

**SYNTHESIS AND CHARACTERIZATION OF
STRONTIUM AND COBALT DOPED AKERMANITE
BIOCERAMICS**

HOSSEIN MOHAMMADI

UNIVERSITI SAINS MALAYSIA

2019

**SYNTHESIS AND CHARACTERIZATION OF STRONTIUM AND COBALT
DOPED AKERMANITE BIOSCERAMICS**

by

HOSSEIN MOHAMMADI

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

November 2019

ACKNOWLEDGEMENT

The author wishes to acknowledge with immense gratitude, his supervisor, Prof. Dr. **Ahmad Fauzi Mohd Noor**, for his assistance, continuous support and personal involvements in all the aspects of this PhD research. The author is grateful to his co-supervisors, Dr. Yanny Marliana Baba Ismail and Dr. Khairul Anuar Shariff for their assistance in this PhD research. Working with them was an opportunity for great learning and experience. The author would also like to extend his gratitude to Dean Prof. Dr. Syed Fuad B. Saiyid Hashim and School of Materials and Mineral Resources Engineering (SMMRE). The author would also gratitude all the technical staff of the School of Materials and Mineral Resources Engineering, Univeristi Sains Malaysia, most especially, Encik Mokhtar Bin Mohamad, Encik Muhammad Khairi Bin Khalid, Encik Abdul Rashid Bin Selamat and Encik Mohammad Azrul Bin Zainol Abidin for making available the needed facilities in the accomplishment of this research work.

The author would also like to thank specially his parents and for their prayers, guidance, encouragement, and support. To all my friends especially Mona all over the world and in Iran, I say thank you all for being there for me.

Best wishes

Hossein Mohammadi

November 2019

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENT	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	ix
LIST OF FIGURES	xii
LIST OF SYMBOLS	xx
LIST OF ABBREVIATIONS	xxv
ABSTRAK	1
ABSTRACT	3
CHAPTER ONE	5
1.1 Research background	5
1.2 Synthetic calcium silicate bone substitutes	6
1.3 Problem statement	8
1.4 The objective of this research	11
1.5 Scope of the work	12
CHAPTER TWO	14
2.1 Introduction	14
2.2 Bone graft substitute	14
2.2.1 Autologous bone grafting	14
2.2.2 Allogeneic bone grafting	15

2.2.3	Xenografting	16
2.3	Biological bone	16
2.4	Bone anatomy	19
2.4.1	Bone macrostructure	19
2.4.1(a)	Cortical bone	20
2.4.1(b)	Cancellous bone	20
2.4.1(c)	Cortical bone vs cancellous	21
2.4.2	Inorganic phase	23
2.4.2(a)	Biological apatite	23
2.5	Bone remodeling and formation	25
2.6	Bone mechanical properties	27
2.7	Biomaterials	29
2.8	Biomaterials for bones tissue replacement	33
2.8.1	Bioceramics	33
2.8.2	Bioactive ceramics	35
2.8.2(a)	Calcium silicate (Ca-Si)	35
2.8.2(b)	Akermanite	41
2.8.2.(b)(i)	Mechanical properties	42
2.8.2.(b)(ii)	In vitro bioactivity and cellular behavior	44
2.9	Materials doping	55
2.10	Solid-state reaction	58

2.11 Solid-state sintering	60
2.11.1 Driving force for sintering	62
2.11.2 Matter transport	62
2.11.3 Mechanism of sintering	63
2.11.4 Stages of solid-state sintering	64
CHAPTER THREE	66
3.1 Introduction	66
3.2 Experimental procedure	66
3.2.1 Preliminary studies on akermanite synthesis	66
3.2.2 Dry pressing	68
3.2.3 Sintering regime	69
3.2.3(a) Effect of soaking time and heating rate	70
3.2.4 Strontium-substituted and Co-substituted akermanite synthesis	71
3.3 Characterizations	74
3.3.1 Specific surface area (SSA)	74
3.3.2 Thermal behavior	75
3.3.3 X-ray diffraction (XRD)	76
3.3.4 Fourier Transform Infrared (FTIR) Spectroscopy	78
3.3.5 Field Emission Scanning Electron Microscopy (FESEM)	79
3.3.6 Linear shrinkage measurement	79
3.3.7 Density/porosity measurement	80

3.3.8	Mechanical properties	82
3.3.8(a)	Diametral Tensile Strength (DTS)	82
3.3.8(b)	Hardness	83
3.3.8(c)	Indentation fracture toughness	85
3.3.9	Statistical analysis	86
3.3.10	Bioactivity evaluation	86
3.3.11	<i>In vitro</i> cytotoxicity evaluation	88
3.3.11(a)	Preparation of buffers and chemicals	88
3.3.11(b)	Preparation of growth media	89
3.3.11(c)	Preparation of cell culture	89
3.3.11(d)	Direct cytotoxicity tests on the pellets	90
CHAPTER FOUR		90
4.1	Introduction	90
4.2	Synthesis of akermanite	91
4.2.1	Preliminary studies on the effect of milling time	91
4.2.1(a)	BET Analysis	92
4.2.1(b)	DTA analysis and formation mechanism by XRD analysis	94
4.2.1(c)	FTIR analysis	106
4.2.2	Effect of sintering temperature on akermanite	107
4.2.2(a)	Linear shrinkage	111
4.2.2(b)	Relative density	113

4.3	Effect of heating rate and soaking time	116
4.3.1	XRD analysis	116
4.3.2	Microstructural evaluation	118
4.3.3	Porosity and relative density measurement	121
4.3.4	Linear shrinkage	127
4.3.5	Diametral tensile strength (DTS)	130
4.4	Sintering of Sr-substituted akermanite	131
4.4.1	Surface area analysis of Sr-substituted akermanite	132
4.4.2	XRD analysis	133
4.4.3	FTIR analysis	144
4.4.4	FESEM analysis	146
4.4.5	Porosity and relative density measurement	150
4.4.6	Linear shrinkage	152
4.4.7	Mechanical properties (DTS, hardness and fracture toughness)	153
4.4.7(a)	Diametral tensile strength (DTS)	153
4.4.7(b)	Hardness (HV)	155
4.4.7(c)	Indentation fracture toughness (K_{Ic})	156
4.4.7(d)	<i>In vitro</i> bioactivity	158
4.4.7(e)	<i>In vitro</i> biodegradation	163
4.4.7(f)	<i>In vitro</i> cell cytotoxicity	167
4.5	Sintering of Co-substituted akermanite	169

4.5.1	BET analysis	169
4.5.2	XRD analysis	170
4.5.3	FTIR analysis	179
4.5.4	FESEM analysis	181
4.5.5	Porosity and relative density measurements	184
4.5.6	Linear shrinkage	185
4.5.7	Mechanical properties (DTS, hardness and fracture toughness)	186
4.5.7(a)	Diametral tensile strength (DTS)	186
4.5.7(b)	Hardness (HV)	188
4.5.7(c)	Indentation fracture toughness (K_{Ic})	190
4.5.7(d)	<i>In vitro</i> bioactivity	192
4.5.7(e)	<i>In vitro</i> biodegradation	193
4.5.7(f)	<i>In vitro</i> cell cytotoxicity	195
4.6	Summary of the important finding	197
5.	CHAPTER FIVE	199
5.1	Conclusion	199
5.2	Recommendation	200
	REFERENCES	201
	APPENDICES	236
	LIST OF PUBLICATION	237

LIST OF TABLES

	Page
Table 2.1: The components of human hard tissue in adults .	23
Table 2.2: Comparison between the structural characteristics and mechanical properties of cortical bone and cancellous bone	29
Table 2.3: Example and function of biomaterials used in the body system, in contact with the internal tissues.	30
Table 2.4: A list of trace elements in the human body.	40
Table 2.5: Mechanical properties of dense akermanite in comparison with CaSiO_3 and HA.	44
Table 2.6: The <i>in vitro</i> and <i>in vivo</i> studies of akermanite-and doped-akermanite ceramic.	53
Table 3.1: Chemical reagents and solvent employed to synthesis akermanite and Sr and Co-substituted akermanite powders.	67
Table 3.2: Chemical compositions of the $\text{Ca}_2\text{MgSi}_2\text{O}_7$, $\text{Ca}_{2-x}\text{Sr}_x\text{MgSi}_2\text{O}_7$ and $\text{Ca}_2\text{Mg}_{1-y}\text{Co}_y\text{Si}_2\text{O}_7$ powders.	72
Table 3.3: The order, molecular weight and amounts of reagents for the preparation of 1000 ml SBF	86
Table 4.1: Specific surface area and particle size of as-synthesized powder versus milling time.	92
Table 4.2: Crystallographic data of sintered akermanite samples at 1200°C for 1–4 h milling.	104
Table 4.3: Functional groups detected from the FTIR spectra of the sintered samples sintered at 1200°C after 1–4 milling time.	107
Table 4.4: The crystallite size obtained at three different soaking time and heating rates after sintering at 1200°C .	117

Table 4.5:	The crystallographic data obtained at three different soaking time and heating rates after sintering at 1200°C.	118
Table 4.6:	A summary synthesis conation for akermanite ceramic.	124
Table 4.7:	BET surface area and corresponding particle size for as-milled unsubstituted and Sr-substituted powders	133
Table 4.8:	Crystallographic data obtained from XRD results after sintering at 1200°C.	136
Table 4.9:	Crystallographic data obtained from XRD results after sintering at 1225°C. Crystallographic data obtained from XRD results after sintering at 1225°C.	141
Table 4.10:	Crystallographic data obtained from XRD results after sintering at 1250°C.	142
Table 4.11:	Functional groups detected from the FTIR spectra of the sintered akermanite and Sr-substituted akermanite at 1200°C and 1250°C.	145
Table 4.12:	Grain size measurements (μm) for sintered akermanite and Sr-substituted akermanite samples at 1200°C, 1225°C and 1250°C, respectively	148
Table 4.13:	Specific surface area and particle size of Co-substituted and unsubstituted as milled powders for 3 h milling time.	170
Table 4.14:	Crystallographic data obtained from XRD results after sintering at 1200°C.	173
Table 4.15:	Crystallographic data obtained from XRD results after sintering at 1225°C.	174
Table 4.16:	Crystallographic data obtained from XRD results after sintering at 1250°C.	175

Table 4.17: Functional groups detected from the FTIR spectra of the sintered akermanite and Sr-substituted akermanite at 1200°C.	180
Table 4.18: Grain size measurements (μm) for sintered akermanite and Co-substituted akermanite.	181
Table 4.19: Summary of important findings in the present study	198

LIST OF FIGURES

	Page
Figure 1.1: Flowchart of the scope of the research	13
Figure 2.1: Hierarchical structural units of bone on different scales, comprising extracellular matrix.	17
Figure 2.2: Cross-sectional view of human bone.	19
Figure 2.3: Schematic of bone organization in the cortical and trabecular bone Molecular structure.	22
Figure 2.4: A schematic of cellular activity during the bone remodeling process	26
Figure 2.5: Evolution of biomaterials from 1 st generation to 3 rd generation with enhanced functionality.	33
Figure 2.6: The schematic illustration of the apatite formation process on the Ca–Si-based ceramics in the SBF solution.	36
Figure 2.7: Material transport pathways during the sintering process.	63
Figure 3.1: Flowchart of the experimental procedure.	68
Figure 3.2: Pelletizing process.	69
Figure 3.3: Sintering regime for the sintering of akermanite pellet.	70
Figure 3.4: Flowchart of the experimental procedure for Sr-substituted and Co-substituted akermanite samples	74
Figure 3.5: Density measurement by Archimedes method for sintered pellets.	81
Figure 3.6: A schematic of the diametral compression test.	83
Figure 3.7: A summary of the Vickers microhardness test.	84
Figure 3.8: A schematic of radial crack by indentation method.	85
Figure 3.9: Graphical representation of sintered akermanite, Sr-substituted and Co-substituted samples immersed into SBF solution.	88
Figure 4.1: XRD patterns of as-milled powders before calcination.	95

- Figure 4.2: (a) DTA graph of as-milled powers for 3 h and (b) XRD patterns of 3 h milled powders after calcination, (c) XRD pattern of sintered pellet at 1000°C, 1100°C and 1200°C; symbols denote (♦) akermanite, (♣) diopside, (♠) monticellite, (♥) enstatite, (*) merwinite and (●) silica, respectively. 97
- Figure 4.3: The phase diagram of MgO–CaO–SiO₂ ternary system calculated from thermodynamic parameters (Temperatures in °C). 98
- Figure 4.4: XRD patterns of samples for 1–4 h milling sintered at (a)1000°C, (b)1100°C and (c)1200°C and symbols (♠), (*) and (♦) denotes monticellite, merwinite, and akermanite phases, respectively and (d) XRD patterns of the sharpest peaks in the 2θ range of 31°–31.5° after sintering at 1200°C. 102
- Figure 4.5: (a–d) average crystallite size estimated from modified Scherrer equation ($\ln\beta = \ln(k\lambda/L) + \ln(1/\cos\theta)$) after 1–4 milling time, respectively. 103
- Figure 4.6: Lattice parameter (a) (a–d) estimated from Nelson-Riley function ($F(\theta) = [\cos 2\theta / \sin \theta + \cos 2\theta / \theta] / 2$) for 1–4 h milling time after sintering at 1200°C. 105
- Figure 4.7: (a–d) Lattice parameter (c) estimated from Nelson-Riley function ($F(\theta) = [\cos 2\theta / \sin \theta + \cos 2\theta / \theta] / 2$) for 1–4 h milling time after sintering at 1200°C. 105
- Figure 4.8: Fourier transform infrared spectroscopy (FTIR) spectra of the samples after 1–4 h milling time and sintered at 1200°C. 106
- Figure 4.9: FESEM micrographs of the thermally-etched surface microstructure of sintered akermanite samples at 1200°C and 1250°C for 1–4 milling time with a heating rate of 5°C/min (Magnification 5k). 108
- Figure 4.10: FESEM micrographs of the fracture surface of sintered akermanite samples at 1200°C and 1250°C for 1–4 milling time, with a heating rate of 5°C/min (Magnification 5k). 109
- Figure 4.11: Effect of milling time and sintering temperature on the linear shrinkage of sintered samples 112

- Figure 4.12: Effect of milling time and sintering temperature on the open porosity and relative density of sintered samples. 113
- Figure 4.13: Effect of milling time and sintering temperature on the densification factor of sintered ceramics. 115
- Figure 4.14: XRD patterns of sintered samples at 1200°C for different heating rates (a) 2°C/min and (b) 5°C/min after 2,4 and 6 h soaking time. 117
- Figure 4.15: FESEM micrographs of thermally etched and fracture surface of akermanite samples sintered at 1200°C with 2°C/min for different soaking time, respectively (Magnification 10k). 119
- Figure 4.16: FESEM micrographs of thermally etched and fracture surface of akermanite samples sintered at 1200°C with 5°C/min for different soaking time, respectively (Magnification 10k). 120
- Figure 4.17: (a) Relative density and (b) porosity of sintered samples for 3 h milling time for different soaking time with a heating rate of 5°C/min. 122
- Figure 4.18: Effect of soaking time and sintering temperature on the densification factor of sintered akermanite. 123
- Figure 4.19: FESEM micrographs of thermally etched akermanite samples sintered at 1200°C, 1225°C and 1250°C with 5°C/min for 2,4, 6 h soaking time, respectively (Magnification 5k). 125
- Figure 4.20: Effect of soaking time and heating rate on sintering shrinkage of sintered akermanite pellets at 1200°C for 2,4 and 6 h respectively. 129
- Figure 4.21: Effect of soaking time on sintering shrinkage of sintered akermanite pellets at different temperatures, for 2,4 and 6 h respectively, with a heating rate of 5°C/min. 129
- Figure 4.22: (a) Effect of milling time and sintering temperature and (b) effect of sintering temperatures on the tensile strength of sintered samples for 3 h milling time and a heating rate of 5°C /min. 131
- Figure 4.23: (a–c) XRD patterns of akermanite (ak) and Sr-substituted samples; (d–f) XRD patterns of the sharpest peak in the 2θ range of 30–34° after sintering at 1200°C, 1225°C and 1250°C, respectively. 134

Figure 4.24: Average crystallite size estimated from modified Scherrer equation ($\ln\beta = \ln(k\lambda/L) + \ln(1/\cos\theta)$) for (a) ak, (b) 0.05Sr, (c) 0.10Sr and (d) 0.15Sr, respectively sintered at 1200°C. 136

Figure 4.25: Lattice parameter (a) estimated from Nelson-Riley function ($F(\theta) = [\cos^2\theta/\sin\theta + \cos^2\theta/\theta]/2$) for (a) ak, (b) 0.05Sr, (c) 0.10Sr and (d) 0.15Sr, respectively sintered at 1200°C. 137

Figure 4.26: (a–d) Lattice parameter (c) estimated from Nelson-Riley function ($F(\theta) = [\cos^2\theta/\sin\theta + \cos^2\theta/\theta]/2$) for ak, 0.05Sr, 0.10Sr and 0.15Sr, respectively sintered at 1200°C. 138

Figure 4.27: Average crystallite size estimated from modified Scherrer equation ($\ln\beta = \ln(k\lambda/L) + \ln(1/\cos\theta)$) for (a) ak, (b) 0.05Sr, (c) 0.10Sr and (d) 0.15Sr, respectively sintered at 1225°C. 139

Figure 4.28: Lattice parameter (a) estimated from Nelson-Riley function ($F(\theta) = [\cos^2\theta/\sin\theta + \cos^2\theta/\theta]/2$) for (a) ak, (b) 0.05Sr, (c) 0.10Sr and (d) 0.15Sr, respectively sintered at 1225°C. 140

Figure 4.29: Lattice parameter (c) estimated from Nelson-Riley function ($F(\theta) = [\cos^2\theta/\sin\theta + \cos^2\theta/\theta]/2$) for (a) ak, (b) 0.05Sr, (c) 0.10Sr and (d) 0.15Sr, respectively sintered at 1225°C. 141

Figure 4.30: Average crystallite size estimated from modified Scherrer equation ($\ln\beta = \ln(k\lambda/L) + \ln(1/\cos\theta)$) for (a) ak, (b) 0.05Sr, (c) 0.10Sr and (d) 0.15Sr, respectively sintered at 1250°C. 142

Figure 4.31: Lattice parameter (a) estimated from Nelson-Riley function ($F(\theta) = [\cos^2\theta/\sin\theta + \cos^2\theta/\theta]/2$) for (a) ak, (b) 0.05Sr, (c) 0.10Sr and (d) 0.15Sr, respectively sintered at 1250°C. 143

Figure 4.32: Lattice parameter (c) estimated from Nelson-Riley function ($F(\theta) = [\cos^2\theta/\sin\theta + \cos^2\theta/\theta]/2$) for (a) ak, (b) 0.05Sr, (c) 0.10Sr and (d) 0.15Sr, respectively sintered at 1250°C. 143

Figure 4.33: (a) Fourier transform infrared spectroscopy (FTIR) spectra akermanite and Sr-substituted akermanite sintered at 1200°C, (b and c) the enlarged spectra of akermanite and 0.10Sr-substituted akermanite at 1250°C in the range of 600–1400 cm^{-1} , respectively 145

Figure 4.34: FESEM micrographs of the thermally etched surface of akermanite and Sr-substituted akermanite sintered at 1200°C, 1225°C, and 1250°C (Magnification 10k).	147
Figure 4.35: FESEM micrographs fracture of akermanite and Sr-substituted akermanite sintered at 1200°C, 1225°C, and 1250°C (Magnification 10k).	149
Figure 4.36: FESEM micrographs of unetched surface and fracture surface of akermanite sintered at 1250°C (Magnification 10k).	150
Figure 4.37: Effect of Sr substitution on (a) porosity and (b) relative density of akermanite at different sintering temperatures 1200°C, 1225°C, and 1250°C.	151
Figure 4.38: Effect of Sr substitution on the sintering shrinkage of akermanite at different sintering temperatures 1200°C, 1225°C, and 1250°C.	152
Figure 4.39: Effect of Sr substitution on DTS of akermanite at different sintering temperatures 1200°C, 1225°C, and 1250°C.	153
Figure 4.40: Effect of Sr^{2+} substitution on microhardness of akermanite at different sintering temperatures 1200°C, 1225°C, and 1250°C.	155
Figure 4.41: Effect of Sr substitution on fracture toughness of akermanite at different sintering temperatures 1200°C, 1225°C, and 1250°C.	157
Figure 4.42: FESEM micrographs of (a) akermanite (ak), (b) 0.05Sr, (c) 0.10Sr, and (d) 0.15Sr samples sintered at 1200°C after soaking in SBF solution for 21 days (Magnification 5k).	160
Figure 4.43: Mechanism of apatite formation in SBF solution for silicate biomaterials (Rahmati <i>et al.</i> , 2018).	161
Figure 4.44: (a) XRD and (b) FTIR of sintered akermanite and Sr-substituted akermanite samples at 1200°C after soaking in SBF solution for 21 days	162
Figure 4.45: (a) weight loss and (b) pH variations of sintered akermanite and Sr-substituted akermanite samples at 1200°C after soaking in SBF solution for 21 days.	164

- Figure 4.46: (a) Ca (b) Mg, (c) Sr and (d) P ion concentration after soaking in SBF solution for 21 days for sintered akermanite and Sr-substituted akermanite samples at 1200°C. 166
- Figure 4.47: Cell proliferation of human fetal osteoblast (hFOB) on akermanite and Sr-substituted akermanite after 1,2 and 7 days. 168
- Figure 4.48 (a–c): XRD patterns of akermanite (ak) and Co-substituted samples after sintering at 1200°C, 1225°C and 1250°C; (d–f) XRD patterns .of the sharpest peak in the 2θ range of 30°–34° after sintering at 1200°C, 1225°C and 1250°C, respectively. 171
- Figure 4.49: (a–c) average crystallite size estimated from modified Scherrer equation ($\ln\beta = \ln(k\lambda/L) + \ln(1/\cos\theta)$) for ak, 0.02Co and 0.05Co at 1200°C, respectively. 172
- Figure 4.50: (a–c) average crystallite size estimated from modified Scherrer equation ($\ln\beta = \ln(k\lambda/L) + \ln(1/\cos\theta)$) for ak, 0.02Co and 0.05Co at 1225°C, respectively. 174
- Figure 4.51: (a–c) average crystallite size estimated from modified Scherrer equation ($\ln\beta = \ln(k\lambda/L) + \ln(1/\cos\theta)$) for ak, 0.02Co and 0.05Co at 1250°C, respectively. 175
- Figure 4.52: Lattice parameter (a) estimated from Nelson–Riley function ($F(\theta) = [\cos^2\theta/\sin\theta + \cos^2\theta/\theta]/2$) for (a)ak, (b)0.02Co and (c)0.05Co, respectively sintered at 1200°C. 176
- Figure 4.53: Lattice parameter (c) estimated from Nelson–Riley function ($F(\theta) = [\cos^2\theta/\sin\theta + \cos^2\theta/\theta]/2$) for (a)ak, (b)0.02Co and (c)0.05Co, respectively sintered at 1200°C. 177
- Figure 4.54: Lattice parameter (a) estimated from Nelson–Riley function ($F(\theta) = [\cos^2\theta/\sin\theta + \cos^2\theta/\theta]/2$) for (a)ak, (b)0.02Co and (c)0.05Co, respectively sintered at 1225°C. 177
- Figure 4.55: Lattice parameter (c) estimated from Nelson–Riley function ($F(\theta) = [\cos^2\theta/\sin\theta + \cos^2\theta/\theta]/2$) for (a)ak, (b)0.02Co and (c)0.05Co, respectively sintered at 1225°C. 178

- Figure 4.56: Lattice parameter (a) estimated from Nelson–Riley function ($F(\theta) = [\cos^2\theta/\sin\theta + \cos^2\theta/\theta]/2$) for (a)ak, (b)0.02Co and (c)0.05Co, respectively sintered at 1250°C. 178
- Figure 4.57: Lattice parameter (c) estimated from Nelson–Riley function ($F(\theta) = [\cos^2\theta/\sin\theta + \cos^2\theta/\theta]/2$) for (a)ak, (b)0.02Co and (c)0.05Co, respectively sintered at 1250°C. 179
- Figure 4.58: FTIR spectra of the akermanite (ak) and Co-substituted samples sintered at 1200°C. 180
- Figure 4.59: FESEM micrograph of the thermally etched surface of akermanite and Co-substituted akermanite sintered at 1200°C, 1225°C and 1250°C (Magnification 10k). 182
- Figure 4.60: FESEM micrograph of the fracture surface of akermanite and Co-substituted akermanite sintered at 1200°C, 1225°C, and 1250°C (Magnification 5k). 183
- Figure 4.61: Effect of Co substitution on (a) porosity and (b) relative density of akermanite at different sintering temperatures 1200°C, 1225°C, and 1250°C 185
- Figure 4.62: Effect of Co^{2+} substitution on the sintering shrinkage of akermanite at different sintering temperatures (a)1200°C, (b)1225°C and (c)1250°C. 186
- Figure 4.63: Effect of Co^{2+} substitution on DTS of akermanite at different sintering temperatures 1200°C, 1225°C, and 1250°C. 187
- Figure 4.64: Effect of Co substitution on the hardness of akermanite at different sintering temperatures 1200°C, 1225°C, and 1250°C. 189
- Figure 4.65: Effect of Co substitution on fracture toughness of akermanite at different sintering temperatures 1200°C, 1225°C, and 1250°C. 191
- Figure 4.66: FESEM images of the akermanite (ak), 0.02Co, and 0.05Co, samples sintered at 1200°C after soaking in SBF solution for 21 days (Magnification 5k). 192

Figure 4.67: (a) weight loss and (b) pH variations of sintered akermanite and Co-substituted akermanite samples at 1200°C after soaking in SBF solution for 21 days. 193

Figure 4.68: (a) Ca (b) Mg, (c) Co and (d) P ion concentration of sintered akermanite and Co-substituted akermanite samples at 1200°C after soaking in SBF solution for 21 days. 195

Figure 4.69: Cell proliferation of human fetal osteoblast (hFOB) on akermanite and 2 mol% Co-substituted akermanite after 1,2 and 7 days. 197

LIST OF SYMBOLS

\AA	Angstrom
cm	centimeter
$^{\circ}\text{C}$	Degree Celsius
$^{\circ}\text{K}$	Kelvin
$^{\circ}/\text{min}$	Degree/minute
T	Temperature
ΔH	Enthalpy
ΔG	Gibbs Free Energy
θ	Bragg Angle
λ	Wavelength
d	Distance between Planes
l	Diagonal Length
hkl	Miller Indices
d_{hkl}	Interplanar Spacing
kV	Kilovolt
mA	Milliampere
kgf	Kilogram Force

s	Seconds
a	Lattice Parameter a
c	Lattice Parameter c
V	Lattice Volume
β	Diffraction Peak Full Width at Half Maximum Intensity
L	Crystallite Size
Ca	Calcium
P	Phosphorous
k	Scherrer Constant
Sr	Strontium
Co	Cobalt
Mg	Magnesium
Si	Silicon
Au	Gold
KBr	Potassium Bromide
ρ	Density
P_o	Apparent Porosity
ψ	Theoretical Density

V_s	Volume of SBF
g	Gram
h	Hour
D	Diffusion Coefficient
D_0	Constant for Diffusion
t	Thickness
W	Weight
S_a	Surface Area
Z	Number of Molecules Per Unit Cell
M	Molecular Weight
σ	Tensile Strength
HV	Hardness Number
N	Newton
F	Force
mol	Mole
rpm	Rotation Per Minute
<	Less than
m	Meter

mm^2	Millimeter Square
cm^2	Centimeter Square
MPa	Mega Pascal = 1 N/mm^2
GPa	Giga Pascal
K_{Ic}	Fracture Toughness
a_i	Half Diagonal Length
c_i	Radial Crack Dimension
l_i	Indentation Crack Length
ml	millilitre
N_A	Avogadro's number
n	Number of Samples
p	Significance Level
r	radius
h	height
min	Minute
$>$	More than
M	Molarity
nm	Nanometer