



Faculty of Engineering

**Mechanical and Thermal Behaviour of Thermal Insulated Cement
Mortar With Silica Aerogel**

Tay Lee Thin

**Master of Engineering
2022**

Mechanical and Thermal Behaviour of Thermal Insulated Cement Mortar
With Silica Aerogel

Tay Lee Thin

A thesis submitted


In fulfillment of the requirements for the degree of Master of Engineering

(Civil Engineering)

Faculty of Engineering
UNIVERSITI MALAYSIA SARAWAK
2022

DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

.....

Signature

Name: Tay Lee Thin

Matric No.: 19020093

Faculty of Engineering

Universiti Malaysia Sarawak

Date : 07/07/2022

ACKNOWLEDGEMENT

I would like to take this opportunity to those who have helped me directly or indirectly to this research.

Furthermore, I would like to extend my gratitude to Dr. Lee Yee Yong for guiding me and giving me encouragement through this project. Without her support, I will not be able to complete my study.

Finally, deeply thankful to my parents and siblings for morally support me. Without them, I cannot overcome all the obstacles and challenges.

ABSTRACT

Cities or towns are having a higher temperature compared to the rural area and it is known as urban heat island (UHI). UHI indirectly induces the rising of indoor temperature. The heat tends to move from outdoor toward indoor by passing through building envelope. Consequently, human indoor discomfort level is increased. As a result, application of thermal insulator to the building envelope has been put in place to address the issue of thermal discomfort. There are various thermal insulators that are available and it is important to have thermal insulators to resist the heat flow from outdoor towards indoor. Conventional thermal insulation materials are mineral wool, EPS, XPS and cork. In the meantime, silica aerogel (SA) is a newly introduced insulation material. Silica aerogel was introduced with thermal insulation criteria where it possesses properties such as, lightweight, high specific surface area, high porosity, low density and high thermal insulation value. Therefore, silica aerogel was studied in this project in the form of powder and mat to produce silica aerogel mortar and silica aerogel sandwiched mortar respectively. The objectives of the study were to determine the mechanical properties and thermal properties of mortar incorporating silica aerogel powder and silica aerogel mat as well as to evaluate the thermal performance of the silica aerogel mortar panel and silica aerogel sandwiched mortar panel. Firstly, the experiment of mechanical properties was conducted to determine the mechanical properties and obtain the optimum ratio for silica aerogel powder mortar. Based on the results, 15% vol. silica aerogel (by replacing sand) was the optimum ratio for the SA powder mortar. Meanwhile, flatwise compressive test and edgewise compressive test were investigated for silica aerogel sandwiched mortar with three different thicknesses (9 mm, 12 mm and 15 mm) and 15 mm core thickness sandwiched mortar achieved highest flatwise compressive strength. Next, all the sandwiched mortar samples and silica aerogel mortar with optimum

ratio were further prepared and used for thermal conductivity and thermal resistivity test which were conducted in laboratory, while field testing for thermal performance was carried out in open space under exposure of sunlight. It was concluded that 15% vol. silica aerogel mortar and silica aerogel sandwiched mortars were determined to have lower thermal conductivity than type N mortar (exterior, non-load bearing wall component) and possess better thermal insulation property compared to type N mortar. By replacing concrete block and red clay brick with silica aerogel mortar panel or silica aerogel sandwiched mortar panel, heat flow was expected to reduce and bring least indoor temperature fluctuation, hence maintain indoor thermal comfort level.

Keywords: UHI, indoor thermal comfort, thermal insulator, silica aerogel, mortar

Sifat-sifat Berkaitan Mekanikal dan Haba untuk Mortar Simen Mengandungi Silica Aerogel

ABSTRAK

Kawasan bandar mempunyai suhu yang lebih tinggi berbanding dengan luar bandar dan dikenali sebagai pulau haba bandar (UHI). UHI secara tidak langsung menyebabkan peningkatan suhu bilik. Haba bergerak dari luar bangunan ke dalam bangunan melalui "building envelope". Kesannya, ia meningkatkan tahap ketidakselesaan dalam bilik dan menjejaskan kesihatan manusia. Oleh itu, penggunaan penebat haba di bangunan telah diperkenalkan. Terdapat pelbagai jenis penebat haba di pasaran dan penebat haba amat penting untuk menghalang kemasukan haba dari luar bangunan ke dalam bangunan. Penebat haba yang ada di pasaran adalah "mineral wool", "EPS", "XPS" dan "cork". Selain itu, "silica aerogel" adalah penebat haba yang baru. Silica aerogel diperkenalkan dengan ciri-ciri tahan haba seperti ringan, keluasan permukaan yang tinggi, bilangan keliangan yang banyak, ketumpatan yang rendah dan nilai tahan haba yang tinggi. Dengan itu, silica aerogel telah dikaji di dalam projek ini sebagai silica aerogel mortar dalam bentuk serbuk dan tikar untuk menghasilkan "silica aerogel mortar" dan "silica aerogel sandwiched mortar". Matlamat untuk projek ini adalah untuk menentukan "mechanical properties" dan "thermal properties" untuk mortar yang mengandungi silica aerogel dalam bentuk serbuk dan tikar. Selain itu, penentuan prestasi tahan haba untuk mortar mengandungi silica aerogel dalam bentuk serbuk dan tikar juga adalah salah satu matlamat dalam penyelidikan ini. Daripada hasil penyelidikan, 15% isipadu silica aerogel (dengan menggantikan pasir) telah dikesan sebagai maksimum nisbah. Di samping itu, silica aerogel bentuk tikar dengan 3 jenis ketebalan (9 mm, 12mm & 15 mm) telah disiasat untuk mendapat "flatwise compressive strength" dan "edgewise compressive strength" dan didapati maksimum

ketebalan ialah “15 mm core thickness sandwiched mortar”. Seterusnya, semua sampel untuk “sandwiched mortar” dan “silica aerogel mortar” dengan maksimum nisbah digunakan untuk kajian seterusnya seperti konduksi haba dan prestasi tahan haba. Kajian untuk konduksi haba dan ketahanan haba dijalankan di makmal ujian, manakala kajian prestasi haba dijalankan di kawasan lapang dan dijemari bawah matahari. Kesimpulannya, 15% isipadu silica aerogel mortar dan silica aerogel sandwiched mortar mempunyai konduksi haba yang rendah berbanding mortar jenis N dan dikesan menebat haba lebih baik daripada mortar jenis N. Pengantian blok konkrit dan batu bata dengan “SA mortar panel” atau “silica aerogel sandwiched mortar panel”, dijangkakan dapat mengurangkan pergerakan haba dan mengekalkan suhu rumah. Selain itu, tahap keselesaan dalam bilik juga dapat dikekalkan.

Kata kunci: Pulau haba bandar, keselesaan dalam bilik, penebat haba, silica aerogel, mortar

TABLE OF CONTENTS

	Page
DECLARATION	i
ACKNOWLEDGEMENT	ii
ABSTRACT	iii
<i>ABSTRAK</i>	v
TABLE OF CONTENTS	vii
LIST OF TABLES	xiii
LIST OF FIGURES	xv
LIST OF ABBREVIATIONS	xxiv
CHAPTER 1: INTRODUCTION	1
1.1 Study Background	1
1.2 Problem Statement	5
1.3 Objectives	6
1.4 Research Questions	6
1.5 Scope of Study	7
1.6 Significance of the Study	7
1.7 Chapter Summary	8
CHAPTER 2: LITERATURE REVIEW	9
2.1 Overview	9

2.2	Urban Heat Island	9
2.3	Urban-Built Environment	12
2.4	Heat Transfer Mechanism	17
2.4.1	Conduction	18
2.4.2	Convection	19
2.4.3	Radiation	20
2.5	Thermal Insulation	22
2.5.1	Thermal Properties of Insulation Materials	26
2.5.2	Conventional Thermal Insulation	31
2.5.3	Silica (Silicon Dioxide)	34
2.5.4	Silica Aerogel	36
2.5.5	Silica Gel	40
2.5.6	Silica Xerogel	41
2.5.7	Fumed silica	41
2.6	Silica Fume as Additive in Silica Aerogel Mortar	43
2.7	Indoor Thermal Comfort	44
2.8	Chapter Summary	48
CHAPTER 3: MATERIALS AND METHODS		50
3.1	Introduction	50
3.2	Framework Design	51

3.3	Material	53
3.3.1	Portland Cement (PC) CEM I	55
3.3.2	Fine Aggregate	56
3.3.3	Water	56
3.3.4	Silica Fume (Microsilica)	56
3.3.5	Superplasticizer	57
3.3.6	Silica Aerogel Powder / Mat	58
3.4	Mould	60
3.5	Instruments	61
3.5.1	TA 888 Hot Wire Anemometer	61
3.5.2	UCAM-60B All in One Data Logger and Thermocouple	62
3.5.3	HOBO U-Series Data Logger	63
3.6	Mix Proportion	64
3.7	Mixing Procedures	66
3.8	Curing	66
3.9	Laboratory Testing	67
3.9.1	Compressive Strength Test	67
3.9.2	Bending / Flexural Strength Test	67
3.9.3	Young's Modulus Test	67
3.9.4	Flatwise Compressive Test (ASTM C 365-00)	68

3.9.5	Edgewise Compressive Test (ASTM C364/ C364M-07)	68
3.9.6	Thermal conductivity	68
3.9.7	SEM Microstructural Analysis	70
3.10	Field Measurement for Thermal Performance Testing	70
3.11	Analytical Procedure	71
3.12	Calculation of Heat Transfer	72
3.12.1	Conduction	72
3.12.2	Convection	72
3.12.3	Radiation	72
CHAPTER 4: MECHANICAL PROPERTIES FOR SILICA AEROGEL		
POWDER MORTAR AND SILICA AEROGEL SANDWICHED		
MORTAR		
		73
4.1	Introduction	73
4.2	Mixed Design Preparation	73
4.3	Fresh State Properties	74
4.4	Silica Aerogel Powder Mortar	77
4.4.1	SEM Microstructural Analysis	77
4.4.2	Compressive Strength	81
4.4.3	Flexural Strength	90
4.4.4	Correlation Between Compressive Strength and Flexural Strength	92
4.4.5	Modulus of Elasticity (Young's Modulus)	96

4.5	Sandwiched Mortar (Silica Aerogel Mat)	98
4.5.1	Flatwise Compressive Test	98
4.5.2	Edgewise Compressive Test	100
4.5.3	Comparison of Flatwise and Edgewise Compressive Strength Test	104
4.6	Summary between Compressive Strength for Sandwiched Mortar and Silica Aerogel Mortar	106
4.7	Potential Applications of SA as Mortar and Sandwiched Panel	108
4.8	Summary	109
CHAPTER 5: THERMAL PROPERTIES AND THERMAL PERFORMANCE		
FOR SILICA AEROGEL POWDER MORTAR AND SILICA		
AEROGEL SANDWICHED MORTAR		
		111
5.1	Introduction	111
5.2	Thermal Conductivity and Thermal Resistivity	111
5.2.1	Thermal Conductivity of SA Mortar	112
5.2.2	Thermal Conductivity of Sandwiched Mortar	115
5.3	Thermal Performance	117
5.3.1	External Surface Temperature	118
5.3.2	Influence of Meteorological Measurement Towards External Surface Temperature	124
5.3.3	Influence of Meteorological Measurement Towards Internal Surface Temperature	151

5.4	Time lag and Decrement Factor	174
5.5	Heat transfer	186
5.5.1	Conduction	187
5.5.2	Radiation	201
5.6	Summary	203
	CHAPTER 6: CONCLUSION AND RECOMMENDATIONS	205
6.1	Introduction	205
6.2	Conclusion	205
6.2.1	Objective 1 - To determine the mechanical properties of mortar incorporating silica aerogel powder and silica aerogel mat	205
6.2.2	Objective 2 - To determine the thermal properties of mortar incorporating silica aerogel powder and silica aerogel mat	206
6.2.3	Objective 3 - To evaluate the thermal performance of the silica aerogel powder mortar panel and silica aerogel sandwiched mortar panel	207
6.3	Recommendations	209
	REFERENCES	211
	APPENDICES	239

LIST OF TABLES

		Page
Table 2.1	The Impacts of Thermal Insulating Building Material	25
Table 2.2	Thermal Properties of Common Materials for Conventional Building (Long & Ye, 2016)	29
Table 2.3	Thermal Conductivity of Conventional Thermal Insulation Materials (Jelle et al., 2012)	31
Table 2.4	Properties of silica aerogel (Gurav et al., 2010)	38
Table 2.5	Summary of thermal insulation materials	43
Table 3.1	Abbreviated version of Table X1.1 in the Annex ASTM C270-06	54
Table 3.2	Physical Properties of Mortar Cements (ASTM C1329-03)	54
Table 3.3	Properties of silica aerogel	60
Table 3.4	Mix proportion design	65
Table 4.1	Flow of mortar and water cement ratio	75
Table 4.2	Mortar mix design	76
Table 4.3	EDS of normal mortar	78
Table 4.4	EDS of 20% vol. silica aerogel mortar	80
Table 4.5	Density of samples	85

Table 4.6	Empirical relationships of compressive strength and flexural strength for plain concrete (Yusuf et. al., 2016)	93
Table 4.7	Correlation empirical formula between flexural strength and compressive strength for silica aerogel mortar	95
Table 4.8	Result of testing of Modulus of elasticity	97
Table 4.9	Review of flatwise and edgewise compressive tests	106
Table 5.1	Thermal conductivity of SA mortar and type N mortar	112
Table 5.2	Thermal conductivity of sandwiched mortars	116
Table 5.3	Maximum difference between external ambient temperature and internal surface temperature	152
Table 5.4	Average time lag of samples	176
Table 5.5	Decrement factor of samples	182

LIST OF FIGURES

	Page
Figure 2.1 Concept of Urban Heat Island (World Meteorological Organisation, 2020)	10
Figure 2.2 Concept of Heat Conduction	19
Figure 2.3 Concept of Convection	20
Figure 2.4 Concept of Radiation	21
Figure 3.1 Flow Chart of Experiment	51
Figure 3.2 PC CEM I	55
Figure 3.3 Silica Fume	57
Figure 3.4 Superplasticizer	58
Figure 3.5 Silica Aerogel powder	59
Figure 3.6 Silica Aerogel mat	59
Figure 3.7 TA 888 Hot wire anemometer	62
Figure 3.8 Data Logger	63
Figure 3.9 Hobo data logger	64
Figure 3.10 Linear Heat Transfer Unit H112A	69

Figure 3.11	Set up of field testing	71
Figure 4.1	Fresh mortar within mould of flow table	74
Figure 4.2	Measurement of diameter of mortar after dropping flow table	75
Figure 4.3	SEM image of normal mortar	78
Figure 4.4	SEM image of 20% vol. silica aerogel mortar	79
Figure 4.5	SEM image of 25% vol. silica aerogel mortar	80
Figure 4.6	SEM image of 25% vol. silica aerogel mortar	81
Figure 4.7	Compressive strength of samples	82
Figure 4.8	SEM image of 20% volume of silica aerogel mortar	84
Figure 4.9	SEM image of normal (type N) mortar	84
Figure 4.10	Existence of silica aerogel inside pore of cement matrix (15% vol. silica aerogel mortar)	86
Figure 4.11	SEM image of 25% vol. SA mortar	88
Figure 4.12	SEM image of normal mortar	89
Figure 4.13	SEM image of 15% SA mortar	89
Figure 4.14	SEM image of 20% SA mortar	90
Figure 4.15	Result of flexural strength	91

Figure 4.16	Comparison of flexural strength	94
Figure 4.17	Empirical correlation formula between flexural strength and compressive strength for silica aerogel powder mortar	95
Figure 4.18	Set up of sample for testing of modulus of elasticity after 28 days	96
Figure 4.19	15mm thick mat sandwiched mortar for flatwise compressive strength testing	98
Figure 4.20	Flatwise compressive strength	99
Figure 4.21	View of 12 mm thick core thickness sandwiched mortar after compressive strength test	100
Figure 4.22	View of 15 mm thick core thickness sandwiched mortar after compressive strength test	100
Figure 4.23	Edgewise compressive strength	101
Figure 4.24	Type of failure mode (ASTM C364 / C364M-07, 2012)	102
Figure 4.25	Facesheet compression failure for 9mm thick mat mortar	103
Figure 4.26	Facesheet compression failure for 12mm thick mat mortar	103
Figure 4.27	Facesheet compression failure for 15mm thick mat mortar	104
Figure 5.1	External surface temperatures (day 1- day 4)	119
Figure 5.2	External surface temperatures (day 5- day 8)	120

Figure 5.3	External surface temperatures (day 9- day 12)	121
Figure 5.4	External surface temperatures (day 13- day 16)	122
Figure 5.5	External surface temperatures (day 17- day 20)	123
Figure 5.6	View of SA mortar	124
Figure 5.7	View of Type N mortar	124
Figure 5.8	Relationship of heat transfer and meteorological data	126
Figure 5.9	Relationship of external surface temperature and ambient temperature (day 1 – day 4)	129
Figure 5.10	Relationship of external surface temperature and ambient temperature (day 5 – day 8)	130
Figure 5.11	Relationship of external surface temperature and ambient temperature (day 9 – day 12)	131
Figure 5.12	Relationship of external surface temperature and ambient temperature (day 13 – day 16)	132
Figure 5.13	Relationship of external surface temperature and ambient temperature (day 17 – day 20)	133
Figure 5.14	Relationship of external surface temperature and relative humidity (day 1 – day 4)	136

Figure 5.15	Relationship of external surface temperature and relative humidity (day 5 – day 8)	137
Figure 5.16	Relationship of external surface temperature and relative humidity (day 9 – day 12)	138
Figure 5.17	Relationship of external surface temperature and relative humidity (day 13 – day 16)	139
Figure 5.18	Relationship of external surface temperature and relative humidity (day 17 – day 20)	140
Figure 5.19	Relationship of external surface temperature and light intensity (day 1 – day 4)	141
Figure 5.20	Relationship of external surface temperature and light intensity (day 5 – day 8)	142
Figure 5.21	Relationship of external surface temperature and light intensity (day 9 – day 12)	143
Figure 5.22	Relationship of external surface temperature and light intensity (day 13 – day 16)	144
Figure 5.23	Relationship of external surface temperature and light intensity (day 17 – day 20)	145
Figure 5.24	Relationship of external surface temperature and wind speed (day 1 – day 4)	146

Figure 5.25	Relationship of external surface temperature and wind speed (day 5 – day 8)	147
Figure 5.26	Relationship of external surface temperature and wind speed (day 9 – day 12)	148
Figure 5.27	Relationship of external surface temperature and wind speed (day 13 – day 16)	149
Figure 5.28	Relationship of external surface temperature and wind speed (day 17 – day 20)	150
Figure 5.29	Relationship of internal surface temperature and ambient temperature (day 1 – day 4)	154
Figure 5.30	Relationship of internal surface temperature and ambient temperature (day 5 – day 8)	155
Figure 5.31	Relationship of internal surface temperature and ambient temperature (day 9 – day 12)	156
Figure 5.32	Relationship of internal surface temperature and ambient temperature (day 13 – day 16)	157
Figure 5.33	Relationship of internal surface temperature and ambient temperature (day 17 – day 20)	158
Figure 5.34	Relationship of internal surface temperature and relative humidity (day 1 – day 4)	159

Figure 5.35	Relationship of internal surface temperature and relative humidity (day 5 – day 8)	160
Figure 5.36	Relationship of internal surface temperature and relative humidity (day 9 – day 12)	161
Figure 5.37	Relationship of internal surface temperature and relative humidity (day 13 – day 16)	162
Figure 5.38	Relationship of internal surface temperature and relative humidity (day 17 – day 20)	163
Figure 5.39	Relationship of internal surface temperature and light intensity (day 1 – day 4)	164
Figure 5.40	Relationship of internal surface temperature and light intensity (day 5 – day 8)	165
Figure 5.41	Relationship of internal surface temperature and light intensity (day 9 – day 12)	166
Figure 5.42	Relationship of internal surface temperature and light intensity (day 13 – day 16)	167
Figure 5.43	Relationship of internal surface temperature and light intensity (day 17 – day 20)	168
Figure 5.44	Relationship of internal surface temperature and wind speed (day 1 – day 4)	169

Figure 5.45	Relationship of internal surface temperature and wind speed (day 5 – day 8)	170
Figure 5.46	Relationship of internal surface temperature and wind speed (day 9 – day 12)	171
Figure 5.47	Relationship of internal surface temperature and wind speed (day 13 – day 16)	172
Figure 5.48	Relationship of internal surface temperature and wind speed (day 17 – day 20)	173
Figure 5.49	Heat conduction of SA mortar and normal mortar (day 1 – day 4)	191
Figure 5.50	Heat conduction of SA mortar and normal mortar (day 5 – day 8)	192
Figure 5.51	Heat conduction of SA mortar and normal mortar (day 9 – day 12)	193
Figure 5.52	Heat conduction of SA mortar and normal mortar (day 13 – day 16)	194
Figure 5.53	Heat conduction of SA mortar and normal mortar (day 17 – day 20)	195
Figure 5.54	Heat conduction of sandwiched mortar (day 1 – day 4)	196
Figure 5.55	Heat conduction of sandwiched mortar (day 5 – day 8)	197
Figure 5.56	Heat conduction of sandwiched mortar (day 9 – day 12)	198
Figure 5.57	Heat conduction of sandwiched mortar (day 13 – day 16)	199
Figure 5.58	Heat conduction of sandwiched mortar (day 17 – day 20)	200