

**EFFECT OF CRUMB RUBBER AGGREGATE ON TOUGHNESS
AND IMPACT ENERGY OF STEEL FIBER CONCRETE**

by

AHMED TAREQ NOAMAN

**Thesis submitted in fulfillment of the
requirements for the degree
of Doctor of Philosophy**

May 2017

ACKNOWLEDGEMENT

I would like to express my warmest appreciations to my supervisor, Prof. Dr. Badorul Hisham Abu Bakar for his generous guidance, motivation, advice, and kindness throughout this research. In addition, I would like to extend my appreciation, gratitude and sincere thanks to my co-supervisor Prof. Dr. Hazizan Md. Akil, for his continuous support, advice and encouragement.

A special thank dedicated to the lab technicians of Schools of Civil, and Materials and Minerals Resources Engineering for their help. Furthermore, I would like to thank Assc. Prof. Dr. Norazura Muhamad Bunnori, School of Civil Engineering, on assisting in supplying clip displacement transducers.

Special thanks to the school of Civil Engineering for supporting this study. Thank you very much goes to Universiti Sains Malaysia (Cluster for Polymer Composite:449 1001/PKT/8640013) for financial support.

Furthermore, I would like to express my gratitude to Ministry of Higher Education and Scientific Research-Iraq, for giving me the opportunity to study in Malaysia.

I would like to express my deepest gratitude to Dr. Tan Chin Khoon, orthopedic surgeon from Hospital Lam Wah Ee-Penang for the excellent care that he have provided for my injury.

Finally, my sincere appreciation also extends to all my friends and people who supported me during my study especially my wife.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENT	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	x
LIST OF FIGURES	xiii
LIST OF ABBREVIATIONS	xxii
LIST OF SYMBOLS	xxiv
ABSTRAK	xxvi
ABSTRACT	xxviii
CHAPTER ONE: INTRODUCTION	
1.1 Background	1
1.2 Production of rubberized concrete	4
1.3 Impact resistance and energy absorption capacity of rubberized concrete	5
1.4 Synergy between steel fiber and rubberized concrete	8
1.5 Problem statement	12
1.6 Research Objectives	14
1.7 Scope of the work	15
1.8 Structure of thesis	16
CHAPTER TWO: LITERATURE REVIEW	
2.1 Introduction	18

2.3	Mixing and preparation of rubberized concrete	19
2.4	Plain rubberized concrete	21
2.4.1	Effect of crumb rubber inclusion on workability of plain concrete	21
2.4.2	Hardened density	23
2.4.3	Compressive, tensile, and flexural strengths	24
2.4.4	Energy absorption, toughness, and ductility of plain rubberized concrete	28
2.4.5	Dynamic modulus of elasticity	32
2.4.6	Damping ratio	33
2.5	Properties of steel fiber reinforced rubberized concrete (SFRRRC)	33
2.5.1	Workability	36
2.5.2	Compressive, tensile and flexural properties	37
2.5.3	Toughness, energy absorption capacity and ductility of SFRRRC	41
2.6	Behavior of concrete under impact loads	43
2.6.1	Plain concrete	43
2.6.2	Steel fiber reinforced concrete	45
2.6.2 (a)	Repeated-drop weight impact	45
2.6.2 (b)	Flexural bending low velocity impact	46
2.6.2 (c)	Effects of high velocity impact	48
2.6.2 (d)	Impact caused by blast loads	49
2.6.3	Rubberized concrete	50
2.6.3 (a)	Repeated drop weight impact	50
2.6.3 (b)	Flexural bending impact	55

2.6.3 (c)	Behavior at high loading rate	56
2.6.3 (d)	Behavior under crash and blast effects	58
2.7	The layered distribution of rubberized concrete	61
2.8	Mathematical modelling of impact behavior of rubberized concrete using Finite element method	64
2.9	Summary	71

CHAPTER THREE: RESEARCH METHODOLOGY

3.1	Introduction	75
3.2	Materials	75
3.2.1	Cement	75
3.2.2	Fine and coarse aggregate	76
3.2.2 (a)	Coarse aggregate	76
3.2.2 (b)	Fine Aggregate	77
3.2.2 (c)	Crumb rubber aggregate	78
3.2.3	Hooked-ended steel fiber	79
3.2.4	Chemical admixture	79
3.3	Mix design	80
3.3.1	Plain Portland cement concrete mixture (PC)	80
3.3.2	Steel fiber concrete mixture (SFC)	81
3.3.3	Plain rubberized concrete mixtures (PRC)	81
3.3.4	Steel fiber reinforced rubberized concrete mixtures (SFRRC)	83
3.4	Mixing, Casting and curing procedures	84

3.5	Testing (Methods and Procedures)	91
3.5.1	Workability (Slump test)	91
3.5.2	Bulk density	91
3.5.3	Compressive strength	90
	3.5.3 (a) Cubes	92
	3.5.3 (b) Cylinders	92
3.5.4	Splitting-tensile test	94
3.5.5	Flexural strength test	95
	3.2.2 (a) Four point bending test	96
	3.2.2 (b) Three-point bending test	96
3.5.6	Fracture toughness parameters	98
3.5.7	Flexural test of slabs	102
3.5.8	Ultra-pulse velocity and dynamic modulus of elasticity	104
3.5.9	Preliminary low velocity impact strength evaluation	105
3.5.10	Flexural bending under impact loads	107
3.5.11	Low velocity impact test of concrete slabs	112
3.6	Summary	115

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1	Introduction	116
4.2	Slump	116
4.3	Density	118
4.4	Compressive strength of concrete	120

4.4.1	Cubes	119
4.4.2	Cylinders	124
4.5	Stress-strain curves	130
4.6	Static modulus of elasticity	133
4.7	Compression toughness	137
4.8	Splitting tensile strength	142
4.9	Flexural behavior of beams	145
4.9.1	Four point bending test	146
4.9.1 (a)	Load-deflection curves	146
4.9.1 (b)	Flexural strength	149
4.9.1 (c)	Strain capacity	152
4.9.1 (d)	Flexural stiffness	157
4.9.2	Three-point bending static test	158
4.10	Fracture toughness parameters	159
4.10.1	Fracture energy	159
4.10.2	Fracture toughness	165
4.10.3	Characteristic length	168
4.11	Flexural behavior of concrete slabs	171
4.12	Ultrasonic pulse velocity	184
4.13	Dynamic modulus of elasticity	190
4.14	Preliminary repeated drop weight impact test	193
4.15	Flexural low velocity instrumented impact test	202
4.15.1	Tup load	203

4.15.2	Impulsive impact load	206
4.15.3	Acceleration and deflection	208
4.15.4	Impact bending load	212
4.15.5	Flexural impact energy	221
4.15.6	Layered plain rubberized (LPRC) and layered steel fiber reinforced rubberized (LSFRRC) concrete beam	225
4.15.7	Comparison between layered and non-layered beams results obtained during static and impact bending tests	229
4.16	Low velocity impact test of concrete slabs	234
4.16.1	Impact resistance and energy absorption capacity	234
4.16.2	Cracks measurement and observations	241
4.16.3	Failure patterns	243
4.17	Summary	249

CHAPTER FIVE: FINITE ELEMENT SIMULATION

5.1	Introduction	250
5.2	Finite element simulation using LUSAS	251
5.2.1	Element type	251
5.2.2	Material properties	253
5.2.3	Specimen geometry and meshing	259
5.2.4	Loading and boundary conditions	258
5.3	Verification of the FE modelling using LUSAS	263
5.3.1	Plain concrete	263

5.3.1	Plain rubberized concrete	270
5.3.1	Steel fiber concrete	273
5.3.1	Steel fiber reinforced rubberized concrete	278
5.3.1	Layered plain rubberized concrete and layered steel fiber-reinforced rubberized concrete	287
5.4	Summary	296

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

6.1	General	297
6.2	Conclusions	297
6.3	Recommendations for future research	302

REFERENCES	304
-------------------	------------

LIST OF PUBLICATIONS

LIST OF TABLES

		Page
Table 2.1	Mix proportions and slump of fresh rubberized concrete (Batayneh et al., 2008)	21
Table 2.2	Effect of rubber content (by replacement of aggregate volume) and size on the mechanical properties of plain concrete (results at 28 days)	27
Table 2.3	Comparison between static and impact test results of rubberized and hybrid rubberized concrete beams (Al-Tayeb et al., 2013)	62
Table 3.1	Chemical composition of Tasek cement (Ibrahim et al., 2014)	76
Table 3.2	Concrete mix design for plain concrete mixture (PC)	80
Table 3.3	Concrete mix design for steel fiber concrete (SFC)	81
Table 3.4	Concrete mix design for plain rubberized concrete (PRC)	82
Table 3.5	Concrete mix design for steel fiber reinforced rubberized concrete (SFRRC)	83
Table 3.6	Total number of specimens and volumes for mixtures	89
Table 3.7	Accelerometer specifications	109
Table 4.1	Density of PRC and SFRRC at 28 days age	120
Table 4.2	Compressive strength results of concrete cubes at different ages	1

Table 4.3	Compressive strength results of concrete cylinders at 28 day age	125
Table 4.4	Results from compression toughness calculations	138
Table 4.5	The maximum load, strength, deflection and flexural stiffness of PRC	147
Table 4.6	The maximum load, strength, deflection and flexural stiffness of SFRRC	148
Table 4.7	Parameters obtained from load-deflection and load CMOD curves	159
Table 4.8	Fracture toughness parameters	160
Table 4.9	Results obtained from flexure test of concrete slabs	172
Table 4.10	Values of UPV of concrete mixes (m/sec)	187
Table 4.11	Classification of concrete based on UPV (Solis-Carcaño and Moreno, 2008)	187
Table 4.12	Preliminary impact test results for PRC and SFRRC	194
Table 4.13	Impulsive loads (N.sec) measured from impact tests	207
Table 4.14	Impulsive loads (N.sec) measured from impact tests of layered beams	228
Table 4.15	Experimental static and impact bending results for PRC and LPRC specimens	229
Table 4.16	Experimental static and impact bending results for SFRRC and LFRRC specimens	230
Table 4.17	Results of impact test of concrete slabs	235

Table 4.18	First crack width	242
Table 5.1	Mechanical parameters adopted in this study	256
Table 5.2	Predicted and experimental values of deflection during impact loading of PRC specimen	274

LIST OF FIGURES

		Page
Figure 1.1	Waste tire landfills around the world (Rashad, 2015)	2
Figure 1.2	Some of waste tire recycling applications in civil engineering works	3
Figure 1.3	Main types of recycled rubber aggregate from waste tires	4
Figure 1.4	Damage during impact (Kennedy, 1976)	5
Figure 1.5	Bond defect (B.D.) between rubber aggregate (R.A.) and cement paste (Turatsinze et al., 2006)	8
Figure 1.6	Simulation of concrete (a) with voids; (b) tensile cracks generated perpendicularly to load direction; and (c) fiber-bridging action against tensile cracks (Carroll and Helminger, 2016)	11
Figure 2.1	Relationship between SSA and slump (Najim and Hall, 2013, Najim, 2012)	22
Figure 2.2	Effect of cylinder compressive strength on modulus of elasticity (Zheng et al., 2008a)	25
Figure 2.3	Results of fracture energy for notched specimens (Grinys et al., 2013)	29
Figure 2.4	Fracture of beam containing rubber shreds after failure	31
Figure 2.5	Waste tire rubber beads subjected to tensile strength, (a) steel beads (b) splitting tensile load-deflection curves (Papakonstantinou and Tobolski, 2006).	35

Figure 2.6	Compressive strength with respect to rubber aggregate content and influence of fiber reinforcement (Turatsinze et al., 2005)	38
Figure 2.7	Effect of rubber content on elastic modulus (Carroll and Helminger, 2016).	39
Figure 2.8	Tensile stress-displacement relationship (Nguyen et al., 2010)	40
Figure 2.9	Use of the concrete ballastless track railway system (Bjegovic et al., 2013)	41
Figure 2.10	Damage regions in concrete subjected to an impact loading (Zhang et al., 2007) cited from (Erdem et al., 2011)	44
Figure 2.11	Impact strength at: (a) first crack, (b) failure strength (Mahmoud and Afroughsabet, 2010)	46
Figure 2.12	Impact test and specimen setup (Wang et al., 1996)	47
Figure 2.13	Impact bending load vs. deflection (Wang et al., 1996)	48
Figure 2.14	Experimental and numerical values of force-deflection	50
Figure 2.15	Impact resistance at crack propagation (Aliabdo et al., 2015)	51
Figure 2.16	Toughness of SFRC under different rubber sizes and contents (Liu et al., 2012)	58
Figure 2.17	The energy absorbed vs. rubber content during the impact test (Atahan and Sevim, 2008)	60
Figure 2.18	Concrete beams cross section subjected to base isolation test (Li et al., 1998)	61

Figure 2.19	Effect of bottom steel fiber reinforced concrete layer depth on ultimate moment of partially reinforced beams (Ravindrarajah and Tam, 1984)	63
Figure 2.20	A two-phase composite model (Li et al., 2004a)	66
Figure 2.21	FE numerical model of concrete girder (Kishi and Bhatti, 2010)	68
Figure 2.22	Experimental and FE predicted impact loads vs. displacement of different concrete mixtures: (a) plain, (b) 5% crumb rubber, (c) 20% crumb rubber (Al-Tayeb et al., 2013)	70
Figure 3.1	Sieve analysis of fine aggregate (sand)	77
Figure 3.2	Crumb rubber used in this study	78
Figure 3.3	Hooked-end steel fibers	79
Figure 3.4	Mixing of SFRRRC, (a) Crumb rubber blended with aggregate, (b) spreading of steel fiber into the mix, and (c) appearance of fresh steel fiber-reinforced concrete	85
Figure 3.5	Pouring of steel fiber reinforced rubberized concrete into the molds	86
Figure 3.6	Concrete specimens after vibration and compaction	85
Figure 3.7	Layered and non-layered specimens 400 ×100 ×50 mm casting details and layers arrangement	88
Figure 3.8	Methodology and tests adopted in the experimental work	90
Figure 3.9	Evaluation of toughness index (Khaloo, 2008)	94
Figure 3.10	Test set-up of the four-point bending test	95

Figure 3.11	Test set-up of the three-point bending test	97
Figure 3.12	Fracture toughness test: (a) experimental test set-up (b) data logger and laptop and (c) geometry of the notched beams	100
Figure 3.13	Flexural test of slabs: (a) experimental test set-up (b) schematic of slab and supports	103
Figure 3.14	Preliminary impact test rig with specimen	106
Figure 3.15	The flexural impact test rig	108
Figure 3.16	Typical load-time curve during impact (Barr and Baghli, 1988)	110
Figure 3.16	Curing of concrete slabs	112
Figure 3.17	Impact test rig of concrete slabs	113
Figure 4.1	Effect of crumb rubber inclusion in plain concrete on slump	117
Figure 4.2	Effect of crumb rubber inclusion in steel fiber concrete on slump	118
Figure 4.3	Effect of crumb rubber inclusion on densites of PRC and SFRRC	119
Figure 4.4	Effect of crumb rubber content on cube compressive strength at 28 days	124
Figure 4.5	The compressive strength of different mixes with respect to time (7, 14, 28, 56, and 90 days)	126
Figure 4.6	Effect of crumb rubber content on cylinder compressive strength at 28 day	126

Figure 4.7	Relationship between compressive strength and density of PRC and SFRRRC mixes	129
Figure 4.8	Post-failure patterns of concrete cylinders	130
Figure 4.9	Stress-strain curve of plain concrete with different ratios of crumb rubber aggregate	129
Figure 4.10	Stress-strain curve of steel fiber concrete with different ratios of crumb rubber aggregate	131
Figure 4.11	Effect of crumb rubber content on static modulus of elasticity of PC and SFC	133
Figure 4.12	Percentage of reduction ratios of static modulus of elasticity of different mixes	134
Figure 4.13	Effect of crumb rubber ratio on the modulus of elasticity (experimental and ACI equation)	136
Figure 4.14	Relationship between compressive strength and modulus of elasticity of concrete	137
Figure 4.15	Effect of crumb rubber content on compression toughness	139
Figure 4.16	Effect of crumb rubber content on toughness index	141
Figure 4.17	Effect of crumb rubber content on specific toughness ratio	142
Figure 4.18	Effect of crumb rubber content on splitting tensile strength	143
Figure 4.19	Correlation between compressive and splitting tensile strength of PRC and SFRRRC mixes	144
Figure 4.20	Load-deflection curve of PRC mixes beams under four-point	146

Figure 4.21	Load-deflection curve of SFRRRC mixes beams under four- point bending load	147
Figure 4.22	Effect of crumb rubber content on flexural strength	150
Figure 4.23	Correlation between compressive and flexural strengths of PRC and SFRRRC	151
Figure 4.24	Strain capacity of different mixes	152
Figure 4.25	Simulation of the effect of steel fiber and crumb rubber on crack bridging in cement paste	155
Figure 4.26	Microstructure of rubberized concrete (a) steel fiber within the cement matrix; (b) rubber to concrete interface	156
Figure 4.27	Effect of crumb rubber aggregate content on stiffness	157
Figure 4.28	Load-midspan deflection curves of notched specimens of (a) PRC, and (b) SFRRRC	161
Figure 4.29	Load vs. CMOD of: (a) PRC, and (b) SFRRRC	162
Figure 4.30	Fracture energy versus rubber content by sand aggregate volume fractions	163
Figure 4.31	Relationship between K_{IC} and compressive strength of cubes at 28 days	166
Figure 4.32	Relationship between J_{IC} and rubber content	167
Figure 4.33	The effect of crumb rubber content on characteristic length	169
Figure 4.34	Load-deflection curves of concrete slabs	174

Figure 4.35	The effect of crumb rubber content on toughness of (a) plain concrete, (b) steel fiber concrete slabs	182
Figure 4.36	Failure of steel fiber reinforced rubberized concrete slabs, (a) cracks after failure, (b) crack pattern at the back of slab, and (c) observed slab integrity after failure.	184
Figure 4.37	Effect of crumb rubber aggregate content on UPV	186
Figure 4.38	Zones of rubberized concrete based on UPV (Marie, 2016)	188
Figure 4.39	Relationship between UPV and density	189
Figure 4.40	Relationship between UPV and compressive strength	190
Figure 4.41	Effect of crumb rubber content on dynamic modulus of elasticity of plain and steel fiber concrete	191
Figure 4.42	Relationship between ED and compressive strength of cubes at 28 days	193
Figure 4.43	Effect of crumb rubber on first crack impact resistance	198
Figure 4.44	Effect of crumb rubber on ultimate failure impact resistance	198
Figure 4.45	First crack flexural impact energy against volume fraction of crumb rubber	201
Figure 4.46	Ultimate failure flexural impact energy versus volume fraction of crumb rubber	201
Figure 4.47	Tup load history of (a) PRC, and (b) SFRRC	204
Figure 4.48	Impulsive load vs. crumb rubber content	208
Figure 4.49	The acceleration vs. time of PRC and SFRRC	209

Figure 4.50	Deflection history of PRC and SFRRC	211
Figure 4.51	History of tup, inertial and impact bending loads of different beams	213
Figure 4.52	Calculated impact-bending load vs. deflection	222
Figure 4.53	Flexural impact energy of PRC and SFRRC	223
Figure 4.54	Impact tup load history of (a) LPRC, and (b) LSFRRRC	226
Figure 4.55	Impulsive load against crumb rubber content for layered beams	228
Figure 4.56	Impact resistance of concrete slabs	232
Figure 4.57	Distribution of steel fiber and rubber aggregate in the cement matrix	238
Figure 4.58	Bridging of concrete provided by steel fiber	239
Figure 4.59	Comparison of energy absorption capacities of slabs	241
Figure 4.60	Failure patterns of concrete specimens after conducting impact test	245
Figure 5.1	The hexahedron 8 element node and natural coordinates	251
Figure 5.2	Constitutive law for Concrete 94 model (Bahrami et al., 2011)	254
Figure 5.3	Geometry of the different models used in this study and their materials representation	260
Figure 5.4	Loading and support condition (side view)	264
Figure 5.5	Load deflection curves for plain concrete specimen	266

Figure 5.6	Deflection vs. time of plain concrete	266
Figure 5.7	Distribution of stress contours at different time intervals of PC	268
Figure 5.8	Load deflection curves for plain rubberized concrete specimen at different crumb rubber ratios	270
Figure 5.9	Deflection history of PRC25	275
Figure 5.10	Deflection history of different plain rubberized concrete mixes	276
Figure 5.11	Distribution of stresses contours at different time intervals of PRC15	277
Figure 5.12	Load-deflection trend of SFC	278
Figure 5.13	Deflection against time of SFC	279
Figure 5.14	Stress distribution at different time intervals of SFC	280
Figure 5.15	Load deflection curves for steel fiber reinforced rubberized concrete specimen with different crumb rubber ratios	282
Figure 5.16	Deflection history of SFRRC5	285
Figure 5.17	Deflection history of different steel fiber reinforced rubberized mixes	286
Figure 5.18	Stress contours at 0.8 ms of SFRRC5	287
Figure 5.19	Load deflection curves of layered plain rubberized concrete specimen with different crumb rubber ratios	288
Figure 5.20	Load deflection curves of layered steel fiber rubberized concrete specimens with different crumb rubber ratios	292

LIST OF ABBREVIATIONS

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
BI	Brittleness index
BS	British Standards
C	Cement
C agg.	Coarse aggregate
CMOD	Crack mouth opening displacement
CR	Crumb rubber
CRED	Completely random experimental design
EU	European Union
FEM	Finite element method
FRC	Fiber reinforced concrete
GHGs	Greenhouse gases
HQRR	High quality recycled rubber
I	Industrial steel fiber
ITZ	Interfacial transition zone
LUSAS	London University Stress Analysis System
MS	Malaysian Standards
OPC	Ordinary Portland cement
PC	Plain concrete
PRC	Plain rubberized concrete
R	Recycled steel fiber
RILEM	Reunion Internationale des Laboratoires et Experts des Materiaux, Systemes de Construction et Ouvrages
RHFRC	Rubberized hybrid fiber reinforced concrete
S	Sand

SEM	Scanning electron microscope
SF	Steel fiber
SFC	Steel fiber concrete
SFRRC	Steel fiber-reinforced rubberized concrete
SHPB	Split-Hopkinson pressure bar
SP	Superplasticizer
STC	Shredded tire chips
UPV	Ultrasonic-pulse velocity
w/c	Water to cement ratio

LIST OF SYMBOLS

A	Cross sectional are of concrete section
a	Notch depth
b	Width of beam
β_r	Uniaxial principal stress ratio
D	Cylinder diameter
d	Depth of beam
E	Modulus of elasticity of concrete
E_d	Dynamic modulus of elasticity of concrete
ε	Strain of concrete
ε_o	Strain at effective end of the tensile softening
ε_c	Strain of concrete at ultimate compressive strength
f_{cu}	Uniaxial compressive strength
f_{tu}	Maximum tensile strength
g	Gravitational acceleration
G_f	Fracture energy
G_{IC}	The critical energy release rate
H	Depth of the beam
h	Falling height
J_{IC}	The critical J-integral
K	Flexural stiffness
L	Sample length
l_{ch}	Characteristic length
m	Mass
P_b	Impact bending load
P_c	Compression load
P_f	Flexural load