PSZ 19:16 (Pind. 1/13)

UNIVERSITI TEKNOLOGI MALAYSIA

DECLARATION OF THESIS / POSTGRADUATE PROJECT REPORT AND COPYRIGHT

Author's full name : NELLY BINTI MAJAIN

Date of Birth : 19 MAY 1979

Title : BOND BEHAVIOUR OF DEFORMED STEEL REBARS IN STEEL FIBRE HIGH-STRENGTH SELF-COMPACTING CONCRETE

Academic Session : 2022/2023 - 1

I declare that this thesis is classified as:

☐ **CONFIDENTIAL** (Contains confidential information under the Official Secret Act 1972)*

☐ **RESTRICTED** (Contains restricted information as specified by the organization where research was done)*

☑ **OPEN ACCESS** I agree that my thesis to be published as online open access (full text)

1. I acknowledged that Universiti Teknologi Malaysia reserves the right as follows:
2. The thesis is the property of Universiti Teknologi Malaysia
3. The Library of Universiti Teknologi Malaysia has the right to make copies for the purpose of research only.
4. The Library has the right to make copies of the thesis for academic exchange.

Certified by:

SIGNATURE OF STUDENT

SIGNATURE OF SUPERVISOR

PKA 173103

MATRIX NUMBER

PROF. DR. AHMAD BAHARUDDIN B. ABD. RAHMAN

NAME OF SUPERVISOR

Date: 07 NOVEMBER 2022

Date: 07 NOVEMBER 2022

NOTES : If the thesis is CONFIDENTIAL or RESTRICTED, please attach with the letter from the organization with period and reasons for confidentiality or restriction

UMS UNIVERSITI MALAYSIA SABAH

"We hereby declare that we have read this thesis and in our opinion this thesis is sufficient in term of scope and quality for the award of the degree of Doctor of Philosophy in Civil Engineering"

Signature :
Name of Supervisor I : AHMAD BAHARUDDIN B. ABD. RAHMAN
Date : 7 NOVEMBER 2022

Signature :
Name of Supervisor II : AZLAN BIN ADNAN
Date : 7 NOVEMBER 2022

Signature :
Name of Supervisor II : ROSLLI BIN NOOR MOHAMED
Date : 7 NOVEMBER 2022

UMS
UNIVERSITI MALAYSIA SABAH

BAHAGIAN A – Pengesahan Kerjasama*

Adalah disahkan bahawa projek penyelidikan tesis ini telah dilaksanakan melalui kerjasama antara ______________________ dengan ______________________

Disahkan oleh:

Tandatangan : .... Tarikh : ....

Nama : ....

Jawatan : ....
(Cop rasmi)

* *Jika penyediaan tesis/projek melibatkan kerjasama.*

BAHAGIAN B – Untuk Kegunaan Pejabat Fakulti Kejuruteraan Awam

Tesis ini telah diperiksa dan diakui oleh:

Nama dan Alamat Pemeriksa Luar 1 : **Dato' Prof. Ir. Dr. Wan Hamidon Bin Wan Badaruzzaman**
Fakulti Kejuruteraan dan Alam Bina
Universiti Kebangsaan Malaysia
43600 UKM Bangi
Selangor

Nama dan Alamat Pemeriksa Dalam : **Prof. Madya Dr. Suhaimi Bin Abu Bakar**
Fakulti Kejuruteraan Awam
Universiti Teknologi Malaysia
81310 Johor Bahru, Johor

Nama Penyelia Lain (Jika ada) :

Disahkan oleh Naib Pengerusi (Akademik & Pembangunan Pelajar), Fakulti Kejuruteraan Awam

Tandatangan : -- Tarikh : ----------

Nama : --

UMS UNIVERSITI MALAYSIA SABAH

BOND BEHAVIOUR OF DEFORMED STEEL REBARS IN STEEL FIBRE HIGH- STRENGTH SELF-COMPACTING CONCRETE

NELLY BINTI MAJAIN

UMS
UNIVERSITI MALAYSIA SABAH

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

Faculty of Civil Engineering
Universiti Teknologi Malaysia

NOVEMBER 2022

DECLARATION

I declare that this thesis entitled *"Bond behaviour of deformed steel rebars in steel fibre high-strength self-compacting concrete"* is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

UMS
UNIVERSITI MALAYSIA SABAH

Signature : ....
Name : NELLY BINTI MAJAIN
Date : 7 NOVEMBER 2022

DEDICATION

This thesis is dedicated to my late father, who passed away while I was studying. All this hard work is inspired by him who always taught me that through hard work I can achieve anything. It is also dedicated to my mother, who never stopped praying for me from the day I was born. I love you both with all my heart.

UMS
UNIVERSITI MALAYSIA SABAH

ACKNOWLEDGEMENT

First and foremost, I would like to thank God for giving me the strength and grace I needed to complete this thesis. I am nothing without Him.

I would like to express my sincere gratitude to my supervisor Prof. Dr. Ahmad Baharuddin Abd. Rahman for trusting me to conduct the research work and for always supporting, guiding and sharing his wisdom with me. Thank you for believing in me. I am also thankful to my co-supervisors Prof. Ir. Dr. Azlan Adnan and Assoc. Prof. Dr. Roslli Noor Mohamed for their continuous support and guidance throughout my studies.

I am also indebted to Universiti Malaysia Sabah (UMS) for funding my Ph.D. studies and I am especially grateful to Assoc. Prof. Ts. Dr. Ismail Saad, the Dean of Faculty of Engineering, Universiti Malaysia Sabah, for his continuous support. Also, a special thank you to Prof. Ir. Dr. Abdul Karim Mirasa, the former Dean of Faculty of Engineering, Universiti Malaysia Sabah, for giving me the opportunity to pursue my Ph.D. studies.

My thanks and appreciation also goes to all the technicians of the Materials and Structure Laboratories (D04) especially to Ms. Mazlina Binti Ngah and Mr. Muhammad Anwarrasyid Bin Mohd Alwi for helping me a lot in the experimental work. Thank you to all of my postgraduate friends from D04 especially to Ir. Dr. Zuraida, Zanariah, Shariwati, Dianah, Ayun, Azie, Nadirah, Nur Fatin, Fazlin, Nur Suhadah, Annur, Azura and Chiew Shing Mei for assisting me in the experimental work and for their generosity in sharing knowledge and information. Their views and tips were useful indeed.

I also want to thank my family members especially my beloved father, the late Fabian Majain Lajini and to my mother Jovita Moinin, siblings (Genevive, Jonas, Regina, Sr. Marie Carmen and Emily), sister and brothers-in-law, nieces and nephews and also my uncles and aunties for consistently praying for me to complete my studies successfully and also for being so understanding.

I am forever thankful to the most faithful of friends in my life, Melissa Nicholas and Melissa Audrey Francis for their unending prayers, support, and encouragement. Thank you for always being there for me throughout all of my ups and downs in my study life.

Finally, I would like to thank all of my friends in GIFT UTM especially Joanne and Jason for helping me in my research work. Also, my deepest appreciation to all of my friends in Eramaju Synergy Sdn. Bhd., especially to Ir. Dr. Tom Ngui and Ir. Roland Ng for their continuous support and encouragement throughout my studies.

UMS
UNIVERSITI MALAYSIA SABAH

ABSTRACT

Studies on the bond behaviour of deformed steel rebars in conventional concrete have been widely covered. However, the studies on the bond behaviour between deformed steel rebars and high-strength self-compacting concrete (HSSCC), particularly with the addition of steel fibres, are still very limited. Hence, in this research, an in-depth study was conducted to investigate the effects of steel fibres on the bond behaviour of deformed steel rebars embedded in steel fibre high-strength self-compacting concrete (SFHSSCC). Experimental works were carried out in two phases. Phase 1 involved the design of concrete mixes and the testing of fresh and mechanical properties of the normal vibrated concrete (NVC), HSSCC and SFHSSCC. The steel fibres used in SFHSSCC were the hooked-end type with 35 mm length and an aspect ratio of 63.6. The research works in Phase 2 involved the direct pullout testing conducted according to the RILEM RC6 Part 2 standard. A total of 72 pullout specimens with a dimension of 200 mm x 200 mm x 200 mm were prepared and tested at 30 ± 2 days. A few of SFHSSCC specimens were tested at the 6 months of concrete age. The pullout specimens comprised high yield deformed steel rebars of 12, 16, and 20 mm diameters. The pullout specimens were subjected to increasing axial pullout load. The test results in Phase 1 showed the proposed design mix of self-compacting concrete managed to achieve high compressive strength of 60-80 N/mm^2. As compared to HSSCC, the concrete compressive strength of SFHSSCC had increased slightly, but the splitting tensile strength had increased tremendously. The results showed that SFHSSCC with 1.0% of steel fibre volume fraction was the best mix that satisfy the self-compacting and harden concrete requirements and therefore was selected for further study in Phase 2. The test results of Phase 2 showed that the effect of steel fibres in increasing bond strength between rebar and the high-strength self-compacting concrete is seen to be insignificant as the results of bond strength of rebars in HSSCC and SFHSSCC concrete showed small differences only. However, the addition of steel fibres in SFHSSCC had improved the concrete ductility very significantly. At the age of 6 months, the confinement energy of the SFHSSCC improved substantially by about 80% as compared to the confinement energy at 30 ± 2 days. Based on the stress-strain behaviour in concrete, it was observed that the SFHSSCC was able to expand significantly under large stresses with controllable strains which justifies that the presence of steel fibres had contributed to improved confinement effects to the extent that the SFHSSSCC had the ability to provide high confinement energy and good ductility. Subsequently, based on the pullout test results, two new bond strength equations are proposed to predict the bond strengths of deformed steel rebars embedded in HSSCC and SFHSSCC. Finally, it can be concluded that the presence of steel fibres in SFHSSCC could overcome the brittle failure in high strength self-compacting concrete and significantly improves the concrete ductility, which delay the loss of bond between rebars and concrete.

UMS
UNIVERSITI MALAYSIA SABAH

ABSTRAK

Kajian mengenai kelakuan ikatan tetulang keluli berbunga dalam konkrit konvensional telah dilaksanakan dengan meluas. Bagaimanapun, kajian mengenai sifat ikatan antara tetulang keluli berbunga dan konkrit kekuatan tinggi terpadat sendiri (HSSCC), terutamanya dengan penambahan gentian keluli, masih sangat terhad. Oleh itu, dalam penyelidikan ini, kajian lebih mendalam telah dilakukan untuk menyelidik kesan gentian keluli terhadap sifat ikatan tetulang keluli berbunga yang tertanam dalam konkrit kekuatan tinggi terpadat sendiri dengan gentian keluli (SFHSSCC). Kerja-kerja ujikaji dijalankan dalam dua fasa. Fasa 1 melibatkan reka bentuk campuran konkrit dan ujian sifat konkrit segar dan mekanikal bagi konkrit bergetar normal (NVC), HSSCC dan SFHSSCC. Gentian keluli yang digunakan dalam SFHSSCC adalah jenis hujung bercangkuk dengan panjang 35 mm dan nisbah aspek 63.6. Kerja penyelidikan Fasa 2 melibatkan ujian tarik-keluar langsung yang dijalankan mengikut piawaian RILEM RC6 Bahagian 2. Sejumlah 72 spesimen tarik-keluar dengan dimensi 200 mm x 200 mm x 200 mm telah disediakan dan diuji pada 30 ± 2 hari. Beberapa spesimen SFHSSCC juga telah diuji pada umur konkrit 6 bulan. Spesimen tarik-keluar menggunakan tetulang keluli berbunga alahan tinggi berdiameter 12, 16, dan 20 mm. Spesimen tarik-keluar dikenakan beban tegangan paksi yang meningkat. Keputusan ujian Fasa 1 menunjukkan reka bentuk campuran konkrit terpadat sendiri yang dicadangkan dapat mencapai kekuatan mampatan tinggi di antara 60-80 N/mm^2. Berbanding dengan HSSCC, kekuatan mampatan konkrit SFHSSCC meningkat sedikit, tetapi kekuatan tegangan pecah meningkat dengan sangat tinggi. Keputusan menunjukkan SFHSSCC dengan 1.0% pecahan isipadu gentian keluli adalah campuran terbaik yang memenuhi keperluan konkrit terpadat sendiri dan konkrit keras dan telah dipilih untuk kajian lanjut di Fasa 2. Keputusan ujian Fasa 2 menunjukkan kesan gentian keluli dalam peningkatan kekuatan ikatan di antara tetulang keluli dengan konkrit kekuatan tinggi terpadat sendiri dilihat tidak ketara kerana hasil kekuatan ikatan tetulang keluli dalam konkrit HSSCC dan SFHSSCC menunjukkan perbezaan yang sedikit. Bagaimanapun, penambahan gentian keluli dalam SFHSSCC telah meningkatkan kemuluran konkrit SFHSSCC dengan sangat ketara. Pada umur 6 bulan, tenaga pengurungan SFHSSCC meningkat dengan ketara sehingga 80% berbanding tenaga pengurungan pada 30 ± 2 hari. Berdasarkan penyelidikan sifat tegasan-terikan dalam konkrit, telah diperhatikan bahawa SFHSSCC dapat mengembang dengan ketara di bawah tegasan yang besar dengan terikan terkawal yang membuktikan bahawa kehadiran gentian keluli telah menyumbang kepada kesan pengurungan yang lebih baik sehingga SFHSSSCC mempunyai keupayaan untuk memberikan tenaga pengurungan yang tinggi dan kelakuan mulur yang baik. Seterusnya, berdasarkan keputusan ujian tarik keluar, dua persamaan kekuatan ikatan baharu telah dicadangkan untuk meramalkan kekuatan ikatan tetulang keluli berbunga yang tertanam dalam HSSCC dan SFHSSCC. Akhirnya, dapat disimpulkan bahawa kehadiran gentian keluli dalam SFHSSCC dapat mengatasi kegagalan rapuh dalam konkrit kekuatan tinggi terpadat sendiri serta meningkatkan kemuluran konkrit dengan ketara, yang melambatkan kegagalan ikatan di antara tetulang keluli dan konkrit.

UMS
UNIVERSITI MALAYSIA SABAH

TABLE OF CONTENTS

	TITLE	PAGE
	DECLARATION	iii
	DEDICATION	iv
	ACKNOWLEDGEMENT	v
	ABSTRACT	vi
	ABSTRAK	vii
	TABLE OF CONTENTS	viii
	LIST OF TABLES	xiii
	LIST OF FIGURES	xv
	LIST OF ABBREVIATIONS	xxi
	LIST OF SYMBOLS	xxii
	LIST OF APPENDICES	xxiv
CHAPTER 1	**INTRODUCTION**	**1**
1.1	Introduction	1
1.2	Problem Statement	3
1.3	Objectives of the Study	5
1.4	Scope of Study	5
1.5	Significance of Study	6
1.6	Outline of the Thesis	6
CHAPTER 2	**LITERATURE REVIEW**	**9**
2.1	Introduction	9
2.2	SCC	10
	2.2.1 Background of SCC	10
	2.2.2 Practical Applications of SCC	11
	2.2.3 Characteristics of SCC	13
	2.2.4 SCC Mix Design	14
	2.2.4.1 Basic Mix Design of SCC	16

UMS
UNIVERSITI MALAYSIA SABAH

2.2.4.2 Mechanical Properties of SCC 16
2.3 SFSCC 17
2.3.1 Background of SFSCC 18
2.3.2 Types of Steel Fibres 19
2.3.3 SFSCC in the Fresh State 20
2.3.4 Mechanical Properties of SFSCC 22
2.3.4.1 Compressive Strength Test 23
2.3.4.2 Splitting Tensile Strength 23
2.3.5 Steel Fibres Mechanism in Concrete 24
2.3.5.1 Steel Fibre Confinement and Ductility 24
2.4 Bond of Reinforcing Rebar in Concrete 25
2.4.1 Bond Mechanism 26
2.4.2 Factor Influencing Bond Behaviour 29
2.4.3 Confinement Effects on Bond Behaviour 33
2.4.4 Pullout Tests to Investigate Bond Behaviour and Performance 35
2.4.5 Previous Study on Bond between Reinforcing Rebar and Concrete 40
2.4.6 Existing Analytical Bond Models 54
2.5 Summary 58

CHAPTER 3 RESEARCH METHODOLOGY 61

3.1 Introduction 61
3.2 Constituent Materials 65
3.2.1 Cement 65
3.2.2 Fly Ash 65
3.2.3 Fine and Coarse Aggregate 66
3.2.4 Water 68
3.2.5 Superplasticiser 68
3.2.6 Steel Fibres 69
3.2.7 Deformed Steel Rebars 70
3.3 Mix Design and Casting Procedure 74

UMS
UNIVERSITI MALAYSIA SABAH

3.4 Specimen Details and Preparation 78

3.4.1 Specimen Detail for Mechanical Properties Testing 79

3.4.2 Specimen Detail for Direct Pullout Testing 80

3.5 Phase 1: Fresh Properties and Mechanical Properties Testing 90

3.5.1 Fresh Properties Testing 90

3.5.1.1 Slump Test 90

3.5.1.2 Slump Flow Test 91

3.5.1.3 V-Funnel Test 92

3.5.1.4 L-Box Test 93

3.5.2 Mechanical Properties Testing 94

3.5.2.1 Compressive Strength Test 94

3.5.2.2 Splitting Tensile Strength 95

3.6 Phase 2: Bond Test - Pullout Test 97

3.6.1 Loading Rate Determination 97

3.6.2 Strain Gauges Installation on Pullout Specimen 99

3.6.3 Pullout Test 100

3.6.4 Concrete Coring Sampling 103

3.7 Summary 105

CHAPTER 4 FRESH AND MECHANICAL PROPERTIES OF CONCRETE 107

4.1 Introduction 107

4.2 Fresh Properties of Concrete 107

4.2.1 Slump Test 108

4.2.2 Slump Flow 109

4.2.3 V-Funnel 111

4.2.4 L-Box 113

4.3 Mechanical Properties of Concrete 114

4.3.1 Concrete Compressive Strength 115

4.3.2 Splitting Tensile Strength 117

4.4 Confirmation of Concrete Mix Design 120

UMS UNIVERSITI MALAYSIA SABAH

4.5 Summary 121

CHAPTER 5 BOND BEHAVIOUR OF DEFORMED STEEL REBARS IN STEEL FIBRE HIGH-STRENGTH SELF-COMPACTING CONCRETE 123

5.1 Introduction 123

5.2 Pullout Test Results 123

5.3 Mode of Failure 129

5.3.1 Effects of Rebar Size on Mode of Failures 133

5.3.2 Effects of Concrete Cover on Mode of Failures 142

5.3.3 Effects of Rebar Embedment Length on Mode of Failures 151

5.4 Bond Stress-Slip Relationship 159

5.4.1 Effects of Concrete Compressive Strength on Bond Strength and Mode of Failure 165

5.4.2 Effects of Concrete Tensile Strength on Bond Strength and Mode of Failure 167

5.4.3 Normalised Bond Strength 169

5.4.4 Top-Bar Effect on Uniformity of Bond 172

5.4.5 Effect of Specimen Shape on Bond Strength 176

5.5 Summary 182

CHAPTER 6 CONFINEMENT EFFECTS OF STEEL FIBRE REINFORCED HIGH-STRENGTH SELF-COMPACTING CONCRETE ON BOND BEHAVIOUR 185

6.1 Introduction 185

6.2 Steel Fibre Confinement Mechanism 185

6.3 Effects of Steel Fibre Confinement on Bond Behaviour 191

6.3.1 SFHSSCC Confinement Energy 195

6.4 Stress–Strain of Concrete and Deformed Steel Rebars in Pullout Specimens and the Relationship to Confinement 199

6.5 Theoretical Analysis of Predicted Bond Strength 209

6.5.1 Experimental Data for Theoretical Analysis 209

UMS
UNIVERSITI MALAYSIA SABAH

6.5.2 Evaluation of Existing Bond Strength Equations 212

6.5.3 Proposed Bond Strength Equation from Pullout Failure 220

6.5.4 Proposed Equation to Estimate Bond Strength Due to Premature Splitting and Rebar Yielding Failures 223

6.5.5 Recommended Bond Equations 228

6.6 Summary 229

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS 233

7.1 Introduction 233

7.2 Conclusions 233

7.2.1 Fresh and Mechanical Properties of Concrete 233

7.2.2 Bond Behaviour and Performance of Deformed Steel Rebars in HSSCC and SFHSSCC 235

7.2.3 Effects of steel fibre confinement on the bond behaviour of deformed steel rebars in SFHSSCC 236

7.2.4 Recommendation of Bond Strength Equations 238

7.3 Recommendation for Future Research 238

REFERENCES 241

LIST OF PUBLICATIONS 263

UMS
UNIVERSITI MALAYSIA SABAH

LIST OF TABLES

TABLE NO.	TITLE	PAGE
Table 2.1	Requirements of SCC (EFNARC, 2002)	14
Table 2.2	Typical range of SCC mix composition (European Project, 2005)	16
Table 2.3	Factors influencing bond behaviour	31
Table 2.4	Method of concrete confinement and testing	36
Table 2.5	Previous study on bond of rebar in NVC and SFRC	41
Table 2.6	Bond of reinforcing rebar in SCC/HSSCC	46
Table 2.7	Bond of reinforcing rebar in SFSCC/SFHSSCC	51
Table 2.8	Previous study on analytical bond models	55
Table 3.1	Results of sieve analysis for fine aggregate	67
Table 3.2	Properties of hooked-end steel fibre	70
Table 3.3	Measured dimension of deformed steel rebar	71
Table 3.4	Mechanical properties of deformed steel rebars	74
Table 3.5	NVC, HSSCC and SFHSSCC materials compositions (1 m^3 volume)	75
Table 3.6	HSSCC and SFHSSCC mixtures mixing process	77
Table 3.7	Nos. of specimens for mechanical properties testing	79
Table 3.8	Concrete batches for pullout specimens and nos. of samplings for mechanical properties testing	81
Table 3.9	Pullout specimens prepared for loading rate testing	82
Table 3.10	Pullout specimens of plain HSSCC	83
Table 3.11	Pullout specimens of SFHSSCC	84
Table 3.12	Pullout specimens of NVC	85
Table 4.1	Test results of fresh concrete of NVC, HSSCC and SFHSSCC	108
Table 4.2	Slump flow test results	109
Table 4.3	Mechanical properties test results	115

UMS
UNIVERSITI MALAYSIA SABAH

Table 5. 1 Pullout test results of specimens with 12 mm diameter deformed steel rebars 125
Table 5. 2 Pullout test results of specimens with 16 mm diameter deformed steel rebars 126
Table 5. 3 Pullout test results of specimens with 20 mm diameter deformed steel rebars 127
Table 5. 4 Percentage difference of the normalised bond strength of the top and bottom rebars in HSSCC, SFHSSCC and NVC 174
Table 5. 5 Pullout results for Normal Vibrated Concrete (NVC) 179
Table 6. 1 Confinement energy of HSSCC and SFHSSCC pullout specimens with 35 mm thickness of concrete cover 198
Table 6. 2 Pullout specimens installed with concrete and steel strain gauges 200
Table 6. 3 Proposed bond strength equations by various researchers 210
Table 6. 4 Experimental data of pullout failure specimens used as input data for all equations in Table 6. 3 212
Table 6. 5 Comparison of predicted bond strength versus experimental bond strength by Orangun *et al.*, Kemp, Chapman and Shah, Harajli, Bae, Hadi, Desnerck *et al.*, Aslani and Nejadi, Pop and Chu and Kwan 213
Table 6. 6 Predicted bond strength versus experimental bond strength using Equation 6. 11 221
Table 6. 7 Experimental data of premature splitting and rebar yielding failure specimens used as input data to modify Equation 6. 11 225
Table 6. 8 Predicted bond strength versus experimental bond strength using Equation 6. 12 226
Table 6. 9 Recommended bond strength equations by the author 229

UMS
UNIVERSITI MALAYSIA SABAH

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
Figure 1.1	Super high-rise building, Burj Khalifa, Dubai constructed using SCC material (Baker *et al.*, 2009)	2
Figure 2.1	Construction of bridges using SCC (a) Towers of the Shin-Kiba Ohashi bridge, (b) Anchorage 4A of Akashi-Kaikyo bridge (Okamura and Ouchi, 2003)	12
Figure 2.2	Construction of high-rise buildings using SCC (a) Burj Khalifa under construction (Baker *et al.*, 2009) (b) World Financial Centre Shanghai, China under construction (Katz and Robertson, 2008)	13
Figure 2.3	Comparison of mix proportions between SCC and conventional concrete (Okamura and Ouchi, 2003)	15
Figure 2.4	Types of steel fibres (a,b,c) (Manufacturer Remix Steel Fibres Co., Ltd., Hebei Province, China), (d) (Abdallah *et al.*, 2018).	20
Figure 2.5	Reinforcing rebar and concrete interaction (Reinhardt and Balázs, 1995)	26
Figure 2.6	Bond stresses and radial stresses exerted at the concrete and rebar interface (Garcia-Taengua *et al.*, 2016)	27
Figure 2.7	Modes of bond failure: (a) pullout, (b) splitting induced pullout (c) splitting failure (FIB, 2000)	27
Figure 2.8	Local bond stress versus slip for plain rebar and deformed steel rebars (FIB, 2000)	28
Figure 2.9	Failure in concrete specimens with and without confinement (Yeih *et al.*, 1997)	34
Figure 2.10	Pullout test according to RILEM RC6 (a) Testing setup (b) Specimen view from bottom (c) Details of pullout specimen (Carvalho *et al.*, 2017)	40
Figure 2.11	Pullout specimens: Unconfined and confined with fibres (Hameed *et al.*, 2013)	44
Figure 2.12	Mechanism of fibres crack arrest (Harajli *et al.*, 1995)	44
Figure 3.1	Overview of research methodology framework	62
Figure 3.2	Detailed methodology for Phase 1	63
Figure 3.3	Detailed methodology for Phase 2	64

UMS
UNIVERSITI MALAYSIA SABAH

Table 5.1 Pullout test results of specimens with 12 mm diameter deformed steel rebars 125

Table 5.2 Pullout test results of specimens with 16 mm diameter deformed steel rebars 126

Table 5.3 Pullout test results of specimens with 20 mm diameter deformed steel rebars 127

Table 5.4 Percentage difference of the normalised bond strength of the top and bottom rebars in HSSCC, SFHSSCC and NVC 174

Table 5.5 Pullout results for Normal Vibrated Concrete (NVC) 179

Table 6.1 Confinement energy of HSSCC and SFHSSCC pullout specimens with 35 mm thickness of concrete cover 198

Table 6.2 Pullout specimens installed with concrete and steel strain gauges 200

Table 6.3 Proposed bond strength equations by various researchers 210

Table 6.4 Experimental data of pullout failure specimens used as input data for all equations in Table 6.3 212

Table 6.5 Comparison of predicted bond strength versus experimental bond strength by Orangun *et al.*, Kemp, Chapman and Shah, Harajli, Bae, Hadi, Desnerck *et al.*, Aslani and Nejadi, Pop and Chu and Kwan 213

Table 6.6 Predicted bond strength versus experimental bond strength using Equation 6.11 221

Table 6.7 Experimental data of premature splitting and rebar yielding failure specimens used as input data to modify Equation 6.11 225

Table 6.8 Predicted bond strength versus experimental bond strength using Equation 6.12 226

Table 6.9 Recommended bond strength equations by the author 229

UMS
UNIVERSITI MALAYSIA SABAH

Figure 3.30 Splitting tensile strength test 96

Figure 3.31 Load vs slip with different loading rate 98

Figure 3.32 Strain gauges location on pullout specimen 100

Figure 3.33 Pullout specimen 101

Figure 3.34 Pullout specimen setup 102

Figure 3.35 Direct pullout testing setup 103

Figure 3.36 Concrete coring on pullout specimens 104

Figure 4.1 True slump of NVC mix 109

Figure 4.2 Slump flow of (a) plain HSSCC, (b) SFHSSCC-0.5% 110

Figure 4.3 Slump flow of (a) SFHSSCC-1.0%, (b) Modified SFHSSCC-1.0% 111

Figure 4.4 V-funnel test result for plain HSSCC 112

Figure 4.5 Accumulated steel fibres at the tapered area of V-funnel 113

Figure 4.6 L-box test result 114

Figure 4.7 Average compressive strength test result of NVC, HSSCC & SFHSSCC 116

Figure 4.8 Failure modes of NVC, HSSCC, SFHSSCC-0.5% and SFHSSCC-1.0% 117

Figure 4.9 Average splitting tensile strength results of NVC, HSSCC & SFHSSCC 118

Figure 4.10 Splitting tensile strength failure modes of NVC, HSSCC, SFHSSCC-0.5% and SFHSSCC-1.0% 120

Figure 5.1 Forces generated at the interface of rebar and concrete 129

Figure 5.2 Splitting Failure 130

Figure 5.3 Pullout Failure 132

Figure 5.4 Load versus slip for HSSCC & SFHSSCC specimens with different rebar sizes and corresponding pullout or splitting bond failures 134

Figure 5.5 Load versus slip for HSSCC & SFHSSCC specimens with combined rebar sizes 137

Figure 5.6 Bond failures of specimens with 12 mm rebars 138

Figure 5.7 Bond failures of specimens with 16 mm rebars 139

Figure 5.8 Bond failures of specimens with 20 mm rebars 141

UMS
UNIVERSITI MALAYSIA SABAH

Figure 3.4 Fly Ash Class F 66

Figure 3.5 (a) Fine aggregate (b) Coarse aggregate 67

Figure 3.6 Sieve analysis results for fine aggregate 68

Figure 3.7 Sika Viscocrete-2044 admixture 69

Figure 3.8 STAHLCON steel fibres HE 0.55/35 70

Figure 3.9 Geometry of deformed steel rebars 71

Figure 3.10 Samples of rebars and tensile strength test 72

Figure 3.11 Stress versus strain curve for T12 deformed steel rebar 72

Figure 3.12 Stress versus strain curve for T16 deformed steel rebar 73

Figure 3.13 Stress versus strain curve for T20 deformed steel rebar 73

Figure 3.14 Rotary drum mixer 78

Figure 3.15 Curing tank 78

Figure 3.16 Concrete cube samplings for compressive strength test 80

Figure 3.17 Concrete cylinder samplings for splitting tensile strength test 80

Figure 3.18 Specimen identification for pullout specimens 82

Figure 3.19 Pullout steel mould and specimen with installed ribbed rebar 86

Figure 3.20 Embedment length of rebar in pullout specimens 87

Figure 3.21 Concrete cover thickness and position of rebar in pullout specimens 88

Figure 3.22 Casting of pullout specimens and samples for mechanical properties testing 88

Figure 3.23 Pullout specimens under curing 89

Figure 3.24 Some of the pullout specimens and cubes for compressive strength tests 89

Figure 3.25 Slump test 91

Figure 3.26 Making of slump flow test 92

Figure 3.27 V-Funnel test 93

Figure 3.28 L-Box test 94

Figure 3.29 Compressive strength test 95

Figure 5.9 Cracks pattern of HSSCC specimen with 20 mm rebar which is influenced by the horizontal ribs of the rebar 142

Figure 5.10 Load versus slip for HSSCC & SFHSSCC specimens with different thickness of concrete cover and corresponding pullout or splitting bond failures 144

Figure 5.11 Load versus slip for HSSCC & SFHSSCC specimens with 35 mm concrete cover 147

Figure 5.12 Bond failures of HSSCC and SFHSSCC specimens with 12 mm rebars and 35 mm concrete cover 148

Figure 5.13 Bond failures of HSSCC and SFHSSCC specimens with 16 mm rebars and 35 mm concrete cover 149

Figure 5.14 Bond failures of HSSCC and SFHSSCC specimens with 20 mm rebars and 35 mm concrete cover 150

Figure 5.15 Cracks patterns of HSSCC and SFHSSCC specimens with 20 mm diameter rebar and 35 mm concrete cover which is influenced by the horizontal rib of the rebar 151

Figure 5.16 Load versus slip of HSSCC & SFHSSCC specimens with 3Ø and 5Ø embedment length and corresponding pullout or splitting bond failures 153

Figure 5.17 Load versus slip for HSSCC & SFHSSCC specimens with different rebar sizes and with embedment length of 5Ø 155

Figure 5.18 Bond failures of HSSCC and SFHSSCC specimens with 12 mm rebars and 3Ø and 5Ø embedment length 156

Figure 5.19 Bond failures of HSSCC and SFHSSCC specimens with 16 mm rebars and 3Ø and 5Ø embedment length 157

Figure 5.20 Bond failures of HSSCC and SFHSSCC specimens with 20 mm rebars and 3Ø and 5Ø embedment length 158

Figure 5.21 Bond stress versus slip of HSSCC and SFHSSCC specimens 161

Figure 5.22 Bond strength versus cover/diameter for all rebar sizes in HSSCC and SFHSSCC 164

Figure 5.23 Bond strength versus concrete compressive strength 165

Figure 5.24 Bond strength versus concrete tensile strength 168

Figure 5.25 Concrete tensile strength versus concrete compressive strength 169

Figure 5.26 Normalised bond strength of HSSCC, SFHSSCC and NVC specimens 171

UMS
UNIVERSITI MALAYSIA SABAH

Figure 5.27 Top and bottom rebars in pullout specimens 173

Figure 5.28 Coring samples of the SFHSSCC, HSSCC and NVC pullout specimens 175

Figure 5.29 Dimensions of the cylindrical and cube pullout specimens 177

Figure 5.30 Comparison between cylinder (Zaini Rijal, 2019) and cube specimens embedded with 16 mm diameter rebar 180

Figure 6.1 Forces transfer mechanism and its effect on surrounding concrete in unreinforced HSSCC 187

Figure 6.2 Steel fibre confinement 188

Figure 6.3 Sewing effect by steel fibres on concrete 189

Figure 6.4 Steel fibres distribution in coring samples 190

Figure 6.5 Stages of pullout behaviour and confinement effects 192

Figure 6.6 Steel rebar-concrete interaction at different stages of pullout testing and confinement effects 193

Figure 6.7 The confinement energy parameters to estimate the confinement energy 197

Figure 6.8 Pullout specimens with top and bottom rebars and installed with concrete and steel strain gauges 201

Figure 6.9 Stress – strain curves of HSSCC, SFHSSCC and NVC specimens embedded with 12 mm rebar 203

Figure 6.10 Stress – strain curves of HSSCC, SFHSSCC and NVC specimens embedded with 16 mm rebar 204

Figure 6.11 Stress – strain curves of HSSCC, SFHSSCC and NVC specimens embedded with 20 mm rebar 206

Figure 6.12 Stress – strain curves of HSSCC and SFHSSCC specimens embedded with 12, 16 and 20 mm bottom rebars 208

Figure 6.13 Comparison of predicted bond strength versus experimental bond strength from Orangun *et al.* (1997), Kemp (1986), Chapman and Shah (1987), Harajli (1994), Bae (2006) and Hadi (2008) models 216

Figure 6.14 Comparison of predicted bond strength versus experimental bond strength from Desnerck *et al.* (2010b), Aslani and Nejadi (2012a), Pop (2014) and Chu and Kwan (2019) models 217

Figure 6.15 Predicted bond strength versus experimental bond strength using proposed bond strength equation (Equation 6.11) 222

UMS
UNIVERSITI MALAYSIA SABAH

Figure 5.9 Cracks pattern of HSSCC specimen with 20 mm rebar which is influenced by the horizontal ribs of the rebar

Figure 5.10 Load versus slip for HSSCC & SFHSSCC specimens with different thickness of concrete cover and corresponding pullout or splitting bond failures

Figure 5.11 Load versus slip for HSSCC & SFHSSCC specimens with 35 mm concrete cover

Figure 5.12 Bond failures of HSSCC and SFHSSCC specimens with 12 mm rebars and 35 mm concrete cover

Figure 5.13 Bond failures of HSSCC and SFHSSCC specimens with 16 mm rebars and 35 mm concrete cover

Figure 5.14 Bond failures of HSSCC and SFHSSCC specimens with 20 mm rebars and 35 mm concrete cover

Figure 5.15 Cracks patterns of HSSCC and SFHSSCC specimens with 20 mm diameter rebar and 35 mm concrete cover which is influenced by the horizontal rib of the rebar

Figure 5.16 Load versus slip of HSSCC & SFHSSCC specimens with 3Ø and 5Ø embedment length and corresponding pullout or splitting bond failures

Figure 5.17 Load versus slip for HSSCC & SFHSSCC specimens with different rebar sizes and with embedment length of 5Ø

Figure 5.18 Bond failures of HSSCC and SFHSSCC specimens with 12 mm rebars and 3Ø and 5Ø embedment length

Figure 5.19 Bond failures of HSSCC and SFHSSCC specimens with 16 mm rebars and 3Ø and 5Ø embedment length

Figure 5.20 Bond failures of HSSCC and SFHSSCC specimens with 20 mm rebars and 3Ø and 5Ø embedment length

Figure 5.21 Bond stress versus slip of HSSCC and SFHSSCC specimens

Figure 5.22 Bond strength versus cover/diameter for all rebar sizes in HSSCC and SFHSSCC

Figure 5.23 Bond strength versus concrete compressive strength

Figure 5.24 Bond strength versus concrete tensile strength

Figure 5.25 Concrete tensile strength versus concrete compressive strength

Figure 5.26 Normalised bond strength of HSSCC, SFHSSCC and NVC specimens

UMS
UNIVERSITI MALAYSIA SABAH

Figure 6.16 Comparison of existing bond strength equations with the proposed bond strength equation (Equation 6.11) 223

Figure 6.17 Experimental peak load of specimens with premature splitting and rebar yielding failure as compared to peak load of specimens with pullout failure 224

Figure 6.18 Predicted bond strength versus experimental bond strength using proposed model (Equation 6.12) 227

UMS
UNIVERSITI MALAYSIA SABAH