HYDROXYAPATITE AND MONTMORILLONITE FILLED HIGH DENSITY POLYETHYLENE HYBRID COMPOSITES FOR BIOMEDICAL APPLICATIONS

MUHAMAD RASYIDI BIN HUSIN

UNIVERSITI TEKNOLOGI MALAYSIA

HYDROXYAPATITE AND MONTMORILLONITE FILLED HIGH DENSITY POLYETHYLENE HYBRID COMPOSITES FOR BIOMEDICAL APPLICATIONS

MUHAMAD RASYIDI BIN HUSIN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Polymer)

Faculty of Chemical Engineering
Universiti Teknologi Malaysia

APRIL 2012

To my beloved mother, wife and three sweet daughters

ACKNOWLEDGEMENT

In the name of the Almighty ALLAH, the most gracious and merciful, with his grace and blessing has led to the success in completing this thesis. Peace be upon the Prophet Muhammad (pbuh), may Allah bless him.

First and foremost, I would like to express my heartfelt gratitude to my supervisor, Assoc. Prof. Dr. Mat Uzir Wahit for his patience, encouragement, excellent advice and great concern to my work. Sincere thanks to my co-supervisors, Assoc. Prof. Eng. Dr. Mohammed Rafiq Dato' Abdul Kadir and Assoc. Prof. Dr. Wan Aizan Wan Abdul Rahman for their helpful comments, ideas and advices.

I also wish to express my appreciation to all lecturers in the Department of Polymer Engineering, the Quality Control staff in Poly-Star Compounds Sdn. Bhd. and Malaysian Institute of Nuclear Technology Research (MINT) for their help and support in my research. Then, my sincere thanks to all technicians who have given special effort with valuable technical guidance during this project.

Finally, thanks also go to all my family who is very understanding, especially my beloved wife, Nursalasawati Rusli, for providing the necessary atmosphere of understanding and support during untold amount of hours at home required for writing this thesis. To my daughters, Nadiah Husna, Nabilah Najwa and Hana Nadzirah, for taking too much times from you to complete this research. Also friends of high degree, especially Mazatusziha Ahmad, Mutmirah Ibrahim, Ahmad Ramli Rashidi and Khairul Anuar for their tips, and cooperation for the endless time I needed. To all of you, I say a most heartfelt thank you.

ABSTRACT

In this study, new composite formulation for biomedical applications was investigated. The effects of hydroxyapatite (HA) and montmorillonite (MMT) on the mechanical, morphological, thermal and biological properties of high density polyethylene (HDPE) composites which compatibilized with high density polyethylene grafted maleic anhydride (HDPE-g-MAH) were studied. These formulations were compounded using a single screw nano-mixer extruder followed by injection moulding. The effect of HA loadings up to 50 phr were studied and the compositions of MMT and HDPE-g-MAH were kept constant at 5 phr. The performance of the single screw nanomixer extruder was compared with a twin screw extruder. The mechanical properties were studied through tensile, flexural and izod impact testing. X-ray diffraction (XRD) was used to investigate the dispersibility of MMT layers. The thermal properties were analyzed using differential scanning calorimetry (DSC). The morphology of the composites were characterized by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The study of biological properties was carried out through bioactivity test using simulated body fluid (SBF) immersion. The morphology and calcium-phosphate (Ca-P) precipitation in SBF was characterized by SEM, accompanied by energy dispersive analysis x-ray (EDX) and XRD. The result showed that, the addition of HA significantly increased the strength and stiffness of composites but the elongation at break and impact strength were decreased. The HDPE-HA composites containing 50 phr of HA had the highest elastic modulus, tensile and flexural strength. However, with addition of MMT and HDPE-g-MAH, the composites containing 30 phr HA exhibited high tensile and flexural strength. The melting temperature (T_m) and crystallisation temperature (T_c) of the composite were not affected by the addition of HA particles, and the crystallinity of the HDPE matrix was increased with increasing of HA content. Incorporation of HA increased the thermal stability of the composites significantly. Based on the mechanical properties of the composite, the performance of single screw extruder nanomixer was more effective in enhancing the HA dispersion compared to twin screw extruder. The bulk formation of apatite layer covering at the composites surface indicated the excellent bioactivity properties of HA and depiction of bioactive composites. Results showed that the composite with 30 phr of HA had optimal mechanical and biological properties.

ABSTRAK

Dalam kajian ini, satu formula baru komposit bagi aplikasi bioperubatan telah dikaji. Kesan-kesan hidroksiapatit (HA) dan montmorilonit (MMT) terhadap sifat-sifat mekanikal, morfologi, terma dan biologi komposit polietilena berketumpatan tinggi (HDPE) yang diserasikan dengan polietilena berketumpatan tinggi asetik malic (HDPE-g-MAH) telah dikaji. Formulasi-formulasi ini telah diadun menggunakan penyemperit skru tunggal berpenyebati nano diikuti oleh acuan penyuntikan. Kesan penambahan HA sehingga 50 phr telah dikaji dan komposisi MMT dan HDPE-g-MAH ditetapkan pada 5 phr. Prestasi penyemperit skru tunggal berpenyebati nano dibandingkan dengan penyemperit skru berkembar. Sifat-sifat mekanikal dikaji melalui ujian regangan, lenturan dan hentaman. Pembelauan sinar-x (XRD) telah digunakan untuk mengkaji kebolehsebaran lapisan MMT. Sifat terma telah dianalisa menggunakan kalorimetri pengimbasan pembezaan (DSC). Ciri-ciri morfologi telah dicirikan oleh mikroskop pengimbas elektron (SEM) dan mikroskop pemancaran elektron (TEM). Kajian sifat-sifat biologi telah dijalankan melalui ujian bioaktiviti secara rendaman ke dalam cecair badan simulasi (SBF). Morfologi dan pemendakan kalsium fosfat (Ca-P) dalam SBF telah dicirikan oleh SEM, diiringi oleh analisis penyerakan tenaga sinar-X (EDX) dan XRD. Keputusan menunjukkan bahawa penambahan HA meningkatkan kekuatan dan kekukuhan komposit dengan ketara, tetapi menurunkan pemanjangan pada takat putus dan kekuatan hentaman. Komposit HDPE-HA dengan kandungan 50 phr-HA mempunyai modulus anjal, kekuatan regangan dan kekuatan lenturan tertinggi. Walau bagaimanapun, dengan penambahan MMT dan HDPE-g-MAH, komposit yang mengandungi 30 phr HA mempamerkan kekuatan regangan dan kekuatan lenturan yang tinggi. Suhu peleburan (T_m) dan suhu penghabluran (T_c) komposit tidak terjejas dengan penambahan zarah HA, dan penghabluran matrik HDPE telah bertambah dengan peningkatan kandungan HA. Penambahan HA meningkatkan kestabilan terma komposit dengan ketara. Berdasarkan sifat-sifat mekanikal komposit, prestasi penyemperit skru tunggal berpenyebati nano adalah lebih berkesan dalam meningkatkan keserakan HA berbanding penyemperit skru berkembar. Pembentukan pukal lapisan apatit yang meliputi pada permukaan komposit, menunjukkan sifat-sifat bioaktiviti HA yang bagus dan menunjukkan komposit adalah bioaktif. Keputusan-keputusan menunjukkan bahawa komposit dengan 30 phr-HA mempunyai sifat-sifat mekanik dan biologi yang optimum.

TABLE OF CONTENTS

CHAPTER	TITLE		PAGE
	TITLE		i
	DECLARATION		ii
	DEDICATION		iii
	ACKNOWLEDGEMENTS		iv
	ABSTRACT		v
	ABSTRAK		vi
	TABLE OF CONTENTS		vii
	LIST OF TABLES		xi
	LIST OF FIGURES		xii
	LIST OF ABBREVIATIONS		xv
	LIST OF SYMBOLS		xvi
1	**INTRODUCTION**		1
	1.1	Background of Research	1
	1.2	Problem Statement	4
	1.3	Objectives of Research	5
	1.4	Scopes of Research	6
	1.5	Significance of Study	7
2	**LITERATURE REVIEW**		8
	2.1	Natural Bone	8
	2.2	Hip Joint	10

2.3	Biomaterials		11
	2.3.1	Ceramics as a Biomaterials (Bioceramics)	11
	2.3.2	Hydroxyapatite (HA)	13
	2.3.3	Polymer as a Biomaterial	14
	2.3.4	High Density Polyethylene	16
	2.3.5	Montmorillonite (MMT)	16
	2.3.6	Clay Distribution	17
	2.3.7	Melt Intercalation	18
2.3	Nanocomposites		20
	2.3.1	HDPE in Polymer Layered Silicate (PLS)	21
2.4	Characterization of Composites		23
	2.4.1	X-Ray Diffraction (XRD)	23
	2.4.2	Transmission Electron Microscopy (TEM)	24
	2.4.3	Bone-analogue Polymer Composites	25
	2.4.5	HDPE/HA Composites	29
3	**METHODOLOGY**		31
3.1	Materials		31
	3.1.1	High Density Polyethylene (HDPE)	31
	3.1.2	Hydroxyapatite (HA)	32
	3.1.3	Montmorillonite (MMT)	32
	3.1.4	Compatibilizer (HDPEgMAH)	32
3.2	Composition and Designation of Materials		33
3.3	Sample Preparation		34
	3.3.1	Melt Compounding (Extrusion)	34
	3.3.2	Injection Moulding	35
3.4	Physical Testing		35
	3.4.1	Density Measurement	35
3.5	Mechanical tests		35
	3.5.1	Tensile Test	35
	3.5.2	Flexural Test	36
	3.5.3	Impact Test	36

3.6 Sample Characterization 37
3.6.1 Differential Scanning Calorimetry (DSC) 37
3.6.2 X-Ray Diffraction (XRD) 37
3.6.3 Brunauer-Emmet-Teller (BET) 38
3.6.4 Morphological Study 39
3.6.4.1 Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) 39
3.6.4.2 Transmission Electron Microscop (TEM) 39
3.7 Biological Testing 40
3.7.1 Biocompatibility Testing 40

4 RESULTS AND DISCUSSION 41

4.1 Characterization of HA 41
4.2 Mechanical Properties of Uncompatibilized and Compatibilized HDPE-HA Composites 43
4.2.1 Effect of HA loading on Tensile and Flexural Strength of Uncompatibilized and Compatibilized HDPE Composites 43
4.2.2 Effect of HA loading on Elastic and Flexural Modulus of Uncompatibilized and Compatibilized HDPE Composites 46
4.2.3 Effect of HA loading on Elongation at Break uncompatibilized and compatibilized HDPE-HA Composites 48
4.2.4 Effect of HA loading on Impact Strength of uncompatibilized and compatibilized HDPE-HA composites 49
4.2.5 Thermal Analysis 51
4.2.5.1 Differential Scanning Calorimetry (DSC) 51
4.2.6 Morphological Properties 53
4.2.6.1 Scanning Electron Microscopy (SEM) 53

4.3 Effect MMT on Mechanical, Thermal and Morphological Properties of mHDPE/MMT-HA Composites 57
4.3.1 Effect of MMT on Tensile and Flexural Strength of Compatibilized HDPE-HA Composites 57
4.3.2 Effect of MMT on Elastic and Flexural Modulus of Compatibilized and Uncompatibilized HDPE-HA Composites 60
4.3.3 Effect of MMT on Elongation at Break of Compatibilize HDPE-HA Composites 62
4.3.4 Effect of MMT on Impact Strength of Compatibilize HDPE-HA Composites 63
4.3.5 Thermal Analysis 63
4.3.5.1 Differential Scanning Calorimetry (DSC) 64
4.3.6 Morphological Properties 65
4.4 The Effect of Processing Method on Mechanical Properties of Compatibilized mHDPE/MMT-HA Composites 67
4.4.1 Structural Characterization and Morphological Properties 71
4.4.1.1 X-Ray Diffraction (XRD) 71
4.4.1.1 Transmission Electron Microscopy (TEM) 75
4.5 Biological Test 78
4.5.1 SEM-EDX Analysis 78
4.5.2 XRD Analysis of Bioactivity Properties 83

5 CONCLUSIONS AND RECOMMENDATIONS 86

5.1 Conclusions 86
5.2 Recommendations 88

REFERENCES 89

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Calcium phosphates and their Ca/P ratios	12
2.2	Mechanical properties of common biomaterial and cortical bone	26
3.1	Material properties of HDPE (HDPE 5403AA)	31
3.2	Blend formulation of HDPE composites	33
4.1	Particle size properties of HA	41
4.2	DSC of neat HDPE, uncompatibilized and compatibilized MMT filled HDPE composites	52
4.3	DSC of neat HDPE, mHDPE-MMT and compatibilized HDPE-HA composites	65
4.4	XRD parameters of montmorillonite, neat HDPE and mHDPE/MMT composites	71
4.5	XRD parameters of mHDPE/MMT-HA composites using single and twin screw with different HA content	74

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	Hierarchical structure of human cortical bone	9
2.2	Anatomy of human hip joint.	10
2.3	Crystal structure of HA	13
2.4	Schematic representation of the different classes of polyethylene	15
2.5	Structure of 2:1 phyllosilicates	17
2.6	Three possible structures of polymer-silicate composites	18
2.7	Schematic representation of polymer-layered silicate Nanocomposite obtained direct melt intercalation	19
2.8	XRD pattern of intercalated and exfoliated nanocomposites	24
2.9	TEM images of intercalated and exfoliated nanocomposites	25
2.10	Various applications of different polymer composites biomaterials	28
3.1	Single screw extruder with special design nano-mixer	34
4.1	Particles size distribution of HA powder	42
4.2	SEM micrograph of HA particles	42
4.3	XRD pattern of HA powder	43
4.4	The effect of HA content on tensile strength of compatibilized and compatibilized HDPE-HA composites	45
4.5	The effect of HA content on flexural strength of compatibilized and compatibilized HDPE-HA composites	45
4.6	The effect of HA content on elastic modulus of compatibilized and compatibilized HDPE-HA composites	47
4.7	The effect of HA content on flexural modulus of compatibilized and compatibilized HDPE-HA composites	47

4.8	The effect of HA content on elongation at break of compatibilized and compatibilized HDPE-HA composites	49
4.9	The effect of HA content on impact strength of compatibilized and compatibilized HDPE-HA composites	51
4.10	Crystallinity of neat HDPE, uncompatibilized and compatibilized HDPE-HA composites at various content	53
4.11	SEM micrograph of uncompatibilized HDPE-HA composites	55
4.12	SEM micrograph of compatibilized HDPE-HA composites	56
4.13	Tensile strength of compatibilized mHDPE/MMT-HA composites	58
4.14	Flexural strength of compatibilized mHDPE/MMT-HA composites	59
4.15	Schematic representation of interaction diagram of HA, MMT, HDPE and HDPE-g-MAH.	59
4.16	The effect of MMT on elastic modulus of compatibilized HDPE-HA composites	61
4.17	The effect of HA content on flexural modulus of compatibilized MMT filled HDPE composites	61
4.18	The effect of HA content on elongation at break of compatibilized HDPE-HA composites	62
4.19	The effect of HA content on impact strength of compatibilized HDPE-HA composites	64
4.20	SEM micrographs of compatibilized MMT filled HDPE-HA composites	66
4.21	Effect of MMT on tensile strength of compatibilized mHDPE/MMT-HA composites	68
4.22	Effect of MMT on flexural strength of compatibilized mHDPE/MMT-HA composites	68
4.23	Effect of MMT on elastic modulus of compatibilized mHDPE/MMT-HA composites	69
4.24	Effect of MMT on flexural modulus of compatibilized mHDPE/MMT-HA composites	69
4.25	Effect of MMT on elongation at break of compatibilized mHDPE/MMT-HA composites	70
4.26	Effect of MMT on impact strength of compatibilized	

	mHDPE/MMT-HA composites	70
4.27	Comparison XRD patterns neat HDPE, pristine MMT (Nanomer 1.30P) and mHDPE/MMT composites	72
4.28	X-ray diffraction patterns of mHDPE/MMT-HA composites processing by using single screw extruder	73
4.29	X-ray diffraction patterns of mHDPE/MMT-HA composites processing by using twin extruder	75
4.30	TEM micrograph showing the structure of mHDPE/MMT composites using single screw extruder	76
4.31	TEM micrograph showing the structure of mHDPE/MMT-30HA composites using single screw extruder	77
4.32	TEM micrograph showing the structure of mHDPE/MMT composites using twin screw extruder	77
4.33	SEM micrograph of uncompatibilized HDPE-HA composites soaked in the simulated body fluid for various periods. (a) 3 days, (b) 5 days and (c) 7 days	80
4.34	SEM micrograph of compatibilized mHDPE-HA composites soaked in the simulated body fluid for various periods. (a) 3 days, (b) 5 days and (c) 7 days	81
4.35	SEM micrograph of compatibilized mHDPE/MMT-HA composites soaked in the simulated body fluid for various periods. (a) 3 days, (b) 5 days and (c) 7 days	82
4.36	EDX analysis of (a) HDPE-HA, (b) mHDPE-HA and (c) mHDPE/MMT-HA composites soaked in simulated body fluid for various periods	83
4.37	XRD trace of HDPE-HA composites before and after immersed in SBF different period time	84
4.38	XRD trace of mHDPE-HA composites before and after immersed in SBF different period time	85
4.39	XRD trace of mHDPE/MMT-HA composites before and after immersed in SBF different period time	85

LIST OF ABBREVIATIONS

ASTM	-	American Standards Test Method
DSC	-	Differential scanning calorimetry
MMT	-	Montmorillonite
MPa	-	Mega pascal
GPa	-	Giga pascal
HDPE	-	High density polyethylene
HDPE-g-MAH	-	Maleic anhydride grafted high density polyethylene
XRD	-	X-ray diffraction
EDX	-	Energy dispersive X-ray
SBF	-	Simulated body fluid
BET	-	Brunauer-Emmet-Teller
TEM	-	Transmission electron microscopy

LIST OF SYMBOLS

cm^2	-	centimeter square
cm^3	-	centimeter cubic
d	-	Spacing between diffractional lattice plane (interspacing)
g	-	gram
H_f	-	Heat of Fusion
ΔH_{100}	-	Heat of Fusion of theoretically 100% crystalline polymer
mg	-	milligram
T_g	-	Glass transition temperature
T_m	-	Melting temperature
T_c	-	Crystallization temperature
w_i	-	weight fraction
wt%	-	weight percent
X_c	-	Crystallinity content
^oC/min	-	Degree celsius per minute
θ	-	Diffraction angle
λ	-	Wave length
Cu	-	Copper
K	-	Pottasium
α	-	Alpha

CHAPTER 1

INTRODUCTION

1.1 Background of Research

Nanocomposites, in the sense of hybrid materials with novel properties beyond the realm of unfilled polymers and conventional composites, bear high promise for enabling new uses and applications of polymer materials. In the simplest approach, they can expand the window of applications of a given polymer, and in the best case they can enable the use of polymer–matrix composites in applications where metal or ceramic materials are currently used.

Nowadays, the commercial interest of polymer nanocomposites applications are widely used in motor vehicle parts and packaging. With further research and development, the applications of nanocomposites have been explored intensively in medical area especially in medical device, drug-delivery systems, diagnostic and bio-analytical systems, surgical implants, and innovative packaging. Polymers which represent the largest class of biomaterials continue to replace metals, glass and other conventional materials in the medical field. Polymers of biomaterial class have been studied to cater usage in biomedical devices that include orthopaedic, dental, soft tissue, and cardiovascular implants.

Biomaterials artificial material used to make implants, to replace crocked biological structure and restore form and function. Thus, this biomaterials help to improve the quality of life and longevity human beings. Field of biomaterials have shown rapid growth to keep demands from an aging population. These materials are

used in different parts of the human body as a replacement for artificial valves in the heart, replacement implants in shoulders, hips, elbows, ears and orodental structures stents in blood vessels, knees (Ramakrishna *et al.,* 2001). The number of implants used for knee and hip replacements are significantly high. There is substantial increase in the demand for the new type of long lasting implants.

Based on the data collected on total joint replacements surgery, the number of total hip replacements is estimated to rise by 174% (572,000 replacements) by the end of 2030. Meanwhile total knee arthoplasties is projected to grow up to 3.48 million replacements (Kurtz *et al.,* 2007). The number of replacements in Asian countries is significantly lower than the revision of primary total hip replacement in some countries of Central Europe which was 2.2 per 1000 population. However, the fastest growth is expected in emerging markets of Asia (Kiefer, 2007). The incidence rates of hip fractures in Korea were 173 per 100,000 in women and 91 per 100,000 in men. Statistic obtained for other Asian countries including Taiwan (505 per 100,000 in women and 225 per 100,000 in men), Hong Kong (459 and 180 per 100,000), Singapore (442 and 164 per 100,000), and Thailand (269 and 114 per 100,000) (Ko *et al.,* 2011). The incidence of hip fracture in the city of Kuala Lumpur and the surrounding districts has increased from 1981 to 0.7 per 1,000 population in 1989 with the mean age was 73 (50-103) years (Lee *et al.,* 1993). the development of specific Asian implant designs started for cemented in the year 1980s, followed with cementless implants in the 1990s with a greater focus on specific sizing needs for smaller patients anatomy and different bone morphology according to ethnology and regions (Kiefer, 2007).

The reason for joint replacements is caused by diseases such as osteoporosis (weakening of the bones), osteoarthritis (inflammation in the bone joints) and trauma. The effect of degenerative diseases leads to degradation of the mechanical properties of the bone due to excessive loading or absence of normal biological self-healing process. Thus the solution for these problems is artificial biomaterials since the three critical issues in today's biomedical implants and devices are the design, material selection and biocompatibility.

The properties of material used for orthopaedic implants especially for load bearing applications need to be excellent biocompatibility and superior corrosion resistance in body environment. Recently, the materials that have been used for these applications are high density polyethylene (HDPE), ultra high molecular weight (UHMWPE), polypropylene (PP), polyetheretherketone (PEEK), polymethyl methacrylate (PMMA) and polysulfone (PSU). In the development of biomaterials for biomedical applications, as far as mechanical properties are concerned, the main target is to strike balance of stiffness, strength, toughness and biocompatibility.

At present, two approaches have been identified as potential route to achieving this goal. This involves inclusion of fillers or nanofillers into thermoplastic matrix or compound to form thermoplastic biocomposites or nanocomposites. The second approaches is compounding of thermoplastic biomaterials with compatibilizer. Hydroxyapatite (HA) reinforced HDPE composite has been under study since 1980s, when Bonfield *et al.,* (1981) lead pioneering work to develop of composite as an alternative for bone replacement. Much attention has been paid towards the development of material for bone tissue engineering with HA as bioactive filler in polymer composites (Fang *et al.,* 2006, Albano *et al.,* 2006). Applying of HA filler particles to form composites has been shown to enhance bone-bonding rates and mechanical properties. The emerging interest of using HA is due to its chemical and structural similarity with natural bone mineral. Liang *et al.,* (2003) has been reported on the use of montmorillonite (MMT) filled HDPE in enhancing the mechanical and thermal properties of the composites for the purpose of biomedical application. MMT offers special properties due to its small size and huge specific surface area. Thus, the excellence performance of MMT leads to the development of nanocomposites materials system in combining the advantages of polymers, HA and MMT.

However, the interfacial problem between HA and the polymer matrix is one of the major factors in determining the properties of the composites. A number of researchers have conducted improvement of interfacial strength between the HA and polymer matrix using coupling agent and grafting methods. Wang *et al.,* (2001) and Deb *et al.,*(1996) used silane coupling agent and acrylic acid grafting to improve

interfacial bonding between HDPE and HA as it was revealed that only mechanical interlocking occurred between the two phases.

Therefore, this work introduces HA as a particulate bioactive phase with combination of MMT in development of biomedical composite. In order to improve the properties of the composite, the interfacial bond strength between HA and HDPE was improved by using compatibilizer. Thus, this research focuses on the preparation of MMT-reinforced HA/HDPE composites and its effects on mechanical, thermal and biocompatibility properties.

1.2 Problem Statement

In the last few decades, the use of HA reinforced HDPE composite as bone analogue materials has been successfully used clinically in minor load bearing applications such as orbital floor implants and middle ear bone replacement. The main advantage of polyethylene as polymer matrix is due to the biocompatible properties and the ability to allow the incorporation of a large amount of bioceramic particles in the system. However, the use of HDPE as polymer matrix in load bearing applications is limited due to the low stiffness and strength of HDPE. In addition, the mechanical properties of the composites still greatly lower than cortical bone due to the micron-sized reinforcement. Thus, the incorporation of MMT provides an alternative choice to improved the HDPE/HA composite properties which can be melt-processed using current plastics technologies.

In order to improve the strength and stiffness of HDPE, various methods have been explored. Filler surface coated with coupling agents and polymer graft treatment were used to improve the interface adhesion which produced marginal enhancement (Wang and Bonfield, 2001), but the bioactivity of the filler might lose after treatment. Hydrostatic extrusion or shear controlled orientation in injection moulding (SCORIM) was also tried to align polymer chains, the stiffness was significantly enhanced but the yield strength was not improved much (Reis *et al.,* 2001; Sousa *et al.,* 2002).

Therefore, in the present work, the HA was incorporated into HDPE in combination of MMT as reinforcement filler processed through single screw extrusion nanomixer was developed. It is expected that, by using an established manufacturing route, the HA and MMT particles would be finely disperse and distribute in the HDPE matrix. The effect of HA concentration ranging from 10 to 50 phr on the mechanical, thermal and morphology properties were explored. Further, the addition of compatibilizer to improve the interface adhesion between polymer matrix and filler without the expense of bioactivity properties was also investigated.

1.3 Objectives of Research

The present work aims to develop new biocomposites materials namely HDPE/HA/MMT composite. In this research HDPE/HA composites with the presence of MMT and compatibilizer HDPE grafted maleic anhydride (HDPE-g-MAH) were produced using single screw extruder and twin screw extruder nanomixer followed by injection moulding method. The target application of these new materials is for biomedical application such as load bearing (acetabular cup). In this work, five alternative approaches have been investigated to achieve a good combination of properties and processability of bioactive ceramic reinforced polymer composites. The aims are:

i) To investigate the effect of HA on mechanical properties and determine the optimum percentage of HA in the composites.
ii) To investigate the effect of MMT and the HDPE-g-MAH incorporation into the HDPE/HA composites on the mechanical properties.
iii) To study in vitro test on bioactive properties for biocompatibility testing using simulated body fluid (SBF).
iv) To examine the performance of the composite produced using single screw extruder nanomixer as compared to twin screw extruder from–particle distribution and mechanical properties point of view.

1.4 Scopes of Research

In order to achieve the objectives of the research, the following activities have to be carried out:

1. Sample preparation
   Sample preparation was conducted via melt intercalation method.
   Is involves:

   a) Single screw extrusion nanomixer process of compounding HDPE, HA, MMT and HDPE-g-MAH.
   b) Injection moulding to prepare test specimen according to standard.
   c) Twin screw extruder process to compare with single screw extruder nanomixer.

2. Mechanical properties studies

   a) Tensile test
   b) Flexural test
   c) Impact test

3. Sample characterization and morphological study. To characterize the composites, the following apparatus were used:

   a) Differential Scanning Calorimeter (DSC)
   b) Brunauer-Emmett-Teller (BET)
   c) Scanning Electron Microscope (SEM)
   d) Transmission Electron Microscopy (TEM)
   e) X-ray Diffraction (XRD)
   f) Biological Testing

4. Data analysis

1.5 Significance of the Study

From this research, a new HDPE/HA composites formulation with nanofiller MMT for biomedical implant applications was developed which has the potential to be commercialized. The incorporation of MMT and compatibilizer have significantly improved the mechanical and bioactivity properties of HDPE/HA composite.

REFERENCES

Albano, C., Karam, A., Domínguez, N., Sánchez, Y., Puerta, J., Perera, R. and González, G. (2006). Optimal Conditioning for the Preparation of HDPE-HA Composites in an Internal Mixer. *Molecular Crystals and Liquid Crystals*. 448(1): 251-259.

Albano, C., Perera, R., Cataño, L., Alvarez, S., Karam, A. and González, G. (2010). Compatibilization of Polyolefin/Hydroxyapatite Composites Using Grafted Polymers. *Polymer-Plastics Technology and Engineering*. 49(4): 341-346.

Alexandre, M. and Dubois, P. (2000). Polymer-Layered Silicate Nanocomposites: Preparation, Properties and Uses of a New Class of Materials. *Materials Science and Engineering*. 28(1-2):1-63.

Bakar, A., M. S., Cheang, P. and Khor, K. A. (2003). Mechanical Properties of Injection Molded Hydroxyapatite-polyetheretherketone Biocomposites. *Composites Science and Technology*. 63(3-4): 421-425.

Bonfield, W., Grynpas, M. D., Tully, A. E., Bowman, J. and Abram, J. (1981). Hydroxyapatite Reinforced Polyethylene- a Mechanically Compatible Implant Material for Bone Replacement. *Biomaterials*. 2(3): 185-l86.

Boskey, A. L. (1998). Biomineralization: Conflicts, Challenges, and Opportunities. *Journal of Cellular Biochemistry Supplement*. 72(30-31): 83-91.

Bureau, M. N., Perrin-Sarazin, F. and Ton-That, M. -T. (2004). Polyolefin Nanocomposites: Essential Work of Fracture Analysis. *Polymer Engineering and Science*. 44(6): 1142-1151.

Burg, K. J. L., Porter, S. and Kellam, J. F. (2000) Biomaterial developments for bone tissue engineering. *Biomaterials* 21(23): 2347-2359

Cao, W. and Hench, L. L, (1996). Bioactive Materials. *Ceramics International*. 22(6): 493-507.

Chrissafis, K., Paraskevopoulos, K. M., Tsiaoussis, I. and Bikiaris D. (2009). Comparative Study of the Effect of Different Nanoparticles on the Mechanical Properties, Permeability, and Thermal Degradation Mechanism of HDPE. *Journal of Applied Polymer Science*. 114(3): 1606–1618.

Cheang, P. and Khor, K. A. (2003). Effect of Particulate Morphology on the Tensile Behaviour of Polymer-hydroxyapatite Composites. *Materials Science and Engineering A*. 345(l-2): 47-54.

Chen, L., Wong, S-C. and Pisharath, S. (2003). Fracture Properties of Nanoclay-Filled Polypropylene. *Journal Applied Polymer Science*. 88(14): 3298-3305.

Chow, W. S., Mohd. Ishak, Z. A., Ishiaku, U. S., Karger-Kocsis, J. and Apostolov, A. A. (2004). The Effect of Organoclay on the Mechanical Properties and Morphology of Injection-molded Polyamide 6/polypropylene Nanocomposites. *Journal of Applied Polymer Science*. 91(1): 175-189.

Chu, K. T., Oshida, Y., Hancock, E. B., Kowolik, M. J., Barco, T. and Zunt, S. L. (2004). Hydroxyapatite/PMMA Composites as Bone Cements. *Bio-Medical Materials and Engineering*. 14(1): 87-105

Coombes, A. G. A. and Meikle, M. C. (1994). Resorbable synthetic polymers as replacements for bone graft. *Clinical Materials*. 17(1): 35-67

Cotterell, B., Chia, J. Y. H., and Hbaieb, K. (2007). Fracture Mechanisms and Fracture Toughness in Semicrystalline Polymer Nanocomposites. *Engineering Fracture Mechanics*. 74(7): 1054-1078.

Daniels, A. U., Chang, M. K. O. and Andriano, K. P. (1990). Mechanical Properties of Biodegradable Polymers and Composites Proposed for Internal Fixation of Bone. *Journal of Applied Biomaterials*. 1(1): 57-78

Dasari A., Yu Z-Z., Mai Y-W., Hu G-H. and Varlet J. (2005). Clay Exfoliation and Organic Modification on Wear of Nylon 6 Nanocomposites Processed by Different Routes. *Composites Science and Technology*. 65(15-16): 2314-2328.

Deb, S., Wang, M., Tanner, K. E. and Bonfield, W. (1996) Hydroxyapatite-Polyethylene Composites: Effect of Grafting and Surface Treatment of Hydroxyapatite. *Journal of Materials Science: Materials in Medicine*. 7(4): 191-193,

Elliott, J. C. (1994). Structure and Chemistry of the Apatite and Othercalcium Orthophosphates. Amsterdam: Elsevier.

Espigares, I., Elvira, C., Mano, J. F., Vazquez, B., Roman, J, S., and Reis, R. L. (2002). New Partially Degradable and Bioactive Acrylic Bone Cements Based on Starch Blends and Ceramic Fillers. *Biomaterials*. 23(8): 1883-1895

Evans, S. L. and Gregson, P. J. (1998). Composite Technology in Load-bearing Orthopaedic Implants. *Biomaterials*. 19(15): 1329-1342.

Fang, L., Leng, Y. and Gao, P. (2005). Processing of Hydroxyapatite Reinforced Ultrahigh Molecular Weight Polyethylene for Biomedical Applications. *Biomaterials*. 26(17): 3471-3478

Fang, L., Gao, P. and Leng, Y. (2006). Processing and Mechanical Properties of HA/UHMWPE Nanocomposites. *Biomaterials*. 27(20):3701-3707.

Fornes, T. D., Yoon, P. J., Keskkula, H. and Paul, D. R. (2001). Nylon 6 Nanocomposites : The Effect of Matrix Molecular Weight. *Polymer*. 42(25): 9929-9940.

Fornes, T. D., and Paul, D. R. (2003). Crystallization Behavior of Nylon 6 Nanocomposites. *Polymer*. 44(14): 3945–3961.

Fried, J. R. (2003). Polymer Science and Technology. 2nd Edition. Prentice Hall

Freemont, A. J. (1998). The Tissues We eal with. (I) Bone. *Current Orthopaedics*. 12(3): 181-192.

Geetha M., Singh A. K., Asokamani R. and Gogia A. K. (2009). Ti Based Biomaterials, the Ultimate Choice for Orthopaedic Implants – A review. *Progress in Materials Science*. 54(3): 397-425.

Giannelis E. P., Krishnamoorti R. and Manias, E. (1999). Polymer-Silicate Nanocomposites: Model Systems for Confined Polymers and Polymer Brushes. *Advances in Polymer Science*. 138: 107-147.

Glimcher, M. J., (2001). The Nature of the Mineral Phase in Bone: Biological and Clinical Implications. *Bone Mechanics Handbook*. (23-49).

Gopakumar, T. G., Lee, J. A., Kontopoulou, M. and Parent, J. S. (2002) Influence of Clay Exfoliation on the Physical Properties of Montmorillonite/Polyethylene Composites. *Polymer*, 43(20): 5483-5491

Gorrasi, G., Tortora, M., Vittoria, V., Kaempfer, D., and Mülhaupt, R. (2003). Transport Properties of Organic Vapors in Nanocomposites of Organophilic Layered Silicate and Syndiotactic Polypropylene. 44(13): 3679–3685

Griffith, L. G. and Naughton, G. (2002). Tissue Engineering--Current Challenges and Expanding Opportunities. *Science*. 295(5557): 1009-1014.

Gu, Y.W., Khor, K.A. and Cheang, P. (2003). In Vitro Studies of Plasma-Sprayed Hydroxyapatite/Ti-6Al-4V Composite Coatings in Simulated Body Fluid (SBF)". *Biomaterials*. 24(9), 1603-1611.

Guo, C-Y., Ke, Y., Liu, Y., Mi, X., Zhang, M. and Hu, Y. (2009). Preparation and Properties of Polyethylene/Montmorillonite Nanocomposites Formed via Ethylene Copolymerization. *Polymer International*. 58(11): 1319–1325.

Han, G., Lie, Y., Wu, Q., Kojima, Y. and Suzuki, S. (2008). Bamboo–Fiber Filled High Density Polyethylene Composites: Effect of Coupling Treatment and Nanoclay. *Journal of Polymers and the Environment*. 16(2):123-130

Hasegawa, N., Kawasumi, M., Kato, M., Usuki, A. and Okada, A. (1998). Preparation and Mechanical Properties of Polypropylene-Clay Hybrids Using a Maleic Anhydride Modified Polypropylene Oligomer. *Journal of Applied Polymer Science*. 67(1): 87–92.

Heggli, M. (2001). *Elastomeric Nanocomposites*. Zurich: Institute of Polymers, ETH Zurich.

Heinemann, J., Reichert, P., Thomann, R. and Mülhaupt, R. (1999). Polyolefin Nanocomposites Formed by Melt Compounding and Transition Metal Catalyzed Ethene Homo- and Copolymerization in the Presence of Layered Silicates. *Macromolecular Rapid Communications*. 20(8): 423-430.

Hench, L. L., (1980). Biomaterials. *Science*. 208(4446):826-31.

Hench, L. L. and Wilson, J. (1984). Surface-active biomaterials. *Science*. 226(4675):630-6.

Hench, L. L. (1988). Bioactive ceramics. *Annals of the New York Academy of Sciences*. 523:54-71.

Hench, L. L. (1998). Bioactive Materials: The Potential for Tissue Regeneration. *Journal of Biomedical Materials Research*. 41(4): 511-518.

Herrera-Franco, P. J. and Valadez-González, A. (2004). Mechanical Properties of Continuous Natural Fibre-Reinforced Polymer Composites. *Composites: Part A: Applied Science and Manufacturing*. 35(3): 339-345.

Hole, J. W. (1990). Human Anatomy and Physiology. 5th ed. Dubuque, Iowa W.C. Brown Publishers.

Joseph, R., McGregor, W. J., Martyn, M. T., Tanner, K. E. and Coates. P. D. (2002). Effect of Hydroxyapatite Morphology/Surface Area on the Rheology and Processability of Hydroxyapatite Polyethylene Composite. *Biomaterials*. 23(21): 4295-4302

Juhasz, J. A., Best, S. M., Brooks, R., Kawashita, M., Miyata, N. and Kokubo, T. (2004). Mechanical Properties of Glass-ceramic A-W-Polyethylene Composites: Effect of Filler Content and Particle Size. *Biomaterials*. 25(6): 949-955.

Kato, M., Usuki, A. and Okada, A. (1997). Synthesis of Polypropylene Oligomer-clay Intercalation Compounds. *Journal of Applied Polymer Science*. 66(9): 1781-1785.

Kato, M., Okamoto, H., Hasegawa, N., Tsukigase, A. and Usuki, A. (2003). Preparation and Properties of Polyethylene-Clay Hybrids. *Polymer Engineering Science*. 43(6): 1312-1316

Kiefer, H. (2007). Differences and Opportunities of THA in the USA, Asia and Europe. *Bioceramics and Alternative Bearings in Joint Arthroplasty, Ceramics in Orthopaedics, 12th BIOLOX® Symposium Proceedings*. 7-8 September. Seoul, Republic of Korea: Springer, Session 1A, 3 - 8.

Knowles, J. C., Hastings, G. W., Ohta, H., Niwa, S. and Boeree, N. (1992) Development of a Degradable Composite for Orthopaedic Use: In Vivo Biomechanical and Histological Evaluation of Two Bioactive Degradable Composites Based on the Polyhydroxybutyrate Polymer. *Biomaterials*. 13(8): 491-6.

Ko, K., Narayanasamy, S., Wee, L. H., Lo, N. N., Yeo, J. S., Yang, K. Y., Yeo, W., Chong, C. H. and Thumboo, J. (2011). Health-Related Quality of Life after

Total Knee Replacement or Unicompartmental Knee Arthroplasty in an Urban Asian Population. *Value in Health* 14(2): 322–328

Kokubo, T. (1998). Apatite Formation on Surfaces of Ceramics, Metals and Polymers in Body Environment. *Acta Materialia*. 46(7): 2519-2527.

Kokubo, T., Kim, H. M. and Kawashita, M. (2003). Novel Bioactive Materials with Different Mechanical Properties. *Biomaterials*. 24(13): 2161-2175.

Koo, C. M., Ham, H. T., Kim, S. O., Wang, K.H, Chung, I., Kim, D. C. and Zin, W. C. (2002). The Effect of Crystallization on the Structure and Morphology of Polypropylene/Clay Nanocomposites. *Macromolecules***.** 35(13): 5116-5122

Kornmann, X., Lindberg, H., and Berglund, L. A. (2001). Synthesis of Epoxy-clay Nanocomposites: Influence of the Nature of the Clay on Structure. *Polymer*. 42: 1303-1310.

Kornmann, X., Berglund, L. A., Sterte, J. and Giannelis, E. P. (1998). Nanocomposites Based on Montmorillonite and Unsaturated Polyester. *Polymer Engineering and Science*. 38(8): 1351-1358.

Kurtz, S.M., Ooij, V. A., Ross, R., Malefijt, J. D. W., Peloza. J., Ciccarelli, L. and Villarraga, M. L. (2007). Polyethylene Wear and Rim Fracture in Total Disc Arthroplasty. *The Spine Journal*. 7(1):12-21

Liang, G., Xu, J., Bao, S., and Xu, W. (2004). Polyethylene/Maleic Anhydride Grafted Polyethylene/Organic-montmorillonite Nanocomposites. I. Preparation, Microstructure, and Mechanical Properties. *Journal of Applied Polymer Science*. 91(6):3974–3980

Liu, Y. and Wang, M. (2007). Developing a Composite Material for Bone Tissue Repair. *Current Applied Physics*. 7(5):547-554

LeBaron, P. C., Wang, Z. and Pinnavaia, T. J. (1999). Polymer-Layered Silicate Nanocomposites: An Overview. *Applied Clay Science*. 15(1-2): 11-29.

Lee, J. H., Jung, D., Hong, C. E., Rhee, K. Y. and Advani, S. G. (2005). Properties of Polyethylene-layered Silicate Nanocomposites Prepared by Melt Intercalation with a PP-g-MA Compatibilizer. *Composites Science and Technology*. 65(13): 1996-2002.

Lee, M. C., Sidhu, S. J. and Pan, L. K. (1993) Hip fracture incidence in Malaysia 1981-1989. *Acta Orthopaedica Scandinavica*. 64 (2): 178-180

Lee, Y. H., Park, C. B., Sain, M., Kontopoulou, M. and Zheng, W. (2007). Effects of Clay Dispersion and Content on the Rheological, Mechanical Properties, and Flame Retardance of HDPE/Clay Nanocomposites. *Journal of Applied Polymer Science* 105(4):1993–1999

LeGeros, R. Z. (2008). Calcium-Phosphate Based Osteoinductive Materials. *Chemical . Reviews*. 108(11):4742-4753

Leuteritz, A., Pospiech, D., Kretzschmar, B., Willeke, M., Jehnichen, D., Jentzsch, U., Grundke, K. and Janke, A. (2005). Polypropylene-Clay Nanocomposites: Comparison of Different Layered Silicates. *Macromolecular Symposia*. 221(1): 53-62.

Liang, G., Xu, J., Bao, S. and Xu, W. (2004). Polyethylene/Maleic Anhydride Grafted Polyethylene/Organic-Montmorillonite Nanocomposites. I. Preparation, Microstructure, and Mechanical Properties. *Journal of Applied Polymer Science*. 91(6): 3974-3980.

Lim, K. L. K., Mohd Ishak, Z. A., Ishiaku, U. S., Fuad, A. M. Y., Yusof, A. H., Czigany, T., Pukanzsky, B. and Ogunniyi, D. S. (2006). High Density Polyethylene/Ultra High Molecular Weight Polyethylene Blend. II. Effect of Hydroxyapatite on Processing, Thermal, and Mechanical Properties. *Journal of Applied Polymer Science*. 100(5): 3931-3942.

Liu, Y. and Wang, M. (2007). Fabrication and Characteristics of Hydroxyapatite Reinforced Polypropylene as a Bone Analogue Biomaterial. *Journal of Applied Polymer Science*. 106(4): 2780-2790.

Maiti, S. N. and Sharma, K. K. (1992). Studies on Polypropylene Composites Filled with Talc Particles. Part I Mechanical Properties. *Journal Of Materials Science*. 27(17): 4605-4613.

Mano, J. F., Sousa, R. A., Boesel, L. F., Neves, N. M. and Reis, R. L. (2004). Bioinert, Biodegradable and Injectable Polymeric Matrix Composites for Hard Tissue Replacement: State of the Art and Recent Developments. *Composites Science and Technology*. 64(6): 789-8l7.

Mehrabzadeh, M. and Kamal, M. R. (2004). Melt Processing of PA-66/Clay, HDPE/Clay and HDPE/PA-66/Clay Nanocomposites. *Polymer Engineering and Science*. 44(6): 1152-1161.

Min, K. D., Kim, M. Y., Choi, K. Y., Lee, J. H. and Lee, S. G. (2006). Effect of Layered Silicates on the Crystallinity and Mechanical Properties of HDPE/MMT Nanocomposite Blown Films. *Polymer Bulletin*. 57(1): 101-108.

Minkova, L. and Magagnini, P. L. (1993). Crystallization Behaviour and Thermal Stability of HDPE Filled During Polymerization. *Polymer Degradation and Stability*. 42(1): 107-115.

Miyagawa, H., Jurek, R. J., Mohanty, A. K., Misra, M., and Drzal, L. T. (2006). Biobased Epoxy/clay Nanocomposites as a New Matrix for CFRP. *Composites A*. 37: 54-62.

Morawiec, J., Pawlak, A., Slouf, M., Galeski, A., Piorkowska, E. and Krasnikowa, N. (2005). Preparation and Properties of Compatibilized LDPE/organo-modified Montmorillonite Nanocomposites. *European Polymer Journal*. 41(5): 1115-1122.

Nguyen, Q. T. and Baird, D. G. (2006). Preparation of Polymer–Clay Nanocomposites and their Properties. *Advances in Polymer Technology*. 25(4): 270–285

Osman, M. A., Rupp, J. E. P. and Suter, U. W. (2005). Tensile Properties of Polyethylene-layered Silicate Nanocomposites. *Polymer*. 46(5): 1653-1660.

Pandey, A., Jan, E. and Aswath, P. B. (2006). Physical and Mechanical Behaviour of Hot Rolled HDPE/HA Composites. *Journal of Materials Science*. 41(11): 3369-3376.

Parija, S., Nayak, S. K., Verma, S. K., and Tripathy, S. S. (2004). Studies on Physico-Mechanical Properties and Thermal Characteristics of Polypropylene/Layered Silicate Nanocomposites. *Polymer Composite*. 25: 646-652.

Park, J., B. Hip Joint Prosthesis Fixation-Problems and Possible Solutions. In: Bronzino JD, editor. *The biomedical engineering handbook*. 2nd ed. Boca Raton,FL:CRC Press, 2000.

Patricia, M. A. M. P., Vargas, M. D., Werlang, M. M., Yoshida, V. P. and Mauler, R. S. (2001). High-Density Polyethylene Modified by Polydimethylsiloxane. *Journal of Applied Polymer Science*. 82(14): 3460-3467.

Paul, D. R., and Robeson, L. M. (2008). Polymer Nanotechnology: Nanocomposites. *Polymer*. 49(15): 3187-3204.

Peacock, A. J. (2000). Handbook of Polyethylene: Structures, Properties and Applications. New York: Marcel Dekker, Inc.

Petersson, L. and Oksman, K. (2006). Biopolymer Based Nanocomposites: Comparing Layered Silicates and Microcrystalline Cellulose as Nanoreinforcement. *Composites Science and Technology*. 66: 2187-2196.

Pilliar, R. M., Blackwell, R., Macnab, I. and Cameron, H. U. (1976). Carbon Fiber Reinforced Bone Cement in Orthopedic Surgery. *Journal of Biomedical Materials Research*. 10(6): 893-906.

Pötschke, P., Bhattacharyya, A. R. and Janke, A. (2004). Melt Mixing of Polycarbonate with Multiwalled Carbon Nanotubes: Microscopic Studies on the State Dispersion. *European Polymer Journal*, 40(1):137-148.

Ramakrishna, S., Mayer, J., Wintermantel, E. and Leong, K. W. (2001). Biomedical Applications of Polymer-Composite Materials: A Review. *Composites Science and Technology*. 61(9): l189-1224.

Ramakrishna, S., Huang, Z. M., Kumar, G. V., Batchelor, A. W. and Mayer, J. (2004). An Introduction to Biocomposites. London: Imperial College Press. Series on Biomaterials & Bioengineering (1): 1-33.

Ramirez, C., Albano, C., Karam, A., Domingueical,. N, Sanchez, Y., Gonzalez, G. (2005) Mechanical, Thermal, Rheological and Morphological Behaviour of Irradiated PP/HA Composites. *Nuclear Instruments and Methods in Physics Research*. 236B(1-4):531-535.

Ray, S. S., Yamada, K., Okamoto, M., Ogami, A. and Ueda, K. (2003). New Polylactide/Layered Silicate Nanocomposites. 3. High-Performance Biodegradable Materials. *Chemistry of Materials*. 15: 1456-1465.

Ray, S., and Okamoto, M. (2003). Polymer/Layered Silicate Nanocomposites: A Review from Preparation to Processing. *Progress in Polymer Science*. 28: 1539-1641.

Rea, S. M., Best, S. M. and Bonfield, W. (2004). Bioactivity of Ceramic-Polymer Composite with Varied Composition and Surface Topography. *Journal of Materials Science: Material in Medicine*. 5(5):997-1005

Reis, R. L., Cunha, A. M., Oliveira, M. J., Campos, A. R. (2001). Relationship Between Processing and Mechanical Properties of Injection Molded High Molecular Mass Polyethylene Plus Hydroxyapatite Composites. *Materials Research Innovations*. 4(5-6): 263-272

Reichert, P., Nitz, H., Klinke, S., Brandsch, R., Thomann, R. and Mülhaupt, R. (2000). Poly(propylene)/Organoclay Nanocomposite Formation: Influence of Compatibilizer Functionality and Organoclay Modification. *Macromolecular Materials and Engineering*. 275(1): 8-17.

Rezwan, K., Chen, Q. Z., Blaker, J. J. and Boccaccini, A. R. (2006). Biodegradable and Bioactive Porous Polymer/inorganic Composite Scaffolds for Bone Tissue Engineering. *Biomaterials*. 27(18): 3413-3431.

Rho, J. Y., Kuhn-Spearing, L. and Zioupos, P. (1998). Mechanical Properties and the Hierarchical Structure of Bone. *Medical Engineering and Physics*. 20(2): 92-102.

Ruhé, P. Q., Wolke, J. G. C. and Spauwen, P. H. M. (2006). Calcium Phosphate Ceramics for Bone Tissue Engineering. In: Jansen, J. A. Tissue Engineering and Artificial Organs. *Taylor & Francis Group*. Chapter 38.

Russias, J., Saiz, E., Nalla, R. K., Gryn, K., Ritchie, R. O., Tomsia A. P. (2006). Fabrication and Mechanical Properties of PLA/HA Composites: A Study of in Vitro Degradation. *Materials Science and Engineering*. 26C(8): 1289–1295

Roeder, R. K., Sproul, M. S. and Turner, C. H. (2003). Hydroxyapatite Whiskers Provide Improved Mechanical Properties in Reinforced Polymer Composites. *Journal of Biomedical Materials Research*. 67A(3):801-12.

Rosales,C., Perera, R., Gonzalez, J., Ichano, M., Rojas, H. and Sánchez, A. (1999). Grafting of Polyethylenes by Reactive Extrusion. II. Influence on Rheological and Thermal Properties. *Journal of Applied Polymer Science*. 73(13): 2549-2567

Saha, S. and Pal, S. (1984). Improvement of Mechanical Properties of Acrylic Bone Cement by Fiber Reinforcement. *Journal of Biomechanics*. 17(7): 467-478

Smolko, E. and Ramero, G. (2007). Studies on Crosslinked Hydroxyapatite-polyethylene Composites as a Bone-analogue Material. *Radiation Physics and Chemistry*. 76(8-9): 1414-1418.

Sousa, R. A., Reis, R. L., Cunha, A. M. and Bevis, M. J. (2002). Structure Development and Interfacial Interactions in High-Density Polyethylene/Hydroxyapatite (HDPE/HA) Composites Molded With Preferred Orientation. *Journal of Applied Polymer Science*. 86(11): 2873–2886

Sousa, R. A., Reis, R. L., Cunha, A. M. and Bevis, M. J. (2003a). Processing and Properties of Bone-analogue Biodegradable and Bioinert Polymeric Composites. *Composites Science and Technology*. 63(3-4): 389-402.

Sousa, R. A., Oliveira, A. l., Leis, R. L., Cunha, A. M. and Bevis, M. J. (2003b). Bi-composite Sandwich Molding: Processing, Mechanical Performance and Bioactive Behavior. *Journal of Materials Science: Material in Medicine*. 14(5):385-397

Spencer, M. W., Cui, L., Yoo, Y. and Paul, D. R. (2010). Morphology and Properties of Nanocomposites Based on HDPE/HDPE-g-MA Blends. *Polymer*. 51(5): 1056-1070.

Stewart, R., (2007). Medical Plastic & Markets. *Society of Plastic Engineering*. 63(5): 27-30.

Suchanek, W. and Yoshimura, M. (1998). Processing and Properties of Hydroxyapatite-based Biomaterials for Use as Hard Tissue Replacement Implants. *Journal of Material Research*. 13(1): 94-117.

Sun, L., Berndt, C. C., Gross, K. A. and Kucuk, A. (2001). Material Fundamentals and Clinical Performance of Plasma-Sprayed Hydroxyapatite Coatings: A Review. *Journal of Biomedical Materials Research*. 58(5):570-592.

Százdi, L., Pozsgay, A., and Pukánszky, B. (2007). Factors and Processes Influencing the Reinforcing Effect of Layered Silicates in Polymer Nanocomposites. *European Polymer Journal*. 43: 345–359.

Tanniru, M.., Yuan, Q., Misra, R.. D. K. (2006). On Significant Retention of Impact Strength in Clay-Reinforced High-Density Polyethylene (HDPE) Nanocomposites. *Polymer*. 7(6): 2133-2146.

Vallet-Regi, M. and González-Calbet, J. M. (2004). Calcium Phosphates as Substitution of Bone Tissues. *Progress in Solid State Chemistry*. 32(1-2): 1-31.

Wang, M., Porter, D. and Bonfield, W. (1994). Processing, Characterisation, and Evaluation of Hydroxyapatite Reinforced Polyethylene Composites. *British Ceramic Transaction*. 93(3): 91-95.

Wang, M., Joseph, R. and Bonfield, W. (1998). Hydroxyapatite-polyethylene Composites for Bone Substitution: Effects of Ceramic Particle Size and Morphology. *Biomaterials*. 19(24): 2357-2366.

Wang, M, Ladizesky, N. H., Tanner, K. E., Ward, I. M. and Bonfleld, W. (2000). Hydrostatically Extruded HAPEX. *Journal of Materials Science*. 35(4): 1023-1030.

Wang, K. (1996). The use of titanium for medical applications in the USA, *Materials Scence Enineering A*. 213(1-2): 134–137.

Wang, K. H., Choi, M. H., Koo, C. M., Choi, Y. S. and Chung, I. J. (2001a). Synthesis and Characterization of Maleated Polyethylene/Clay Nanocomposites. *Polymer*. 42(24): 9819-9826.

Wang, M., and Bonfield, W. (2001b). Chemically Coupled Hydroxyapatite-Polyethylene Composites: Structure and Properties. *Biomaterials*. 22(11): 1311-1320.

Wang, M., Yue, C. Y. and Chua, B. (2001c). Production and Evaluation of Hydroxyapatite Reinforced Polysulfone for Tissue Replacement. *Journal Of Materials Science: Materials in Medicine*. 12(9): 821-826.

Wang, M. (2003). Developing Bioactive Composite Materials for Tissue Replacement. *Biomaterials*. 24(13): 2133-2151.

Wang, K. H., Chung, I. J., Jang, M. C., Keum, J. K. and Song, H. H. (2002) Deformation Behavior of Polyethylene/Silicate Nanocomposites As Studied by Real-Time Wide-Angle X-ray Scattering. *Macromolecules*, 2002, 35 (14), pp 5529–5535

Wang, Y., Chen, F. B., Li, Y. C. and Wu K. C. (2004). Melt Processing of Polypropylene/Clay Nanocomposites Modified with Maleated Polypropylene Compatibilizers. *Composites Part B: Engineering*. 35(2): 111–124.

Wang, Z., Wang, X., Li, G., and Zhang, Z. (2008). Enhanced Exfoliation of Montmorillonite Prepared by Hydrothermal Method. *Applied Clay Science*. 42: 146-150.

Wang, T., Chow, L. C., Frukhtbeyn, S. A., Ting, A. H., Dong, Q., Yang, M. and Mitchell, J. W. (2011). Improve the Strength of PLA/HA Composite Through the Use of Surface Initiated Polymerization and Phosphonic Acid Coupling Agent. *Journal of Research of the National Institute of Standards and Technology*. 116(5): 785-796.

Way, J. L., Atkinson, J. R. and Nutting, J. (1974) The effect of spherulite size on the fracture morphology of polypropylene. *Journal of Materials Science*. 9(2): 293-299

Weiner, S. and Wagner, H. D. (1998). The Material Bone: Structure-mechanical Function Relations. *Annual Review of Material Science*. 28(1): 271-298.

Weinans, H., Sumner, D. R., Igloria, R. and Natarajan, R. N. (2000). Sensitivity of Periprosthetic Stress-shielding to Load and the Bone Density-modulus

Relationship in Subject-specific Finite Element Models. *Journal of Biomechanics*. 33(7): 809-817.

Wenk, H. R. and Heidelbach, F. (1999). Crystal Alignment of Carbonated Apatite in Bone and Calcified Tendon: Results from Quantitative Texture Analysis. *Bone*. 24(4): 361-369.

Wunderlich, B. and Czornyj, G. (1977). A Study of Equilibrium Melting of Polyethylene. *Macromolecules*. 10(5): 906–913.

Yoon, P. J., Hunter, D. L. and Paul, D. R. (2003). Polycarbonate Nanocomposites. Part 1. Effect of Organoclay Structure on Morphology and Properties. *Polymer*. 44(18): 5323-5339.

Younesi, M. and Bahrololoom, M. E. (2009). Producing toughened PP/HA-LLDPE ternary bio-composite using a two-step blending method. *Materials and Design*. 30 (10):4253-4259

Zanetti, M., Lomakin, S., and Camino, G. (2000). Polymer layered silicate nanocomposites. *Macromolecular Materials and Engineering*. 279(1):1-9

Zeng, J., Saltysiak, B., Johnson, W. S., Schiraldi, D. A. and Kumar, S. (2004). Processing and Properties of Poly(methyl metacrylate)/carbon Nano Fiber Composites. *Composites B: Engineering*. 35(2):173-178.

Zhai H., Xu W., Guo H., Zhou Z., Shen S. and Song Q. (2004) Preparation and Characterization of PE and PE-g-MAH/montmorillonite Nanocomposites. *European Polymer Journal*. 40(11):2539-2545

Zhang Y. and Tanner K. E. (2003). Impact Behavior of Hydroxyapatite Reinforced Polyethylene Composites. *Journal Of Materials Science: Materials in Medicine*. 149(1): 63-68.

Zhong, Y. and Kee, D. D. (2005). Morphology and Properties of Layered Silicate-Polyethylene Nanocomposite Blown Films. *Polymer Engineering & Science*. 45(4): 469-477.

Ziv, V., Sabanay, I., Arad, T., Traub, W. and Weiner, S. (1996). Transitional Structures in Lamellar Bone. *Microscopy Research and Technique*. 33(2):203-213.

Zuo, Y., Li, Y. B., Zhang, X., Yang, W. H., Li, J. D., Mo, L. R. and Wang, H.N. (2006). Effect of Compatibilizers on the Properties of Nano-Hydroxyapatite Reinforced Polyamide 66 and High Density Polyethylene Blends.*Materials Science Forum*. 510 – 511: 978-981