

PERFORMANCE OF UNDERSIDE SHAPED
CONCRETE BLOCKS FOR PAVEMENT

AZMAN BIN MOHAMED

A thesis submitted in fulfilment
Of the requirements for the award of the degree of
Doctor of Philosophy (Civil Engineering)

Faculty of Civil Engineering
University Teknologi Malaysia

MAY 2014

*Dedicated to Allah S.W.T,
my beloved wife Nur Hafizah Binti Abd Khalid
and my gorgeous kids,
Puteri Nurina Akhtar, Putera Naqib Akhtar and Ariff Akhtar.
Thanks for your valuable sacrifice and love.*

*To my beloved parents and in laws,
Mohamed Bin Jaffar – Jamilah Bt Sulaiman and
Abdul Khalid M.Latiff – Rukiah Abdul Rahman.
Thanks for your support and always being there for me in happiness and sadness.*

~~~~~ Love you all ~~~~~

ACKNOWLEDGEMENT

I would like to thank Allah S.W.T for blessing me with excellent health and ability during the process of completing my thesis.

Special thanks to my supervisor Professor Ir. Dr. Hasanan Bin Md Nor and co-supervisor Professor Dr. Mohd Rosli Bin Hainin who have given me the opportunity to learn a great deal knowledge, and guiding me towards fulfilling this achievement.

My gratitude is also extended to the Highway and Transportation Laboratory, Geotechnic Laboratory and Structures and Materials Laboratory staff. Thank you for the support and friendship showered upon me throughout the experimental periods.

I would like to thank the Ministry of Science, Technology and Innovation (MOSTI), University Teknologi Malaysia (UTM) as my Research University, and the Research Management Centre (RMC) for the financial and management support provided under VOT ; FRGS - 78556, RUG – 00H93 and IRGS-78928.

Finally, I would like to thank my lovely wife Nur Hafizah Binti Abdul Khalid for her unconditional support and assistance in various occasions. All your kindness will not be forgotten.

ABSTRACT

This study presents an innovative concrete block pavement (CBP) of rectangular blocks with grooves and web on the underside of the underside shaped concrete block (USCB). This new concrete block concept intends to address known causes of failure for CBP due to vertical, horizontal and repetitive traffic loading. Interaction between CBP and underlying bedding sand layer may lead to significant pavement deformation due to vertical traffic loading. The USCB provides an additional underside mechanical interlocking, compared with traditional rectangular concrete block. Twelve USCB with different groove depths (15 mm, 25 mm, and 35 mm) and four different bottom shapes (Shell – Rectangular (Shell–R), Trench Groove – Triangular (TG–T), Trench Groove – 2 Rectangular (TG–2R), and Trench Groove – 3 Rectangular (TG–3R)) were prepared. These USCB were mechanically tested to investigate the effects of groove depth, groove volume, and groove shape on their mechanical properties. To investigate their interlocking performance, a series of push-in loading test, pull-out loading test, horizontal loading test, and accelerated trafficking test were conducted using the Highway Accelerated Loading Instrument (HALI). A control pavement and with only stretcher bond laying pattern was built to allow for comparisons. The results indicate that triangular grooves exhibit promising compressive strength while rectangular grooves performed better in flexural, with the increase up to 25 % respectively when compared to control block. The optimum USCB groove depth is found at 15 mm and the Shell USCB has the best mechanical properties and resilience under all conditions due to their unique shape. The function of the grooves and web as spike has enhanced the mechanical properties of USCB and improved the interlocking mechanism between CBP and its underlying bedding sand layer. The study shows that USCB is a highly potential concrete block that could enhance pavement performance.

ABSTRAK

Kajian ini membentangkan suatu penurap inovatif untuk turapan blok konkrit (CBP) dalam bentuk blok konkrit segi empat tepat dengan alur dan web pada bahagian bawah bagi blok konkrit terubahsuai permukaan bawah (USCB). Konsep blok konkrit baru ini dibangunkan untuk menangani kegagalan CBP yang berpunca daripada beban menegak, mendatar, dan beban ulangan lalu lintas. Interaksi antara CBP dengan lapisan pasir pengalas boleh mengubah bentuk turapan dengan ketara disebabkan oleh beban menegak lalu lintas. USCB memberi daya rintangan tambahan terhadap penguncian mekanikal permukaan bawah yang tidak disediakan oleh blok konkrit segiempat tradisional. Dua belas USCB dengan kedalaman alur yang berbeza (15 mm, 25 mm dan 35 mm) dan empat bentuk alur yang berbeza (Cengkerang–Segi Empat Tepat (*Shell–R*), Alur–Segi Tiga (TG–T), Alur–2 Segi Empat Tepat (TG–2R), dan Alur–3 Segi Empat Tepat (TG–3R)) telah disediakan. USCB ini diuji secara mekanikal bagi mengkaji kesan kedalaman alur, isipadu alur, dan bentuk alur kepada sifat mekanikal USCB. Untuk mengkaji prestasi penguncian blok-blok tersebut, satu siri ujian yang terdiri daripada ujian bebanan tekan masuk, ujian bebanan tarik keluar, ujian daya mendatar dan ujian lalu lintas dipercepatkan telah dilakukan dengan menggunakan *Highway Accelerated Loading Instrument* (HALI). Satu turapan kawalan dan dengan corak ikatan usungan dipilih untuk tujuan perbandingan. Hasil kajian menunjukkan bahawa alur segi tiga memberikan kekuatan mampatan yang paling baik manakala alur segi empat tepat berfungsi dengan lebih baik di bawah lenturan, masing-masing dengan peningkatan sehingga 25 % berbanding blok kawalan. Kedalaman alur optimum adalah 15 mm dan USCB *Shell* mempunyai sifat mekanikal yang terbaik serta berdaya tahan di bawah semua keadaan kerana bentuknya yang unik. Fungsi alur dan web sebagai pemakuan telah meningkatkan sifat mekanikal USCB dan memperbaiki sifat penguncian antara CBP dan lapisan pasir pengalas. Kajian ini telah menunjukkan USCB merupakan sejenis blok konkrit yang berpotensi untuk meningkatkan prestasi turapan.

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENT	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vii
	LIST OF TABLES	xiv
	LIST OF FIGURES	xvi
	LIST OF ABBREVIATIONS	xxii
	LIST OF SYMBOLS	xxiv
	LIST OF APPENDICES	xxvii
1	INTRODUCTION	1
	1.1 Introduction	1
	1.2 Background of Study	1
	1.3 Problem Statement	2
	1.4 Aim and Objectives	3
	1.5 Scope of Study	4
	1.6 Limitations of Study	6

1.7	Significance of Study	7
2	LITERATURE REVIEW	8
2.1	Introduction	8
2.2	Pavement Components	8
2.2.1	Subgrade	10
2.2.2	Subbase	10
2.2.3	Base Course	11
2.2.4	Bedding Sand	11
2.2.5	Jointing Sand	13
2.2.6	Edge Restraint	14
2.3	The Advantages of Concrete Block Pavements	15
2.4	Factors Affecting the Structural Performance of CBP	17
2.4.1	Block Strength	17
2.4.2	Block Thickness	19
2.4.3	Block Shape	20
2.4.4	Laying Pattern	26
2.4.5	Compaction	27
2.5	Causes of Pavement Failures	28
2.6	Concrete Block Manufacture	30
2.6.1	Dimension Tolerance	31
2.7	Pavement Construction	33
2.8	Interlocking Mechanism	34
2.8.1	Vertical Interlocking	35
2.8.2	Horizontal Interlocking	36
2.8.3	Rotational Interlocking	37
2.9	Mechanical Properties of Concrete Blocks	38

2.10	Type of Trafficking Test on Concrete Block Pavement	39
2.10.1	Static Loading Tests on Prototype Pavements	40
2.10.1.1	Push-In Loading Test	40
2.10.1.2	Pull-Out Loading Test	43
2.10.1.3	Horizontal Loading Test	46
2.10.2	Accelerated Trafficking Test on Prototype Pavements	47
2.10.2.1	Axle and Wheel Loads	50
2.10.2.2	Contact Tyre Pressure	53
2.10.2.3	Permanent Deformation and Rutting	56
2.11	The Importance of Grooves	57
2.12	Concluding Remarks	60
3	METHODOLOGY	61
3.1	Introduction	61
3.2	Determination of USCB Dimensions	65
3.3	Block Manufacturing Process	71
3.4	Engineering Properties	74
3.4.1	Mechanical Properties	75
3.4.1.1	Concrete Block Compressive Strength	77
3.4.1.2	Concrete Block Flexural Strength	79
3.4.1.3	Density and Absorption Test	82
3.4.2	Physical Appearance	84
3.4.2.1	Block Dimension	84
3.4.2.2	USCB Mode of Failures	85
3.5	Laying Procedure	86
3.6	Interaction Between USCB and Bedding Sand Layer	91

3.6.1	Push-In Loading Test	93
3.6.2	Pull-Out Loading Test	97
3.6.3	Horizontal Loading Test	100
3.7	Trafficking Test Under HALI	103
3.7.1	Wheel Applied Load	107
4	EFFECT OF UNDERSIDE SHAPED CONCRETE BLOCK (USCB) ON ENGINEERING PROPERTIES	109
4.1	Introduction	109
4.2	Materials	110
4.2.1	Bedding Sand and Jointing Sand	110
4.2.2	Fine Aggregate and Coarse Aggregate for Concrete	112
4.2.3	Cement	115
4.2.4	Water	115
4.3	Moisture Content	116
4.3.1	Bedding Sand	116
4.3.2	Jointing Sand	117
4.4	Dimensional Geometrical Shape of Manufactured USCB	117
4.5	Mechanical Properties of USCB	120
4.5.1	Density and Water Absorption for USCB	121
4.5.1.1	Density	121
4.5.1.2	Water Absorption	122
4.5.2	Compressive Strength	124
4.5.2.1	Effect of Groove Depth	126
4.5.2.2	Effect of Groove Volume	128

4.5.2.3	Effect of Groove Shape	131
4.5.2.4	Approach for the Development of Compressive Strength Enhancement Model	133
4.5.3	Flexural Strength	137
4.5.3.1	Effect of Groove Depth	140
4.5.3.2	Effect of Groove Volume	143
4.5.3.3	Effect of Groove Shape	145
4.5.3.4	Approach for the Development of Flexural Strength Enhancement Model	148
4.5.4	Relationship of Flexural Strength and Compressive Strength	152
4.6	Summary	153
5	INTERACTION BEHAVIOUR OF USCB PAVEMENT UNDER VARIOUS LOADINGS	157
5.1	Introduction	157
5.2	Compaction of USCB onto Bedding Sand Layer	158
5.2.1	Settlement and Thickness of Bedding Sand Layer	158
5.2.2	Density of Bedding Sand Layer	163
5.3	Push-in Loading	167
5.3.1	Load-Deflection Behaviour	167
5.3.2	Vertical Interlocking Mechanism and Load Transfer Mechanism	170
5.3.3	Rotational Interlocking Mechanism	173

5.3.4	Effects of Groove Depth, Volume and Groove Shape	174
5.4	Pull-out Loading	180
5.4.1	Load-Displacement Behaviour	181
5.4.2	Vertical Interlocking and Load Transfer	183
5.4.3	Rotational Interlocking	186
5.4.4	Effects of Groove Depth, Volume and Shape	188
5.5	Horizontal Loading	195
5.5.1	Horizontal Resistance Behaviour	196
5.5.2	Effects of Groove Depth, Volume, and Shape on Horizontal Resistance	199
5.6	Summary	207
6	STRUCTURAL PERFORMANCE OF USCB PAVEMENT	209
6.1	Introduction	209
6.2	Compaction of USCB Pavement	210
6.2.1	Density of Bedding Sand Layer	210
6.3	USCB Pavement Permanent Deformation	212
6.3.1	The Effect of USCB to Rut Depth under Wheel Path	213
6.3.2	Longitudinal USCB Pavement Deformation	215
6.3.3	Transverse USCB Pavement Deformation	218
6.4	Two-dimensional and Three-dimensional View of Deformed Pavement	220
6.5	Summary	224

7	CONCLUSIONS AND RECOMMENDATIONS	226
7.1	Conclusions	226
7.2	Recommendations	228
	REFERENCES	230
	Appendices A - L	240 - 284

LIST OF TABLES

TABLE NO.	TITLE	PAGE
1.1	Study limitations	6
2.1	Grading requirements for bedding sand and jointing sand (BS 7533, 2009)	13
2.2	Minimum flexural strength (Meyer, 1980)	19
2.3	Specification for concrete blocks (Shackel, 1990)	32
2.4	Mechanical properties of normal block	38
2.5	Typical maximum single axle loads (Shackel, 1994b)	51
2.6	Standard axle loads (Shackel, 1994b)	51
2.7	Load equivalency exponents (Shackel, 1994b)	52
2.8	Damaging effect of different axle loads (AASHTO road test) (Croney and Croney, 1991).	52
3.1	USCB groove shape dimensions	67
4.1	Sieve analysis of fine aggregate	112
4.2	Fineness modulus for fine aggregate	113
4.3	Sieve analysis of aggregate	114
4.4	Fineness modulus of coarse aggregate	115
4.5	Average of USCB dimensional geometrical shape	118
4.6	Dimensional average tolerance range	119
4.7	USCB dimensions analysis (standard deviation of shape dimension)	119
4.8	USCB dimensions analysis (coefficient of variation of shape dimension)	120
4.9	Density of USCB	122

4.10	Comparison of concrete block density between USCB and previous study	122
4.11	Average of water absorption	124
4.12	Comparison in compressive strength	125
4.13	Compressive strength enhancement model	128
4.14	Enhancement of compressive strength	130
4.15	Dimensional limit	135
4.16	Verification of compressive strength model to compressive strength experimental data	136
4.17	MOR enhancement model	143
4.18	MOR enhancement model	145
4.19	Dimensional limit for USCB	150
4.20	Verification of MOR model to the MOR experimental	151
4.21	Ratio of flexural strength to compressive strength	153
4.22	Summary of USCB features and corresponding mechanical properties	156
5.1	Settlement percentage range of bedding sand layer	161
5.2	Settlement of bedding sand model	163
5.3	Maximum displacement of USCB at tested point	170
5.4	Maximum pull-out loading and pull-out movement of USCB at tested point	182
5.5	The number of blocks moved at maximum horizontal load	200
5.6	The sustained horizontal load comparison at 1.5 mm displacement USCB	205
6.1	Density of bedding sand layer for HALI and small scale steel frame	211
7.1	Proposed guideline and potential application of USCB	229

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	Pavement components	9
2.2	Poly-vinyl chloride (PVC) and steel edge restraints (Dimex Corporation, 2002)	14
2.3	Block shape categories (Shackel, 1990)	21
2.4	Description of paving blocks (Westcon Precast Inc, 1990)	23
2.5	Various block shapes	24
2.6	Laying pattern	27
2.7	Vertical interlocking mechanism (O’Grady, 1983)	35
2.8	Creep and opening joint	36
2.9	Rotational interlocking mechanism (O’Grady, 1983)	37
2.10	Movement of blocks under load (O’Grady, 1983)	37
2.11	Push-in loading test setup (1) A steel frame, (2) A hydraulic jack, (3) A load cell, (4) Displacement transducers, (5) CBP, (6) Bedding sand, (7) Sub-base, (8) Cell pressure gauges, (9) Steel plate of 250 mm in diameter (Marios <i>et al.</i> , 2011).	41
2.12	Applied stress versus plate displacement (Marios <i>et al.</i> , 2011)	41
2.13	Deformation of CBP under loading. (a) Deformed cross section of CBP. (b) Hinges required for collapse mechanism (Marios <i>et al.</i> , 2011)	42
2.14	Principal of the collapse mechanism of 3-pin arch (Marios <i>et al.</i> , 2011)	42
2.15	Layout of push-in loading test (Emery and Lazar, 2003)	43
2.16	Pull-out loading test graph (O’Grady, 1983)	44

2.17	Tongue and groove block (Emery and Lazar, 2003)	44
2.18	Pull-out loading test equipment (Ling, 2008)	45
2.19	Relationship between pull-out loading and displacement (Ling, 2008)	46
2.20	Contact surface between pavement and vehicle tyre.	54
2.21	Structure of pavement under compression and tension	54
2.22	The spreading of load from vehicle tyre to the pavement layer	55
2.23	The distribution of loading to pavement layer	55
2.24	Spreading stress during compaction action (Handy and Spangler, 2004)	58
2.25	Boundary effect of (a) Infill-rough joint and (b) Infill-smooth joint (Mohd For <i>et al.</i> , 2008)	59
2.26	Pile-supported mat	59
3.1	Research programme flowchart	63
3.2	Experimental programme flowchart	65
3.3	Categories of groove shape	67
3.4	Movement of sand to fill in the groove/shell area	68
3.5	Bending stress in flexure	69
3.6	Bending stress in flexure (shell groove)	70
3.7	Manufacturing method for concrete blocks	72
3.8	Engineering properties measurements test flowchart	75
3.9	Position of strain gauge	76
3.10	Compression test for concrete block	78
3.11	Schematic diagram of USCB flexural test with centre-point loading	80
3.12	Flexural test for concrete block	80
3.13	Absorption and density test method	83
3.14	Measuring the USCB dimension	85
3.15	Measurement of cracks	86
3.16	Moisture content test	87
3.17	Measurement of the bedding sand height and blocks displacement	87

3.18	Weighing the bedding sand (left) and measuring the thickness of bedding sand in steel box (centre) and in HALI steel frame (right)	88
3.19	The USCB laying procedure in the steel box and HALI steel frame	89
3.20	Layout of push-in loading test and pull-out loading test	91
3.21	Detailed LVDTs locations for push-in loading test and pull-out loading test	92
3.22	Detailed LVDTs locations for horizontal loading test	92
3.23	Push-in loading test flowchart	95
3.24	Push-in loading test procedure	96
3.25	Pull-out loading test flowchart	98
3.26	Pull-out loading test procedure	99
3.27	Horizontal loading test setup	101
3.28	Horizontal loading test flowchart	101
3.29	Horizontal loading test procedure	102
3.30	Grid points of test setup for HALI	104
3.31	Trafficking test flowchart	105
3.32	Trafficking test procedure using HALI	106
4.1	Sieve analysis of bedding sand	111
4.2	Sieve analysis of jointing sand	111
4.3	Sieve analysis of aggregate	114
4.4	Distribution of moisture content	117
4.5	Water absorption of TG-2R category	123
4.6	The average compressive strength of USCB	126
4.7	Relationship between compressive strength and USCB groove depth	127
4.8	Effect of groove depth to compressive strength enhancement	128
4.9	Relationship between compressive strength and USCB groove volume	129
4.10	Effect of groove volume to compressive strength enhancement	130
4.11	Failure mode of USCB web	132

4.12	Failure mode of USCB	133
4.13	Support applications in flexure action; (a) Standard support for block without groove, (b) Roller support for groove block and (c) Square support for groove block	137
4.14	(a) Standard and (b) Modified flexural test setup	138
4.15	Results of standard and modified flexural tests	138
4.16	The average MOR of USCB	139
4.17	Relationship between MOR and USCB groove depth	141
4.18	Effect of groove depth to MOR enhancement	142
4.19	USCB depth dimension	142
4.20	Relationship between MOR and USCB groove volume	144
4.21	Effect of groove volume to MOR enhancement	145
4.22	USCB failure mode under flexural action	147
4.23	USCB failure position; (a) TG-2R category and (b) TG-T category	147
4.24	Relationship of flexural strength to compressive strength	152
5.1	Settlement and thickness of Shell-R25 pavement after compaction	159
5.2	The thickness of compacted bedding sand after complete compaction	159
5.3	Settlement and thicknesses of compacted bedding sand layer for all USCB pavements	161
5.4	Bedding sand settlement model	162
5.5	Relationship of USCB groove volume and settlement of bedding sand	163
5.6	Density of compacted bedding sand layer	164
5.7	Relationship of density and settlement of bedding sand layer	165
5.8	Relationship of density and USCB groove volume	165
5.9	Relationship of density of bedding sand and groove volume on the settlement of bedding sand layer	166
5.10	Push-in loading	167
5.11	Deflection of Shell-R15 at P1	168
5.12	Average Vertical displacement of USCB	169

5.13	After push-in loading test	169
5.14	Transverse deformation of CB and Shell-R15 at point 1	171
5.15	Movement of USCB under load	172
5.16	Deflection contour of Shell-R15 at P1	172
5.17	Small vertical rotational block occurred at 30 kN loading	173
5.18	The deflection and applied load for USCB Shell type (continue)	175
5.19	Variation in USCB deflection pattern	176
5.20	Compacted bedding sand confined in the groove	177
5.21	Correlation between USCB deflection and density of bedding sand layer	178
5.22	Relationship between deflection and USCB groove depth	179
5.23	Relationship between deflection and USCB groove volume	180
5.24	(a) Pull-out loading test setup arrangement; and (b) Block displacement	181
5.25	Displacement of Shell-R15 at P1	181
5.26	The average of USCB maximum displacement at maximum load	183
5.27	Interlocking phenomenon under pull-out loading	184
5.28	Transverse deformation of control block and Shell-R15 USCB at point 1	185
5.29	Displacement contour of Shell-R15 at P1	186
5.30	Small vertical rotational block at maximum displacement for Shell-R35 USCB	187
5.31	The rotational interlock developed stress concentration	188
5.32	Interlock mechanism of control block and USCB	189
5.33	Relationship between displacement and USCB groove depth	191
5.34	Average maximum pull-out displacement of USCB	192
5.35	Displacement performance of USCB at sustained load of 3 kN	193
5.36	Relationship between displacement and USCB groove volume	195

5.37	(a) Before the testing; and (b) After the testing	196
5.38	Horizontal resistance behaviour under horizontal loading for Shell type USCB	197
5.39	Block movement (a) With stress concentration – (CB); and (b) No stress concentration – (TG-2R15)	198
5.40	The average horizontal displacement and maximum horizontal loading at static friction stage	199
5.41	Effect of block weight on USCB horizontal resistance at maximum static friction stage	201
5.42	Effect of groove volume to USCB horizontal displacement at maximum static friction stage	202
5.43	Sustained horizontal load of USCB at 1.5 mm horizontal displacement	203
5.44	Friction resistance of USCB pavement	206
6.1	Bedding sand layer density for the USCB pavements	211
6.2	Accumulated average rut depth of USCB up to 10,000 load repetitions	214
6.3	Projection values from reference line of average deflection of 5.4 mm under 30 kN push-in loading for all USCB and control block	214
6.4	Accumulated average longitudinal rut depth of USCB pavement	216
6.5	Relationship between (a) rut depth and groove volume; and (b) rut depth and groove depth	217
6.6	Average transverse rut depth after 100 and 10,000 load repetitions	219
6.7	Various gap sizes in the joint between blocks	220
6.8	(a) 2D view and (b) 3D view of 100 load repetitions on the USCB pavement	222
6.9	(a) 2D view and (b) 3D view of 10,000 load repetitions on the USCB pavement	223
6.10	Development of rut after several repeated load for USCB and control block	224

LIST OF ABBREVIATIONS

2D	-	Two-dimensional
3D	-	Three-dimensional
AASHTO	-	American Association of State Highway and Transportation Officials
ASTM	-	American Society for Testing and Materials
BS EN	-	British Standard Institution European
BS	-	British Standard Institution
CB	-	Control block
CBP	-	Concrete block pavement
CBR	-	California Bearing Ratio
CF	-	Correction factor
Ch	-	Channel
CMA	-	Concrete Masonry Association
CMAA	-	Concrete Masonry Association of Australia
COV	-	Coefficient of variation
ESA	-	Equivalent standard axle
HALI	-	Highway Accelerated Loading Instrument
HMA	-	Hot Mix Asphalt
ICPI	-	Interlocking Concrete Institute
LL	-	Liquid limit
LVDT	-	Linear variable differential transducer
MOR	-	Modulus of rupture
MOR _C	-	Modulus of rupture for control block
MOR _G	-	Modulus of rupture for grooved block
MS	-	Malaysia Standard
OPC	-	Ordinary portland cement

P	-	Point
PI	-	Plastic index
PL	-	Plastic limit
PVC	-	Poly-vinyl chloride
R ²	-	Regression
RCPB	-	Rubberized concrete paving block
rpm	-	Rotation per minute
SD	-	Standard deviation
Shell-R	-	Shell-Rectangular groove
TG-2R	-	Trench-2Rectangular groove
TG-3R	-	Trench-3Rectangular groove
TG-T	-	Trench-Triangular groove
USCB	-	Underside shaped concrete block

LIST OF SYMBOLS

μ_G	-	Coefficient of groove block surface friction
$\mu_{G_{\max}}$	-	Coefficient of groove block surface friction at maximum force
μ	-	Coefficient of block surface friction
F_S	-	Friction force
δ_{Disp}	-	Displacement
F	-	Force / damage factor - applicable to axle load
$F_{S_{\max}}$	-	Friction force at maximum
F_N	-	Normal force
n_d	-	Number of internal web
P_S	-	Standard axle load
\bar{y}	-	Central axis of the area
$\mu_{BS_{\max}}$		Coefficient of sided and underside surface control block friction at maximum force
A	-	Mass of oven-dried sample in air/ effective area of concrete block /tyre contact area
a	-	Mass of tin
A_e	-	Groove's effective area
ARD	-	Apparent relative density
b	-	Mass of tin and wet bedding sand
B	-	Mass of surface-dried sample in air after immersion
B, b	-	Width of specimen
B_G	-	Groove width
C	-	Apparent mass in the water

c	-	Mass of tin and dry bedding sand
d	-	Internal web / average depth of specimen / distance between groove
D	-	Diameter
e	-	Edge web
h, h_c	-	Block thickness
h_0	-	Height of loose bedding sand
h_1	-	Height of bedding sand and USCB after laying
h_2	-	Height of bedding sand and USCB after first compaction
h_3	-	Height of bedding sand and USCB after second compaction
h_e	-	Effective thickness
h_G	-	Groove depth
I	-	Moment of inertia,
J	-	Average connection distance
L	-	Span length / length
L_G	-	Groove length
M	-	Bending moment,
$m.g$	-	Force of gravity
MOR	-	Modulus of rupture
n	-	Relative damage exponent
n	-	Notch planck
N	-	Traffic repetitions
NA	-	Neutral axis,
n_b	-	Concrete block unit
n_G	-	Number of groove
\emptyset_{avg}	-	Average of bedding sand density
\emptyset_c	-	Minimum and maximum characterization
ODD	-	Oven-dry density
P	-	Maximum load / axle load / breaking load / load
q	-	Load equivalency exponents
S	-	Equivalent standard axle
S_{ett}	-	Settlement
SSD	-	Saturated surface-dry density

T_{hk}	-	Thickness
v	-	Volume of bedding sand
V_C	-	Control block volume
V_G	-	Groove volume
w	-	Mass of bedding sand
W	-	Load
ρ	-	Density
σ	-	Compressive strength / standard deviation
σ_B	-	Bending stress
σ_{block}	-	Stress on the block
σ_c	-	Compressive strength of control block
σ_f	-	Flexural strength
σ_G	-	Compressive strength of grooved block
σ_{HALI}	-	Stress on highway accelerated loading instrument
σ_{site}	-	Stress by tyre loading
π	-	Pi = 3.145

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Water Absorption of USCB	240
B	Dimensional Geometrical Shape of USCB	242
C	Compressive Strength Result of USCB	244
D	Modulus of Rupture Result, Calculation and Derivation Model of USCB	249
E	Bedding Sand Layer Thickness and Settlement of USCB Pavement	257
F	Density of Bedding Sand Layer of USCB	263
G	Deflection of USCB Pavement Under Push-in Loading	264
H	Example of USCB Pavement Deflection Contour	270
I	Displacement of USCB Pavement Under Pull-out Loading	271
J	Horizontal Resistance of USCB Pavement	278
K	Deformation of USCB Pavement Under HALI	279
L	Publications	284

CHAPTER 1

INTRODUCTION

1.1 Introduction

Concrete block pavement (CBP) is an accepted engineering product used mainly as a paving material in pavement applications. Many previous studies on CBP had attempted to modify the traditional rectangular concrete block, introduce additional side interlocking features, and develop better interlocking shapes. CBP is utilized globally because it is durable, non-skidding and dimensionally accurate; available in many sizes; and has good structure and colour. Additionally, these CBP can be installed by unskilled labourers and can be re-used on the same site or elsewhere.

1.2 Background of Study

In developing countries, utilization of CBP as paving material is widespread. Studies on traditional CBP and side shaped CBP have been widely conducted, but

there are still a number of research on beneath CBP and its characterizations. Such beneath CBP, termed as Underside shaped concrete block (USCB) in this study, can actually become a type of innovative paving material. The development of this USCB corresponds to current research trend in modification of existing conventional and side-shaped concrete block to increase paver interlocking and mechanical properties and improve mechanical-laying ability as studied by Emery and Lazar, (2003).

This study presents an innovative paver system featuring groove locking beneath a rectangular concrete block. The overall product is the aforementioned USCB. This new paver concept is intended to resolve known problems associated with small element paving. This USCB is unique because it provides mechanical interlocking additional to underside interlocking commonly provided by most traditional rectangular pavers except sided pavers. During the USCB development process, various groove depths had been tested to test their effectiveness in enhancing interlocking between pavers and bedding sand with improved mechanical properties. To investigate its interlocking performance, the push-in loading test, pull-out loading test, horizontal loading test and accelerated trafficking test were involved. These types of test substantiate the claim made by similar tests on the conventional rectangular concrete block. The use of stretcher bond pattern without edge restraint in this study has also been recognized as having substantial influence on horizontal movement or creep.

1.3 Problem Statement

The main failure criterion for CBP is its serviceability. Most of the time, failure may result in generalized areas of uneven settlement. Block paving reflects movement in the substructure, thus it's very important that the sub-base layer is adequately compacted and to a uniform level. Inadequate vibration of the blocks into the bedding sand layer during the final construction operations can also lead to

problems of local settlements. Moreover, if the bedding sand layer is not of a consistent loose density before laying the blocks, local settlement or punching may occur. This is mainly due to voids beneath the CBP that arise with trafficking in the bedding sand layer that will cause increased deflection. If there is an absence or deterioration of load transfer devices, deflections at both sides of the joints will also be worsened. To tackle this problem, the USCB is a good choice as it can reduce deflection and develop better interlocking between the CBP and bedding sand layer.

Traffic loading is also another major problem for block pavements in areas of channelized traffic like bus stops, fuel terminals and freight terminals. In these areas, failure of CBP is mostly caused by the vertical and horizontal traffic loading as well as repetitive loading. The high pressure load imposed (vertical loading) on the CBP can cause changes in the position of the concrete blocks and lead to undesired settlement. Horizontal movement is induced by horizontal loading caused by vehicle braking and accelerated action. Repetitive loading can cause some sands to break down into finer particles. Another problem often encountered in CBP applications is the wash-out of fine materials between the blocks by rainwater; loss of materials accelerates the production of ruts under traffic load and creep problems.

1.4 Aim and Objectives

The aim of this study was to investigate the potential of USCB to be used as concrete block pavement. The objectives of this study were as follows:

- i. To characterize the engineering properties of different type of USCB.
- ii. To examine the effects of groove depth, groove volume and groove shape on the interlocking mechanism of USCB under various loadings.

- iii. To evaluate the structural performance including rutting and deformation of USCB under Highway Accelerated Loading Instrument (HALI).

1.5 Scope of Study

The scope of this study was established to achieve the objectives mainly through experimental works. The testing methods and procedures were specified according to those recommended by the American Society for Testing and Materials (ASTM), British Standard Institution (BS) and some were proposed by previous researchers as follows:

- i. Push-in loading test by Marios *et al.*, (2011) and Emery and Lazar (2003).
- ii. Pull-out loading test by O'Grady (1983), Emery and Lazar (2003) and Ling (2008).
- iii. Horizontal loading test by Rachmat (2006).
- iv. Accelerated trafficking test by Shackel (1980b) and Ling (2008).

The scopes of the study were divided into three major parts:

- i. Part 1- Development of USCB to characterize their engineering properties.

In order to establish the required information regarding USCB, the following aspects were considered:

- a. Shape development:
 - Number of grooves,
 - Groove depth: 15 mm, 25 mm, and 35 mm of groove depth,

- Groove category: Shell- Rectangular Grooved, Trench-Triangular Grooved and Trench-Rectangular Grooved, and
 - Groove area or groove volume.
- b. Mechanical properties:
- Block compression behaviour (28-days compressive strength),
 - Block flexural behaviour,
 - Block density, and
 - Water absorption.
- c. Physical properties:
- Block dimension,
 - Cracks assessment, and
 - Mode of failures.
- ii. Part 2- Interaction mechanism between USCB and bedding sand layer.
- To investigate interaction between USCB and bedding sand layer, three types of tests were considered:
- a. Push-in loading test - Local settlement and deformation of USCB pavement,
 - b. Pull-out loading test – Local settlement and deformation of USCB pavement, and
 - c. Horizontal loading test- Horizontal resistance of USCB pavement.
- iii. Part 3 - Application of USCB as a structural system to investigate the structural performance

Investigation of USCB structural performance was based on:

- a. Accelerated trafficking test:
 - Longitudinal and transverse rutting profiles,

- Three and two-dimension surface deformation,
- Rut depth under wheel path, and
- Open joint width.

1.6 Limitations of Study

All experimental works and research programme were conducted in this study according to some limitation parameters as listed in Table 1.1.

Table 1.1 : Study limitations

Parameter	Limitation
Concrete block thickness	80 mm
Blocks gap	2 mm to 4 mm
Laying pattern	Stretcher bond
Jointing sand	Passing 2 mm sieve size (dry)
Bedding sand	Passing 5 mm sieve size
Bedding sand layer thickness	70 mm (loose sand)
Base course	Steel base plate with 3 mm neoprene sheet (stimulate 6 % CBR)

1.7 Significance of Study

The significance findings of this study can benefit researchers as follows:

- i. To enhance the use of CBP as an attractive alternative to shaped pavers or other traditional pavers in their interlocking system or other applications.
- ii. To provide database of USCB for future pavement applications.
- iii. To assist the engineers and fabricators in improving the interlocking system of concrete pavers and to provide an established database for paver design work in the future.
- iv. To develop an innovative USCB product that has better engineering properties and comparable service performance in comparison with existing CBP.

REFERENCES

- Agico Group-Gemco Energy Machinery Co, Ltd. (2014, March 19). Block Making Machine. *Gemco Energy Machinery Co, Ltd.* Retrieved March 19, 2014, from <http://www.bio-diesel.com.cn/brick-block-machine.html>.
- American Society for Testing and Materials. (2006). *Standard Test Method for Density , Absorption , and Voids in Hardened Concrete. ASTM C642-06.* United States.
- American Society for Testing and Materials. (2009). *Standard Specification for Solid Concrete Interlocking Paving Units. ASTM C936/C936M - 09.* United States.
- American Society for Testing and Materials. (2010). *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Center-Point Loading). ASTM C293/C293M – 10.* United States.
- American Society of Testing Materials (2011). *Standard Specification for Solid Concrete Interlocking Paving Units. ASTM C-936.* United States.
- American Society for Testing and Materials. (2012). *Standard Specification for Portland Cement. ASTM C150/C150M - 12.* United States.
- Azman, M. (2004). *Prestasi Sambungan Turapan Penguncian Blok Konkrit Menggunakan Pasir Pengalas Dengan Bahan Tambah Simen.* Master Thesis. Universiti Teknologi Malaysia.
- Beatty, A. N. S. and Raymond, G. P. (1992). Geotechnical Aspects of Interlocking Concrete Block Pavements. *Proceedings of the 45th Canadian Geotechnical Conference.* 26 - 28 October. Toronto, Canada, pp. 41–7.
- Beatty, A. N. S (1992). Bedding Sands For Structural Concrete Block Pavements. *Presented to the Transportation Association of Canada at the 1992 annual Conference.* Quebec.

- Beatty, A. N. S. (1996). Laying Course Materials: Specification and Performance. *5th Int. Conference on Concrete Block Paving*, 23 – 27 June, Purdue Univ., West Lafayette, Ind, 12.
- Benitez, A., Bertone, J., and Civitillo, P. (2009). Implementation of the Flexural Strength Test for Concrete Pavers. *9th. International Conference on Concrete Block Paving*. 18 - 21 October, Buenos Aires, Argentina.
- Bergerhof, W. (1979). International Development in Interlocking Paving-Market Potential and Economics Production Methods. *Proceeding Symposium in Precast Concrete Paving Blocks*. November. Johannesburg.
- Bolduc, Y. and Bolduc, M. (2005). *U.S. Patent No. 6,863,469 B2*. Virginia: United States Patent and Trademark Office.
- British Standard Institution (1992). *Guide for Structural Design of Pavements Constructed With Clay or Concrete Block Pavers. BS 7533*. London.
- British Standard Institution. (1981). *Precast concrete masonry units - Part 1: Specification for Precast Concrete Masonry Units (Vol. 3). BS 6073-1*. London.
- British Standard Institution. (1990). *Soils for Civil Engineering Purposes - Part 7 : Shear Strength Tests (Total Stress). BS 1377-7*. London.
- British Standard Institution. (2001a). *Precast, Unreinforced Concrete Paving Blocks - Requirements and Test Methods. BS 6717*. London.
- British Standard Institution. (2001b). *Guide for the Structural Design of Heavy Duty Pavements Constructed of Clay Pavers or Precast Concrete Paving Blocks. BS 7533-1*. London.
- British Standard Institution. (2003a). *Concrete Paving Blocks - Requirements and Test Methods. BS EN 1338*. London.
- British Standard Institution. (2003b). *Concrete Paving Flags - Requirements and Test Methods. BS EN 1339*. London.
- British Standard Institution. (2008). *Aggregates for Concrete. BS EN 12620*. London.
- British Standard Institution. (2009). *Pavements Constructed With Clay, Natural Stone or Concrete Pavers - Part 3. BS 7533-3*. London.
- British Standard Institution. (2011a). *Specification for Masonry Units — Part 3: Aggregate Concrete Masonry Units (Dense and Light-weight Aggregates). BS EN 771-3*. London.

- British Standard Institution. (2011b). *Cement Part 1: Composition, Specifications and Conformity Criteria for Common Cements. BS EN 197-1*. London.
- Brock, J. (1993). *U.S. Patent No. 5,251,997*. Virginia: United States Patent and Trademark Office.
- Cement and Concrete Association of Australia (1986). *Interlocking Concrete Road Pavements (T35)*. Australia.
- Cement Masonry Association of Australia (CMAA). (1997). *Concrete Segmental Pavements- Guide to Specifying. T-44*. Australia.
- Chan, D. and Poon, C. S. (2010). Using Recycled Construction Waste as Aggregates for Paving Blocks. *Waste and Resource Management, 159(WR2)*, pp.83 – 91.
- Clark, A.J. (1981). *Further investigations into the load spreading of a concrete block paving*. Technical Report 545. Cement and Concrete Association.
- Clifford, J.M. (1984). *Some Aspects of the Structural Design of Segmental Block Pavements in Southern Africa*. PhD Thesis. University of Petoria.
- Concrete Manufactures Association. (2004). *Concrete Block Paving: Book 2 – Design Aspects (4th edition.)*. Portland Park, South Africa.
- Concrete Manufactures Association. (2009). *Concrete Block Paving*. Midrand, South Africa.
- Concrete Masonry Association of Australia (CMAA). (1986). *Specification For Concrete Segmental Paving Units (MA20)*.
- Connors, T. P., and Petrilla, E. (2000). *U.S. Patent No. 6,027,280*. Virginia: United States Patent and Trademark Office.
- Crony, D. and Crony, P. (1991). *The Design and Performance of Road Pavements*. (Second edition). England. McGraw-Hill, pp. 62 –83.
- David, R. S. (1989). Structural Design of Concrete Block Pavement. *Journal of Transportation Engineering, 116*, pp. 615 – 635.
- Dimex Corporation (2002). Unpublished note.
- Donald, P. C. (2001). *Foundation Design Principles and practices*. (2nd edition). New Jersey. Prentice Hall.
- Elliott, R. C. (1995). An Assessment of Some Self and Slowly Cementing Industrial By-products for Use in Roadbases. *Unbound Aggregates in Roads*. Nottingham, UK, The University of Nottingham, pp. 205 – 219.

- Emery, J. and Lazar, M. (2003). Innovative Paver System. *Proceedings of the 7th International Conference on Concrete Block Paving*, 44. 12 – 15 October. Sun City, South Africa.
- Fontana, J. D. and Emery, W. J. (1991). *U.S. Patent No. 5,046,887*. Virginia: United States Patent and Trademark Office.
- Frank, J.M.V. (1994). *The performance of bedding sands in Concrete Block Pavements*. Master Dissertation. University of New Brunswick.
- Gambhir, M. L. (2004). *Concrete Technology* (3th edition). New Delhi. McGraw-Hill, pp. 45 – 71.
- Glickman, M. (1984). The G-Block System of Vertically Interlocking Paving. *Second International Conference on Concrete Block Paving*. Delft, Natherland, pp. 1–4.
- Griffiths, G. and Thom, N. (2007). *Concrete Pavement Design Guidance Notes*. London and New York. Taylor and Francis.
- Handy, R.L and Spangler, M.G (2004). *Compaction. Geotechnical Engineering: Soil and Foundation Principles and Practice*. (5th edition). McGraw-Hill
- Hasanan Md Nor. (1996). Towards Better Concrete Block Pavements in Malaysia. *Second Malaysia Road Conference*. 10 - 13 June. Kuala Lumpur.
- Hasanan, M. N. (2005). The Development and Application of Concrete Block Pavement. *International Seminar and Exhibition on Road Construction*. Semarang, Indonesia.
- Hazelton, J. P. (1891). *U.S. Patent No. 449,739*. Virginia: United States Patent and Trademark Office.
- Hodgkinson, J. R. (1982). Specification for Construction of Trafficked Interlocking Concrete Pavements. *Cement and Concrete Association of Australia*. Tech. Note TN41.
- Houben, L. J. M. and Jacob. (1998). *Rut Development in Concrete Block Pavements Due to Permanent Strain in the Substructure*. Highway and Transportation, Vol. 85, No. 4. pp. 30 – 38.
- Huurman, M. (1997). *Permanent Deformation in Concrete Block Pavements*. PhD Thesis. Delft University of Technology, Delft, Netherlands.
- Interlocking Concrete Pavement Institute (ICPI). (2006). *Structural Design of Interlocking Concrete Pavement for Roads And Parking Lots*. (Spec No. 4), pp. 1 - 8.

- Interpave. (2004). *Construction of Concrete Block Pavements*. The Precast Concrete Paving and Kerb Association, The British Precast Concrete Federation.
- Kellersman, G. H. (1980). Urban Block Paving in the Netherlands. *Proc. 1st Int. Conference on Concrete Block Paving*. Newcastle upon Tyne, UK. pp.93 - 100.
- Knapton, J (2000). *The performance of Pavers for Mechanical Installation*. Technical Report. Department of Civil Engineering, University of Newcastle-Upon-Tyne.
- Knapton, J and Barber, S.D (1980). UK Research Into Concrete Block Pavement Design. *Proceeding of the First International Conference on Concrete Block Paving*. 2-5 September. Newcastle-upon-tyne.
- Knapton, J. (1976). *The Design of Concrete Block Roads. Technical Report TRA 42515* (Vol. 42). Cement and Concrete Association of Great Britain, pp. 6.
- Knapton, J. (1988). Pavement Rehabilitation Using Concrete Blocks. *Proc. Third Int. Conf. on Concrete Block Paving*. Rome, Italy, pp. 209 - 216.
- Knapton, J. (1996). The Mathematic Solution to Interlock in Concrete Block Paving. *Proceedings, Fifth International Conference on Concrete Block Paving*. Pave 96. Israel, pp. 261-278.
- Knapton, J. and Barber, S. D. (1979). The Behaviour of a Concrete Block Pavement. *Proceeding of ICE*, Part 1. vol 66, pp. 227-292.
- Knapton, J. and O'Grady, M. (1983). Structural Behaviour of Concrete Block Paving. *Journal Concrete Society*, pp. 17 – 18.
- Kuipers, G. (1992). The Effect of Concrete Block Lock-Up on Pavement Performance. *Fourth Int. Conference on Concrete Block Paving*. New Zealand. pp. 51 – 59.
- Langsdorff, H. Von. (2007). *U.S. Patent No. 7,270,497 B2* (Vol. 2). Virginia: United States Patent and Trademark Office.
- Lay, J. (1998). The Effects of Natural Aggregates on The Properties of Concrete. *Advanced Concrete Technology*.
- Lazar, M. (2006). *U.S. Patent No. 6,988,847 B2* (Vol. 2). Virginia: United States Patent and Trademark Office.
- Lazar, M. and Emery, J. (2009). Construction and Rehabilitation of Aircraft Pavements Using Concrete Blocks Having Mechanical Interlock. *9th. International Conference on Concrete Block Paving* (pp. 1–9). Buenos Aires, Argentina.

- Lekso, S. (1980). The Use of Concrete Block Pavements for Highways. *Proc. 1st Int. Conference on Concrete Block Paving*, Newcastle Upon Tyne, pp. 101 – 103.
- Lilley, A. A. (1980). A Review of Concrete Paving In The UK Over The Last Five Years. *Proc. 1st Int. Conference on Concrete Block Paving*. 2 – 5 September. Newcastle Upon Tyne, pp. 40 – 44.
- Lilley, A.A. and Knapton, J. (1976). Concrete Block Paving for Roads. *Cement and Concrete Association*. Publication 46.021 January 1976, pp 19.
- Ling, T C, Hasanan, N., Rosli, M. H., and Lim, S. (2010). Long-term Strength of Rubberised Concrete Paving Blocks. *Construction Materials*, (163), February, pp. 19–26.
- Ling, T. C. (2012). Effects of Compaction Method And Rubber Content on The Properties of Concrete Paving Blocks. *Construction and Building Materials*, 28(1), pp. 164–175.
- Ling, T.C (2008). *Engineering Properties and Structural Performance of Rubberized Concrete Paving Blocks*. PhD Thesis. Universiti Teknologi Malaysia.
- Liu, C. and Evett, J. B. (2005). *Soils And Foundations* (SI Edition). (pp. 257 – 280). Singapore: Prentice Hall-Pearson,.
- Mackisack, M.S. (1995). Modelling Gaps between Block Pavers. *Math1. Computer Modelling*. 22(10-12). (pp. 193-200). Elsevier. .
- Marios, N.S., Tang, K., Hussain, A.K., and Stephen, G.M. (2011). The effect of Construction pattern and Unit Interlock on the Structural Behaviour of Blocks Pavements. *Construction and Building Materials*. (pp. 3832-3840). Elsevier.
- McQueen, R., Knapton, J., Emery, J., and Smith, D. R. (1993). *Airfield Pavement Design with Concrete Pavers*. TR-98, Herdon, VA: Concrete Paver Institute.
- Meyer, A. (1980). Materials and Specifications in West Germany. *Proc. 1st Int. Conference on Concrete Block Paving*, Newcastle upon Tyne, 2– 5 September, pp. 8 – 21.
- Michael, K. A. (1993). *Concrete Paving Blocks: An Overview*. Final Technical Report. Washington State Transportation Center, Department of Transportation, Washington D.C.
- Miura, Y.T. and Tsuda, T. (1984). Structural Design of Concrete Block Pavements by CBR Method and Its Evaluations. *Second International Conference on Concrete Block Paving*. 10-12 April. Delft.

- Mohd For, M. A., Yau, O.H, Huei, C. S. and Rini, A.A. (2008). Characteristics of filled joint under shear loading. *Geological Society of Malaysia. Buletin* 54, pp. 47-51.
- Morrish, C.F. (1980). Interlocking Concrete Paving- the state of the art in Australia. *Proceeding of the first international conference on concrete block paving*. 2 - 5 September. Newcastle-upon-tyne, pp. 85-92.
- Nur Izzi Md Yusoff, Mohd Rosli Hainin, and Hasanan Md Nor (2012). Cirian Pasir Pengisi Sambungan Turapan Blok Konkrit Saling Mengunci pada Jarak Sambungan dan Kecerunan yang Berbeza. *Sains Malaysiana*, 41(1), pp. 103–110.
- O’Grady, M. (1983). *The Structural Behaviour of Small Element Block Paving*. University of Newcastle Upon Tyne.
- Panda, B. C. and Ghosh, A. K. (2002a). Structural Behaviour of Concrete Block Paving I: Concrete Blocks. *Journal of Transportation Engineering*, (128 (2)), pp. 123 –129.
- Panda, B. C., and Ghosh, A. K. (2002b). Structural Behaviour of Concrete Block Paving II: Concrete Blocks. *Journal of Transportation Engineering*, 128(April), pp. 130–135.
- Papaliangas, T., Hencher, S.R., Lumsden, A.C. and Manolopoulou, S. (1993). The effect of frictional fill thickness on the shear strength of rock discontinuities. *International Journal of Rock Mechanics and Mining Science and Geomechanical Abstracts*. 30(2), pp. 81-91.
- Pereira, J.P. (1990). Mechanics of filled discontinuities. *3rd Proceedings of International Conference on Mechanics of Jointed and Faulted Rock*. 6-9 April. Vienna, pp. 375-380.
- Poon, C. S. and Lam, C. S. (2008). The Effect of Aggregate to Cement Ratio and Types of Aggregates on the Properties of Pre-cast Concrete Blocks. *Cement and Concrete Composites*, 30(4), pp.283–289.
- Poon, C.S., Kou, S.C. and Lam, L. (2002). A Uses of recycled aggregates in molded concrete bricks and blocks. *Construction and Building Materials*. 16 (2002). Elsevier, pp.281-289.
- Portland Cement (Ordinary and Rapid-Hardening): Part 1: Specification (Second Revision)*. (2006). MS 522-1. SIRIM Berhad.

- Portland Cement Association (1984). Structural Design of a Pavement Design Methodology For Concrete Block Pavement in Israel. *Proceeding of 3rd International Conference on Concrete Block Paving. Rome*, pp. 94-101.
- Rachmat, M. (2006). *Performance Of Concrete Block Pavement On Sloped Road Section*. PhD Thesis. Universiti Teknologi Malaysia.
- Rada, G. R., Smith, D. R., Miller, J. S., and Witczak, M. W. (1990). Structural Design of Concrete Block Pavements. *Journal of Transportation Engineering*, (116(5)), pp. 615 – 635.
- Rada, G. R., Stephanos, P. J., and Tayabji, S. D. (1993). *Performance of Interlocking Concrete Pavement in North America*. 72 Annual Transportation Research Board Meeting, Washington, D.C.
- Repasky, J. (1978). *U.S. Patent No. 4,098,865*. Virginia: United States Patent and Trademark Office.
- Rollings, R.S. (1983). *Concrete Block Pavements*. Technical Report GL-83-3:Final Report. US Army Engineer Waterways Experiment Station.
- Rosenberger, H. (1976). *U.S. Patent No. 3,947,192*. Virginia: United States Patent and Trademark Office.
- Scheiwiller, R. (1991). *U.S. Patent No. 5,028,167*. Virginia: United States Patent and Trademark Office.
- Seddon, P. A. (1981). The Behaviour of Concrete Block Paving Under Repetitive Loading. *Precast Concrete* (Vol. 12) (pp. 355 – 360). University of Canterbury, Christchurch, New Zealand.
- Shackel, B. (1978). The Evaluation of Interlocking Block Pavements - An Interim Report. *Proc. Conf. Concrete Masonry of Australian*. Sydney.
- Shackel, B. (1979). *The Design of Interlocking Concrete Block Pavements* (No. 90.). Australian Road Research Board. Research Report ARRB: pp. 53 - 70.
- Shackel, B. (1980a). The Performance of Interlocking Block Pavements Under Accelerated Trafficking. *1st International Conference - Concrete Block Paving*. Newcastle upon Tyne, UK, pp. 113 – 120.
- Shackel, B (1980b). An Experimental Investigation of The Roles of The Bedding and Jointing Sands in The Performance of Interlocking Concrete Block Pavements. *Concrete/Beton*. 19: pp. 5-15.

- Shackel, B (1980c). Use in Ports and Industrial Pavement. *Proceeding of The First International Conference on Concrete Block Paving*. 2-5 September. Newcastle-upon-tyne, pp. 83-85.
- Shackel, B. (1985). The Evaluation and Application of Mechanistic Design Procedure for Concrete Block Pavements. *Proceeding of The 3rd International Conference on Concrete Block Paving*. Rome, pp. 114-120.
- Shackel, B. (1990). *Design and Construction of Interlocking Concrete Block Pavement*. (pp. 73 - 172). NY, USA: Elsevier Science Publishers Ltd.
- Shackel, B. (1994a). Application and Construction of Concrete Block Pavements. *New Directions In Pavement Engineering*. 14 –15 November. Kuala Lumpur, Malaysia, pp. 178 – 184.
- Shackel, B. (1994b). Loads and Environmental Factors Affecting Road Pavements. *New Directions In Pavement Engineering*. November 14 –15. Kuala Lumpur, Malaysia, pp. 84 – 93.
- Shackel, B. and Candy, C.E.E. (1988). Factors affecting the choice of concrete blocks as a pavement surface. *Proceeding of 3rd International Conference on Concrete Block Paving*. Rome, pp. 78-84.
- Shackel, B. and Arora, M. G. (1978). *The Application of a Full-Scale Road Simulator to the Study of Highway Pavements*. Australian Road Research. 8(2), pp. 17 - 31.
- Shackel, B., O’Keeffe, W., and O’Keeffe, L. (1993). Concrete Block Paving Tested as Articulated Slabs. *Proc. 5th Int. Conference on Concrete Pavement Design and Rehabilitation*. 23 – 27 June. Purdue Univ., West Lafayette, Ind, pp. 8.
- Smith, D.R. (1989). Concrete Pavers. *The Construction Specifier*. pp. 95-99.
- Specification No. C254. (2000). *Segmental Paving: Development Construction Specification*. C254. New South Wales.
- Sukonrasukkul, P. and Chaikaew, C. (2006). Properties of Concrete Pedestrian Block Mixed with Crumb Rubber. *Construction and Building Materials*, (20(7)), pp. 450 – 457.
- Tang, K., Soutsos, M. N., and Millard, S. G. (2006). *Developing Precast Concrete Products Made With Recycles Construction and Demolition Waste-Phase II: Concrete Paving Blocks and Flags*. Liverpool: The University of Liverpool.
- Thorkelson, S. (2008). *U.S. Patent No. 7,344,334 B2* (Vol. 2). Virginia: United States Patent and Trademark Office.

- Uchida, K., Ohmori, H., and Nishi, J. (1992). Structural Design of Interlocking Concrete Block Pavement in Japan. *4th International Concrete Block Paving Conference*. 16 - 19 February. Auckland, New Zealand, pp. 71 - 78.
- Ugural, A. C. (1991). *Mechanics of Materials*. Singapore: McGraw-Hill.
- Wada, S. (2004). *U.S. Patent No. 6,705,797 B1*. Virginia: United States Patent and Trademark Office.
- Walker, S. (1944). *Application of Theory of Probability to Design of Concrete for Strength*. Concrete, Vol. 52, No. 5, Part 1. pp. 3 – 5.
- Westcon Precast Inc. (1990). *A Guide to Design and Construction of Segmental Concrete Pavement: Paver Manual*. Calgary, Alberta.
- Whitacre, D. C. (1976). *U.S. Patent No. 3,969,851*. Virginia: United States Patent and Trademark Office.