

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	iii
ABSTRACT (THAI)	v
ABSTRACT (ENGLISH)	vii
LIST OF TABLES	xv
LIST OF FIGURES	xvii
CHAPTER 1 INTRODUCTION	1
1.1 Overview	1
1.2 Objectives of this work	4
1.3 Methodology and Analyses	4
CHAPTER 2 BACKGROUND AND LITERATURE REVIEW	6
2.1 Piezoelectricity	6
2.1.1 History and basis for piezoelectricity Theory	6
2.1.2 Poling	8
2.2 Relationship between g , ε and d coefficients	10
2.3 Electromechanical coupling coefficients	12
2.4 Thermal Expansion	13
2.5 Acoustic Impedance	15

TABLE OF CONTENTS (continued)

	Page
2.6 Background of piezoelectric ceramic and modified barium titanate ceramic	17
2.7 Portland cement	24
2.7.1 Definition of Portland cement	24
2.7.2 Composition of Portland cement	24
2.7.3 The hydration of Portland cement	26
2.7.4 Effect of temperature on the cement paste	29
2.7.5 Aggregates characteristics and their significance for concrete	31
2.8 Composite materials	34
2.8.1 Properties and connectivity of composite materials	34
2.8.2 Models of composites	38
2.9 Literature review of piezoelectric-cement based composites	43
CHAPTER 3 EXPERIMENTAL PROCEDURE	64
3.1 Materials and Fabrication	65
3.1.1 Modified barium titanate ceramic fabrication	65
3.1.2 Composite fabrications	67
3.2 Physical, acoustic impedance and microstructure characterization measurements	74
3.2.1 Density and porosity	75

TABLE OF CONTENTS (continued)

	Page
3.2.2 Thermal expansion measurement	75
3.2.3 Acoustic impedance	77
3.2.4 Scanning electron microscopy, SEM	78
3.3 Electrical and acoustic impedance measurements	79
3.3.1 Sample preparation	79
3.3.2 Dielectric measurement	79
3.3.3 Piezoelectric measurement	80
CHAPTER 4 RESULTS AND DISCUSSION	85
Part I: 0-3 Modified barium titanate-Portland cement composites	85
4.1 Dielectric properties of 0-3 modified barium titanate-Portland cement composites	85
4.1.1 Effect of ceramic particle size on the dielectric properties	85
4.1.2 Effect of ceramic content on the dielectric properties	87
4.2 Piezoelectric properties of 0-3 modified barium titanate-Portland cement composites	90
4.2.1 The degree of poling	90
4.2.2 Effect of ceramic particle size on the piezoelectric properties	91
4.3.3 Effect of ceramic content on the piezoelectric properties	95

TABLE OF CONTENTS (continued)

	Page
4.3 Acoustic impedance properties of 0-3 modified barium titanate-Portland cement composites	101
4.3.1 Effect of ceramic particle size on the acoustic impedance properties	101
4.3.2 Effect of ceramic content on the acoustic impedance properties	102
4.4 Thermal expansion of 0-3 modified barium titanate-Portland cement composites	104
4.5 Microstructure properties of 0-3 modified barium titanate-Portland cement composites	109
4.6 Summary	110
Part II: 1-3 Modified barium titanate-Portland cement composites	113
4.7 Dielectric properties of 1-3 modified barium titanate-Portland cement composites	113
4.8 Piezoelectric properties of 1-3 modified barium titanate-Portland cement composites	115
4.9 Acoustic impedance properties of 1-3 modified barium titanate-Portland cement composites	119
4.10 Microstructure properties of 1-3 modified barium titanate-Portland cement composites	121

TABLE OF CONTENTS (continued)

	Page
4.11 Summary	122
Part III: 2-2 Modified barium titanate-Portland cement composites	124
4.12 Dielectric properties of 2-2 modified barium titanate-Portland cement composites	124
4.13 Piezoelectric properties of 2-2 modified barium titanate-Portland cement composites	126
4.14 Acoustic impedance properties of 2-2 modified barium titanate- Portland cement composites	130
4.15 Microstructure properties of 2-2 modified barium titanate-Portland cement composites	132
4.16 Summary	133
CHAPTER 5 CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK	135
5.1 Conclusions	135
5.2 Suggestions for further work	137
REFERENCES	139
VITA	150

LIST OF TABLES

Table	Page
2.1 Summary of the dielectric properties and piezoelectric coefficient of BaTiO ₃ -based ceramics.	19
2.2 Dielectric constant (ϵ), density, electromechanical coupling coefficients (K), elastic compliance (s), and piezoelectric strain coefficients (d) of Ba(Ti _{1-x} Zr _x)O ₃ ceramics.	22
2.3 Typical oxide and compound compositions of Portland cements.	25
2.4 Examples of product properties.	35
2.5 Summary of the results in comparison to the previous works.	48
2.6 Electrical properties of cement piezoelectric composites.	55
2.7 Electromechanical and acoustic impedance properties of 1-3 piezoelectric ceramic-cement composite with P(MN)ZT ceramic volume fraction.	59
2.8 Designing parameters of receiving piezoelectric composites.	61
2.9 Main properties of the receiving type piezoelectric elements.	62
3.1 Specifications of the starting materials for BZT ceramic.	66
3.2 Composition of 0-3 BZT-PC composites.	67
3.3 Composition of 1-3 BZT-PC composites.	71
3.4 Composition of 2-2 BZT-PC composites.	73
3.5 Poling condition of the modified barium titanate-Portland cement composite.	82

LIST OF TABLES (continued)

Table		Page
5.1	Dielectric, piezoelectric and acoustic impedance properties of piezoelectric-cement based composites.	137

LIST OF FIGURES

Figure	Page
2.1 Classification of the 32 crystallographic crystal classes.	8
2.2 Polarizing (poling) a piezoelectric ceramic; (a) random orientation of polar domains prior to polarization and (b) polarization in DC electric field and (c) after polarization.	9
2.3 Generator and motor actions of a piezoelectric element.	10
2.4 (a) Plot of potential energy versus interatomic distance, demonstrating the increase in interatomic separation with rising temperature. With heating, the interatomic separation increases from r_0 to r_1 to r_2 , and so on. (b) For a symmetric potential energy-versus-interatomic distance curve, there is no increase in interatomic separation with rising temperature (i.e., $r_1 = r_2 = r_3$).	14
2.5 Comparison of the d_{33} value for the piezoelectric ceramic.	17
2.6 Phase diagram for $\text{Ba}(\text{Ti}_{1-x}\text{Zr}_x)\text{O}_3$ ceramics with $0 < x < 0.3$. (For various compositions, data were taken at 1 kHz. Symbols are experimental data: up-triangles: data for ceramics; open circles: single crystal data; Dash curves: guide to the eyes).	21
2.7 Piezoelectric constant d_{33} , planar electromechanical coefficient k_p and mechanical quality factor Q_m of the $\text{Ba}(\text{Zr}_x\text{Ti}_{1-x})\text{O}_3$ ceramics as a function of x .	23
2.8 The strength developed by Portland cement compounds.	29

LIST OF FIGURES (continued)

Figure	Page
2.9 The interface between the aggregate and cement paste.	31
2.10 Connectivity patterns in a diphasic composite system.	37
2.11 The model used in estimating the piezoelectric effect of diphasic solid; (a) series model and (b) parallel model.	40
2.12 (a) A composite with 0-3 connectivity and (b) Unit modified cubes cell of composite with piezoelectric ceramic particle (oblique lined area) without surface layer.	41
2.13 (a) A unit cubes cell equivalent to the unit cell equivalent to the unit cell illustrated in Fig. 2.12 (b) and (b) schematic representation for the modified cube model which is divided into two parts.	42
2.14 Illustration of the series, parallel, and cube models for composite.	43
2.15 Relative dielectric constant versus PZT particles content.	46
2.16 Acoustic impedance versus PZT particles content.	46
2.17 The effect of poling temperature on the piezoelectric coefficient (d_{33}).	49
2.18 The impedance magnitude and the phase spectra of PZT-PC composites; (a) poling temperature at 100 °C, (b) poling temperature at 130 °C and (c) poling temperature at 160 °C.	50
2.19 Relationship between the K_t and the poling temperature.	51
2.20 The effect of poling time on the piezoelectric coefficient (d_{33}).	51
2.21 The compressive strength versus volume fraction of PZT ceramic in composites.	52

LIST OF FIGURES (continued)

Figure	Page
2.22 Curing chamber with controlled environment of 60°C and 98% RH.	53
2.23 SEM micrographs of PSZT70-PC composite; (a) ×1000 magnification and (b) ×5000 magnification.	54
2.24 Compressive strength results of PZT-PC composites.	56
2.25 The relationship between the piezoelectric constant and volume fraction of PMN; (a) d_{33} values and (b) g_{33} values.	57
2.26 Variation of (a) dielectric properties and (b) piezoelectric properties of 1-3 piezoelectric ceramic–cement composites as a function of P(MN)ZT ceramic volume fraction.	58
3.1 Flow chart of research plan, methodology and scope.	65
3.2 The model for fabricating 0-3 BZT-PC composites.	68
3.3 The hydraulic press.	68
3.4 The curing chamber.	69
3.5 Flow chart of 0-3 BZT-PC composites fabrication.	69
3.6 The diamond saw (Buehler ISO- MET Low speed saw).	70
3.7 Flow chart of 1-3 BZT-PC composites fabrication.	72
3.8 Flow chart of 2-2 BZT-PC composites fabrication.	74
3.9 Photograph of the dilatometer used for the thermal strain measurements.	76
3.10 Ultrasonic thickness meter (TM-8812).	77
3.11 Scanning electron microscope (SEM; JEOL JSM-5910LV).	78
3.12 The LCR-meter for dielectric properties measurements at room temperature.	80

LIST OF FIGURES (continued)

Figure	Page
3.13 The d_{33} meter model PM25.	82
3.14 The impedance meter (Hewlett Packard 4194A).	84
4.1 Effect of particle size on dielectric properties results of 0-3 BZT-PC composites.	86
4.2 The dielectric properties and comparison of models with dielectric constant of 0-3 BZT-PC composites.	87
4.3 Models of composite; (a) Series model, (b) Parallel model and (c) Cube model.	89
4.4 The effect of poling temperature on the piezoelectric coefficient (d_{33}).	91
4.5 The impedance and the phase spectra results of 0-3 BZT-PC composites composites with different BZT particle size at (a) $75 \mu\text{m}$ BZT particle size, (b) $212 \mu\text{m}$ BZT particle size and (c) $425 \mu\text{m}$ BZT particle size.	92
4.6 The effect of particle size of 0-3 BZT-PC composites on electromechanical coupling coefficient (K_t), piezoelectric coefficient (d_{33}) and piezoelectric voltage coefficient (g_{33}) results.	94
4.7 The impedance and the phase spectra results of 0-3 BZT-PC composites composites with different BZT content at (a) 40% BZT composite (b) 50% BZT composite (c) 60% BZT composite and (d) 70% BZT composite.	96
4.8 The effect of BZT content of 0-3 BZT-PC composites on electromechanical coupling coefficient (K_t) and piezoelectric coefficient (d_{33}) results.	97

LIST OF FIGURES (continued)

Figure	Page
4.9 Comparison of models with piezoelectric coefficient of 0-3 BZT-PC composites.	98
4.10 Comparison of models with piezoelectric voltage coefficient of 0-3 BZT-PC composites.	101
4.11 The effect of particle size of 0-3 BZT-PC composites on density, porosity and acoustic impedance results.	102
4.12 The density and porosity results of 0-3 BZT-PC composites with different BZT content.	103
4.13 The acoustic impedance results of 0-3 BZT-PC composites with different BZT content.	103
4.14 Thermal expansion as a function of temperature for 0-3 BZT-PC composites for first run; (a) 30% BZT composite, (b) 50% BZT composite and (c) 70% BZT composite.	105
4.15 Thermal expansion as a function of temperature for 0-3 BZT-PC composites, Portland cement and BZT ceramic; (a) heating (first run), (b) cooling (first run), (c) heating (second run) and (d) cooling (second run).	106
4.16 Thermal expansion coefficient for 0-3 BZT-PC composites, Portland cement and BZT ceramic; (a) heating (first run), (b) cooling (first run), (c) heating (second run), (d) cooling (second run), (e) effect of BZT content (heating and first run) and (f) effect of BZT content (cooling and first run).	107

LIST OF FIGURES (continued)

Figure	Page
4.17 Microstructure of 0-3 BZT-PC composite; (a) SEM micrograph and (b) EDX analysis.	110
4.18 The dielectric properties and comparison of models with dielectric constant of 1-3 BZT-PC composites.	114
4.19 The impedance and the phase spectra results of 1-3 BZT-PC composites with different BZT content at (a) 30% BZT composite, (b) 40% BZT composite, (c) 50% BZT composite, (d) 60% BZT composite and (e) 70% BZT composite.	116
4.20 The effect of BZT content of 1-3 BZT-PC composites on electromechanical coupling coefficient (K_t) and piezoelectric coefficient (d_{33}) results.	117
4.21 Comparison of models with piezoelectric coefficient of 1-3 BZT-PC composites.	117
4.22 Comparison of models with piezoelectric voltage coefficient of 1-3 BZT-PC composites.	119
4.23 The density and porosity results of 1-3 BZT-PC composites with different BZT content.	120
4.24 The acoustic impedance (Z_c) results of 1-3 BZT-PC composites with different BZT content.	121
4.25 Microstructure of 1-3 BZT-PC composite; (a) SEM micrograph and (b) EDX analysis.	122

LIST OF FIGURES (continued)

Figure	Page
4.26 The dielectric properties and comparison of models with dielectric constant of 2-2 BZT-PC composites.	125
4.27 The impedance and the phase spectra results of 2-2 BZT-PC composites with different BZT content at (a) 30% BZT composite, (b) 40% BZT composite, (c) 50% BZT composite, (d) 60% BZT composite and (e) 70% BZT composite.	126
4.28 The effect of BZT content of 2-2 BZT-PC composites on electromechanical coupling coefficient (K_t) and piezoelectric coefficient (d_{33}) results.	127
4.29 Comparison of models with piezoelectric coefficient of 2-2 BZT-PC composites.	129
4.30 Comparison of models with piezoelectric voltage coefficient of 2-2 BZT-PC composites.	129
4.31 The density and porosity results of 2-2 BZT-PC composites with different BZT content.	131
4.32 The acoustic impedance (Z_c) results of 2-2 BZT-PC composites with different BZT content.	132
4.33 Microstructure of 2-2 BZT-PC composite; (a) SEM micrograph and (b) EDX analysis.	133