Hilton Hotel in Rotterdam, Holland. It is expected that the conference will cover all aspects of the topic and for the first time in Europe an entire session will be devoted to ferrocement structures.

IFIC will be presenting a paper entitled "A Review of Marine Applications of Ferrocement in Asia" while another contribution from Ferrocement Marine Services of England will review recent developments in Africa and the Indian Ocean. Besides these two informative articles, it is expected that a few other contributions will make the session on ferrocement interesting. The conference is planned as a major event, and its proceedings will subsequently be published in full for the benefit of those who might not be able to attend.

The conference is being organised by Thomas Reed Publications Ltd., of 36 Cock Lane, London ECIA 9BY, who are already well-known in marine engineering circles for their highly successful series of conferences on tugs and on offshore crafts. For further information contact.

Mr. F.H. Turner,
Conference Organiser,
International Conference on Concrete Ships and Floating Structures,
3, Leyburn Close, Woodley,
Reading RG5 4PX, Berkshire, U.K.

Abstract

JEP16 A POSSIBILITY TO INCREASE THE MORTAR STRENGTH OF FERROCEMENT

KEY WORDS : Additives, Compressive Strength, Cracking, Experimental Results, Flexural Strength, Mortar, Sand, Tensile Strength

ABSTRACT : The mortar of ferrocement, that is generally used in practice, is a mixture of cement and sand; its high strength is mainly based on high cement content and low water-cement ratio. Instead of this traditional concept this paper suggests methods which attempt to improve the properties of the mortar by changes in the aggregates used for the mix. Method 1 replaces the normal sand with a type of high quality rock sand and Method 2 finds a new gradation of sand such that a reduction of cement content and a higher mortar strength is achieved.

REFERENCE : YEN, T., SU, C.F. and CHANG, M.F., " A Possibility to Increase the Mortar Strength of Ferroement", Journal of Ferrocement, Vol. 9, No. 2, Paper JFP16, April 1969, pp. 53-64.

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