

Acknowledgment

In the Name of Allah, The Most Gracious, The Most Merciful

I would like to express my sincere thanks and deepest gratitude to my supervisors ***Prof. Dr. Shakir A.Salih and Prof. Dr. Wail N. Alrifai*** for their advice, scientific guidance and continuous encouragement throughout this research work. I would like to extend my appreciation to ***Prof. Dr. Husain M. Husain, Prof. Dr. Kais F. Sarsam and Prof. Dr Hana A. Yousif*** for their valuable comments during the study.

I am also grateful to the staff in the Concrete Laboratory of the Building and Construction Engineering Department for their help, assistance and friendliness.

Finally, my thanks go to my mother, wife, brothers, and sons for their support throughout the period of this work.

Ahmad Jabbar Hussain Alshimmeri

October 2007

ABSTRACT

26 pipes have been cast and tested in this research. **9** specimens were cast with different diameters and thicknesses to study the structural behavior of ferrocement pipes. The mix ratio of the mortar used was 1:2 (cement /sand) by weight and the w/c was 0.45. Through applying simply supported load test to the specimens the deflection on the pipe circumference in the middle were recorded besides the ultimate loads and cracks. The results showed that the increase in thickness causes the ultimate strength of ferrocement pipes to increase when keeping the diameter constant. When changing pipe thickness from 20 to 30 and 40mm and keeping diameter 300mm, the increase in the ultimate strength is about 10.3% and 24.1% respectively. When changing pipe thickness from 20 to 30 and 40mm and keeping diameter 350mm, the increase in the ultimate strength is about 22.0% and 57.7% respectively. When changing pipe thickness from 20 to 30 and 40mm and keeping diameter 400mm, the increase in the ultimate strength is about 31.8% and 72.7% respectively. The increase in diameter causes the ultimate strength of ferrocement pipes to decrease when keeping the thickness constant. When changing pipe thickness from 20 to 30 and 40mm and keeping diameter 400mm, the increase in the ultimate strength is about 31.8% and 72.7% respectively. When changing pipe diameter from 300 to 350 and 400mm and keeping thickness 30mm, the decrease in the ultimate strength is about 8.5% and 17.1% respectively. When changing pipe diameter from 300 to 350 and 400mm and keeping thickness 40mm, the decrease in the ultimate strength is about 8.9% and 15.6% respectively. Adopting the program ANSYS10.0, the theoretical analysis of ferrocement pipes has been conducted. The experimental and theoretical results have been found almost identical.

15 specimens used to assess the performance and durability of ferrocement pipes exposed to aggressive solutions have been constructed with the same diameter and thickness. They were divided into three sets: **5** ferrocement pipes were cast using mortar of mix proportion 1:2 cement : sand by weight with 0.337 w/c ratio by weight and 4% by weight of cement HRWRA. They were designated by SP₀, SP₁, SP₂, SP₃, and SP₄. **5** ferrocement pipes were cast using mortar of mix proportion 1:2 cement : sand by weight with 0.39 w/c ratio by weight, 4% and 10% by weight of cement HRWRA and HRM respectively. They were designated by M₀, M₁, M₂,

M₃, and M₄. 5 ferrocement pipes were cast using mortar of mix proportion 1:2 cement: sand by weight with 0.45 w/c ratio by weight. They were designated by N₀, N₁, N₂, N₃, and N₄. From the results it is found that the ultimate strength of the specimens SP's increases compared to the reference specimens N's, and the increase in the ultimate strength for the specimens M's is more. The ultimate strength of the specimens SP₀ and M₀ increased by 4.0% and 37.6% respectively compared to the reference specimen N₀. The ultimate strength of the specimens SP₁, SP₂, SP₃ and SP₄ increased by 14.2%, 19.3%, 27.4% and 39.9% compared to the reference specimens N₁, N₂, N₃ and N₄ respectively. The ultimate strength of the specimens M₁, M₂, M₃, and M₄ increased by 49.5%, 56.3%, 66.5% and 76.8% compared to the reference specimens N₁, N₂, N₃ and N₄ respectively. The ultimate strength decreases in general with exposure time for the three sets (N₁, N₂, N₃ and N₄), (M₁, M₂, M₃ and M₄) and (SP₁, SP₂, SP₃ and SP₄). All types of cracks and their positions for the 15 ferrocement pipes were not affected by severe salts and time of exposure.

2 ferrocement pipes were used to study the effect of protective layer on the behavior of ferrocement pipes exposed to aggressive solution. The two pipes were prepared with similar dimensions. They were reinforced as other pipes and were cast using the same mix proportion of mortar 1:2 cement : sand by weight with no admixture and 0.45 w/c ratio. From the results it is found that when comparing the ultimate strength of EP's pipes with reference pipe (N₀), an increase by 9.8% is noticed. The suggested method of protection gives ferrocement pipes an efficient protection.

Permeability of ferrocement pipes was tested for six specimens SP₀, SP₄, N₀, N₄, M₀, and M₄ exposed to aggressive solutions for 0 and 360 days. Besides, the effect of admixture and aggressive solutions on pipe permeability was investigated. A decrease was found in the coefficient of permeability for specimens SP₄ and M₄. For absorption the test indicated that there is a decrease in absorption for the specimens SP's and M's.

Contents

<i>Subject</i>	<i>Page</i>
Acknowledgment.....	I
Abstract.....	II
Table of contents.....	IV
List of symbols.....	VIII
<i>CHAPTER ONE</i>	<i>INTRODUCTION</i>
1.1 General	1
1.2 Pipes.....	3
1.3 Historical background.....	4
1.4 Durability of ferrocement.....	6
1.5 Structural behavior of ferrocement.....	7
1.6 Protection of ferrocement.....	7
1.7 Aims of the thesis.....	8
1.8 Thesis layout.....	8
<i>CHAPTER TWO</i>	<i>LITERATURE REVIEW</i>
2.1 General.....	9
2.2 Structural behavior of ferrocement.....	9
2.3 Durability.....	13
2.3.1 Sulfate attack.....	14
2.3.2 External sulfate attack.....	14
2.3.2 Internal sulfate attack.....	15
2.4 Corrosion.....	16
2.5 Protection.....	19
2.6 Mechanical properties of ferrocement.....	20
2.7 Concluding remarks.....	22
<i>CHAPTER THREE</i>	<i>MATERIALS AND EXPERIMENTAL WORK</i>
3.1 General.....	23
3.2 Description of pipes tested.....	23

3.2.1 Structural ferrocement pipes.....	24
3.2.2 Ferrocement pipes exposed to aggressive solutions.....	24
3.2.3 Coated ferrocement pipes.....	26
3.3 Materials.....	30
3.3.1 Cement.....	30
3.3.2 Fine aggregate.....	31
3.3.3 Water.....	32
3.3.4 Reinforcement.....	32
3.3.5 Superplasticizer -High Range Water Reducing Admixture (HRWRA).....	36
3.3.6 High Reactivity Metakaolin (HRM).....	37
3.3.7 Pozzolanic Activity Index of (HRM).....	39
3.3.8 Epoxy.....	40
3.3.9 Plastic pipe.....	41
3.4 Experimental program.....	41
3.5 Mould work.....	44
3.6 Mixing of mortar.....	45
3.7 Determining workability and water reduction of mortar.....	47
3.8 Preparation of salts solution.....	47
3.9 Casting ferrocement pipes.....	48
3.10 Curing and exposure conditions of ferrocement pipes.....	49
3.11 Testing procedure.....	51
3.11.1 Deflections and strains.....	52
3.11.2 Loads.....	53
3.11.2.1 Simply supported load.....	53
3.11.2.2 Three edge bearing load.....	53
3.11.3 Permeability.....	56
3.11.4 Absorption.....	57
3.12 Control specimens.....	57
CHAPTER FOUR	FINITE ELEMENT MODEL FOR
	FERROCEMENT PIPES
4.1 General.....	58
4.2 Nonlinear solution techniques.....	58

4.2.1 Incremental techniques.....	59
4.2.2 Iterative techniques.....	60
4.2.3 Incremental-Iterative techniques	60
4.3 Convergence criterion	63
4.4 Modeling of materials properties	63
4.4.1 Uniaxial compressive behavior	64
4.4.2 Uniaxial tensile behavior	65
4.4.3 Biaxial stress behavior of concrete	66
4.4.4 Modulus of elasticity.....	66
4.4.5 Poisson's ratio.....	66
4.5 Concrete models adopted in this study.....	67
4.5.1 Stress-strain relationship.....	67
4.5.2 Failure criteria for concrete.....	68
4.5.2.1 General properties of failure surface.....	70
4.5.2.2 Determination of the model parameters.....	71
4.5.2.3 Modes of failure.....	72
4.5.3 Modeling of cracking.....	77
4.5.4 Modeling of crushing of concrete and steel reinforcement	80
4.6 Types of element used.....	81
4.7 Outline of the ANSYS computer program.....	83
4.8 Modeling of tested ferrocement pipes with ANSYS Program...	83
<i>CHAPTER FIVE DISCUSSION AND COMPARISON BETWEEN RESULTS OF STRUCTURAL FERROCEMENT PIPES</i>	
5.1 General.....	86
5.2 Load-deflection relationship of structural ferrocement pipes tested.....	86
5.3 Ultimate load and ductility.....	88
5.3.1 Effect of pipe thickness on ultimate strength.....	88
5.3.2 Effect of pipe diameter on ultimate strength.....	89
5.3.3 Effect of pipe thickness on ductility.....	90
5.3.4 Effect of pipe diameter on ductility.....	91
5.4 Deflected shape.....	92

5.5 Crack patterns and general behavior.....	92
5.6 Strains	94
CHAPTER SIX DISCUSSION AND COMPARISON BETWEEN	
RESULTS OF FERROCEMENT PIPES	
EXPOSED TO AGGRESSIVE	
SOLUTION	
6.1 General.....	109
6.2 Results for ferrocement pipe exposed to aggressive solutions...	109
6.2.1 Effect of HRWRA on ultimate strength of the pipes.....	109
6.2.2 Effect of HRM-HRWRA on ultimate strength of the pipes	110
6.2.3 Effect of exposure time on ultimate strength of the pipe....	111
6.2.4 Effect of HRWRA and HRM-HRWRA on compressive strength of cubes.....	111
6.2.5 Load-deflection relationship of pipes exposed to aggressive solution.....	112
6.2.6 Visual observations.....	113
6.2.7 Crack patterns and general behavior.....	114
6.2.8 Absorption of ferrocement pipes.....	115
6.2.9 Permeability of ferrocement pipes.....	115
6.3 Results of protected ferrocement pipe.....	116
6.3.1 Ultimate strength of protected ferrocement pipes.....	116
6.3.2 Behavior of protected ferrocement pipes.....	117
CHAPTER SEVEN CONCLUSIONS AND RECOMMENDATIONS	
7.1 Conclusions.....	129
7.1.1 Structural ferrocement pipes.....	129
7.1.2 Ferrocement pipes exposed to aggressive solutions.....	131
7.1.3 Protected ferrocement pipes.....	132
7.2 Recommendations for further research.....	132
REFERENCES	133
APPENDIXES	

Abbreviations

EP1,EP2	:	Ferrocement pipe specimens submerged partially in the aggressive solutions for 0 and 360 days respectively, with plastic covering and epoxy paint
F.M.	:	Finite element
HRWRA	:	High range water reducing agent
HRM	:	High reactivity metakaolin
M₀,M₁, M₂, M₃ and M₄	:	Ferrocement pipe specimens with HRM and HRWRA, submerged partially in the aggressive solution for 0, 90, 180, 270 and 360days respectively
N₀,N₁, N₂, N₃ and N₄	:	Ferrocement pipe specimens with no admixtures, submerged partially in the aggressive solution for 0, 90, 180, 270 and 360days respectively
SP₀,SP₁, SP₂, SP₃ and SP₄	:	Ferrocement pipe specimens with HRWRA, submerged partially in the aggressive solution for 0, 90, 180, 270 and 360days respectively

General symbols

[A]^T, {a}^T	:	Transpose of matrix [A] and vector {a}
[A]⁻¹	:	Inverse of matrix [A]
d , ∂	:	Differential symbols
det, 	:	Determinant of a matrix or absolute value
{ }	:	Vector
[]	:	Matrix
Δ	:	Denoting Incremental quantity

Scalar

E	:	Modulus of elasticity
E_m	:	Modulus of elasticity of mortar
E_s	:	Modulus of elasticity of steel
F	:	Functions
f_c'	:	Uniaxial compressive strength of concrete (cylinder test)

f_u	: Ultimate strength of steel
f_y	: Yield strength of steel or stress at specified yield
f_t	: Uniaxial tensile strength of concrete
f_r	: Modulus of rupture of concrete
H'	: Hardening parameter
H_s	: Hardening parameter of steel
V	: Volume
u, v, w	: Displacement components, in x, y and z-directions
x, y, z	: Cartesian coordinates
α_1, α_2	: Tension-stiffening parameters
ϵ	: Normal (or direct) strain
ϵ_{cu}	: Ultimate strain of concrete
ϵ_{sy}	: Strain in steel at stress f_y
ϵ_{su}	: Strain in steel at stress f_u
ξ, η, ζ	: Natural (or local) coordinates
ϕ	: Curvature
ν	: Poisson's ratio
σ	: Normal stress
σ_0	: Effective stress at onset of plastic deformation
σ^*	: Effective stress

Matrix

[A]	: Displacement gradient matrix
[B]	: Strain-nodal displacement matrix
[D]	: Constitutive matrix
[J]	: Jacobian matrix
[K]	: Stiffness matrix
[N]	: Shape function
[T]	: Transformation matrix

Vector

$\{\sigma\}$:	Stress vector
$\{\epsilon\}$:	Strain vector
$\{\mathbf{F}^a\}$:	External load vector
$\{\mathbf{F}^{nr}\}$:	Internal load vector
$\{\mathbf{R}\}$:	Residual load vector
$\{\mathbf{U}\}$:	Displacement vector
$\{\mathbf{u}\}$:	Nodal displacement vector

Subscripts and superscripts

c	:	Mortar
cr	:	Cracking
e	:	Elastic component, or element quantity
s	:	Steel
t	:	Tension
y	:	Yielding

