



Cairo University

**ASSESSMENT OF STEEL CORROSION
PERFORMANCE OF CONCRETE MIXTURES
MADE OF EGYPTIAN BLENDED CEMENTS**

By

Mohamed Atef Ibrahim Reyad

A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY

In

STRUCTURAL ENGINEERING

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2018

**ASSESSMENT OF STEEL CORROSION
PERFORMANCE OF CONCRETE MIXTURES
MADE OF EGYPTIAN BLENDED CEMENTS**

By

Mohamed Atef Ibrahim Reyad

A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY

In

STRUCTURAL ENGINEERING

Under the Supervision of

Prof. Dr. Osama A. Hodhod

Prof. Dr. Mohamed M. El-Attar

.....

.....

Professor of Properties and Strength of
Materials
Structural Engineering Department
Faculty of Engineering, Cairo University

Professor of Properties and Strength of
Materials
Structural Engineering Department
Faculty of Engineering, Cairo University

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2018**

**ASSESSMENT OF STEEL CORROSION
PERFORMANCE OF CONCRETE MIXTURES
MADE OF EGYPTIAN BLENDED CEMENTS**

By

Mohamed Atef Ibrahim Reyad

A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY

In

STRUCTURAL ENGINEERING

Approved by the
Examining Committee

Prof. Dr. Osama A. Hodhod, Thesis Main Advisor

Prof. Dr. Mohamed M. El-Attar, Member

Prof. Dr. Mohamed Ismail Serag, Internal Examiner
Professor of Strength of Materials, Structural Engineering Department Faculty of
Engineering, Cairo University

Prof. Dr. Sherif Fakhry M. Abd Elnaby, External Examiner
Professor of Properties and Strength of Materials, Mataria Faculty of Engineering,
Helwan University – President of the Egyptian Russian University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT

2018

Engineer: Mohamed Atef Ibrahim Reyad
Date of Birth: 15/02/1983
Nationality: Egyptian
E-mail: Eng_mohamed.atef@hotmail.com
Phone: +2 0100 8868 232
Address: Nasr City, Cairo - Egypt
Registration Date: 01/10/2012
Awarding Date: / /2018
Degree: Doctor of Philosophy
Department: Structural Engineering
Supervisors: **Prof. Dr. Osama A. Hodhod**
Prof. Dr. Mohamed M. El-Attar



Examiners: **Prof. Dr. Osama A. Hodhod** (Thesis main advisor)
Prof. Dr. Mohamed M. El-Attar (Member)
Prof. Dr. Mohamed Ismail Serag (Internal examiner)
Prof. Dr. Sherif Fakhry M. Abd Elnaby (Internal examiner)
Professor of Properties and Strength of Materials,
Mataria Faculty of Engineering, Helwan University –
President of the Egyptian Russian University

Title of Thesis:

ASSESSMENT OF STEEL CORROSION PERFORMANCE OF CONCRETE MIXTURES MADE OF EGYPTIAN BLENDED CEMENTS

Key Words:

Slag Cement; Fly Ash; Impressed Current; Accelerated Corrosion technique; Lollipop; Water Permeability; Rapid Chloride Penetration; Pull-Out

Summary:

Manufacturing of Blast Furnace Slag Cement (CEM III/A) has boomed since it was specified in the Egyptian Cement Standard ESS 4756:2006. However, corrosion protection efficiency of the Egyptian (CEM III/A) cement has been rarely investigated. Therefore, in this research work corrosion performance was investigated for different concrete mixtures made of Egyptian manufactured (CEM III/A 42.5N), (CEM III/A 42.5N) partially replaced with fly ash and Ordinary Portland cement (CEM I). A total of 432 reinforced concrete (i.e. lollipop) specimens were exposed to impressed current accelerated corrosion technique. In addition to the binder types, the corrosion influence of the concrete mixture water/binder (w/b) ratio and binder content were assessed as well as the impact of reinforcement cover and exposure duration on reinforced concrete specimen's corrosion performance. The corrosion protection was assessed by the corrosion current and it was quantified by measuring the rebar diameter loss. In addition, corrosion performance is correlated with pull-out test results. The chloride ion penetrability, water permeability and measured corrosion current were significantly reduced by replacing (CEM I) with either (CEM III/A) or (CEM III/A+FA) cements specially for large reinforced concrete cover having optimum cement content (400kg/m^3) and minimum w/b ratio with suitable workability.

ACKNOWLEDGMENT

Thanks are due to Almighty *Allah* for enabling me to complete this research as best as I can and peace be upon his Prophet Mohamed. I hope that this thesis results will be useful for me and whoever will follow me.

I would like to express my deepest appreciation to my family “*my mother, my wife, my brothers, and my lovely children Omar, and Lily*” for their strong support along my life and their life, also to *my father spirit*.

I would like to express my utmost gratitude to my thesis supervisors: *Professor Dr. Osama A. Hodhod*, and *Professor Dr. Mohamed M. El-Attar*, for their encouragement, supervision, precious remarks and guidance throughout the planning and execution of this thesis.

Special thanks and gratitude to my non-official supervisor: *Associate professor Dr. Alaa El-Din M. Sharkawi*. The role of Dr. Sharkawi in this thesis is invaluable. Dr. Sharkawi provided the Rapid Chloride penetration apparatus and helped with the design of the accelerated corrosion set up. Discussions with Dr. Sharkawi along this study course have enriched the research work, enhanced the published papers extracted from this study and contributed to the completed form of this thesis.

With all my love and respect
Eng. Mohamed Atef Ibrahim

Table of Contents

ACKNOWLEDGMENTS	i
TABLE OF CONTENT	ii
LIST OF FIGURES	v
LIST OF TABLES	ix
ABSTRACT	x
1 INTRODUCTION	1
1.1 Introduction	1
1.2 Research Scope	2
1.3 Objectives	3
1.4 Organization of the Thesis	3
2 LITERATURE REVIEW	4
2.1 Introduction	4
2.2 Mechanism of Embedded Rebar Corrosion	5
2.3 Corrosion Products	6
2.4 Corrosion Types	8
2.4.1 General Corrosion	9
2.4.2 Pitting Corrosion	9
2.5 Protection Factors Against Embedded Steel Rebar Corrosion	10
2.5.1 Concrete Cover	10
2.5.1.1 Cover Cracks	12
2.5.2 Passivation Layer	13
2.5.3 Curing Time and Conditions	13
2.5.4 Cement Type	14
2.5.5 Cement Content / Compressive Strength	16
2.5.6 Water Cement Ratio	17
2.5.7 Addition of Mineral Admixture	18
2.5.7.1 Fly Ash, and Blast Furnace Slag as a Mineral Admixture	19
2.5.8 Concrete Constituents	24
2.6 Protection Loss for Embedded Steel Rebar Corrosion	25
2.6.1 De-passivation of Embedded Steel Rebar	25
2.6.1.1 Embedded Steel Rebar Corrosion by Carbonation	26
2.6.1.2 Embedded Steel Rebar Corrosion by Chlorides	27

2.7	Corrosion Results	28
2.7.1	Concrete Cracking	28
2.7.2	Embedded Steel Rebar Diameter Loss	28
2.7.3	Concrete-Rebar Bond Loss	28
2.7.3.1	Measurement of Bond	30
2.7.3.2	Factors Affecting Bond Strength	31
2.8	Accelerated Corrosion Short-Time “Impressed Current” Technique	33
2.9	Measuring of Chloride Ingress in to Concrete	35
2.10	Problem Statement	38
2.10.1	Research Objectives	38
3	EXPERIMENTAL WORK	39
3.1	Introduction	39
3.2	Materials Specifications and Testing	39
3.2.1	Coarse and Fine Aggregate	39
3.2.2	Water	42
3.2.3	Cements and Fly Ash	43
3.2.4	Admixtures (Super-plasticizer)	45
3.2.5	Reinforce Bars	45
3.3	Concrete Mixtures Design	46
3.4	Concrete Specimens Preparation	47
3.5	Mixing, Pouring and Curing	49
3.5.1	Introduction	49
3.5.2	Mixing and Pouring	50
3.5.3	Removing, and Curing	52
3.6	Specimens Testing	53
3.6.1	Compressive Strength	53
3.6.2	Accelerated Corrosion by Impressed Current Technique	54
3.6.3	Permeability Test	56
3.6.4	Rapid Chloride Penetration Test (RCPT)	57
3.6.5	Pull-Out Test	60
3.6.6	Determination of Maximum Rebar Diameter Loss	62

4	RESULTS AND DISCUSSIONS	63
4.1	Introduction	63
4.2	Concrete Compressive Strength	63
4.2.1	Ordinary Portland Cement (CEM I 42.5N)	63
4.2.2	Blast Furnace Slag Cement (CEM III/A 42.5N)	70
4.2.3	Manufactured Cement (CEM III/A 42.5N + 20% FA)	76
4.2.4	Compressive Strength Comparison for Concrete Mixtures Cast with Different Type of Cements	82
4.3	Acceleration Corrosion by Impressed current	84
4.4	Permeability Test	94
4.5	Rapid Chloride Penetration Test Results (RCPT)	95
4.6	Pull-Out Test	97
4.6.1	Control Specimens Pull-Out Force Test Results Analysis	97
4.6.2	Specimens Pull-Out Force Test Results Analysis after accelerated corrosion	101
4.7	Determination of Maximum Rebar Diameter loss due to Accelerated Corrosion	107
4.8	Discussion Summary	109
5	CONCLUSIONS AND RECOMMENDATIONS	112
5.1	Summary	112
5.2	Main conclusions	112
5.3	Recommendations for Future Researches	115
	REFERENCES	116

List of Figures

Figure No.	TITLE	PAGE No.
2.1	Deterioration of Concrete Buildings Due to Rebar Corrosion	5
2.2	Corrosion of Steel in Concrete	6
2.3	Volumetric expansion of corrosion products	7
2.4	Schematic Description of Corrosion Layer Structure	7
2.5	Concrete Deterioration Stages due to Corrosion	7
2.6	Common Types of Concrete Damage (Crack, Spall, and Delamination)	8
2.7	Initiation and Propagation of Cracks around Rebar due to Corrosion	8
2.8	Pit Corrosion in steel Rebar	9
2.9	Effect of Concrete Cover on Corrosion Initiation Time	12
2.10	Mechanism and Time for Concrete Cover Cracking	13
2.11	Effect of C ₃ A on Corrosion Current	15
2.12	Water Cement Ratio Effect on Cl ⁻ Penetration Depth	18
2.13	Fly Ash as a By-product from Power Planet	20
2.14	SEM Micrograph for (FA)	20
2.15	GBFS as a By-product from Iron Manufacturing process	21
2.16a	BFS after and before grinding	22
2.16b	SEM Micrograph for (GBFS)	22
2.17	Initiation Mechanism of Steel Corrosion in Concrete	26
2.18	Bond Force Transfer Mechanism (ACI 408)	30
2.19	Schematic of: (a) Pull-Out Specimen; (b) Beam-End Specimen; (c) Beam Anchorage Specimen; and (d) Splice Specimen (ACI 408)	31
2.20	Test Specimen Showing the Difference in Concrete Cover	32
2.21	Schematic Diagram of Impressed Current Method	34
2.22	Specification of Lollipop Sample	34
2.23	The Full instrument of (RCPT)	36
2.24	Schematic Description of Concrete Slice in the Instrument of (RCPT)	37

3.1	Sieve Analysis Curves for Coarse Aggregate	40
3.2	Sieve Analysis Curves for Sand	41
3.3	Cement and Fly Ash used in Concrete Mixtures	43
3.4	Schematic Diagram of Lollipop Specimens Design	47
3.5	Steel Rebars Preparing	48
3.6	Zinc Rich Coat	48
3.7	Rebars after Coating	48
3.8	Set of Cylinders Needed for Each Type of Concrete Mixture Specimens with Fixation Frame	48
3.9	Prepared Formwork for Casting Two Concrete Mixtures per Day (One Day Casting)	49
3.10	Slump for Trial Mixes with different (SP) Percentages	49
3.11	Various Stages of Concrete Production	51-52
3.12	Specimens after 24-Hour	52
3.13	Specimens Curing Processes	53
3.14	Compressive Strength Testing and Cube after Testing	53
3.15	Schematic Diagram of Impressed Current Test Method for Lollipop Samples	54
3.16	Test Setup and Components of Impressed Current Accelerated Corrosion Test	55
3.17	Lollipop Specimens (5, and 10cm) diameter during and after Exposure Time Finished	55
3.18	Permeability Device	56
3.19	RCPT- Preparation Phase	57-58
3.20	RCPT- Testing Phase	59
3.21	Panorama View for Rapid Chloride Penetration Test (RCPT)	60
3.22	Lollipop Specimens after Different time	61
3.23	Laboratory Pull-Out Test Setup Machine	61
3.24	Lollipop Specimens during Pull-Out Testing	61
3.25	Lollipop Specimens after Pull-Out Test	61
3.26	Extracted Rebars from Lollipop Specimens before Cleaning	62
3.27	Steel Rebars after Cleaning Process Ending	62

4.1	Development of Compressive Strength for Concrete Mixtures Cast with (CEM I) Binder	65
4.2	Influence of (CEM I) Binder Content on Compressive Strength Results	66
4.3	Compressive Strength Gained for Concrete Mixtures Cast with (CEM I) Binder	67
4.4	Influence of w/b Ratio on Compressive Strength for Concrete Mixtures Cast with (CEM I) Binder	68-69
4.5	Influence of w/b Ratio, and Binder Content on Final Age Compressive Strength for Concrete Mixtures Cast with (CEM I) Binder	69
4.6	Development of Compressive Strength for Concrete Mixtures Cast with (CEM III/A) Binder	71
4.7	Influence of (CEM III/A) Binder Content on Compressive Strength Results	72
4.8	Compressive Strength Gained for Concrete Mixtures Cast with (CEM III/A) Binder	73
4.9	Influence of w/b Ratio on Compressive Strength for Concrete Mixtures Cast with (CEM III/A) Binder	74-75
4.10	Influence of w/b Ratio, and Binder Content on Final Age Compressive Strength for Concrete Mixtures Cast with (CEM III/A) Binder	75
4.11	Development of Compressive Strength for Concrete Mixtures Cast with (CEM III/A + 20% FA) Binder	77
4.12	Influence of (CEM III/A + 20% FA) Binder Content on Compressive Strength Results	78
4.13	Compressive Strength Gained for Concrete Mixtures Cast with (CEM III/A + 20% FA) Binder	79
4.14	Influence of w/b Ratio on Compressive Strength for Concrete Mixtures Cast with (CEM III/A + 20% FA) Binder	80-81
4.15	Influence of w/b Ratio, and Binder Content on Final Age Compressive Strength for Concrete Mixtures Cast with (CEM III/A + 20% FA) Binder	81

4.16	Average Compressive strength (kg/cm ²) for Different Concrete Mixtures at different ages	83-84
4.17	Current-Time Profile for 5cm-Diameter Lollipop Specimens Cast with Different Binder Types	86-87
4.18	Current-Time Profile for 10cm-Diameter Lollipop Specimens Cast with Different Binder Types	88-89
4.19	Current-Time Profiles for all 5cm- Diameter Specimens Classified According to w/b Ratios and Binder Contents	90
4.20	Current-Time Profiles for all 10cm- Diameter Specimens Classified According to w/b Ratios and Binder Contents	91
4.21	Current-Time Profiles Classified According to w/b Ratios, Binder Contents, and Concrete Lollipop Diameter for Each Binder Type	92
4.22.a	Corrosion Activity -areas under current-time curves- for all 5 cm Diameter Specimens after 168-Hour of Exposure	93
4.22.b	Corrosion Activity -areas under current-time curves- for all 10 cm Diameter Specimens after 168-Hour of Exposure	93
4.22.c	Corrosion Activity -areas under current-time curves- for all 10 cm Diameter Specimens after 480-Hour of Exposure	93
4.23	Average Water Depth after Permeability Test	95
4.24.a	Current Passed Through Specimens during 6-Hour	96
4.24.b	Current Passed during 6-Hour through specimens Cast with (CEM III/A), and (CEM III/A + 20% FA) Binders only	96
4.25	Influence of Binder Content and w/b Ratio on Pull-Out Force	98-99
4.26	Pull-Out Force Comparison for Concrete mixtures Cast with Different Binder Types	100
4.27	Bond loss Percentage of 5cm-Diameter Lollipop Specimens	103-104
4.28	Bond Loss Comparison after 7-Days of Accelerated Corrosion for 5cm-diameter Lollipop Specimens	104
4.29	Bond loss Percentage of 10cm-Diameter Lollipop Specimens	105-106
4.30	Bond Loss Comparison after 20-Days of Accelerated Corrosion for 10cm-diameter Lollipop Specimens	106

4.31a	Percentage of Maximum Rebar Diameter Loss for 5cm-Diameter Lollipop Specimens after 168-Hour of Exposure to Accelerated Corrosion Test	108
4.31b	Percentage of Maximum Rebar Diameter Loss for 10cm-Diameter Lollipop Specimens after 480-Hour of Exposure to Accelerated Corrosion Test	108

List of Tables

TABLE NO.	TITLE	PAGE No.
2.1	Controlling parameter according to Carmen and Renata, 2013	24
2.2	Different Methods of Mesuring of Chloride Ingress	35
2.3	Classification of Penetrability Due To Charge Passed	36
3.1	Coarse Aggregate Sieve Analysis Compared with ASTM & ES	40
3.2	Fine Aggregate Sieve Analysis Compared with ASTM & ES	41
3.3	Coarse and Fine Aggregate Physical and Chemical Tests	42
3.4	Test Results applied on Used Water	42
3.5	Chemical Properties of Cements and Fly Ash	43
3.6	Chemical Specifications of Cements and Fly Ash	44
3.7	Physical Properties of Cements Comparing to Specs.	44
3.8	Physical Properties of Fly Ash	44
3.9	Specific Surface Area of Different Cementitious Materials	44
3.10	Test Results Conducted on Used Admixture	45
3.11	Test Results Conducted on Reinforcement Steel Rebars	45
3.12	Concrete Mixtures Proportions (kg/m ³) and Measured Slump	46
3.13	Recorded Data for Material Percentages, Slump and Temperature	50
3.14	Concrete Mixtures for Permeability Test	56
4.1	Average Compressive Strength (kg/cm ²) for Concrete Mixtures Cast with (CEM I) at different Ages, and w/b Ratios	64
4.2	Average Compressive Strength (kg/cm ²) for Concrete Mixtures Cast with (CEM III/A) at different Ages and w/b Ratios	70
4.3	Average Compressive Strength (kg/cm ²) for Concrete Mixtures Cast with (CEM III/A 42.5N + 20%FA) at different Ages and w/b Ratios	76
4.4	Chloride Ion Penetrability of Concrete Mixtures	96
4.5	Average Pull-Out Force (kN)	97
4.6	Average Pull-Out Force (kN) after Exposure to accelerated corrosion	101

Abstract

Although it has been used worldwide for decades, manufacturing of Blast Furnace Slag Cement (CEM III/A) has boomed since it was specified in the Egyptian Cement Standard ESS 4756 on 2006. However, corrosion protection for reinforced concrete structures efficiency of the Egyptian (CEM III/A) cement has rarely investigated.

The research methodology is to investigated the influence of different concrete mixtures cast with Egyptian manufactured cement (CEM III/A 42.5N), (CEM III/A 42.5N) partially replaced with locally fly ash class F - and Ordinary Portland cement (CEM I) against corrosion exposure.

A total of 432 reinforced concrete (i.e. lollipop) specimens were exposed to accelerated corrosion by impressed current technique. In addition to the binder types, the corrosion influence of the concrete mixture, water/binder (w/b) ratio and binder content were assessed as well as the impact of reinforcement cover thickness and accelerated corrosion duration on reinforced concrete lollipop specimen's corrosion performance. The corrosion protection was assessed by the corrosion current and it was quantified by measuring the rebar diameter loss. In addition, corrosion performance is correlated with pull-out test results

The study results assess the durability role of replacing (CEM I) with (CEM III/A) or (CEM III/A +20% FA) was remarkably dependent on the concrete mixture binder content and water/binder ratio. Optimum blended cement content and minimum water/binder (w/b) ratio, with suitable workability, provided the least concrete water permeability and chloride ion penetrability. Therefore, 400kg/m^3 -of either proposed blended cements- accompany with w/b ratio of 0.45 achieved the best concrete durability characteristics, with advantage to the (CEM III/A +20% FA) cement. Hence, it's clear that the highest blended cement content is not always the optimum content, as commonly specified, to achieve the least concrete permeability and chloride penetrability as well as the best corrosion protection. Therefore, it's possible to reduce the content of the proposed blended cements and the w/b ratio (i.e. paste content) without sacrificing the desired workability, compressive strength and durability