EXPERIMENTAL STUDY OF THE BEHAVIOR OF BIPHASIC MATERIALS

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SUPERVISOR DECLARATION

“I hereby declare that I have read this thesis and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering (Structure & Materials)”

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This report was submitted in fulfillment of the requirement for the award of Bachelor of Degree of Mechanical Engineering with Honours (Structure & Materials)

Faculty of Mechanical Engineering

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DECLARATION

“I hereby declare that the work in this report was my own except for summaries and quotations which have been duly acknowledged.”

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ABSTRAK

Osteoarthritis (OA) merupakan salah satu jenis penyakit sendi yang bergejala dan sering dihidapi oleh kumpulan umur sederhana dan kumpulan warga umur emas yang berlaku di bahagian tangan, lutut, pinggang dan tulang belakang. Ia dicirikan oleh sakit sendi dan disfungsi, dan seterusnya mengakibatkan sendi dan otot atrofi dan kecacatan bahagian tulang belakang. OA yang diakibatkan oleh kemerosotan fungsi sendi sinovia akan semakin mewujudkan kehausan progresif rawan artikular dalam banyak contoh pembentukan tulang subchondral dan osteophytes marginal. Dalam eksperimen yang dilakukan sebelum ini, articular cartilage telah diandaikan secara rata. Walau bagaimanapun, articular cartilage yang sebenarnya berada di dalam sendi sinovia manusia manghasilkan permukaan lengkung dan kejadian ini akan menjadikan ketidaktentuan untuk pencirian cirri-ciri. Oleh itu, projek ini bertujuan untuk mengkaji tindak balas biomekanik bahan bifasa yang berkemukaan rata dan lengkung dengan mengaplikasikan ujian kasturi jalar. Tiga jenis span yang berlainan dipilih untuk mangganti articular cartilage kerana mereka merupakan jenis bahan yang sama. Ujian kasturi jalar dijalankan kerana ia lebih senang untuk ditubuhkan berbanding dengan ujian mampatan terhad dan ujian mampatan tanpa had. Hubungan antara nisbah kering-basah bagi jenis span berbeza dan anjakan dan kesan size permukaan lengkung berbeza terhadap anjakan telah dikaji dalam projek ini.

ABSTRACT

Osteoarthritis (OA) is the most common joint disease and symptomatic health problem for middle aged and senior citizen group which frequently occurs at the hands, knees, hips and spine. It was characterised by joint pain and dysfunction, and in its advanced stages, joint contractures, muscles atrophy and limb deformity spine. OA results from degeneration of a synovial joint which generally progressive loss of articular cartilage in many instances the formation of subchondral bone cysts and marginal osteophytes. In previous experimental studies, the cartilage has been assumed to be flat. However, the actual cartilage surface in human synovial joint possesses curvature and this could contribute to inaccuracy of characterised properties. Hence, this project is aims to study and investigate the biomechanical behavior of flat and curved surfaces of biphasic material by perform creep indentation test. Three different types of sponge were taken as model to replace the actual articular cartilage since it were also biphasic material. The creep indentation test was performed because it was much easier to set up compared to confined compression test and unconfined compression test. The relationship between dry to wet ratio of different types of sponge and the displacement and effect of different size of curved surface to the replacement were studied through this project.

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LIST OF SYMBOLS

E – Young’s Modulus

k – Permeability

v – Poisson’s ratio

r – Indenter radius

H – Aggregate modulus

V_{ave} – Average fluid velocity

ΔP – Pressure gradient

H_A – Equilibrium moduli (constraining parameter)

E_Z – Equilibrium moduli (constraining parameter)

λ – Equilibrium moduli (constraining parameter)

s – Second (time)

P – Load

h – Cartilage thickness

w – Depth of penetration

α – Radius of the contact region between cartilage and indenter pin

V – Voltage

R – Curved radius of specimen

LIST OF ABBREVIATION

AC – Alternating current

BOM – Bill of material

CT – Computed Tomography

DC – Direct current

EDTA – ethylenediaminetetraacetic

LVDT – Linear variable differential transformer

MRI – Magnetic resonance imaging

OA – Osteoarthritis

SD – standard deviation

CHAPTER 1

INTRODUCTION

1.0 INTRODUCTION

Osteoarthritis (OA) was the most common joint disease and symptomatic health problems for middle aged and golden aged group which frequently occurs at the hands, knees, hips and spine (Buckwalter, 2006, Goldring, 2007, Kidd, 2006). It was characterised by joint pain and dysfunction, and in its advanced stages, joint contractures, muscle atrophy and limb deformity spine (Buckwalter, 2006, Goldring, 2007, Kidd, 2006). OA results from degeneration of a synovial joint which generally progressive loss of articular cartilage in many instances the formation of subchondral bone cysts and marginal osteophytes (Buckwalter, 2006, Goldring, 2007). It was important that the biomechanical behavior of the articular cartilage to be characterised. Therefore indentation test rig was developed in this project in order to characterised the biphasic properties of the articular cartilage.

1.1 PROBLEM STATEMENT

In previous experimental studies, the cartilage has been assumed to be flat. However, the actual cartilage surface in human synovial joint possesses curvature and this could contribute to inaccuracy of characterised properties.

1.2 OBJECTIVE

Therefore, the objective of this project is to study the biomechanical behavior of flat and curved surfaces of biphasic material by developing an indentation test apparatus.

1.3 SCOPE

The scopes of this project were:

1. To develop an indentation test apparatus.
2. To perform creep indentation test on biphasic material.
3. To study the mechanical behavior of flat and curved surfaces of biphasic material.

CHAPTER 2

LITERATURE REVIEW

2.0 INTRODUCTION

There are mainly three experimental methods to characterise the biomechanical properties of the articular cartilage, which are confined compression test, unconfined compression test and creep indentation test respectively. The background of the articular cartilage and all this methods shall be studied before conducting the real testing method.

2.1 ARTICULAR CARTILAGE

Articular cartilage which was also known as hyaline was one of the examples of the biphasic materials which composed of a relatively small number of cells known as chondrocytes surrounded by a multi-components matrix. It is a special elastic connective tissue which covers on joint ends surface and its main physiological functions were to transfer load equably, expand bearing surface, amortize concussion load, reduce the contact stress and provide low friction and wear smooth interface for the joint (Wang *et al.*, 2011). It is a composite material that composed by solid matrix phase which consist of collagen and proteoglycans where it were about 20 percent of the total tissue mass by weight and an interstitial fluid phase which was water by containing about 80 percent of the total tissue mass by weight. The intrinsic mechanical properties of each phase as well as the mechanical interaction between these phases afford the tissue its interesting rheological interaction (Mow *et al.*, 1980, Mak *et al.*, 1987, Mow *et al.*, 1989). The location of the articular cartilage in the synovial joint was shown in Figure 2.1.

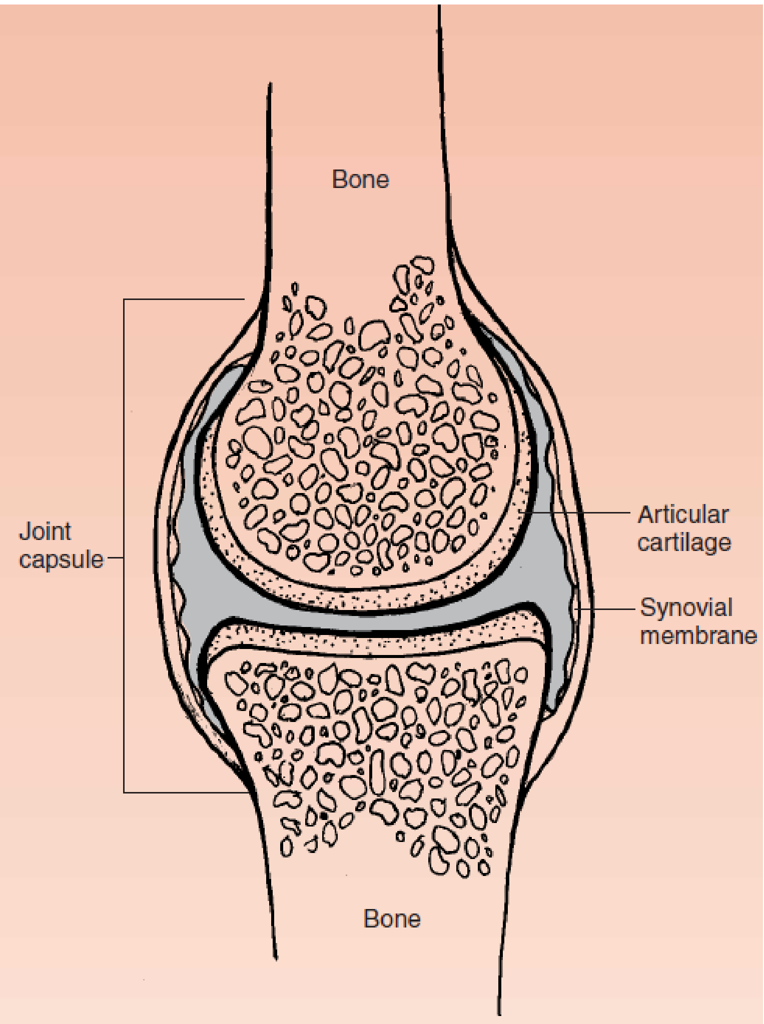


Figure 2.1 The schematic diagram of the synovial joint. Adapted from Mansour (1975).

The Proteoglycans consists of a protein core to which Glycosaminoglycans were attached to form a bottlebrush-like structure where the Glycosaminoglycans were formed by Chondroitin Sulfate and Keratin Sulfate. These Proteoglycans can be bind or aggregated to a backbone of hyaluronic acid in order to form a macromolecule with a weight up to two hundred million. It was about 30 percent of the dry weight of the articular cartilage when composed by the Proteoglycans. The concentration of this Proteoglycans and water content was varied through the depth of the tissue. The concentration of Proteoglycan was relatively low but the water content was highest at near the articular cartilage surface. Otherwise, the Proteoglycan concentration was greatest in the deeper regions of the cartilage which near the subchrondral bone while the water content was the lowest. Furthermore, the collagen was a fibrous protein that makes up sixty to seventy percent of the fry weight of the tissue.

The structure of the articular cartilage as shown in Figure 2.2 was often described in terms of fours zones between the articular surface and the subchrondral bone:

(i) Surface/ superficial tangential zone
(ii) Intermediate/ middle zone
(iii) Deep/ radiate zone
(iv) Calcified zone

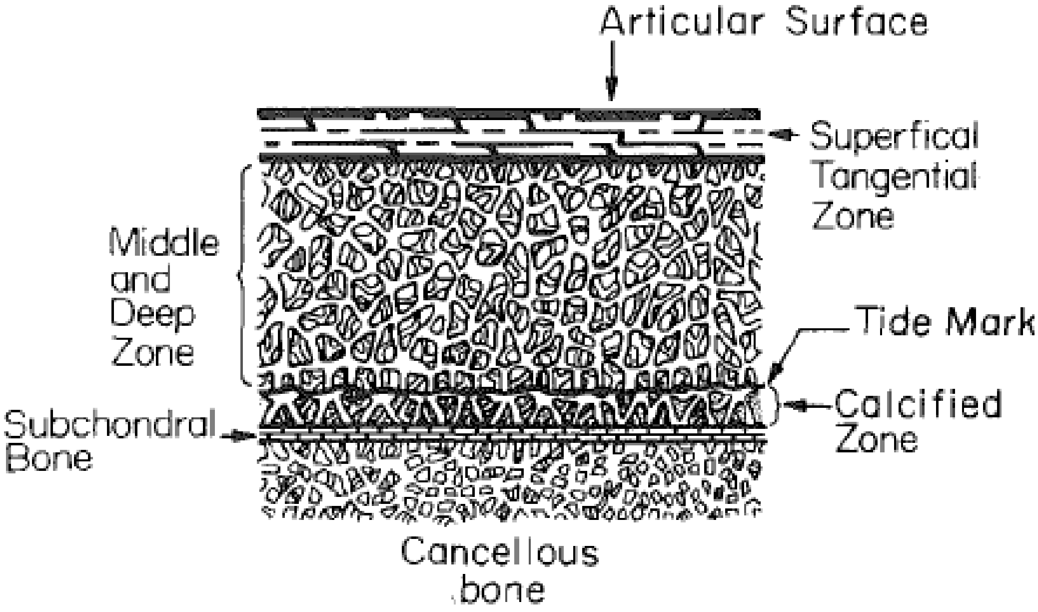


Figure 2.2 The schematic diagram of the articular cartilage. Adapted from Mow (1980).

This composition makes the articular cartilage structure inhomogeneous, and possesses anisotropic and nonlinear properties both in tension and compression. The calcified zone was the boundary layer between the cartilage and the underlying subchrondral bone. In the calcified and deep zones, the collagen fibers with radial orientation were arranged in tightly packed bundles where those bundles were linked by numerous fibrils. The radial orientation becomes less distinct while the collagen fibrils form a network that which the chondrocytes were surrounded from the upper deep zone into the middle zone. The interface between the deep zone and calcified cartilage was known as tidemark. The structure of the articular cartilage has been revealed by using several of microscopy methods such as optical microscopy, scanning electron microscopy and transmission electron microscopy. The fibers in the superficial zone were finer than in the deeper zones and the collagen structure was organised into several layers (Abdul Latif *et al.*, 2012, Mansour, 1975).

Articular cartilage plays a role as the bearing surface which permits the smooth motion between the adjoining bony segments in the freely moveable synovial joints (diarthroses) (Abdul Latif, 2011). Knee and elbow are examples of the synovial joints. In a typical synovial joint, the ends of opposing bones are covered with a thin layer of articular cartilage where it is normally white colour and its surface was smooth and glistening. The articular cartilage does not have a blood supply in normal mature animals since it was aneural (Mansour, 1975). A fluid which was known as synovial fluid was secreted by the inner surface of which was lined with the synovial membrane whereby, the entire joint was enclosed in a fibrous tissue capsule. This synovial fluid was clear to yellowish and was stringy where it was resembles egg white, and this resemblance was giving these joints name, synovia by which means “with egg” (Mansour, 1975).

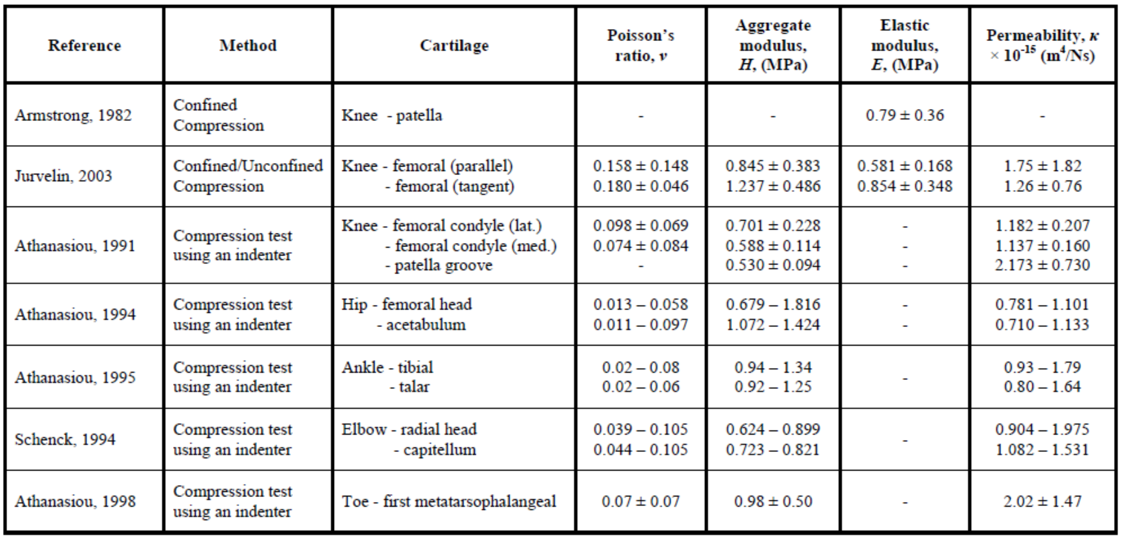
A mechanical function was clearly performed by cartilage by providing a bearing surface with low friction and wear due to its compliance which helps to distribute the loads between opposing bones in a synovial joint (Abdul Latif *et al.*, 2012). So, the mechanical behavior of the articular cartilage was determined by the interaction of its predominant components which including proteoglycans, collagens and interstitial fluid (Mansour, 1975).

The articular cartilage was distributed inhomogeneously and yields a variable thickness within the major synovial joints of human (Adam *et al.*, 1998). There are two types of methods which are compression testing and imaging methods are used to determine the cartilage thickness. Magnetic Resonance Imaging (MRI) use a strong magnetic field and high frequency of radio waves to produce an image of organs inside the body (Eckstein *et al.*, 1995, Millington, 2007, Vanwanseele, 2004). On the other hand, Computed Tomography (CT) uses the ioning radiation (X-ray) to generate detailed images of structures inside the body (Yogananda *et al.*, 2003). The indenter tip needle was used for compression testing to penetrate the cartilage until a significant increase in measured load was obtained (Swann and Seedhom, 1989, Athanasiou *et al.*, 1998, Schenck *et al.*, 1994).

The biomechanical properties of the articular cartilage such as Young Modulus (E), Permeability (k) and Poisson’s ratio (v) were commonly determined by tensile test and compression methods. The tensile tests have been utilised to obtain single phase cartilage properties such as elastic modulus ultimate tensile stress, fracture stress and tensile fatigue properties (Kempson *et al.*, 1968, Weightman *et al.*, 1978, Akizuki *et al.*, 1986, Kempson, 1991).

The most frequent methods used for the determination of the biphasic properties of the articular cartilage in compression test were aggregate modulus (H) and permeability (k) (Abdul Latif *et al.*, 2012). The characterisation of linear biphasic mechanical properties of articular cartilage have been summarised in previous study as shown in table 2.1.

Table 2.1 Linear biphasic biomechanical properties of articular cartilage in human synovial joints. Adapted from Abd Latif (2011).



Reference	**Method**	**Cartilage**	**Poisson's ratio, ν**	**Aggregate modulus, H, (MPa)**	**Elastic modulus, E, (MPa)**	**Permeability, κ $\times 10^{-15}$ (m^4/Ns)**
Armstrong, 1982	Confined Compression	Knee - patella	-	-	0.79 ± 0.36	-
Jurvelin, 2003	Confined/Unconfined Compression	Knee - femoral (parallel) - femoral (tangent)	0.158 ± 0.148 0.180 ± 0.046	0.845 ± 0.383 1.237 ± 0.486	0.581 ± 0.168 0.854 ± 0.348	1.75 ± 1.82 1.26 ± 0.76
Athanasiou, 1991	Compression test using an indenter	Knee - femoral condyle (lat.) - femoral condyle (med.) - patella groove	0.098 ± 0.069 0.074 ± 0.084 -	0.701 ± 0.228 0.588 ± 0.114 0.530 ± 0.094	- - -	1.182 ± 0.207 1.137 ± 0.160 2.173 ± 0.730
Athanasiou, 1994	Compression test using an indenter	Hip - femoral head - acetabulum	0.013 – 0.058 0.011 – 0.097	0.679 – 1.816 1.072 – 1.424	- -	0.781 – 1.101 0.710 – 1.133
Athanasiou, 1995	Compression test using an indenter	Ankle - tibial - talar	0.02 – 0.08 0.02 – 0.06	0.94 – 1.34 0.92 – 1.25	-	0.93 – 1.79 0.80 – 1.64
Schenck, 1994	Compression test using an indenter	Elbow - radial head - capitellum	0.039 – 0.105 0.044 – 0.105	0.624 – 0.899 0.723 – 0.821	-	0.904 – 1.975 1.082 – 1.531
Athanasiou, 1998	Compression test using an indenter	Toe - first metatarsophalangeal	0.07 ± 0.07	0.98 ± 0.50	-	2.02 ± 1.47

2.2 CONFINED COMPRESSION TEST

Confined compression test is one of the methods that which was commonly used to determine the material properties of cartilage. A disc of tissue was cut from the joint and placed in an impervious well (Hori and Mockrous, 1976, Korhonen *et al.*, 2002). The confined compression test is used in either "creep" mode or a "relaxation" mode. In the creep mode, the displacement of the tissue was measured as a function of time when a constant load was applied to the articular cartilage through a porous plate. The force which was needed to maintain the displacement of the tissue was measured when a constant displacement was applied to the tissue in the relaxation mode (Mansour, 1975). The schematic diagram of the confined compression test was shown in Figure 2.3.

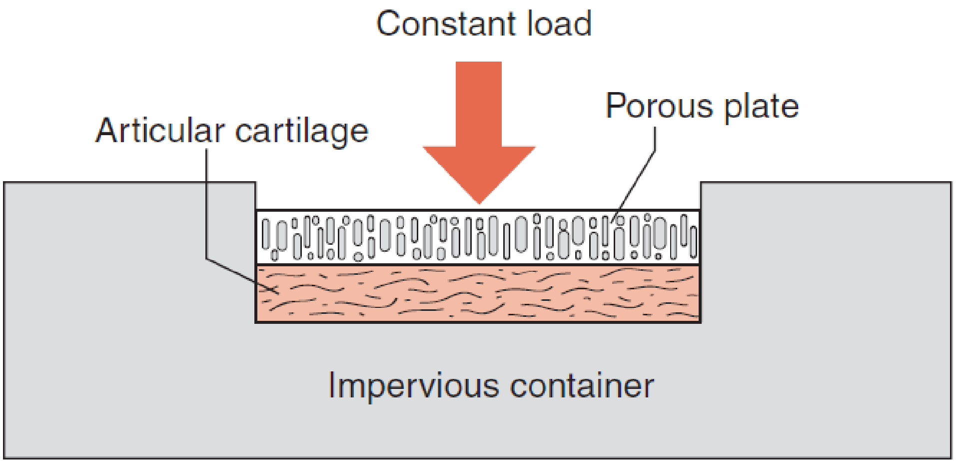


Figure 2.3 The schematic drawing of an apparatus used to perform a confined compression test of cartilage. Adapted from Mansour (1975).

The cartilage was deformed under a constant load in the creep mode as shown in Figure 2.4, but the deformation was not in the instantaneous response, as it would be in a single-phase elastic material such as spring. The fluid cannot escape from the matrix instantaneously caused this displacement of the articular cartilage results that as a function of time. The displacement was rapidly in initially and then this corresponds to a relatively large of the flow of fluid out of the cartilage. The flow of fluid was likewise to slow as the rate of the displacement slows and it was approached a constant value.