# UNIVERSITI PUTRA MALAYSIA

***IN SITU ICE-CREAM STRUCTURE MECHANICAL INVESTIGATION***

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## ABSTRACT

This report shows how to use and upgrade toy bricks, based on the LEGO Mindstorms system, for the construction of a compression tester that is cost effective, comprehensive, portable and flexible. The setup is capable of performing uniaxial presses up to 10mm with velocities up to 14mm/s, for the investigation of in-situ (low temperature) ice cream compression behavior. The use of MATLAB in conjunction with the compression tester has provided greater functionalities in performing desirable action as well as analyzing data collected. Image processing function is adapted in MATLAB to estimate the speed of compression plate that is particularly useful in obtaining the stress-strain curves of tested materials. The recommended motor power level in conducting uniaxial press range from 30% to 70% for a trustworthy result. The results obtained from compression tester shows characteristics property of ice cream is primarily respond as a viscoelastic material. Uniaxial compression and stress relaxation tests that have been carried out show that ice cream exhibited a viscoelastic behavior tended to a liquid one at lower strain rate and viscoelastic solid behavior at higher strain rate. For cyclic compression, texture parameters such as hardness and springiness can be determined. The designed compression tester is proved to deliver a trustworthy trend in the characterization of mechanical behavior of ice cream. However, further improvements on hardware and software are recommended for more accurate and consistent results.

**ABSTRAK**

Laporan ini menunjunkkan bagaimana cara penggunaan dan peningkatan bata mainan, berdasarkan system LEGO Mindstorms untuk pembinaan penguji mampatan yang kos efektif, komprehensif, mudah alih dan fleksibel. Pembinaan tersebut mampu melaksanakan tekanan berporos tunggal sepanjang 10mm dan selaju 14mm/s untuk pengajian sifat mampatan ais krim secara in situ (suhu rendah). Penggunaan MATLAB dengan penguji mampatan telah memberikan fungsi yang lebih luas dalam melaksanakan tindakan yang diinginkan untuk menganalisis data yang dikumpul. Fungsi pemprosesan imej dalam MATLAB telah digunakan untuk menganggarkan kelajuan plat mampatan yang amat penting dalam pembentukan kurva tegangan-regangan bahan yang diuji. Kuasa motor yang sesuai untuk menjalankan tekanan berporos tunggal adalah dari 30% hinnga 70% supaya keputusan yang tepat dapat diperolehi. Keputusan yang diperoleh daripada penguji mampatan menunjunkkan bahawa ais krim bersifat sebagai bahan viskolenting. Tekanan berporos tunggal dan tekanan relaksasi yang telah dijalankan menunjukkan bahawa ais krim bersifat lebih kepada cecair pada kadar ketegangan yang rendah manakala bersifat lebih kepada pepejal viskolenting pada kadar ketegangan yang tinggi. Untuk siklik pemampatan, parameter tekstur seperti kekerasan dan kelentingan dapat diperolehi. Penguji mampatan yang telah direka membukit bahawa keputusan yang diperoleh untuk mengkaji pencirian perilaku mekanikal ais krim dapat dipercaya. Walaubagaimanapun, peningkatan lanjut megenai perangkat keras dan lunak disyorkan untuk mendapatkan keputusan yang lebih tepat dan konsisten.

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# LIST OF ABBREVIATION

| Abbreviation | Description |
| --- | --- |
| MSNF | Milk solid non fat |
| CMC | Carboxymethyl cellulose |
| LBG | Locust bean gum |
| MCC | Microcrystalline cellulose |

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

Hot weather tends to hold people back from their daily excursions. And since hydration is the key, ice cream has become one of the best choices to beat the heat when strolling under the hot sun. The ultimate enjoyment of ice cream is inextricably linked to the mechanical behavior of ice cream. Compression test provides a simple and effective way to characterize the mouthfeel when eating the ice cream. This is similar to the deformation that takes place in the mouth such that ice cream is squashed in between the tongue and roof of the mouth.[1] In order to study the mechanical behavior of the rapidly melting ice cream, LEGO Mindstorms EV3 has been proposed to create a testing device that is capable in conducting mechanical compression of ice cream under a desirable condition.

### 1.1.1 Ice Cream

Ice cream is a popular frozen treat that appeals to people of all ages, from kids to the elders. It consists of fat, milk solids-non-fat, sugar, emulsifiers, stabilizers, flavoring agents and coloring agents.[2] These ingredients blend together and undergo a series of operations such as mixing, pasteurization, homogenization, ageing, freezing and hardening to produce the ice cream microstructure of small ice crystals, air bubbles and fat droplets held together by the matrix. The microstructural components of ice cream is correlated to the amount of these ingredients being added, which define ice cream into different types.

Consumers around the globe are now living in an increasingly fast-paced lifestyle. The rising level of consumption ability is driving growth in the ice cream market. According to Canadean, the volume consumption of ice cream products in Malaysia's market is forecast to grow from 56.4 kg million in 2014 to 70.1 kg million in 2019. [3] Furthermore, with the tropical climate of Malaysia, ice cream is consumed year around. This increasing demand is driving ice cream manufacturers to launch more flavor variants of ice cream in order to increase competitiveness and stimulate the consumption.

### 1.1.2 LEGO Mindstorms EV3

LEGO is one of the most popular toys in the world consisting of interlocking bricks that enables the construction of any object which comes across the creative imagination. This company was established in 1932 by a carpenter Ole Kirk Kristiansen and LEGO brick is its feature product. The present brick with interlocking principle was first launched in 1958 which gives significant stability to build pieces that offers endless possibilities in object buildings.

In 1998, the introduction of LEGO Mindstorms Robotics Invention System has brought life to the LEGO creations via computer programming. Today, the third incarnation of LEGO robotics, LEGO Mindstorms EV3 enables the commanding of LEGO robot in a faster and smarter way. Therefore, using LEGO to build a testing device that is able to perform sophisticated measurements for scientific research is undoubtedly possible. The cost of highly adaptable data acquisition device being made from simple toy is relatively lower compare to the commercial testing device.

## 1.2 Problem Statement

Understanding the mechanical properties of ice cream is essential in developing a new product with desire texture and flavor. However, all new design foods are needed to be thoroughly tested and such testing devices used are rather expensive and required more space as well as qualified personnel for the operation. Commercial testing device that is usually be placed in laboratory under room temperature is difficult to obtain the best result of rapidly melting ice cream. Due to this factor, there will be difficulties in conducting experiments under complex deformation such as stress relaxation compression and cyclic compression. Furthermore, it is also costly to build a special chamber that accommodates such a large commercial testing device for the satisfaction of experiment condition. Besides, the load cells of commercial testing devices are considerably large and this will lead to the inaccuracy of experimental result because the weight of the sample will not be supported entirely by the load cell. Due to the limitation in scientific research financial resources, new testing device that is cost and performance effective is of interest.

## 1.3 Research Objective

The objective of this project is to design a device that is cost effective, comprehensive, portable and flexible for the investigation of in-situ (low temperature) ice cream compression behavior. The capability of device in performing stable mechanical compression should be ensured in delivering trustworthy result. Since the evaluation of mechanical properties of ice cream is essential for the satisfaction of customers, compression tests which include uniaxial compression, stress relaxation and cyclic compression will be carried out.

## 1.4 Scope of Work

This project involves the creation of device that is able to perform uniaxial press while synchronously measuring the compressive strength using LEGO Mindstorms EV3. Uniaxial compression test, stress relaxation test and cyclic compression test will be carried out using the LEGO testing device to study the mechanical behavior of ice cream upon deformation. At the end of the design, the capability of LEGO testing device in delivering accurate and trustworthy results should be ensured.

## 1.5 Structure of Thesis

Chapter 1 introduces the study scope of this project. In chapter 2, the previous researches on properties of ice cream and usability of LEGO Mindstorms System in scientific research are discussed. Next, chapter 3 will be focused on the design of the LEGO system in performing uniaxial press, while measuring the compressive force. The compression method used to study the ice cream properties will also be discussed. In chapter 4, the results obtained from the LEGO system will be discussed to study the mechanical behavior of ice cream. Lastly, chapter 5 concludes the overall study and recommendations will be provided for further investigation.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Structure of Ice Cream

Ice cream is a mixture in which it contains all three states of matter: ice and fat as solid, sugar solution as liquid and gas air. Firstly, the premix of ice cream containing individual components such as fats, proteins, sugar, salts and water is prepared. Then, it undergoes aeration and frozen in a freezer, typically using a scraped surface heat exchanger.[4] During the freezing process, the incorporation of air by agitation will turns the ice cream mix into a viscous foam and part of the water containing will turn into ice crystals. The air cells are initially stabilized by the milk protein with little fat globules on the surface of it. As the agitation continues, some of the fats destabilize and start to coalesce, subsequently forming a network to support the foam.[5] Lastly, ice cream is hardened in a hardening tunnel to minimize the recrystallization. The manufacturing process of ice cream is summarized in Figure 2.1. The typical composition that made up the ice cream is 50% of air, 30% of ice, 15% of sugar solution in matrix form and 5% of fat. The total amount of each component and the microstructure are important in determining the physical and sensory properties of the final ice cream product.[2] Illustration of the structure of ice cream mix and ice cream is shown in Figure 2.2.

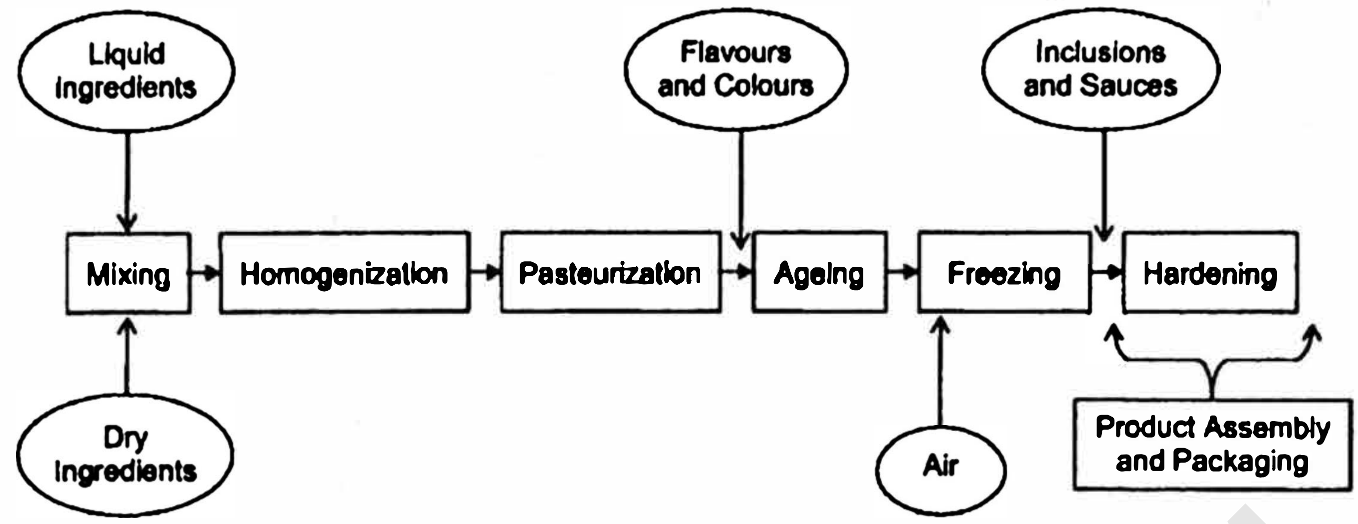


Figure 2.1: Schematic diagram of ice cream manufacturing process

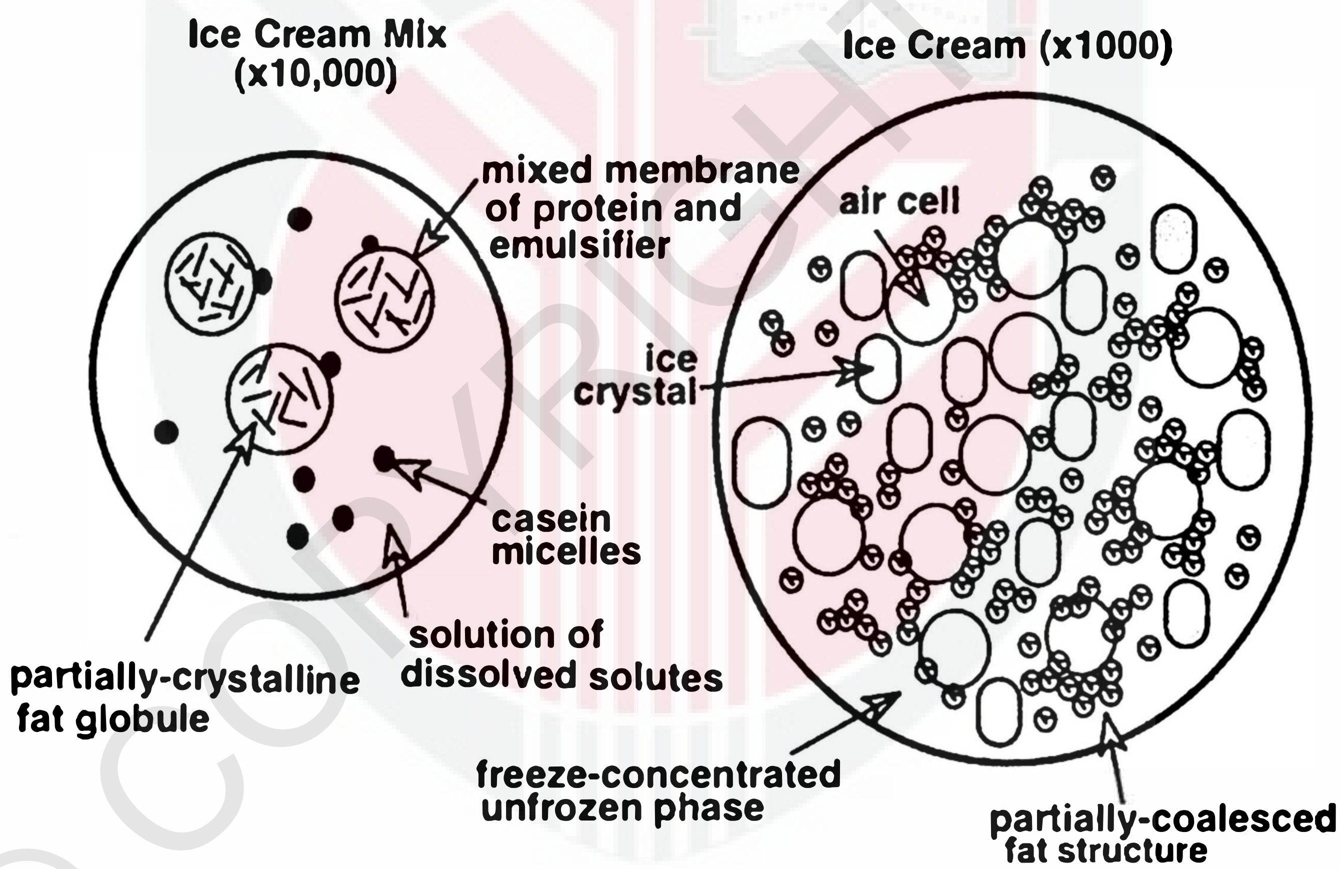


Figure 2.2: Structure of ice cream

### 2.1.1 Serum Phase

Ice cream is a partially frozen complex food product that composed of partially crystalline globular, partially coalesced fat globules cluster, ice crystals and air cells within an unfrozen serum phase. Even at the coldest storage temperature of ice cream, not all water in it is frozen.[1] Serum phase is unfrozen solution that consists of air cells, ice crystals and fat globules as the main structural components of ice cream throughout the continuous phase.[6] It also comprises of whatever dissolved components in the unfrozen water such as unadsorbed casein micelles, unadsorbed whey protein, salt and high molecular mass polysaccharides. At refrigerated temperature, the freezing process will form a network of agglomerated fat due to the partial coalescence of partially-crystalline fat phase, which partially surrounds the air bubbles and give rise to a solid-like structure of ice cream.[7] As the freezing temperature decreases, more water freezes and this will result in an increase in serum viscosity as well as the serum phase concentration. At a point where certain concentration is achieved, no more ice will be formed due to the limitation of water mobility to incorporate into ice crystal lattice. This is very important in determining the transition glass temperature of ice cream in which the critical storage temperature for ice cream can be obtained to achieve the stability of ice cream during storage.[1]

### 2.1.2 Ice Crystal

Ice crystal is an integral component and comprise a large portion of the ice cream bulk in which its size is ranging from a few microns to over 100 $\mu$m. Ice crystal is formed during the freezing process in which approximately half of the water in ice cream mix is frozen and 75-80% of the remaining water will be further frozen upon hardening, depending on the freezing point and storage temperature respectively.[1] The creamy texture, primarily associated with a high fat content, is determined by the average size of ice crystals. A larger ice crystal will impart a grainy texture to the ice cream, whereas the smaller crystals will give ice cream the desired creaminess.[8] Ice crystal should be sufficiently small to provide a smooth texture that is readily to melt in mouth as a frozen dessert. Furthermore, it is also found that larger size of ice crystals will have higher melting rate and resistance upon the deformation of an applied force is also higher, which is also known as the hardness.[6] The size and amount of ice crystals is one of the important considerations in determining the quality of resultant products and they may vary with the incorporation of air, freezing temperature, nucleation rate and agitation performance during the freezing and crystallization stage. [9]

### 2.1.3 Air Cells

Foam structure of ice cream is formed by adding air during the freezing process in which portion of water will also be frozen to increase the volume of product.[10] The amount of air incorporated in a foam is often reported in the terms of overrun, calculated as the percentage of increase in volume of mix as a result of air addition.[2] Control of overrun is essential as it has high impact to the rheological properties of ice cream, which subsequently give rise to certain quality aspects such as melting rate, shape retention during melting and creaminess.[4] Air also has another function in which it scatters light and therefore affect the color and appearance of ice cream.[2] The air cells in ice cream microstructure contain discrete and partially coalesced fat globules on its surface.[11] Both fat and air are hydrophobic and the fat will partly adsorb to the surface of air bubbles and stabilize the foam by the formation of a network within the serum phase separating the air cells and to prevent it from coalescence.[4] The interfaces of air cells that are partly covered by fat globules are as shown in Figure 2.3.

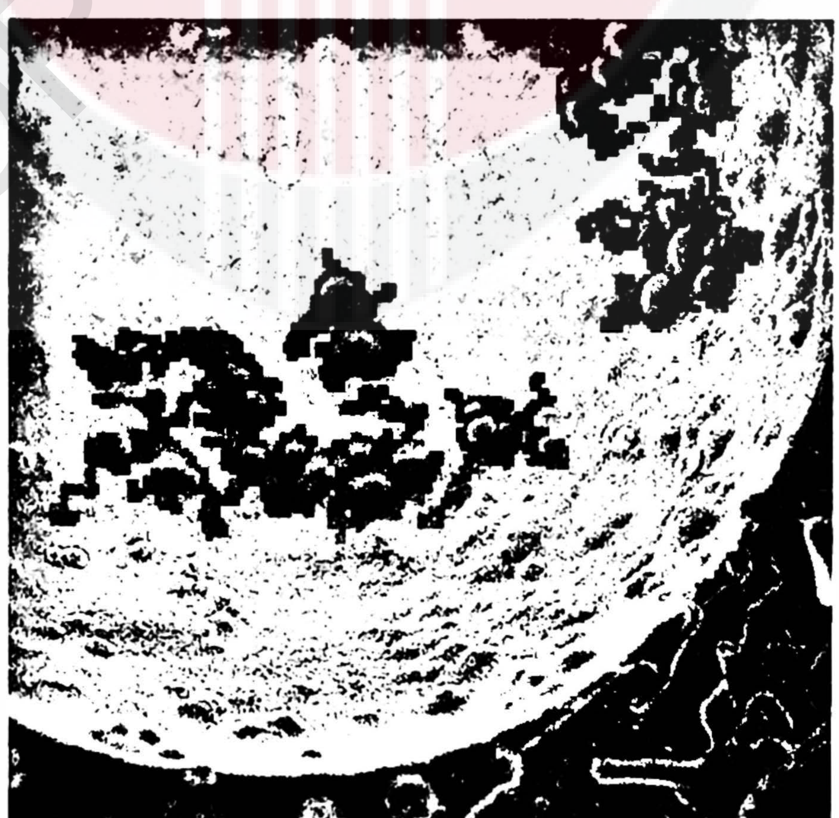

Figure 2.3: LT-SEM micrograph of an air cell with fat globules at its surface

### 2.1.4 Fat Globules

Milk fat is one of the macromolecules present in the ice cream mix for the development of ice cream structure.[12] Milk fat is made up by fat globules in a partially solidified state in which high melting point fats exist in crystalline form whereas low melting point fats exist in liquid form. Figure 2.4 shows that discrete and partially coalesced fat droplets are present in the serum phase and also on the surface of air cells. The formation of fat structure in ice cream is due to the creation of fat droplets during the homogenization process where the size distribution of fat droplets determine characteristics of resultant products by affecting their rheological properties.[1] Fat globules exist in ice cream mix emulsion undergo partial crystallization in cooling and aging step and subsequently agglomerate and destabilize in the freezing process.[10] The aggregate fat globules help to stabilize the air bubbles in which it give a major effect on the sensory properties of ice cream such as thickness and mouth-coating.[4] The use of emulsifiers can increase the fat destabilization, forming more agglomerates and thereby increasing the matrix viscosity to achieve the decrease in melting rate and improve the shape retention during melting.[13] Development of these fat structures in the matrix are as shown in Figure 2.5. The correlation between air and fat in microstructural changes attribute to the rheological behavior of ice cream.

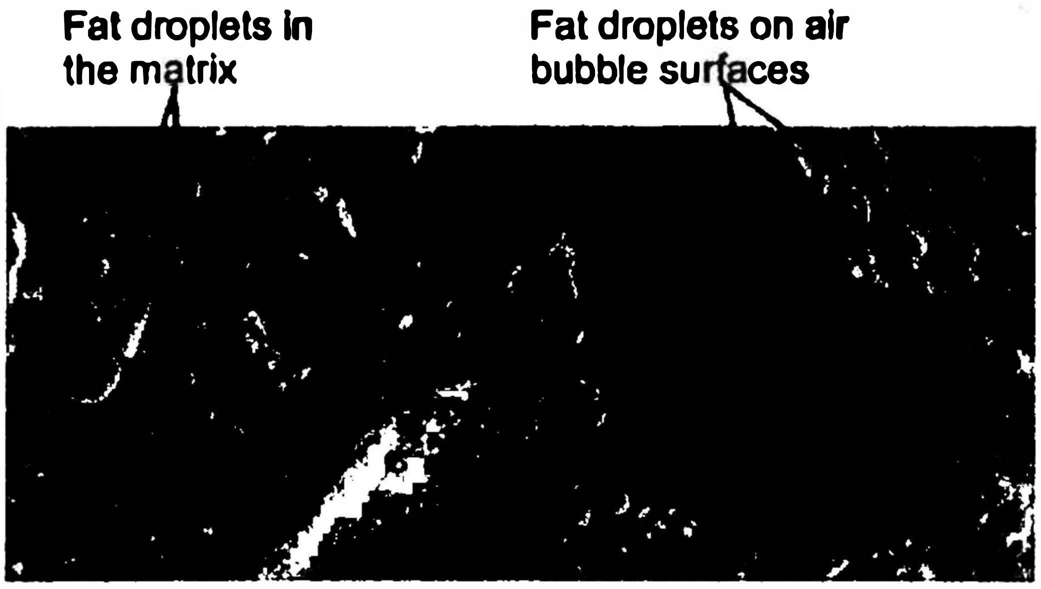


Figure 2.4: Scanning electron micrograph showing fat droplets in the matrix and on the surface of air bubbles

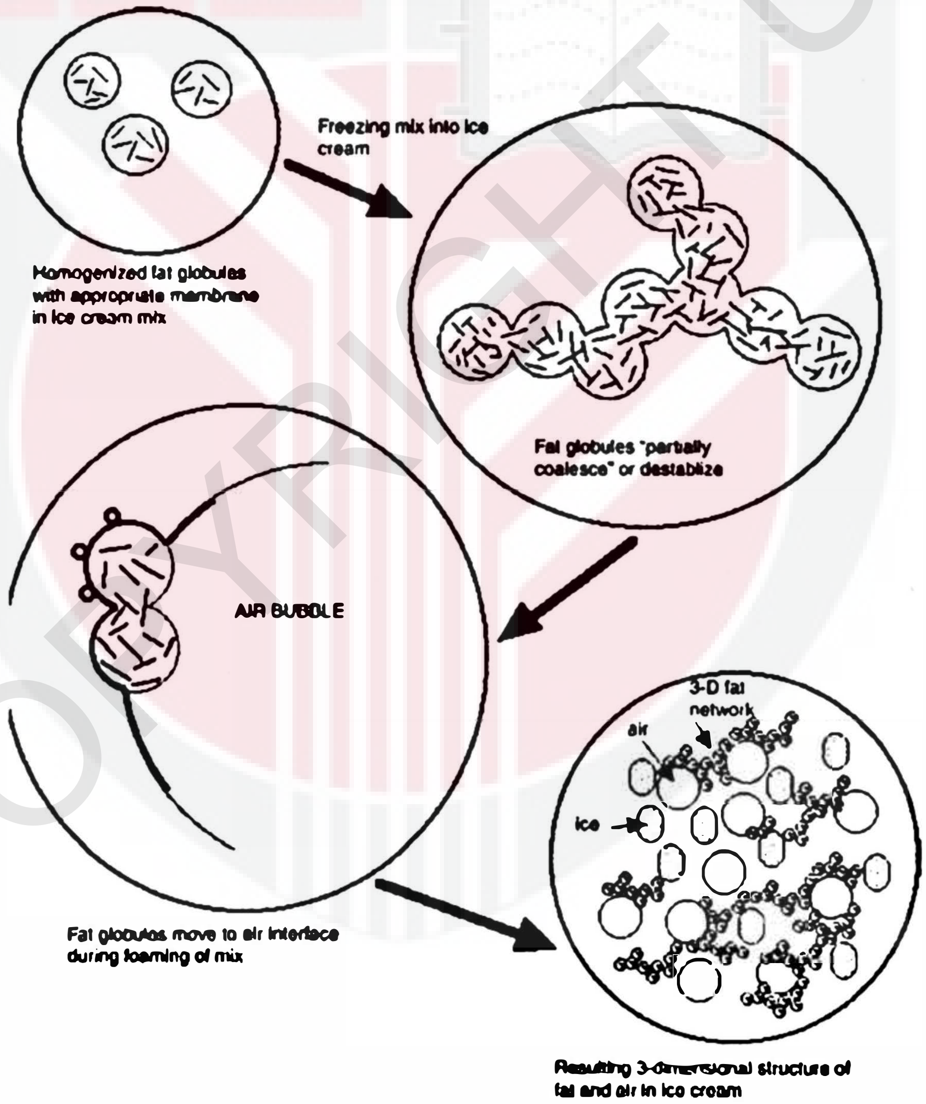


Figure 2.5: Development of Fat Structure in Ice Cream

## 2.2 Key Ingredients in Ice Cream

Ingredients that are solubilized and dispersed in the four main structural components of ice cream also play an important role to determine the characteristics of ice cream. It is essential to formulate and balance the mix with appropriate amount and excellent quality of ingredients in order to produce the ice cream with highest quality. Therefore, selection of ingredients are of important factors as different source of ingredients will contribute to different desired characteristics of the final products.[1]

### 2.2.1 Milk Fat

Milk fat imparts a rich, full, creamy flavor and smooth texture of ice cream. The correct percentage of milk fat being added into the ice cream mix is required to ensure the quality of resultant products as well as to comply the legal requirement. During freezing, milk fat globules will be concentrated at the surface of the air cells. The increase in milk fat globules will then decrease the space available for the ice formation and therefore the size and amount of ice crystal can be limited.[9] Milk fat can be categorized into hard and soft fraction. Soft fraction milk fat has higher aeration ability and able to form uniform air bubble distribution, thereby enhance the foaming properties and foam stability in ice cream. Various source of milk fats are available for the ice cream production, such as fresh cream, frozen cream, plastic cream, sweet butter, butter oil and anhydrous milk fat. The selection of the source of milk fat is based on the manufacturers' requirements.[1]

### 2.2.2 Milk Solid Non-Fat

Milk solid non-fat (MSNF) is one of the ingredients used to improve the texture and flavor of ice cream. Addition of MSNF increases the viscosity of serum phase, therefore making the ice cream more compact and smooth during consumption.[9] Milk solid non-fat consists of protein, lactose and mineral salts. Protein in MSNF helps in several structural development during ice cream production such as emulsification of fat, formation of foam and stabilization of air bubbles which subsequently contribute to the increment of viscosity in serum phase. Besides, lactose will add total solid content of ice cream but excessive concentration should be avoided in order to prevent the creation of sandiness ice cream texture. Lastly, mineral salts from MSNF will contribute to the change of freezing point and imparts a slightly salty flavor which could round out the finished flavor of ice cream.[1]

### 2.2.3 Stabilizer

Stabilizer is a group of ingredients which are being used individually or in combination that will dispersed in the liquid phase of ice cream, binds a large number of water molecules which is known as hydration.[14] The water-binding capacity of stabilizer allows the formation of three-dimensional network of hydrated molecules throughout the system.[15] Therefore, they retard the growth of ice crystal during storage and also improve the mix viscosity, stability of foam, resistance to melting, uniformity and smoothness of product. There are various types of stabilizers that can be used in ice cream, among those are alginate, carboxymethyl cellulose (CMC), carrageenan, gelatin, guar gum, locust bean gum (LBG), microcrystalline cellulose (MCC) and xanthan. Individual stabilizer ingredients have different characteristics and therefore give rise to their functional properties in stabilizing the ice cream.[1]

### 2.2.4 Emulsifier

An emulsifier is a substance that used to produce a stable suspension of two immiscible liquids.[1] However, in ice cream, emulsifiers is used to promote the fat nucleation by lowering the fat or water interfacial tension in the mix more than mix proteins, resulting in protein displacement from the fat globule surface and promotes the partial coalescence of fat during whipping and freezing process.[13] Figure 2.6 shows the surface structure of fat globule when it is with or without the use of emulsifiers. This leads to the formation of the fat structure network that greatly influences the texture and melting properties of ice cream. Traditionally, egg yolk was used as an emulsifier, but it is expensive and less effective. In modern formulation, there are four groups of emulsifiers used by the ice cream manufacturers: glycerin esters, sorbitol esters, sugar esters and esters of animal or vegetable origin.[14] Blending of different types of emulsifiers is common in order to achieve the desired functional properties for fat destabilization.[1]

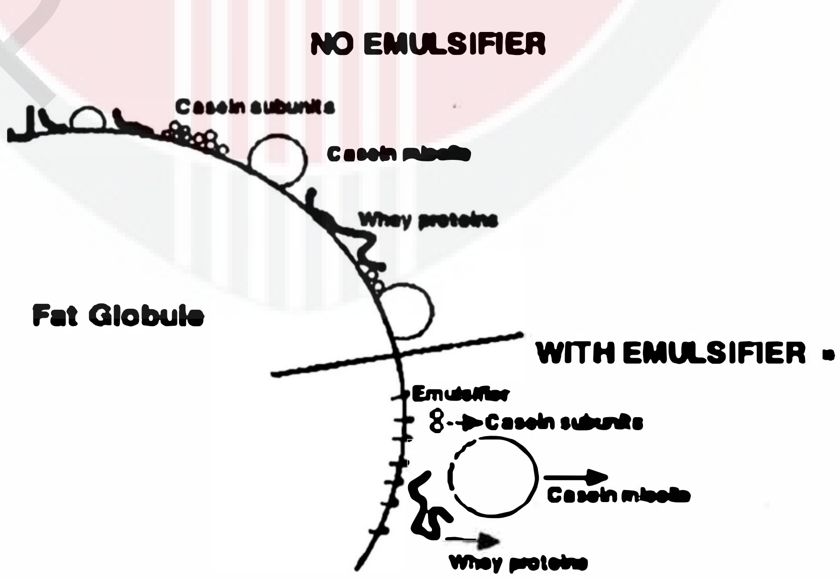


Figure 2.6: Effect of emulsifier on fat destabilization in ice cream

### 2.2.5 Sweetener

Sweeteners are used in the production of all ice cream to increase the acceptance of the products by giving the sweetness that is preferred by customers.[14] Besides that, the addition of sweeteners will also influence the texture of ice cream in another way because of their ability to bind water, thereby increase the viscosity of mix.[9] Sweeteners being dissolved will also lead to freezing point depression that will subsequently affect the melting rate of ice cream. Therefore, addition of sweeteners is also a major considerations in ice cream production as the relative sweetness, contribution to total solids and freezing point depression of mix can have both beneficial and detrimental effects on the resultant products.[2] Many different types of sugars can be used, such as cane and beet sugar, glucose, lactose, sucrose, invert sugar, honey and corn sweeteners. The most common use of sweetener in ice cream is a combination of sucrose and corn sweeteners.[1] The choice of sweeteners to be added into ice cream is very important based on the categories of consumers, especially to the diabetics.[14]

## 2.3 Mechanical Compression Test

Food texture is an important component of food quality perception and ability.[16] Due to the reasons of cost saving and the complication of ethical issues involved in human tests, instrumental methods are used for study the sensory property of food.[17] Compression test is one the methods used to determine the mechanical properties of ice cream such as firmness and hardness by compressing the cylindrical sample with an initial height and cross sectional area that are placed in between two plates. One plate will be moving towards the other at a constant speed until the deformation of ice cream sample occurs.[16] Compression test has been proved to successfully evaluate the textural characteristics of ice cream during lactose hydrolysis.[18] The mechanical properties of ice cream need to be identified so that investigation of the interactions between macromolecules in the ice cream can be done to study the basis of the texture.

Several studies have been carried out in studying the compression behavior of ice cream. Pon, S.Y., Lee, W.J. and Chong, G.H. (2015) have carried out texture profile analysis using texture analyzer under surrounding temperature of 25°C.[19] Another study on the structural development in ice cream was done to study the impact of temperature on rheological behavior of ice cream. The method in carrying out the experiment was using precooled stainless steel flat parallel plate at different temperature to achieve the desired experimental condition. [20] Moreover, similar compression testing on ice cream carried out by students from Worcester Polytechnic Institute showed sign of melting when being performed under room temperature using Instron universal test machine. A more controllable environment to carry out ice cream compression test is recommended for more accurate results.[21]

### 2.3.1 Uniaxial Compression

Uniaxial compression is the most commonly used method to determine the fracture properties of foods due to the commercial availability of testing machines and minimal sample preparation.[16] It consists of applying a force to the sample and the resistance of the sample to deformation developed within the sample and the resistance will be read by the load cell as in unit of force.[22] The instantaneous values of compression force applied $F(t)$ to the deformation of cylindrical ice cream sample in height $h(t)$ with initially known area ($A_o$) can be converted into engineering stress ($\sigma_E$) and engineering strain ($\varepsilon_E$) according to the following definitions[22]:

$$\sigma_E = \frac{F(t)}{A_o} \quad ; \qquad \varepsilon_E = \frac{h_o - h_t}{h_o}$$

where $A_o$ and $h_o$ are the initial cross-sectional area and height of sample; $h_t$ is the sample height after deformation.

The maximum compression force $F(t)$ required to accomplish the breakage of sample is often used as an index of textural quality of it. As in compression, the apparent modulus of elasticity ($E_t$) can also be considered as a measurement of the firmness of the product and is calculated in the zone of linearly elastic zone as the ratio of engineering stress ($\sigma_E$) and engineering strain ($\varepsilon_E$).[22]

$$E_t = \frac{\sigma_E}{\varepsilon_E}$$

Figure 2.7 shows the schematic force-time graph from which the mechanical properties are obtained in compression test.[2]

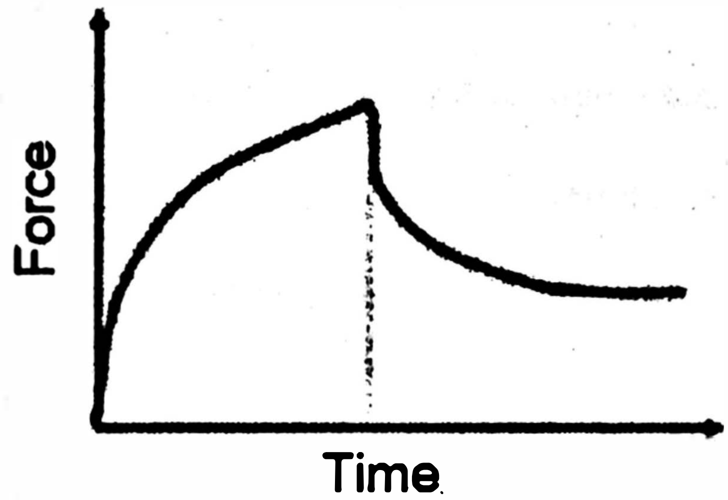


Figure 2.7: General force vs time graph for uniaxial compression of viscoelastic material

### 2.3.2 Stress Relaxation

Stress relaxation test is usually performed to assess the viscoelastic behavior of a material because much simpler uniaxial test is generally incapable of elucidating the elastic nature of the material.[23] The test procedure for stress relaxation is almost the same as uniaxial compression. In stress relaxation, after a fixed percentage of deformation of sample has been achieved, the sample is allowed to relax for a given time and the stress will gradually decrease with time.[22] Maxwell model is often been used to estimate and correlate a series of rheological parameters with the engineering strain applied. [23] Figure 2.8 shows the schematic force-time graph for stress relaxation test of viscoelastic materials.

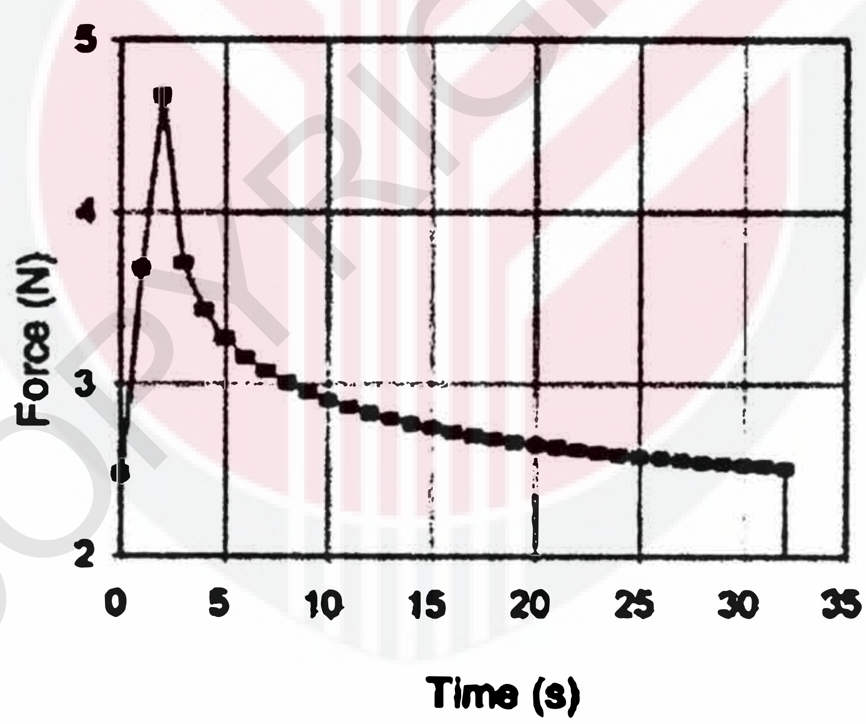


Figure 2.8: General force vs time graph for stress relaxation test of viscoelastic material

### 2.3.3 Cyclic Compression

Cyclic compression test is the process of loading and unloading a sample as a function of time to the stress response (strain is held constant) or in the strain response (stress is held constant). [24] One cycle of the test is regarded as the sample is loaded up to a preselected strain at the compression phase and sample is released in the following tensile phase.[25] Studies have shown that hardness and springiness of food can be accurately predicted by using cyclic compression test. Therefore, the rheology of food deformation can be understand by establishing a relationship between perceived texture and food characteristics.[26] Furthermore, studies of cyclic compressive loadings is also important to the possible occurrence of deformation during the product handling.[27] Figure 2.9 shows the schematic force-time graph for cyclic compression of viscoelastic materials in two cycle.

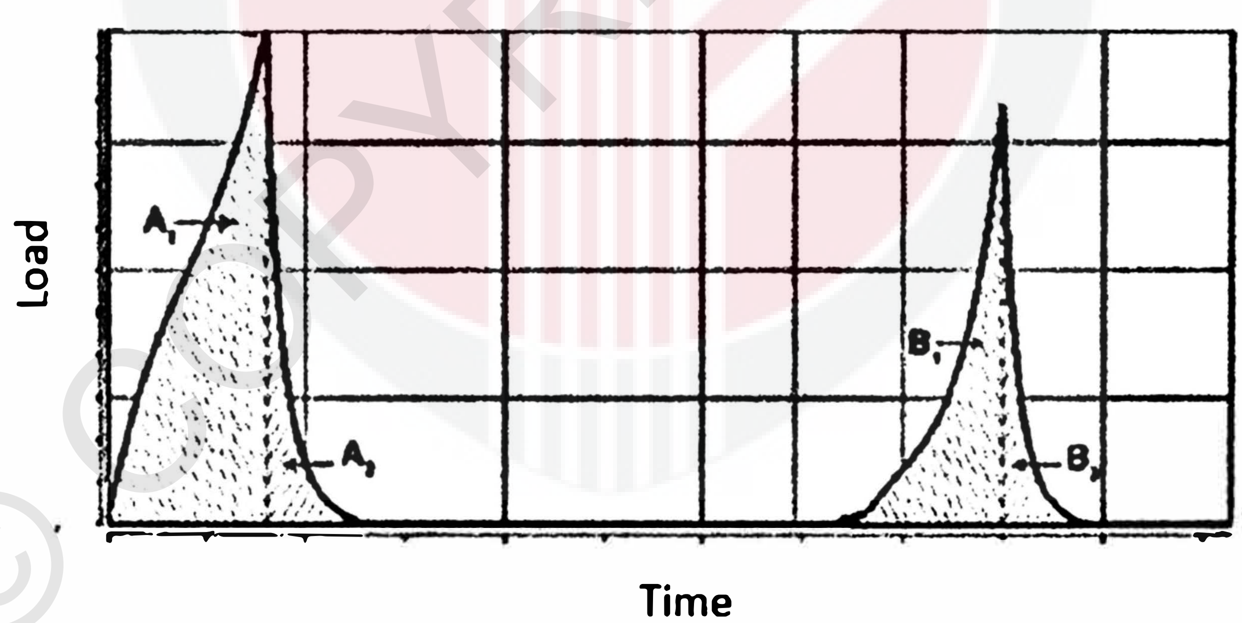


Figure 2.9: General force vs time graph for cyclic compression (n=2) of viscoelastic material

### 2.3.4 General Mechanism of Compression Tester

Compression test machine is used to evaluate static compressive strength characteristics of materials such as ultimate compression strength, yield strength, deflection and modulus. Generally, compression tester consists of several main components such as a vertical drive system, pendulum dynamometer, probe and test frame. The principle of operation of the machine is by hydraulic transmission of load. During the loading operation, pendulum dynamometer housed in the vertical system is constantly rotating to eliminate friction for reliability of operation. As soon as the probe touches the sample, load cell starts to record data and the probe will continue to compress the sample at test speed and travel the target distance or percent strain. Once it has achieved the target distance or strain the probe ascends to the original trigger position. [28] All compression testers allow different test modes for different type of compression tests such as normal compression test, hold time test and cycle count test. A variety of optional accessories are also available so that sample can barrel out and still be fully contacted and properly compressed. [29]

## 2.4 Related Research

LEGO bricks are commercially available interlocking pieces to provide advantages of the creation of building blocks that are inexpensive, reconfigurable and highly scalable. It provides a system design that allows the satisfaction of certain design constraints with a relatively simple setups for the reduction of risk in systematic errors. A biological environment utilizes the LEGO bricks as the foundation of building block has been created by Iowa State University to study the development of plant.[27]

The development of robotic technology nowadays has been an important part of education due to the robotic system that includes computer, control theory, mechanism, information sensing technology, artificial intelligence and so on.[27] With the further development of programming system in LEGO, many instruments are now being created using LEGO bricks and are being controlled to carry out various kinds of experiments. The department of bioengineering in Stanford University has developed a liquid-controlling robot in which it is capable of performing convenient delivery of droplets in a wide variety of science experiments. The materials in constructing the liquid-handling robots is not only limited to LEGO bricks and LEGO Mindstorms software but also involve the use of external parts to further integrate the function of instrument. It is proven that the liquid-handling robot is easy to use for students in which school learning content and robotic knowledge can be integrated in an engaging way.[30]

Students from University of Michigan-Flint have also developed a drawing robot by the extensive use of MATLAB programming with LEGO Mindstorms NXT Kits. The control of LEGO with the programming via MATLAB provides vast functions to various movement of the robot and also to read the image to be drawn, therefore performing drawing like how a human does.[31] This mechanical toy has also contributed in the field of scientific research where department of engineering in University of Cambridge has a LEGO-built robot to carry out the repeatedly procedures in producing synthetic bone. Synthetic bone has a wide range of applications from medical implants possibly to material in building construction. LEGO as a helping hand has greatly reduced the time in producing the bone sample in a simplest and cheapest way.[32]

Richard Moser, an Austrian PhD student has developed toy brick tensometer in which it is a measurement device that is capable of performing uniaxial extension and allow the determination of tensile force to the strain that enable for stress-strain measurement. The concept of the device to perform uniaxial tension by using LEGO linear actuator that drives by motor into concurrent linear motion. The use of LEGO parts with the combination of LEGO Mindstorms system offer the action of recording the strain and tensile force progress. Moreover, external components such as microcontroller, digital caliper, etc. have also been used in order to achieve a fairly accurate displacement measurement during the mechanical testing. This LEGO based measurement device fulfill the requirement in offering a simple and cost effective approach to study the mechanical properties of materials. Figure 2.10 shows the setup of toy brick tensometer.[33]

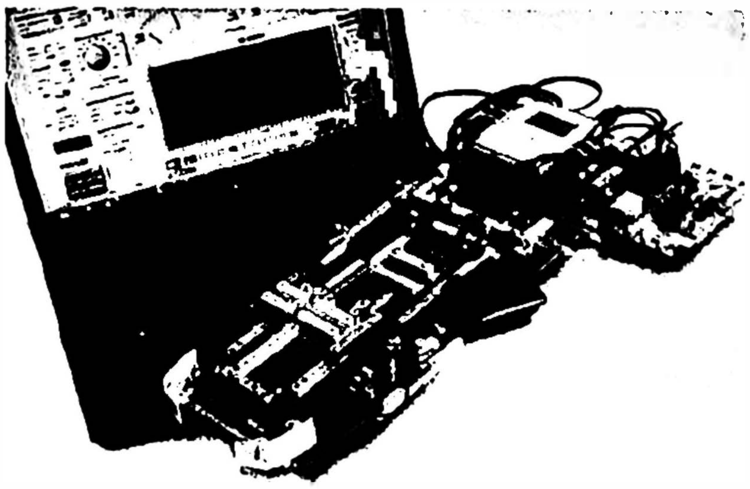

Figure 2.10: The setup of LEGO based tensometer

# CHAPTER 3

# METHODOLOGY

## 3.1 System of Measurement Device

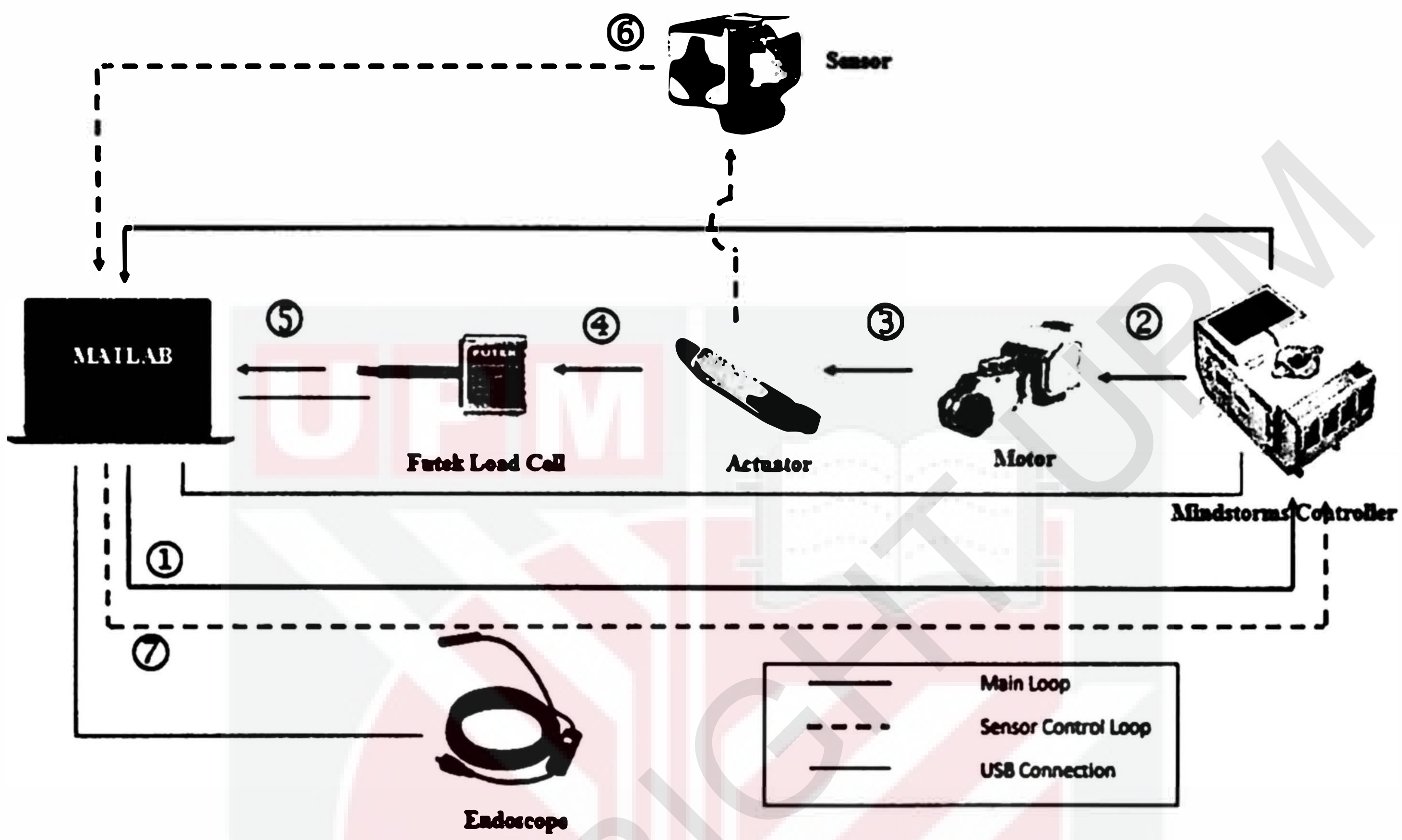


Figure 3.1: Block diagram of measurement device

As shown in Figure 3.1, the working principle of the LEGO device is controlled by Mindstorms controller. Controller will control motor to drive the actuator in a uniaxial direction to perform a variety of compression tests. As the plate attached to the actuator touches the plate attached on Futek load cell, measurements will be recorded. Throughout the experiment, video will be recorded using an endoscope. The video recorded will be analyzed using Computer Vision System Toolbox in MATLAB to obtain the movement speed of compression plate. If sensor is activated during the uniaxial press, the linear actuator will stop immediately to prevent itself from reaching its drive-limitation.

### 3.2 Design of Measurement Device

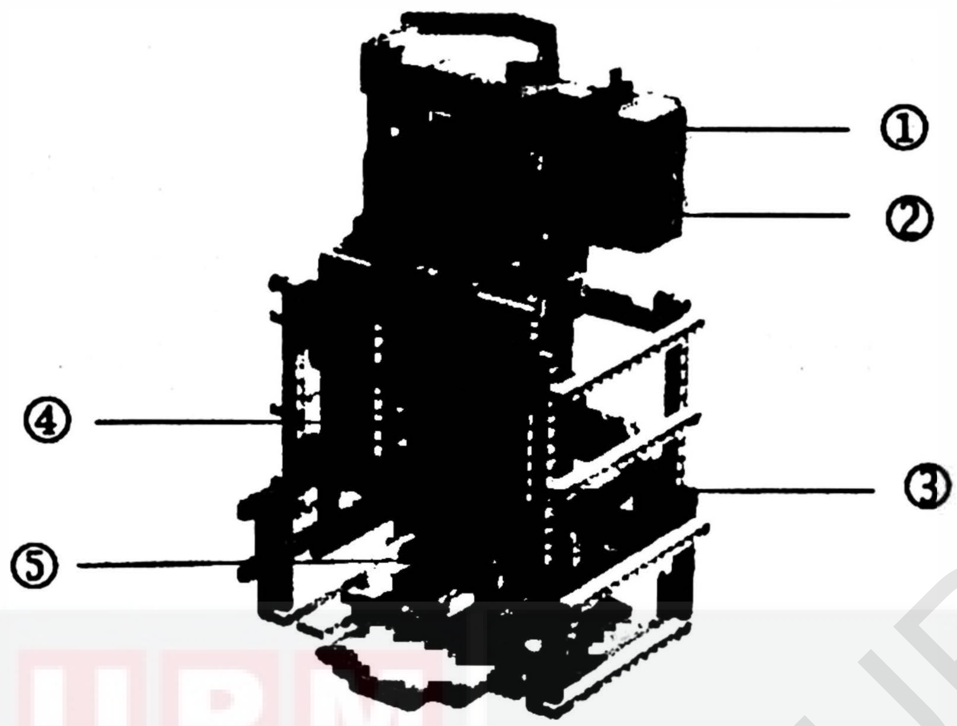


Figure 3.2: The design of LEGO compressive device

1. Mindstorm EV3 controller
2. Rotating motor
3. Compression Plate
4. Linear actuator
5. Load cell

Figure 3.2 shows the complete configuration of the LEGO compression device which consist of important parts such as Mindstorm EV3 controller, gear motor, compression plate, linear actuator and load cell. Mindstorm EV3 controller acts as the main control system in which it receives the command that is executed by MATLAB to control the speed of rotating motor in either clockwise or anticlockwise direction. As a result, the rotating motor will drive the linear actuator to move upward or downward. Downward motion of the linear actuator allows the plate to compress the sample that is being placed on the load cell. Lastly, compression test data obtained from load cell will be collected as force over time.

### 3.2.1 Compression Plate

A compression plate is an essential component of the device in which it is used to compress the ice cream sample. The design of compression plate is as shown in Figure 3.3, a flat plate is built at the bottom tip of linear actuator. It is important to note that the movement of linear actuator is intiated by motor through the connected gears. Therefore, the clockwise or anticlockwise rotation of gears will then actuate the linear actuator moving up or downward accompanied with the respective rotation, as shown in Figure 3.3.

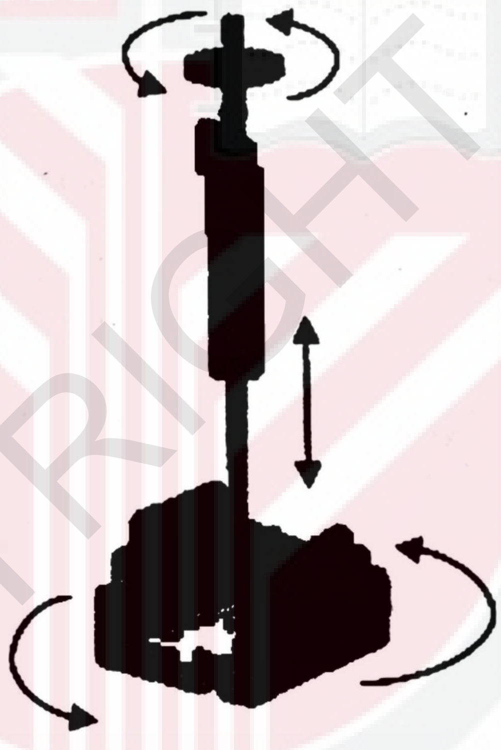

Figure 3.3: Compression plate attached to linear actuator

### 3.2.2 Frame and Sensors

In order to perform uniaxial compression on sample, only one directional movement is needed. Since the rotation of plate is not required during the uniaxial compression, frame is build at around the compressor plate to limit the rotary movement of plate. This gives rise to the design of LEGO device as shown in Figure 3.4. Furthermore, to prevent the linear actuator from reaching their drive-limitations during upward and downward movements, two touch sensors are placed on the top and bottom respectively. As soon as one of the sensors is triggered, the movement of linear actuator will be stopped.

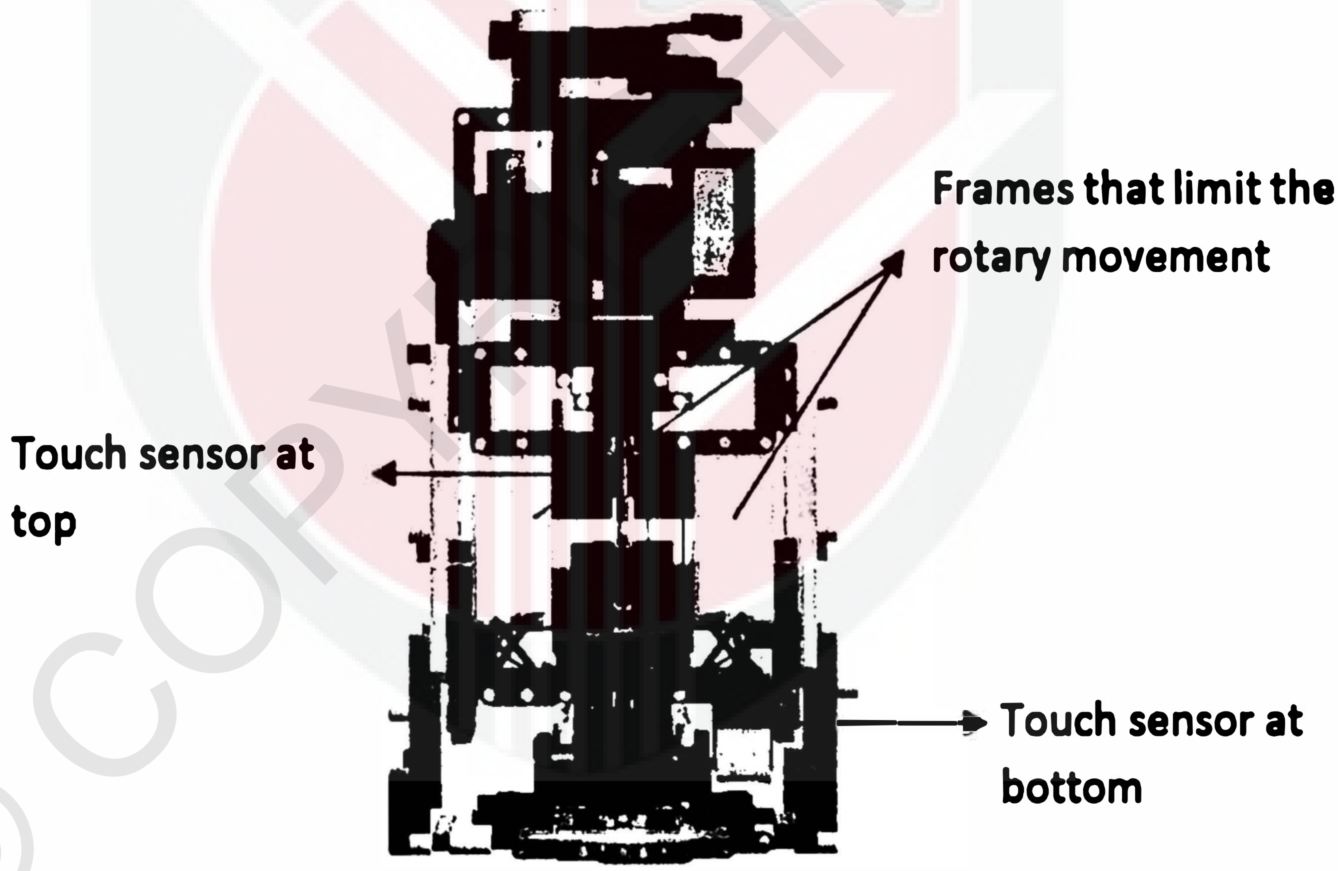


Figure 3.4: Front view of the LEGO compression device

### 3.2.3 Load Cell Placement

Moreover, the device will be placed in a freezer where the space is limited, the placement of load cell should be flexible for easier install and removal to ease the procedure of sample changing and placing. Therefore, the base allows the load cell to be installed or removed freely. Fortunately, the dimension of load cell plate has the precise dimension to allow a stable yet flexible placement of the load cell between the lego bricks.

Figure 3.5: Ice cream sample placed on load cell

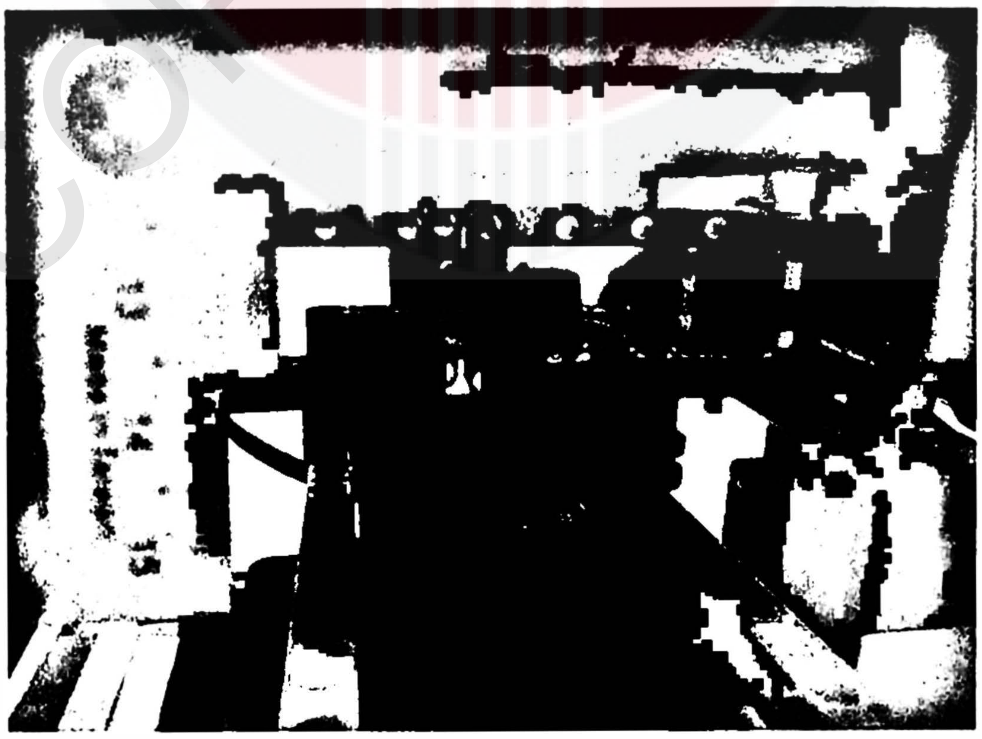

Figure 3.6: Positioning of load cell into the sample testing area

### 3.2.4 Stabilization of Structure

The device is mostly build up from lego bricks that are light in weight. It is important to notice that if the weight of device itself is lower than the compressive force that will be exerted on sample, the device will lift itself upwards and affect the accuracy of results. Therefore, a load of 2 kg will be placed on the top of the device (as shown in Figure 3.7) to stabilize the device during compression test. It can also be seen that a ruler is placed beside the moving plate. The purpose of the ruler is to estimate the velocity of moving plate or more importantly the deformation of ice cream sample. Basically, the framework of device is build up using LEGO parts while only load cell and mass load are the external parts that are used for data acqusition and stabilization.

Figure 3.7: Complete set up of LEGO compression device with load stabilizer

## 3.3 MATLAB Support Package for LEGO Mindstorms EV3 Hardware

MATLAB Support Package for LEGO Mindstorms EV3 Hardware has been used to control the LEGO device. The support package has provided MATLAB functions to control the motors and sensors in performing uniaxial compression. Besides LEGO device, the implementation of Futek load cell is also available using MATLAB to perform data logging functions. There are four types of experiments that can be performed by the LEGO device: uniaxial compression, stress relaxation, step relaxation and cyclic compression. However, the tests that will be performed in this study are only uniaxial compression, stress relaxation and cyclic compression of ice cream sample. In order to ease the procedure in moving the compression plate at a desirable position, single movement to either move upwards or downwards are also provided in the MATLAB command. Lastly, a set of command is input to plot the recorded compression data into graph for data visualization in a clear and easily digestible manner. Figure 3.8 shows the flow chart for MATLAB execution in controlloing the LEGO tester.

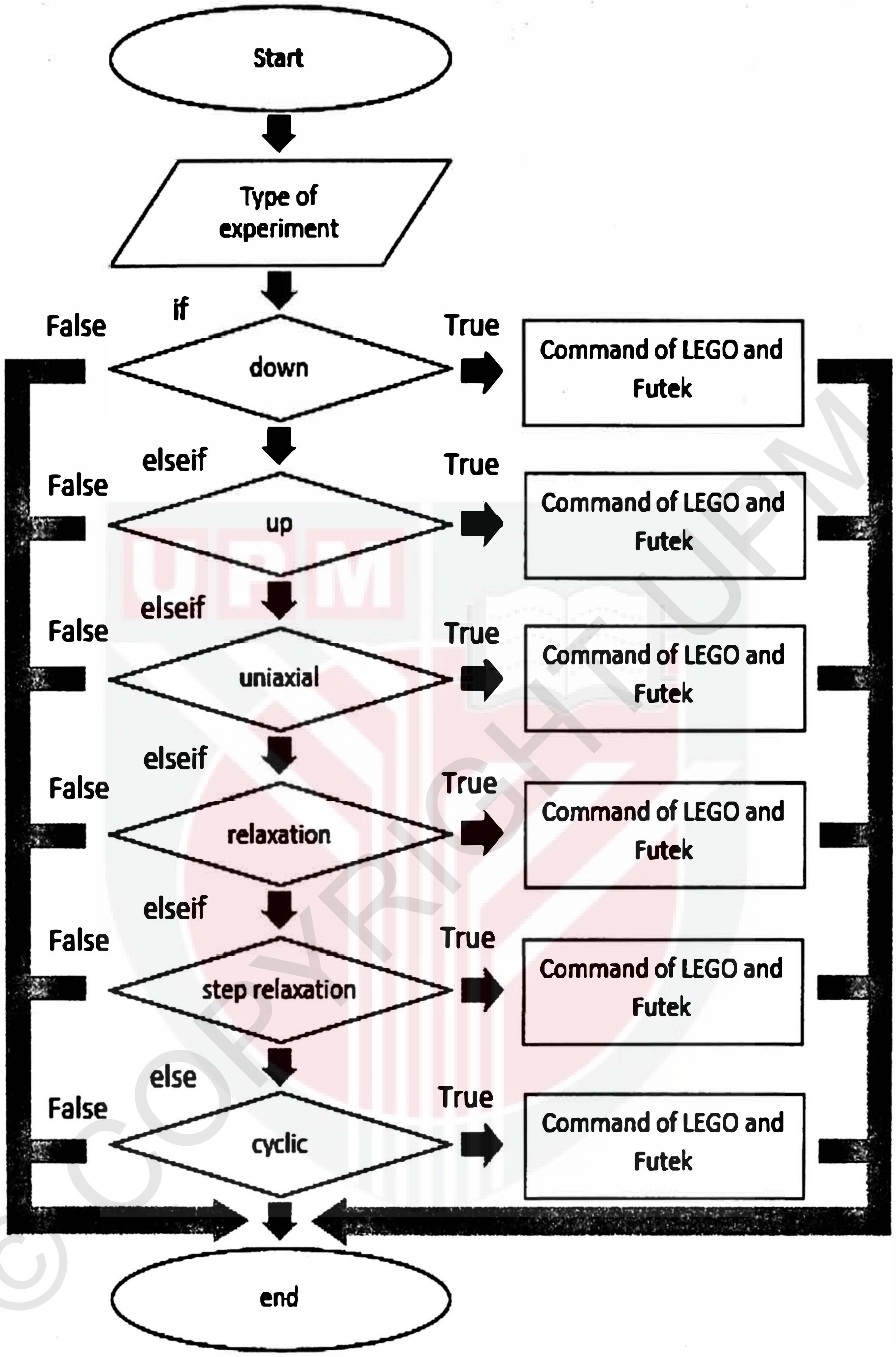


Figure 3.8: Flow chart of LEGO device control system

### 3.3.1 MATLAB Execution for LEGO Mindstorms EV3 Hardware

**Step 1: Identify the threshold of sample**

Input 'down' and set the threshold value as 0. Threshold value of sample the sample will be shown.

**Step 2: Positioning of moving plate**

Run the command again and input 'down' for the type of experiment. Enter the new threshold value that is larger to the threshold value by a unit in the lowest decimal point (eg: 0.001 increase to 0.002, 0.03 increase to 0.04). After entering the new threshold value, the moving plate will move until it slightly touches the ice cream sample.

**Step 3: Insert type of experiment**

Input the type of experiment that user intends to perform.

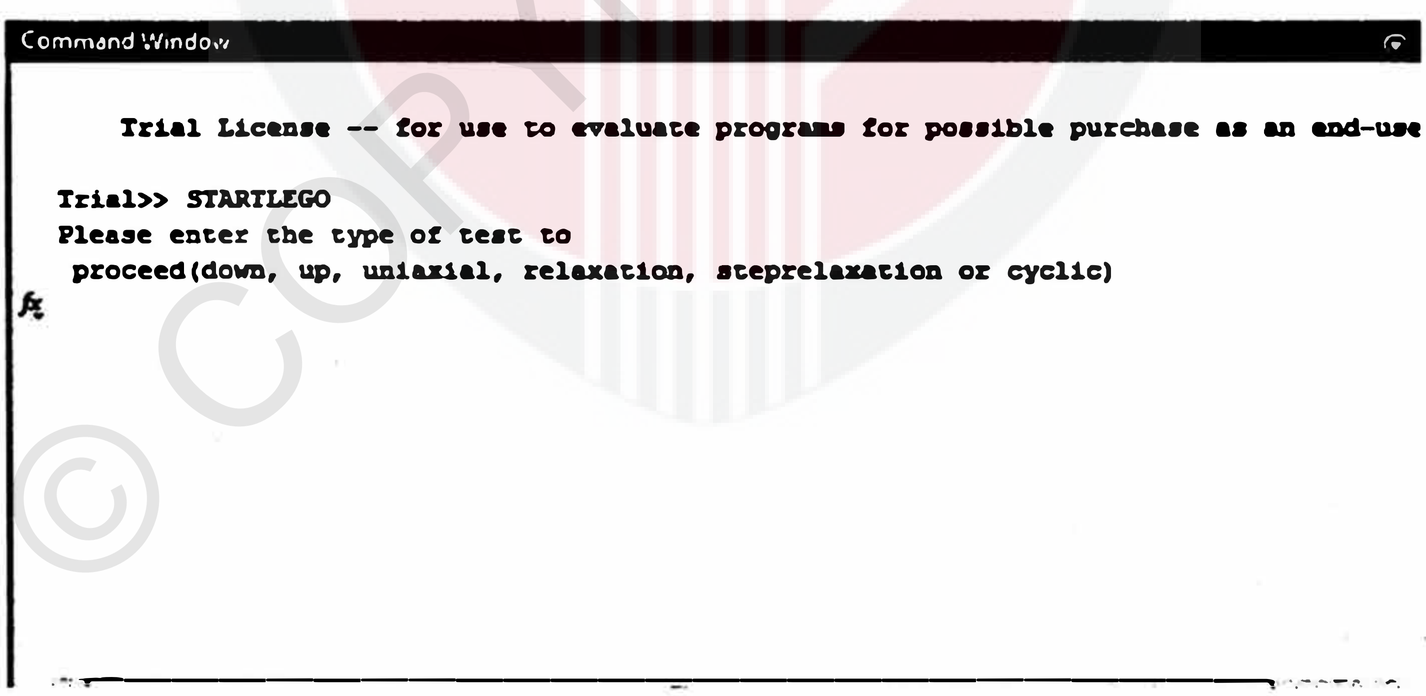


Figure 3.9: Input type of experiment

**Step 4: Input parameter to set operation condition**

Input value of parameter to set the operation condition. Operation condition are as below, some are only required for certain type of experiment

Motor power(%): Percentage of motor power intended to perform the uniaxial press

Time interval of data point: The frequency of data collection of load cell in a unit second

Run time: The time duration of uniaxial press in second

Threshold value: The collected data threshold value in order to initiate the plot of graph

Time taken for relaxation: Time required to rest the sample after uniaxial press

Number of steps: Number of cycle needed to perform stress relaxation compression

Number of cycle: Number of cycle needed for a cylic compression

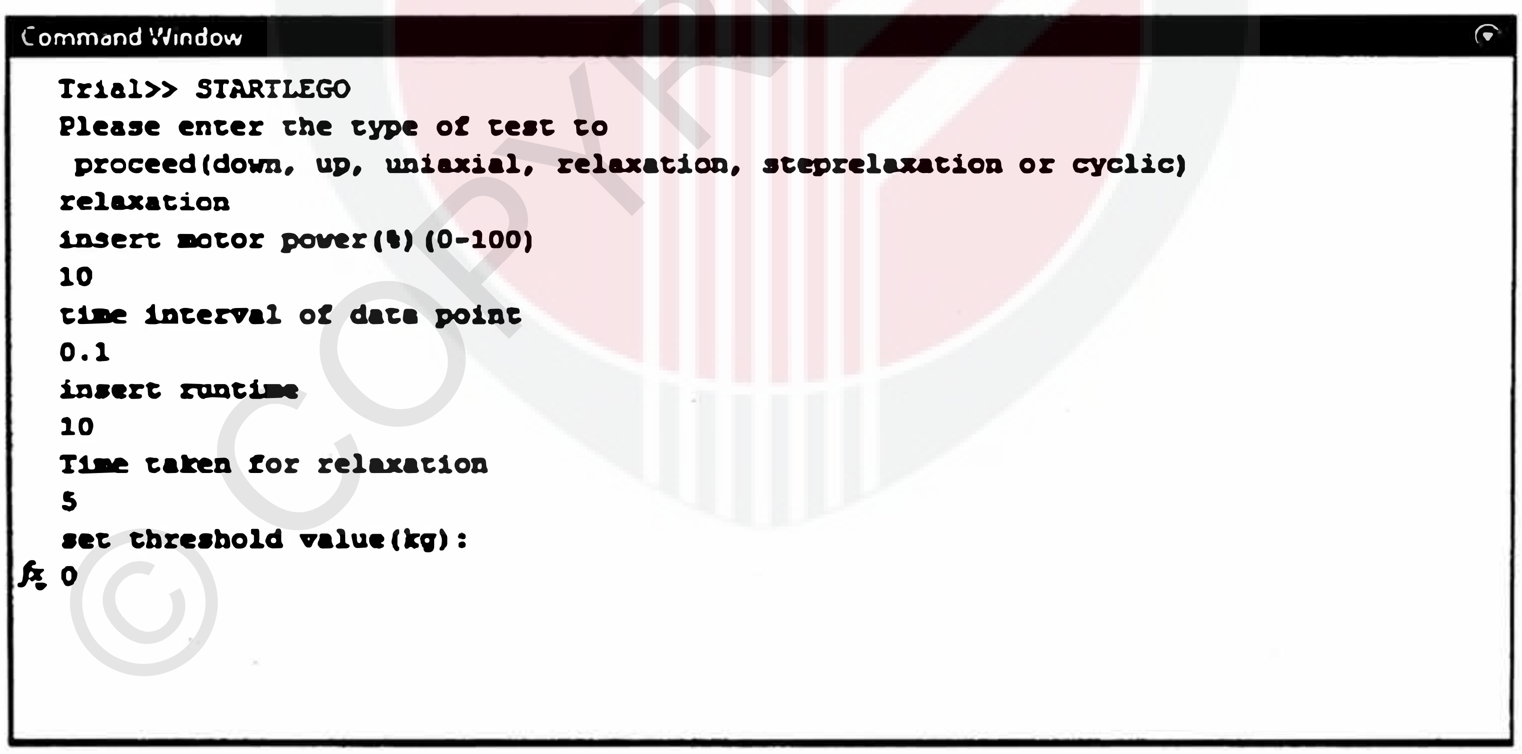


Figure 3.10: Define operational parameters

Table 3.1: Parameters needed to define the operation condition

| | Uniaxial Compression | Stress Relaxation Compression | Step Relaxation Compression | Cyclic Compression |
|---|---|---|---|---|
| Motor power | ✓ | ✓ | ✓ | ✓ |
| Time interval of data point | ✓ | ✓ | ✓ | ✓ |
| Run time | ✓ | ✓ | ✓ | ✓ |
| Threshold value | ✓ | ✓ | ✓ | ✓ |
| Relaxation time | | ✓ | ✓ | |
| Number of steps | | | ✓ | |
| Number of cycle | | | | ✓ |

**Step 5: Data tabulation and graphing**

Uniaxial press will begin right after inserting parameter of the operation condition. Force that is exerted on the sample will be measured by load cell and collected in MATLAB program. A graph of compressive force against time will be plotted throughout the compression test.

**Step 6: Save data and graph**

Save the plotted graph and collected data from MATLAB program before performing next experiment.

## 3.4 Computer Vision System Toolbox

The device is designed to obtain the stress strain properties of the sample, therefore the velocity of the linear motion has to be well-known. Computer Vision System Toolbox in MATLAB has provided tools for the video processing workflow to obtain the velocity of the moving plate. This can be done by subtraction of the background, which identifies moving object from the portion of a video frame that significantly differs from a background model. Background subtraction is a technique that is specifically used to binarize input image and also to detect the moving pixel. The speed of moving plate can then be estimated using the distance travelled by the centroid to the frame rate of the video. Figure 3.11 shows the flow chart for MATLAB execution in estimating the speed of compression plate.

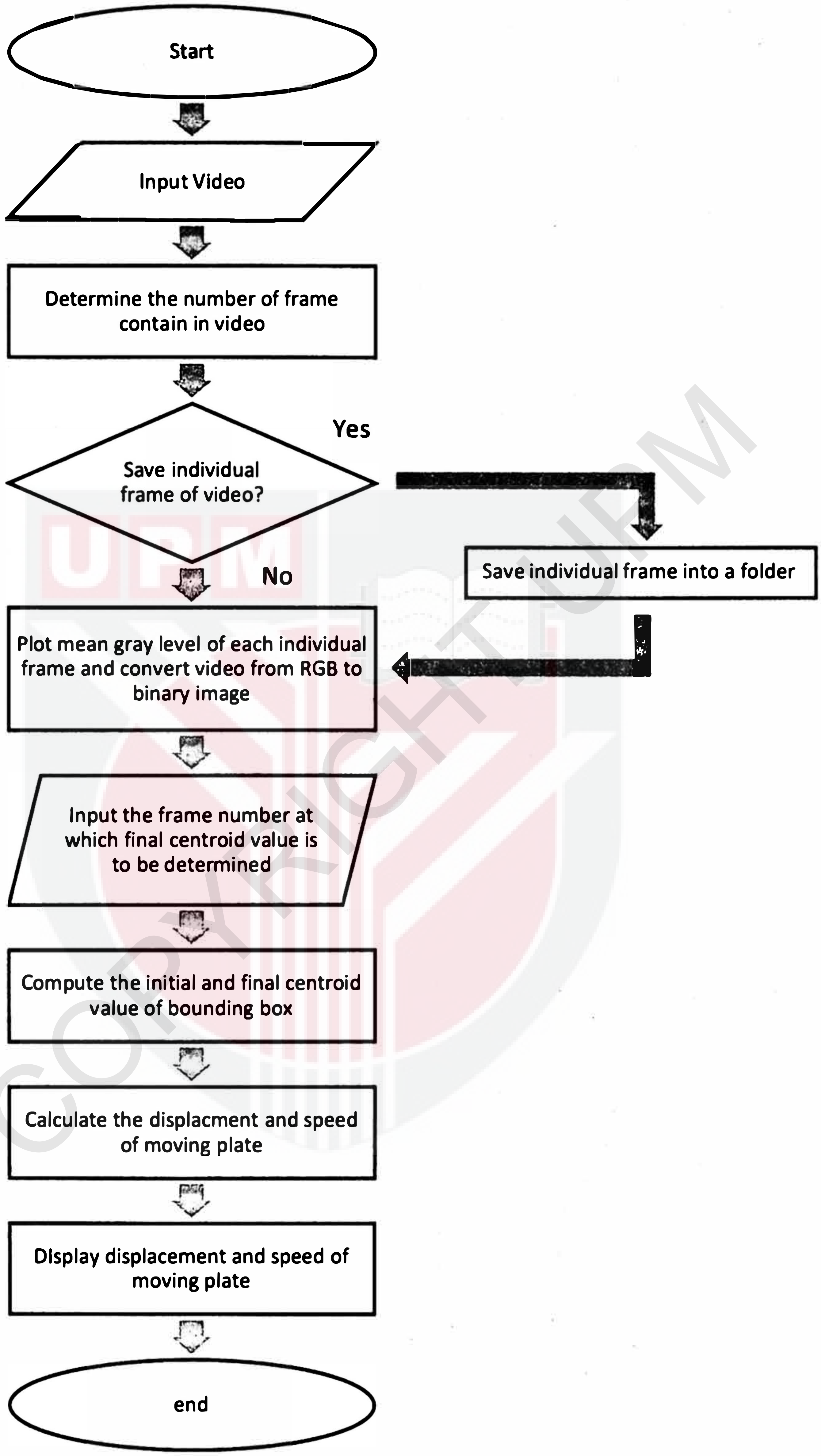


Figure 3.11: Flow chart of speed estimation

### 3.4.1 Matlab Execution for Speed Estimation

**Step 1: Video input**

Input the video that is recorded for compression test. Frame rate and number of frames that contain in the video will be determined automatically. A window will pop out to ask if user wants to save each individual frame of the video as soon as the command is executed.

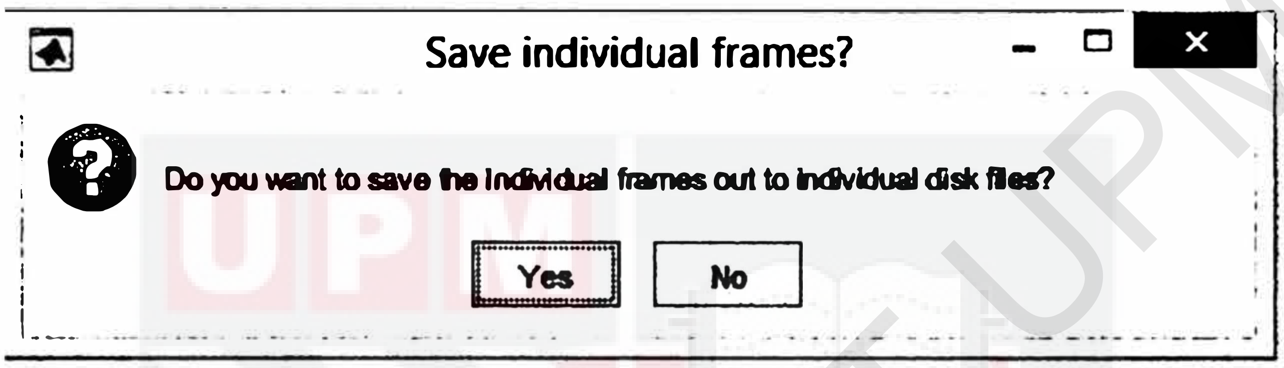


Figure 3.12: Save individual frame

**Step 2: Binary image generation**

Each individual frame that is determined from the video will be binarized in order to produce an abstract representation of moving object.

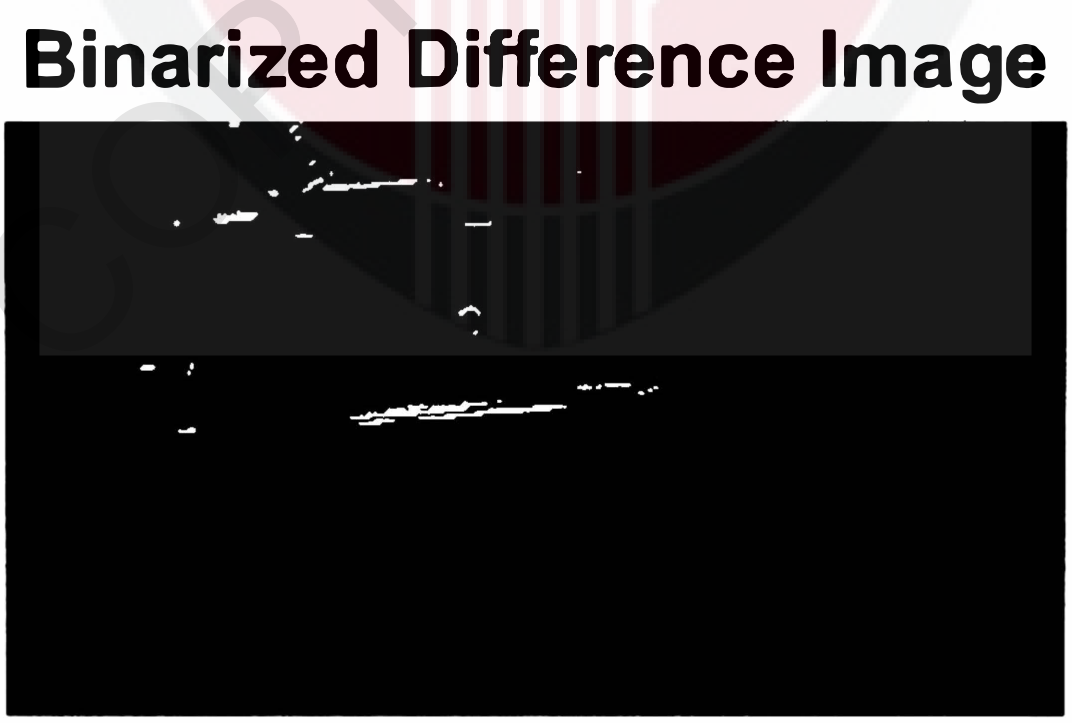


Figure 3.13: Binarized difference image

**Step 3: Plot of mean gray level**

Plot of varying grayscale intensities of the individual frame is shown. At this point, we are required to identify the number of frame at which the moving plate stop moving down.

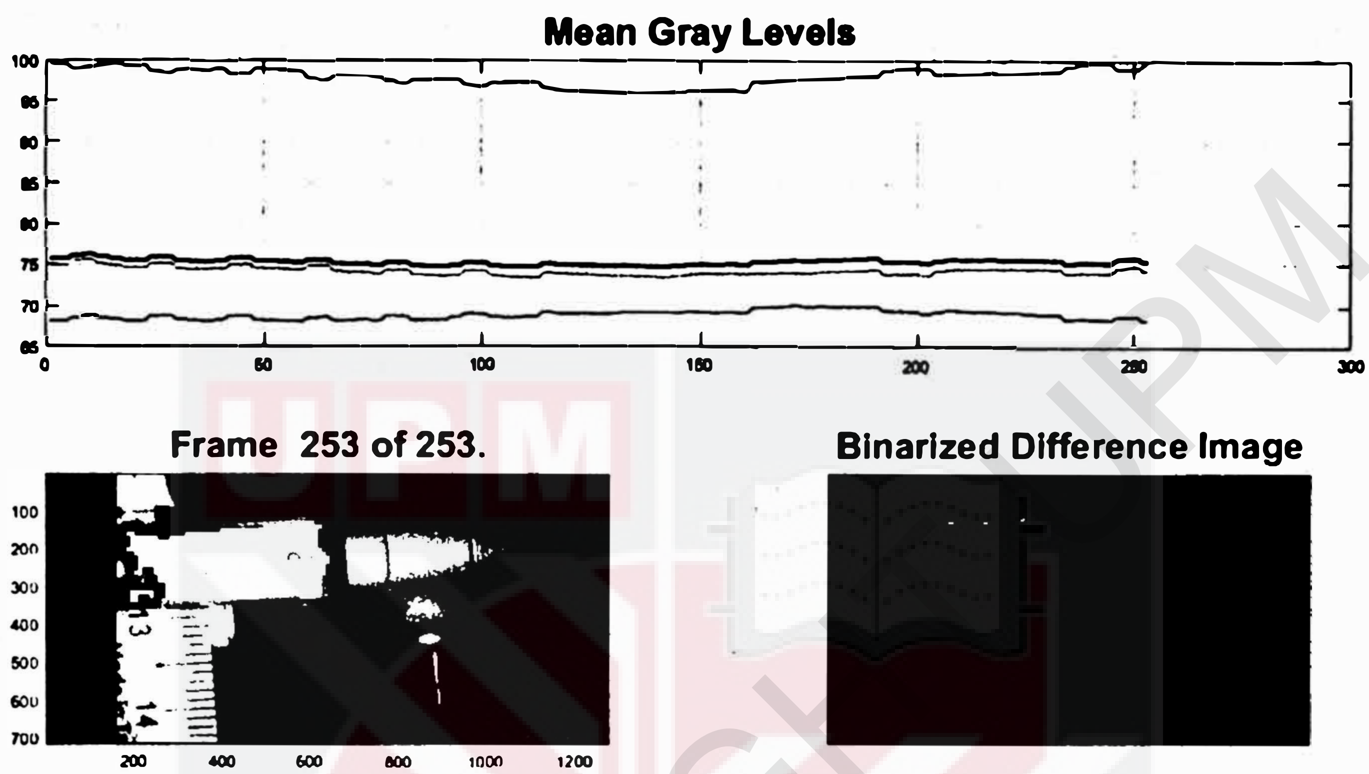


Figure 3.14: Plot of mean gray levels

**Step 4: Input the frame number**

After the plot of mean gray level, input of frame number at which the moving plate stop moving down. Distance travelled of moving plate will be computed by comparing the first frame (moving plate that just above to start moving down) and selected frame (moving plate that just above to stop moving down).

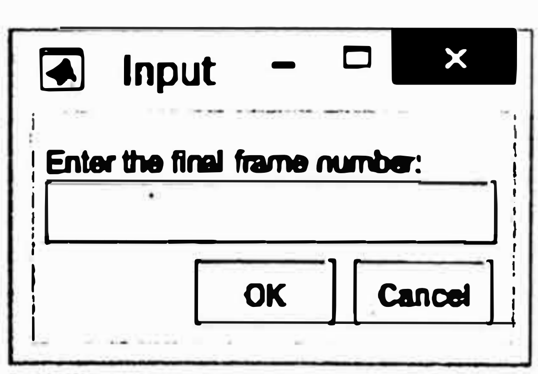


Figure 3.15: Input final frame number

**Step 5: Compute the centroid value**

Properties of the binary images are measured in a struct array. Bounding boxes are drawn for the moving pixel and coordinate of the centroid value in bounding box will be computed.

**Step 6: Calculate distance and speed**

Distance travelled by the compression will be calculated using the computed centroid coordinated for two matched blocks with the two chosen frames. Distance formula is given by

$$D = \sqrt{(x(i) - x(k))^2 + (y(i) - y(k))^2}$$

Where $x(i)$= x coordinate of initial frame, $x(k)$= x coordinate of final frame, $y(i)$= y coordinate of initial frame and $y(k)$= y coordinate of final frame

After distance has been calculated, speed is calculated by dividing the period of time between the two chosen frame. Formula is given by:

$$Speed = \frac{Distance}{final\ frame\ number / Frame\ Rate}$$

Lastly, speed of moving plate will be shown.

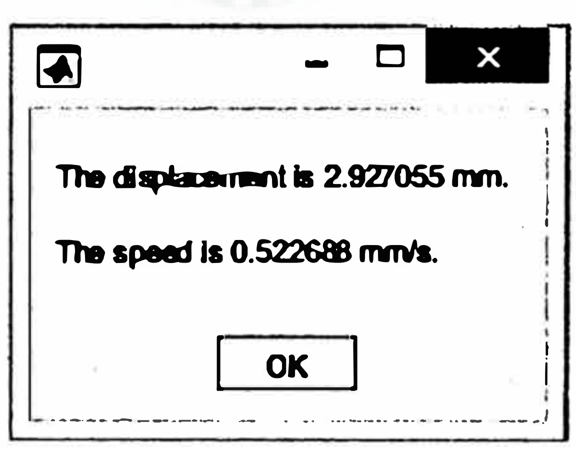

Figure 3.16: Result of video processing

### 3.5 Sample Preparation

Commercial Brand A ice cream has been used as the sample in this study. In order to produce the cylindrical shape ice cream with diameter of 15mm and height of 7.5mm, disposable ice stick mold plastic bag will be used. As shown in Figure 3.17, the desired diameter will be measured and drawn on the mold plastic bag. Then, the plastic bag will be sealed along the line drawn on it. After the bag is sealed, successive marks will be drawn on the extra space of plastic bag to indicate the height of ice cream sample, as shown in Figure 3.18. The ice cream will then being filled up into the ice stick mold plastic bag and the tied up the plastic bag tightly. The mold containing ice cream will be put into freezer for 24 hours. To demold the ice cream sample, the mold will be cut accordingly to the marks and plastic will be peeled away from the sample. Figure 3.19 shows the ice cream samples that are completely peeled off from the mold plastic bag. The demold ice cream sample will be placed into freezer again prior to the running of experiment.

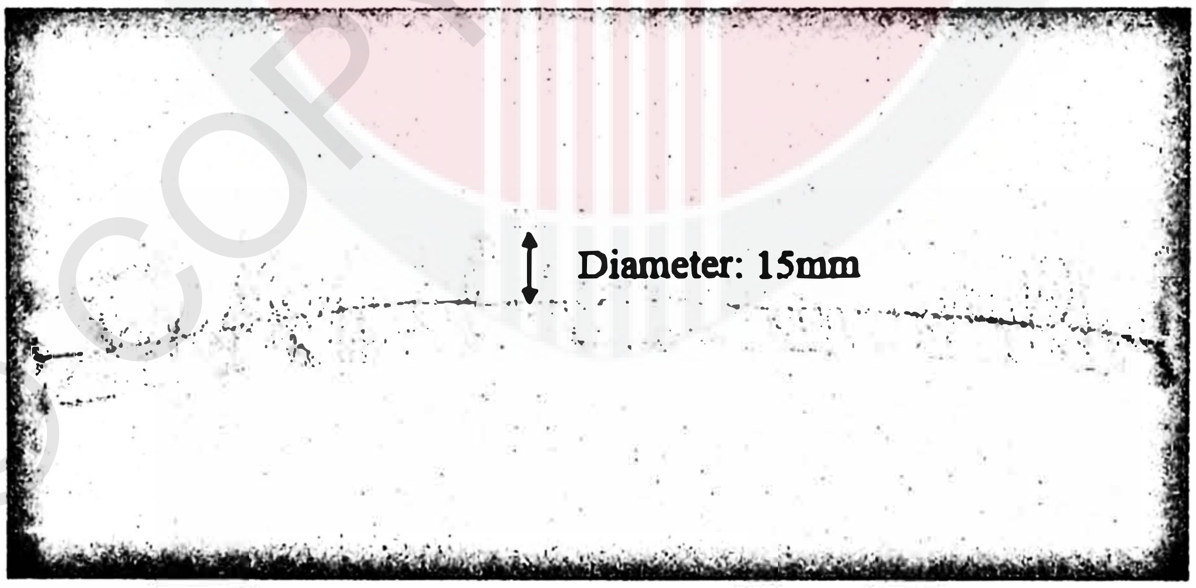


Figure 3.17: Disposable ice stick mold plastic bag

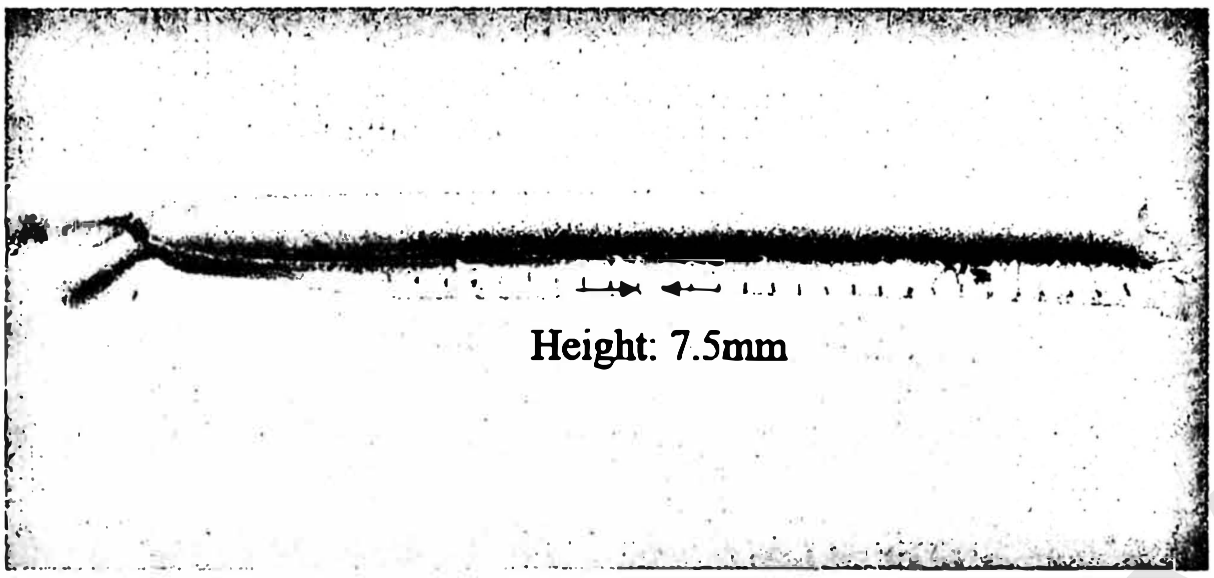


Figure 3.18: Mold plastic bag filled with ice cream sample

Figure 3.19: Ice cream sample

## 3.6 Experimental Setup

Due to the rapidly melting of ice cream, it is essential to carry out the experiment in a low temperature condition where the mechanical investigation of ice cream in situ can be studied. The experiment will be conducted in a freezer where temperature can go down to -40°C, to prevent the melting of ice cream throughout the experiment. One of the reasons behind the design of LEGO based measurement device is due to its flexibility in placing into the freezer for the study of ice cream mechanical behavior. When conducting the experiment, the freezer will be closed and the experiment situation can be viewed in real time with the aid of endoscope. The experimental setup is illustrated in Figure 3.20.

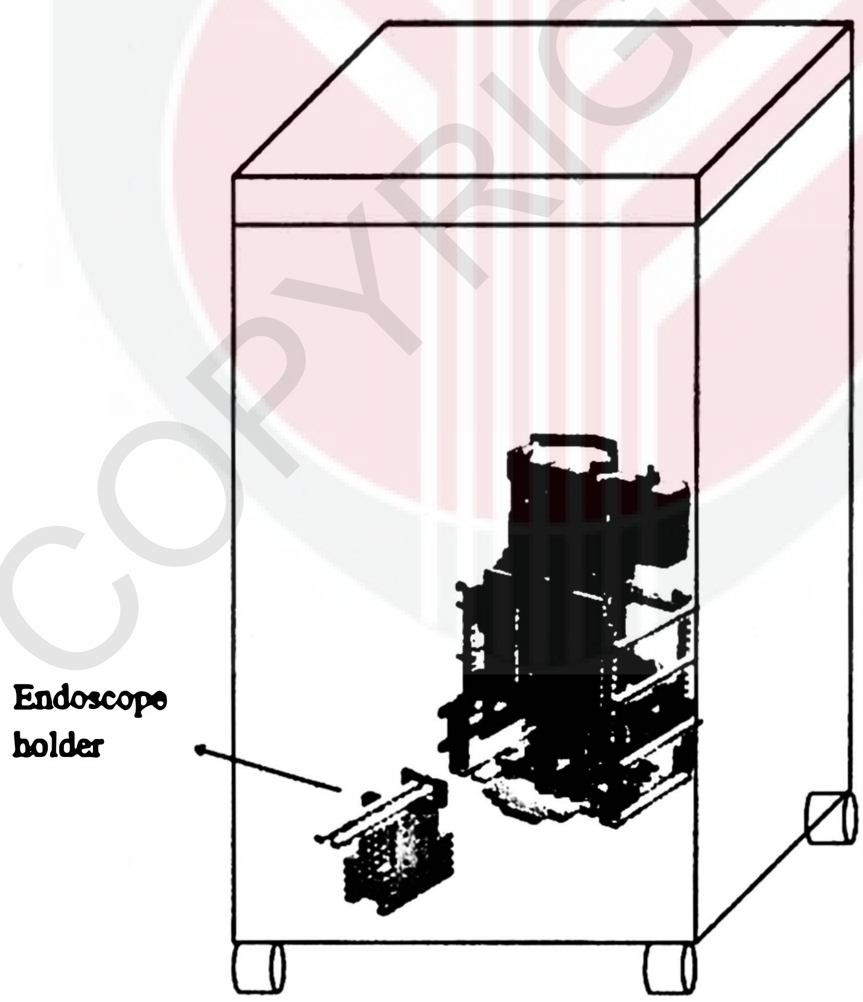


Figure 3.20: Experimental set up in a freezer

### 3.7 Data Acquisition

Uniaxial compression, stress relaxation and cyclic compression tests will be carried out using the design measurement device in the freezer. The deformation of cylindrical ice cream sample having diameter of 15mm and height of 7.5mm will be studied. It is important to note that at different power level, the speed of moving plate will be different. In order to achieve a comparable result, different power level will have different run time to perform uniaxial press. This will correspond to the same deformation for all experiments under different type of compression tests. The results obtained will be useful in determining the mechanical behavior of ice cream sample upon deformation as well as to verify the accuracy and consistency of the LEGO device.

There is a limitation in determining the deformation of an ice cream using this LEGO device. This is because there is no any measurement device being used to measure the deformation of ice cream sample throughout the compression test. We know that as the plate is compressing the sample over time, the deformation will vary.. The current method applied is to assume the plate is compressing at a constant rate, in other words, at a constant speed.

In principle two methods in obtaining speed of moving plate have been taken into consideration, direct and indirect measurements. Direct measurement is by visually measuring the displacement between initial and final point of ruler that is mounted on the frame, then divide by the time for the compression of sample. For indirect measurement, video processing using MATLAB will be applied. Video processing will calculate the distance between centroid of each frame that is obtained from the video recorded.

Both methods have their pros and cons in obtaining the accurate measurement of moving plate speed. Direct measurement is able to ensure the displacement measured will not deviate too much from the real value. However, human error is unavoidable during the measurement taking between two frames. For indirect measurement, video processing is expected to obtain a more accurate measurement. However, video processing is very dependant on the lumimance when video is recorded. Since video recorded is not guarantee to have all same luminance level, the measurement of displacement from video processing may not necessarily as accurate as expected.

When speed is determined, the present deformed height of sample can be obtained by multiplying speed of moving plate to the time at that particular deformed height. Subsequently, the deformation of the ice cream sample, $\varepsilon_E$ can also be calculated.

$$h_t = speed\ of\ moving\ plate\ \times time\ at\ the\ particular\ deformed\ height$$

$$\varepsilon_E = \frac{h_o - h_t}{h_o}$$

# CHAPTER 4

# RESULTS AND DISCUSSION

## 4.1 Overview

This chapter gives an overview of the actual build up of the device and measurement method that used to obtain the stress strain curve of sample. Besides that, results obtained from the compression test at different power levels will be used to verify the consistency of motor hardware that have been used in the LEGO device. Lastly, mechanical behavior of the ice cream will be further dicscussed based on the graph obtained.

## 4.2 Consistency of Motor Power at Different Levels

Uniaxial compression has been conducted under the motor power level at 10%, 30%, 50% 70%, 80% and 100%. For the startup of experiment, 10% of power is set for a run time of 15s, which means the plate will move downward for 15s at a speed of 10%. In order to achieve same deformation under different power levels, run time is adjusted fractionally to the power level, as shown in Table 4.1. Ideally, same deformation can be achieve under different speed of moving plate by varying the time taken to press the sample fractionally.

Table 4.1: Theoretical speed of moving plate at different motor power level

| Motor Power (%) | Time (s) | Speed (mm/s) | Deformation (mm) |
|---|---|---|---|
| 10 | 15 | 0.2 | 3 |
| 20 | 7.5 | 0.4 | 3 |
| 30 | 5 | 0.6 | 3 |
| 40 | 3.75 | 0.8 | 3 |
| 50 | 3 | 1.0 | 3 |
| 60 | 2.5 | 1.2 | 3 |
| 70 | 2.14 | 1.4 | 3 |
| 80 | 1.88 | 1.6 | 3 |
| 90 | 1.67 | 1.8 | 3 |
| 100 | 1.5 | 2.0 | 3 |

Table 4.2: Experimental and theoretical results

| Motor Power (%) | Run Time (s) | Velocity (mm/s) | | |
|---|---|---|---|---|
| | | Matlab | Manual | Theory |
| 10 | 15.00 | 0.21 | 0.19 | 0.2 |
| 30 | 5.00 | 0.53 | 0.49 | 0.6 |
| 50 | 3.00 | 0.55 | 0.83 | 1 |
| 70 | 1.88 | 1.08 | 1.34 | 1.4 |
| 80 | 1.67 | 1.08 | 1.6 | 1.6 |
| 100 | 1.50 | 1.23 | 1.33 | 2 |

It is identified that motor power at 10% has a speed of approximately of 0.2 mm/s. Therefore, in ideal condition, the increase of moving plate speed at different power level should be increased linearly and known as the theoretical speed. The theoretical speed of the moving plate has been tabulated in Table 4.1.

As mentioned in the previous section, direct measurement and indirect measurement method have been applied in order to obtained the speed of moving plate during compression test. For indirect measurement, the speed of moving plate have been estimated through video processing in MATLAB. For direct measurement method, an initial frame and final frame of the uniaxial press will be taken and the displacement will be visually estimated, as shown in Figure 4.1. Then, velocity is obtained by dividing the run time following the run time at different power levels. The results obtained from this direct measurement method are also tabulate in Table 4.2. All the results obtained are plotted in Figure 4.2.

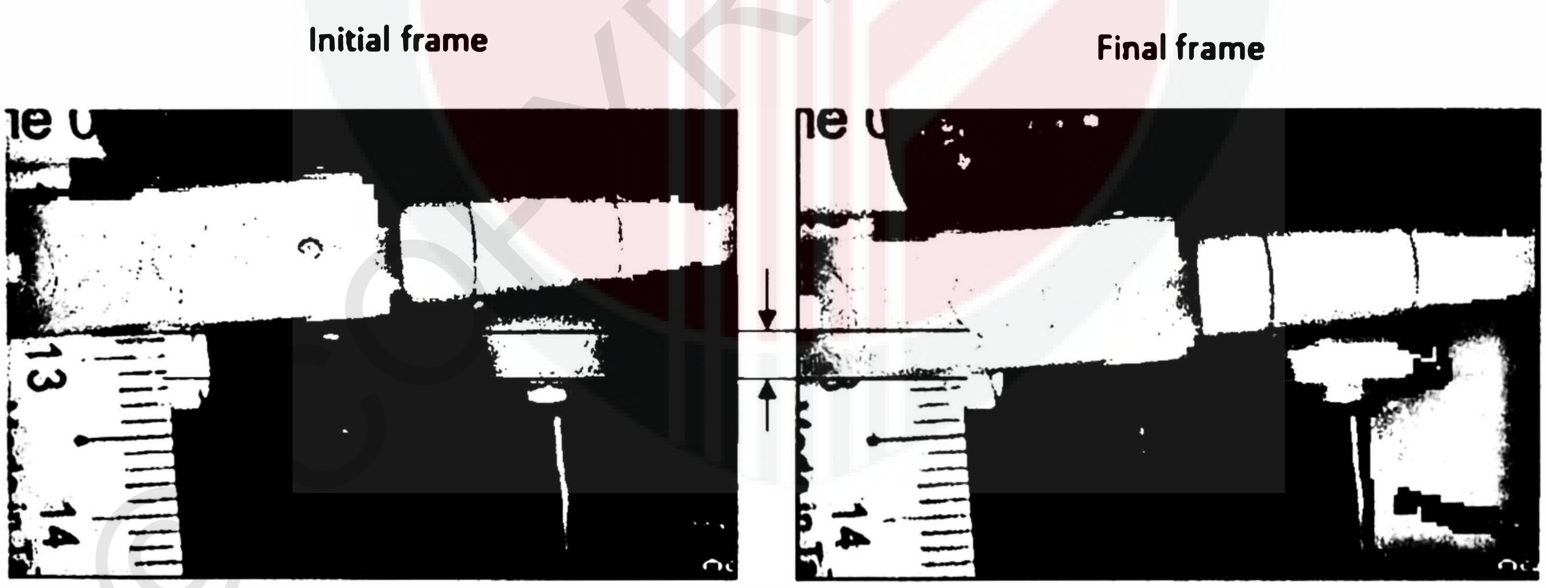


Figure 4.1: Initial frame and final frame of compression test

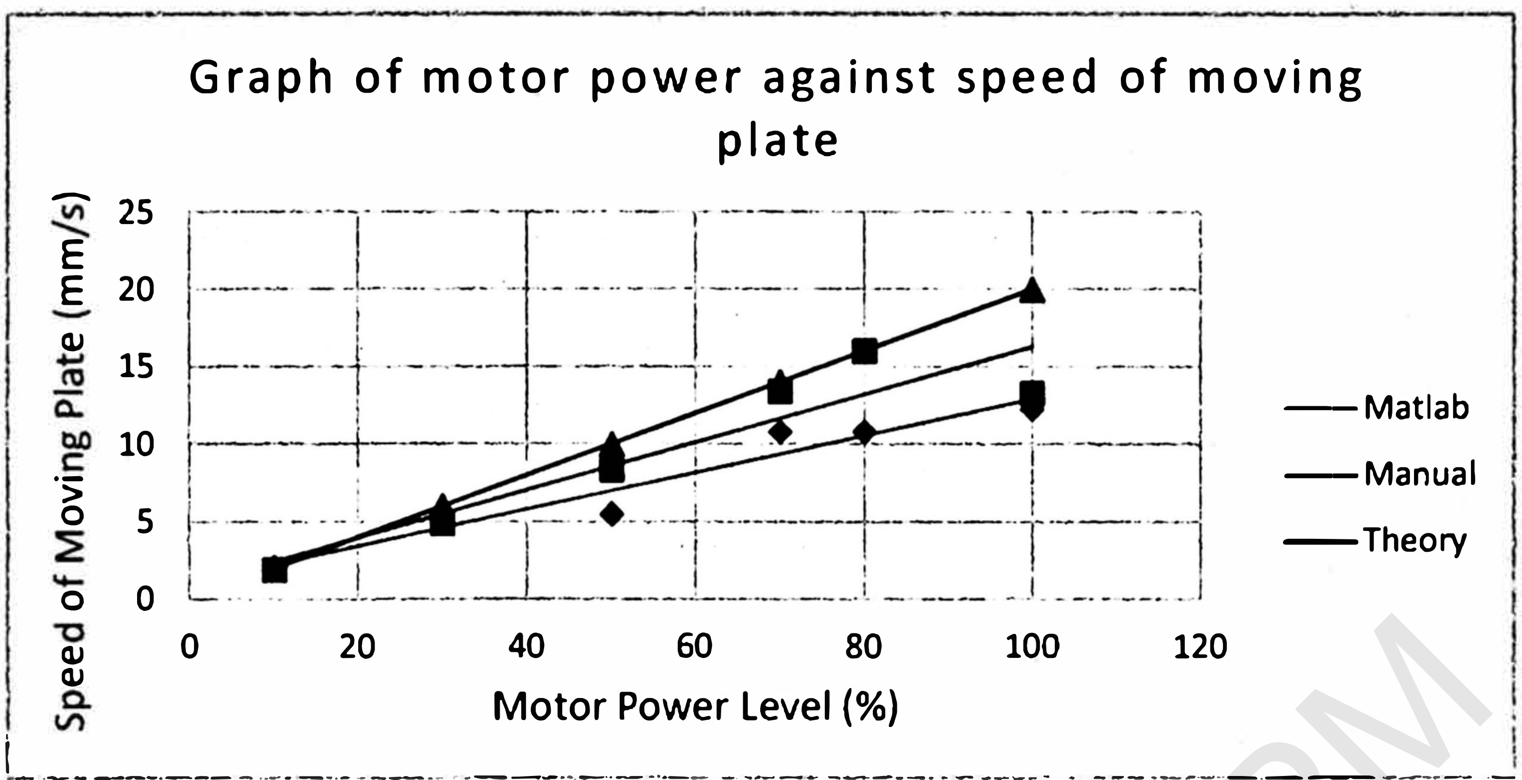

Figure 4.2: Graph of motor power against speed of moving plate for experimental and theoretical results

From Table 4.2, results obtained from direct and indirect measurement methods are different. For direct measurement, the scale of the frame may be ran out and it is not able to measure the displacement by using a ruler. Therefore, the displacement can only be visually estimated based on the ruler that is mounted on the LEGO device. Furthermore, the placement of endoscope when recording the video is not in line with the measurement device and results in a less accurate measurement. For indirect measurement, even though MATLAB provides a very good alternative measurement method, but the inconsistent of luminance in the video recorded may also result in the inaccurate measurement. Another likelihood would be the incorrect MATLAB coding written to perform the video analysis.

Even though both direct and indirect measurement methods may not lead to the most accurate result, but it is clearly show that the speed of the moving plate at different motor power levels are not consistent. It is identified that the LEGO motor used in performing the uniaxial press is incapable in obtaining the most accurate result.

The suggestion is to replace a motor that can perform uniaxial press at a constant speed under different motor power level.

Although the results obtained are not quantitatively accurate, the LEGO device has successfully allowed the study of ice cream mechanical behavior to be carried out in an ideal condition. The deformation of ice cream sample without melting gives a clear trending in the stress strain relationship. Moreover, the consistency of the stress strain trending under different motor power level is considerably acceptable, which is important in determining the mouthfeel quality of ice cream product.

## 4.3 Mechanical Study on Ice Cream

Uniaxial compression, stress relaxation test and cyclic compression are conducted at 10%, 50% and 80% power levels with their respective run time so as to achieve the same deformation of ice cream sample. In this project, 3mm displacement of ice cream sample is desired. Therefore, time taken for 3mm displacement of ice cream to be achieved at 10%, 50% and 80% power motor level will be 15s, 3s and 1.88s respectively. Results will be recorded as the function of force over time. All the experiments are carried out in the freezer under temperature of -11°C. In order to ensure the consistency of results obtained, ice cream sample used for all experiments are bought from one identical batch. Mechanical behavior of ice cream correspond to different types of compression will be discussed based on the graphs obtained.

### 4.3.1 Uniaxial Compression

Uniaxial compression were conducted at motor power levels of 10%, 50% and 80%, under a constant deformation at 3mm, results are as shown in Figure 4.3, Figure 4.4 and Figure 4.5. In uniaxial compression test, maximum compression forces and apparent modulus of elasticity can be determined. These parameters reflect the elastic response capacity of the ice cream structure under compression based on the formulation of ice cream ingredients. Different formulation of ice cream will result in different composition of air, ice, sugar solution in matrix form and fat present in the ice cream structure which will further determine its physical and sensory properties.

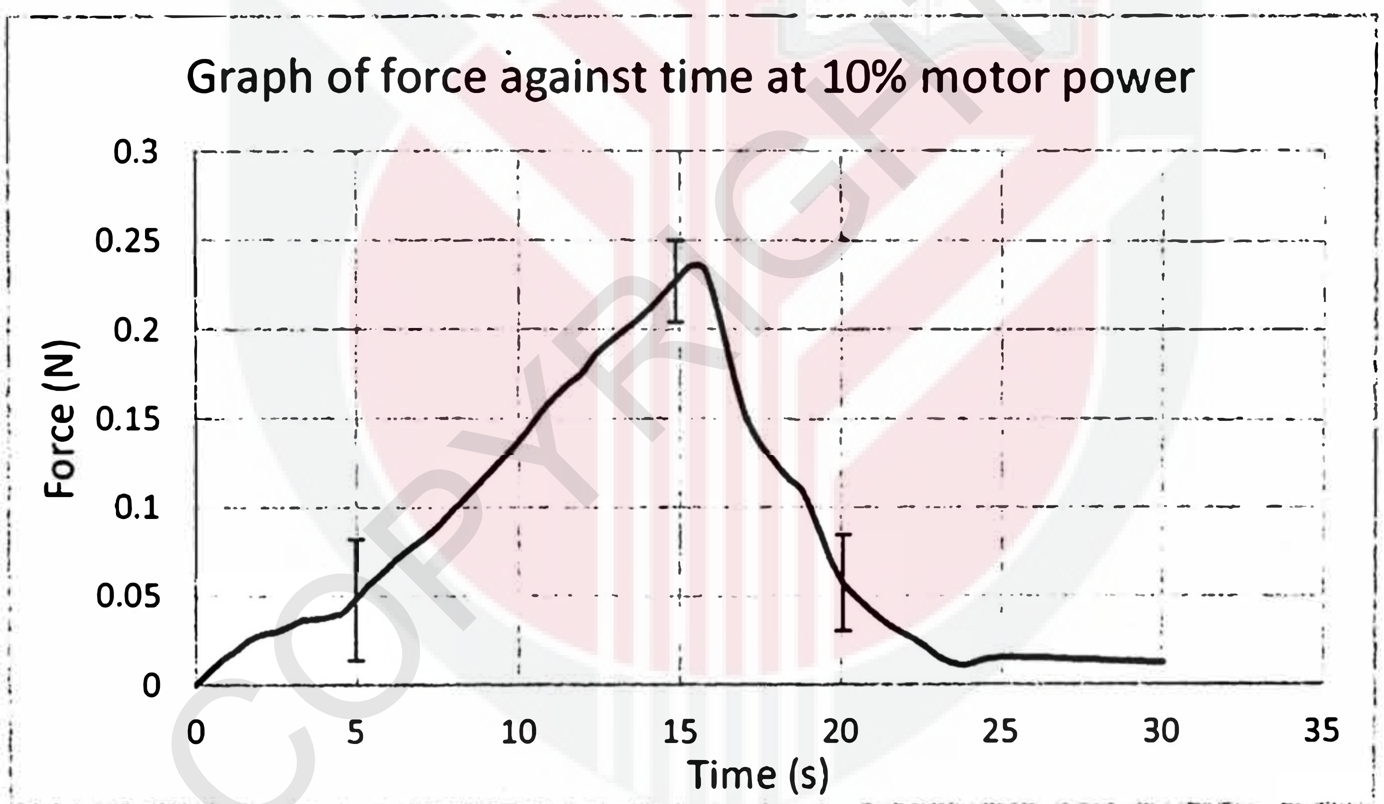


Figure 4.3: Graph of force against time at 10% motor power level under uniaxial compression

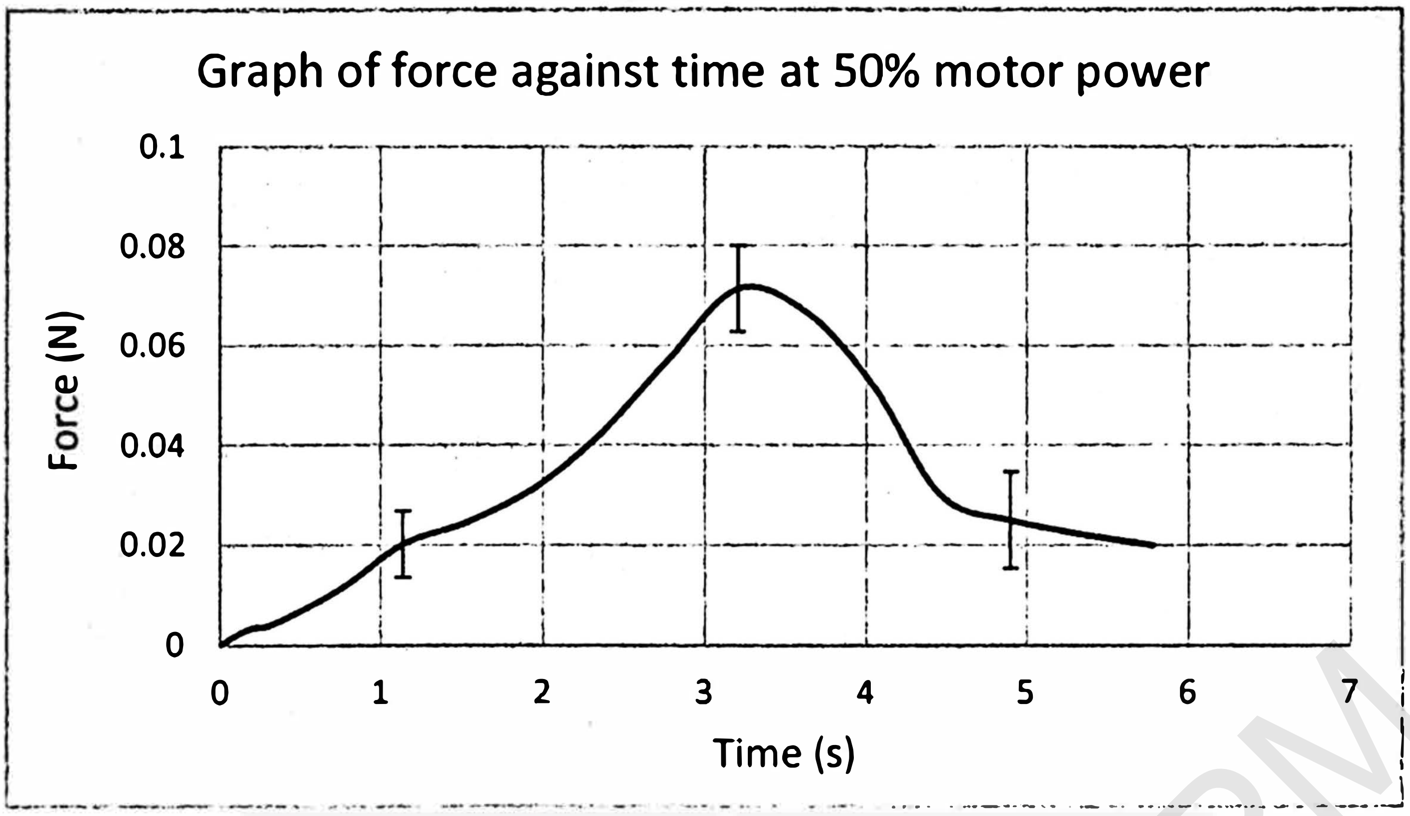


Figure 4.4: Graph of force against time at 50% motor power level under uniaxial compression

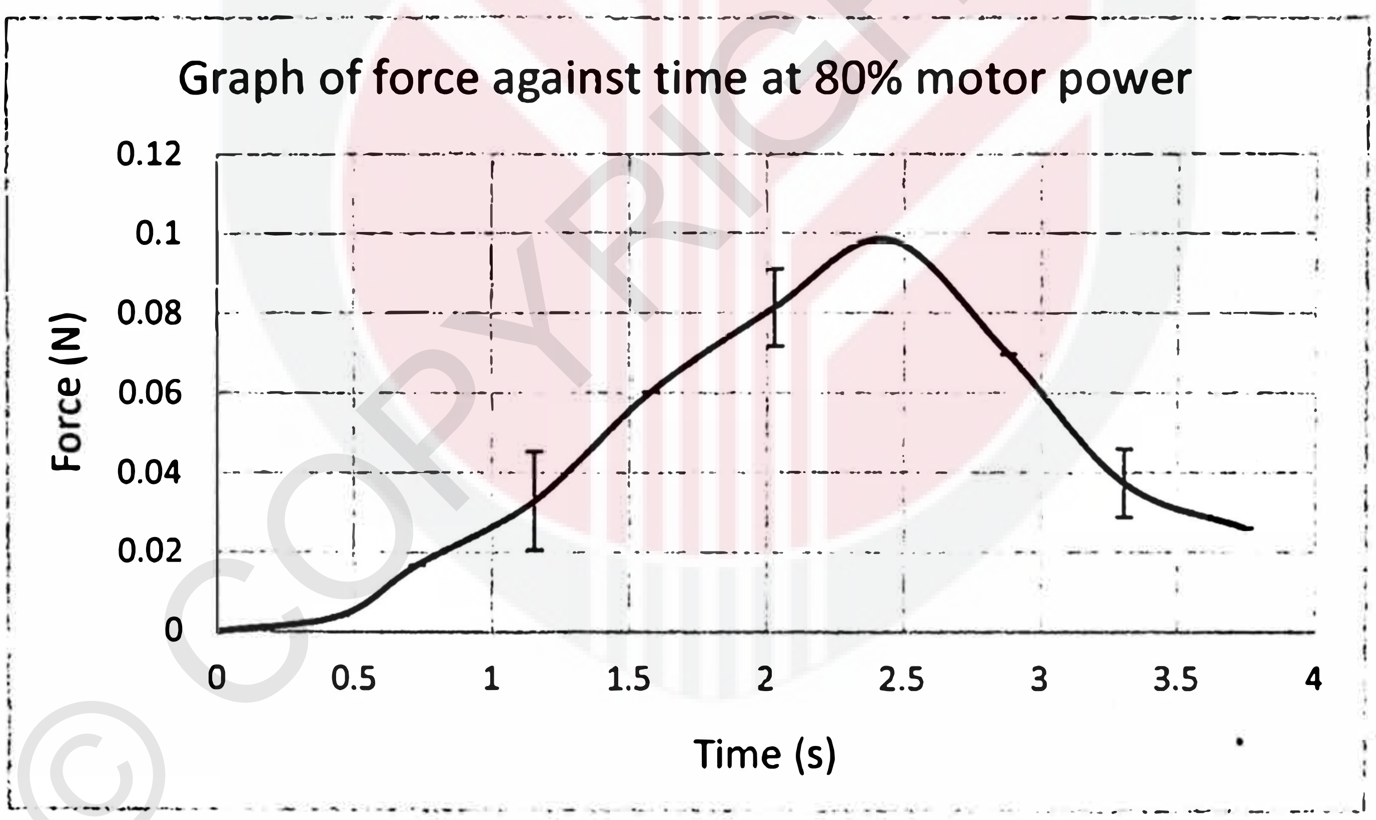


Figure 4.5: Graph of force against time at 80% motor power level under uniaxial compression

Since the deformation of sample at different motor power levels requires different time, it is difficult to make comparison on the mechanical behavior of ice cream under different speed of deformation. Therefore, graph of force against displacement is plotted to clearly show the stress response of ice cream sample under different speed of deformation, as shown in Figure 4.6.

It clearly shows that all three graphs for uniaxial compression at different motor power levels have almost the same trending in the measured stress response over time. As the samples are compressed, the stresses response increased gently. Initially, the curve is a straight line which indicates that the compressive stress is proportional to the compressive strain. After the sample is being pressed to a certain deformation, stress is released. It is noticeable that the initial slope of the curve (displacement less than 1mm) is largest at 10% motor power level and lowest at 80% motor power level. The stress response in ice cream sample at 80% motor power level is relatively low compare to the stress response at 10% power level. This indicates that ice cream behaves as a more cohesive object to resist deformation at higher speed of compression.

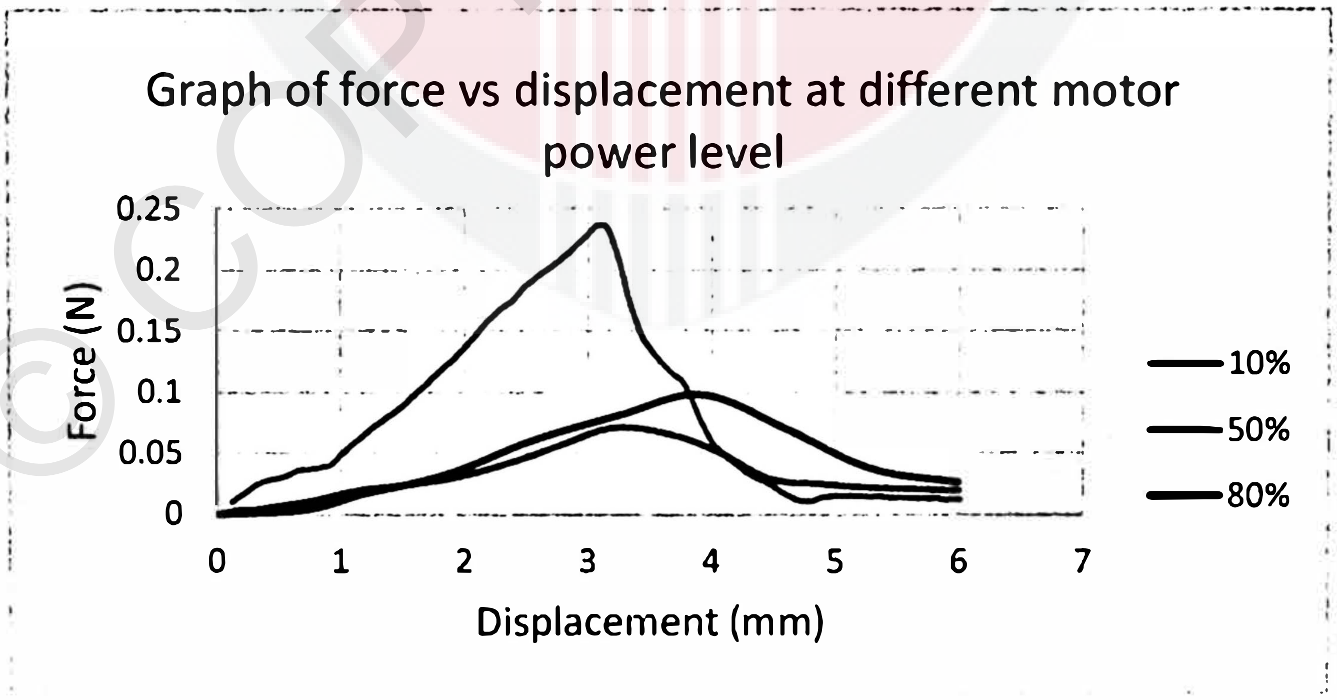


Figure 4.6: Relationship between force against displacement at 10%, 50% and 80% motor power under uniaxial compression

### 4.3.2 Stress Relaxation

Stress relaxation tests were conducted in order to illustrate the viscoelasticity of ice cream and the relaxation time is fixed to a prolonged period until 30$^{th}$ second for all motor power levels (10%, 50% and 80%). From the curves in Figure 4.7, 4.8 and 4.9, stress is applied to deform the sample until it reaches a constant strain, which is 3mm for all experiments. When the desirable displacement of sample is achieved, the displacement of the sample will be held. From the graphs, it can be seen that the stress in the material or the force it takes to hold the material at that displacement decreases over time.

As time goes by, the line becomes horizontal which indicates that the stress is no longer changing and the material has reached equilibrium. This phenomenon is called stress relaxation; it is due to the rearrangement of the material on the molecular or microscale. A higher relaxation time means it a food material requires more time to relax, indicating a more elastic behavior of the food component.

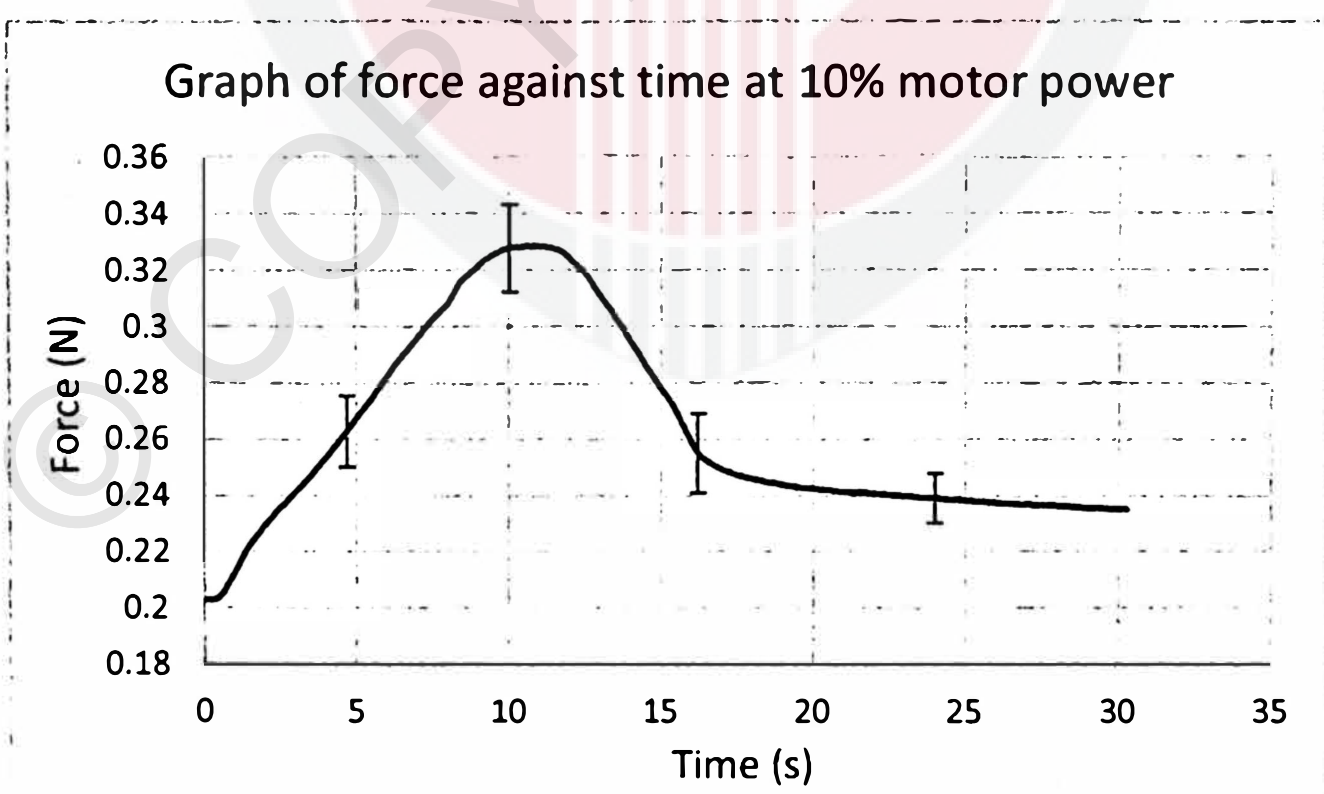


Figure 4.7: Graph of force against time at 10% motor power level under stress relaxation compression

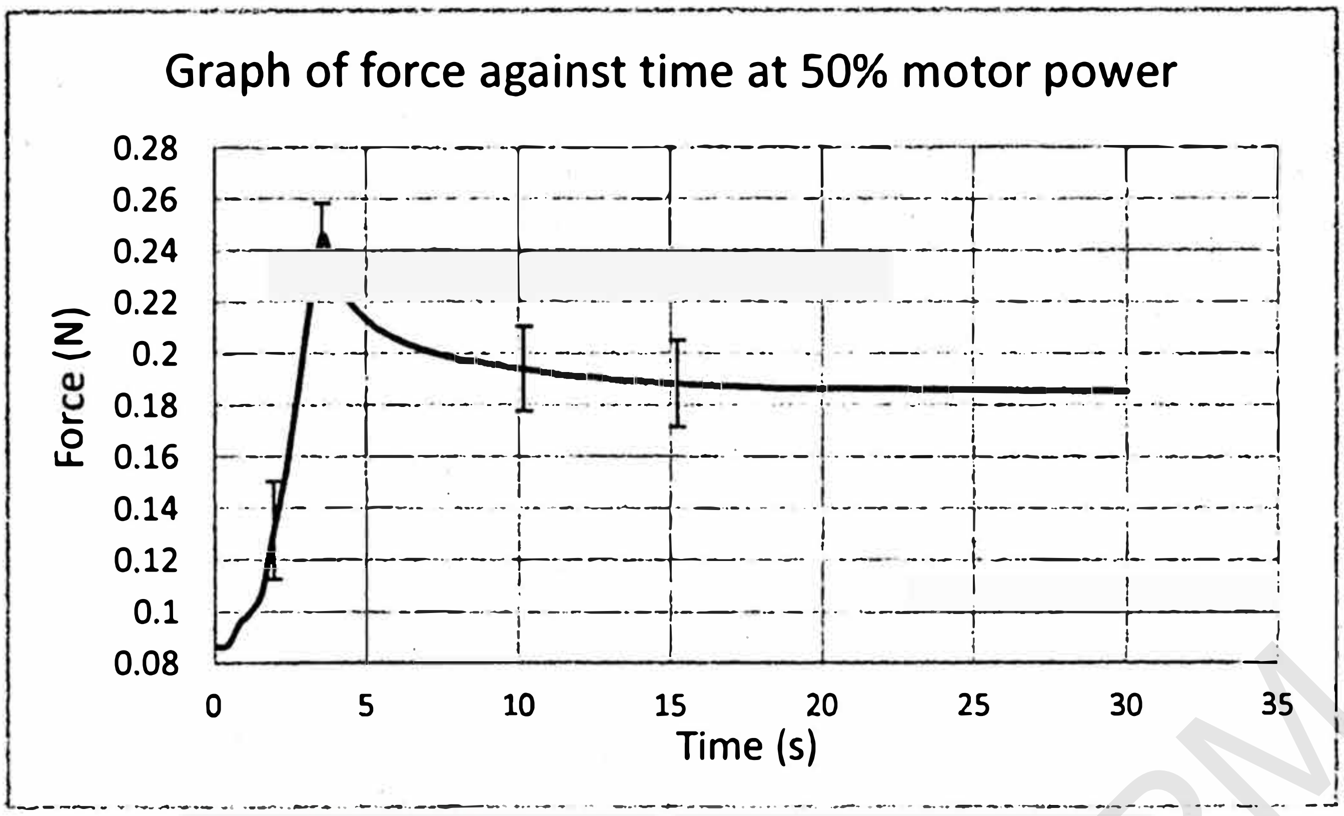


Figure 4.8: Graph of force against time at 50% motor power level under stress relaxation compression

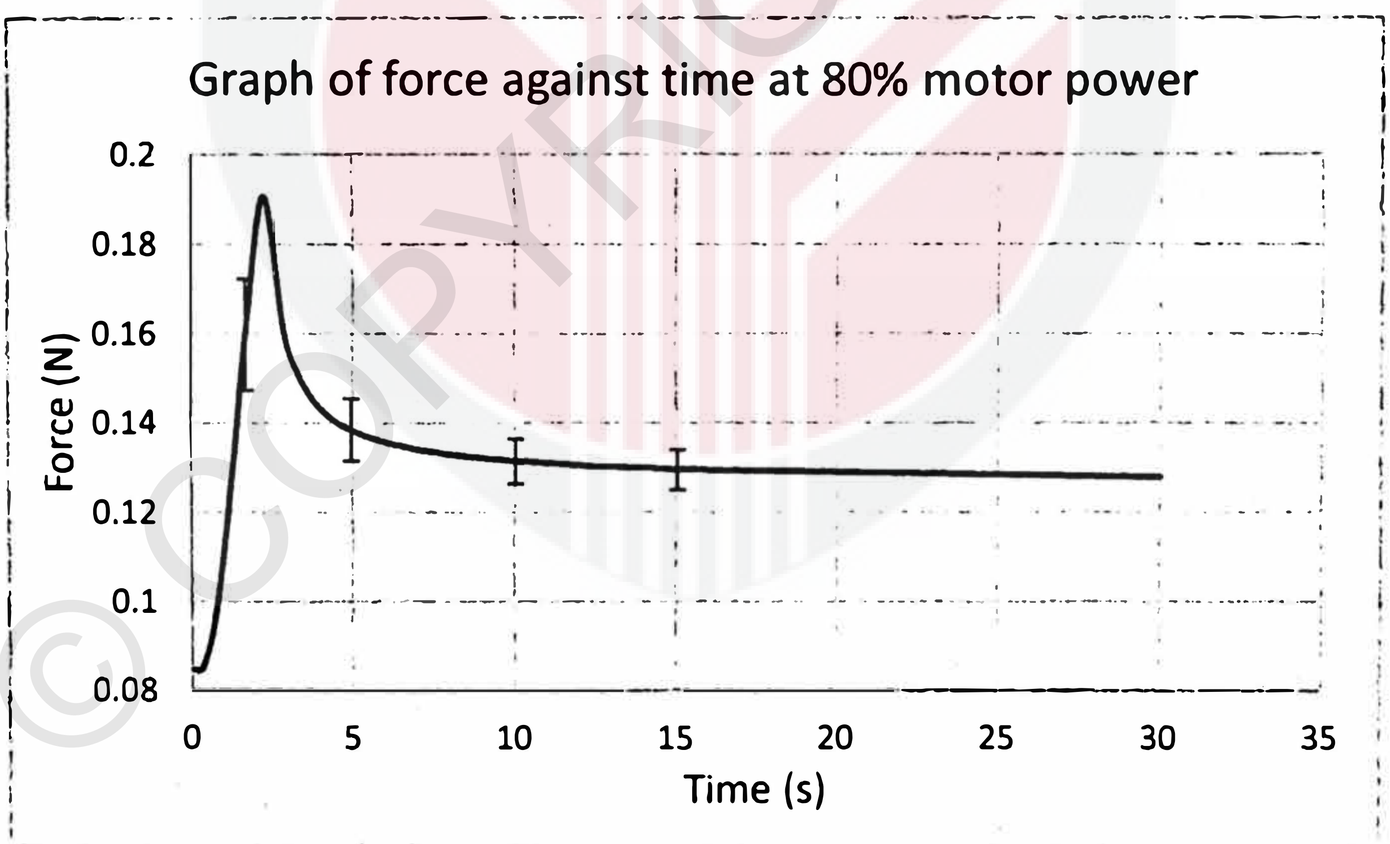


Figure 4.9: Graph of force against time at 80% motor power level under stress relaxation compression

Figure 4.10 shows the force-time graphs that combined results from 10%, 50% and 80% motor power levels. All the curves reveal that the existence of a very fast relaxation during the first 2 seconds after loading following by a very slow rate of relaxation. The curve for stress relaxation compression at 50% and 80% motor power level shows similar trend while stress relaxation compression at 10% motor power level is slightly different. This is because ice cream is a viscoelastic material that respond differently depending on how fast they are being pressed. A common characteristics of viscoelastic material is that it is strain rate dependent. Since different motor power levels are used to press the ice cream sample, therefore it will result in different strain rates to its deformation (a larger motor power level will cause a faster strain rate). At motor power level of 10%, the slower strain rate causes ice cream to behave more like fluid structure and therefore it is less stiff.

The response of the ice cream sample to the stress relaxation test depends on the material's biochemical nature, chemical composition and cellular structure.[34] The force that is measured by load cell plotted against time can also be used to obtain percent of stress relaxation. Percent of stress relaxation can be determined by obtaining the ratio of maximum compression force to equilibrated force. The percent of stress relaxation that nears to 100% indicates a perfect elastic product while the lower percent of stress relaxation indicates a more viscous behavior of the material.[35] By applying an appropriate empirical model, a series of rheological parameters can be estimated in order to determine their response to stress relaxation and thus be useful for successful product and process design.

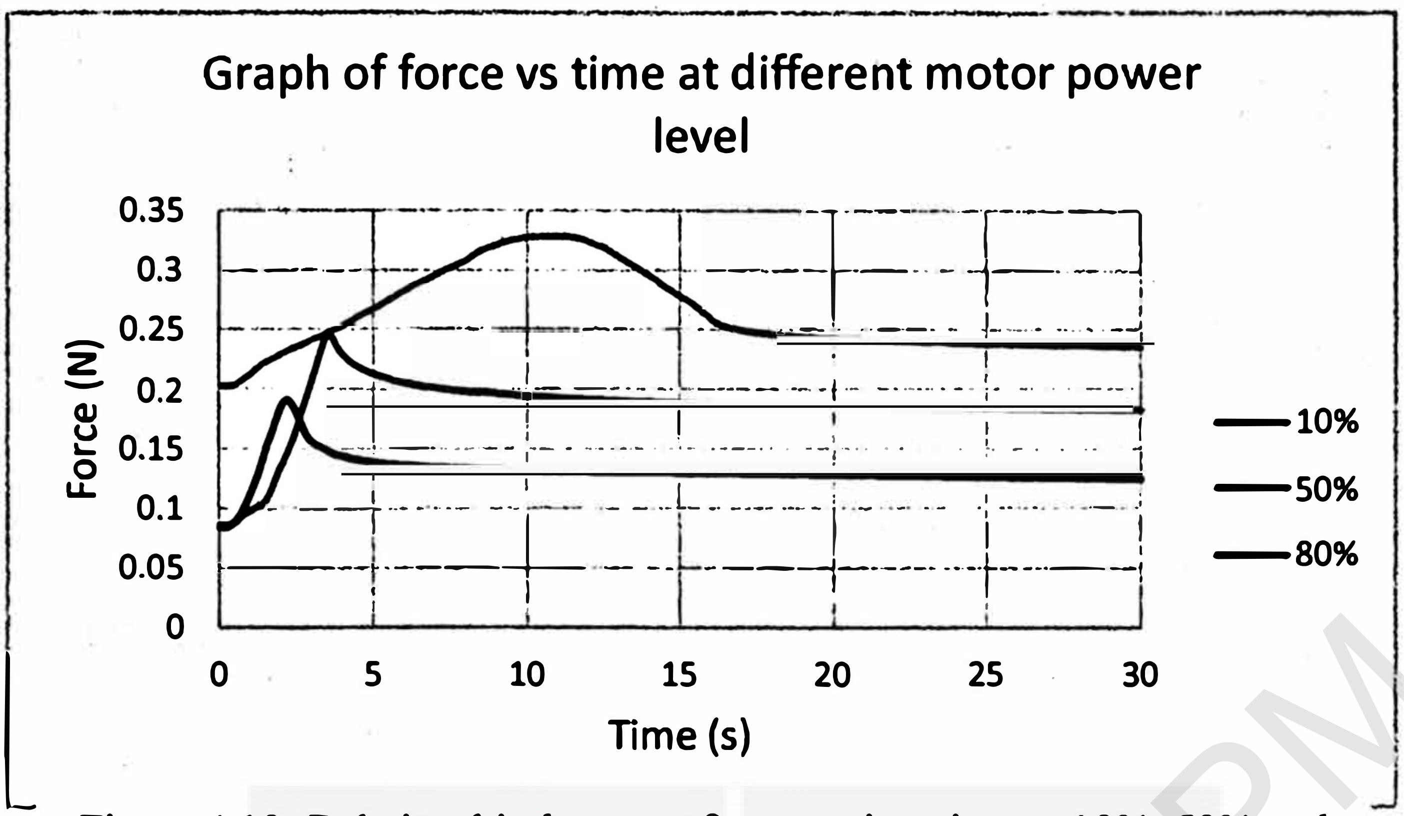


Figure 4.10: Relationship between force against time at 10%, 50% and 80% motor power under stress relaxation

### 4.3.3 Cyclic Compression

The cyclic test involves a repeating pattern of loading-unloading. The strain-controlled experiments at 3mm deformation with 2 cycles at motor power level of 10%, 50% and 80% are conducted, as shown in Figure 4.11, Figure 4.12 and Figure 4.13. The first cycle of loading-unloading indicate a strongly pronounced rate-dependent behavior during loading. The strain rate of ice cream samples are slow at the beginning but it turns out very fast as the stress increases. However, a much weaker rate-dependence are observed during unloading of the sample.

For second cycle, similar rate-dependent behavior can be observed in all experiment with different motor power level. However, the maximum stress response of the ice cream sample at second cycle are relatively lower than the first cycle. This is because ice cream sample are deformed during the first cycle experience a certain degree of permanent deformation. Therefore, the stress response of second cycle will be lower.

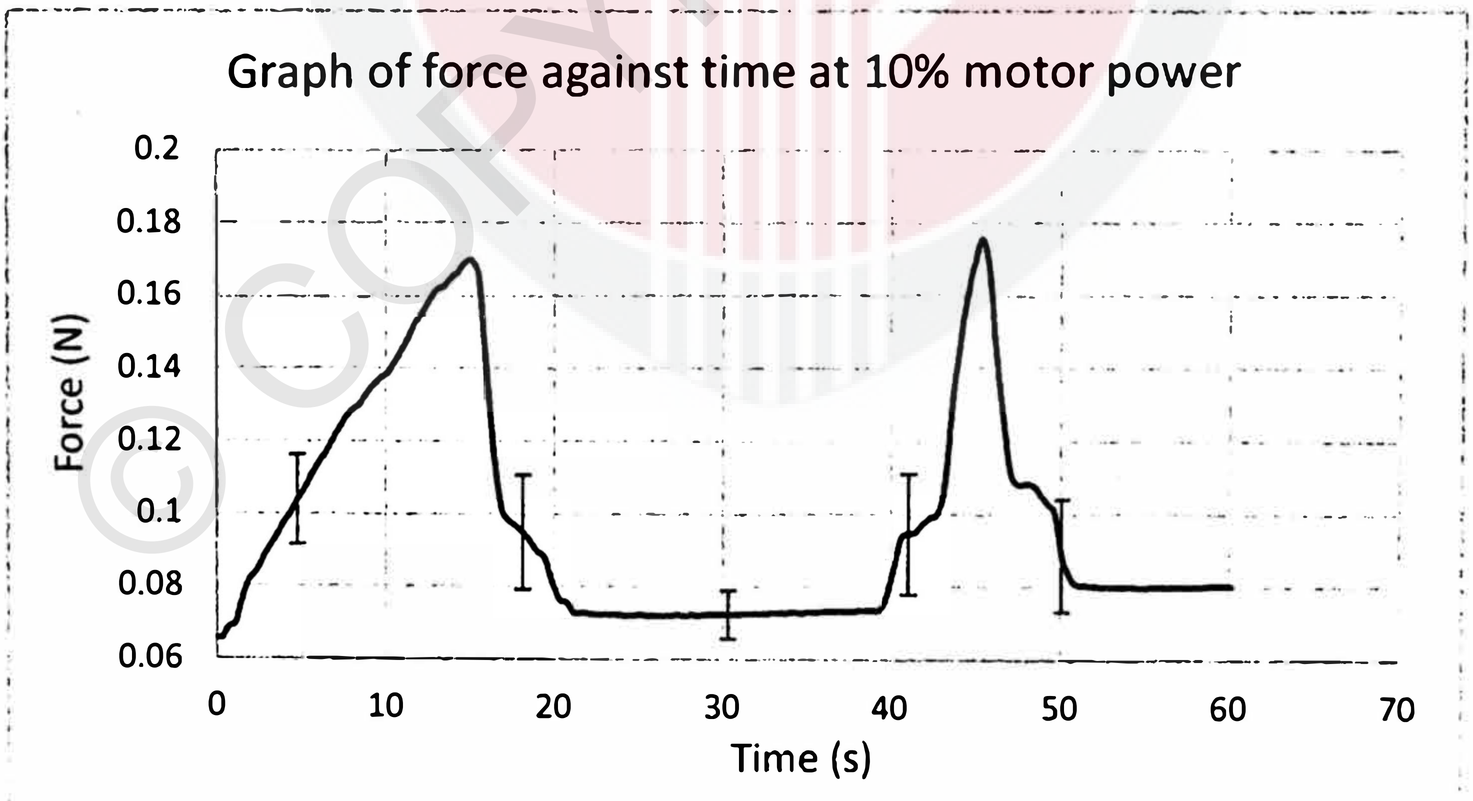


Figure 4.11: Graph of force against time at 10% motor power level under cyclic compression

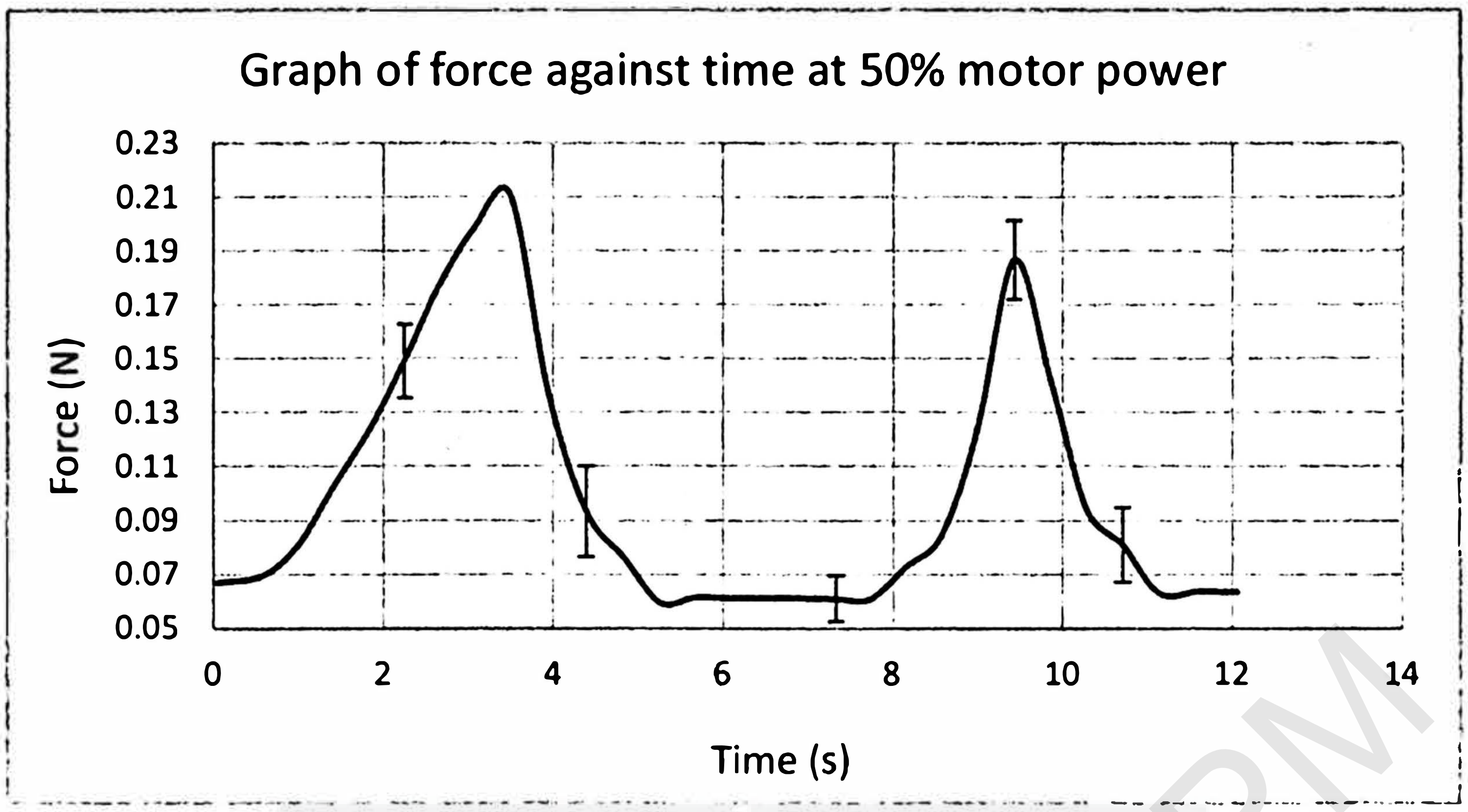


Figure 4.12: Graph of force against time at 50% motor power level under cyclic compression

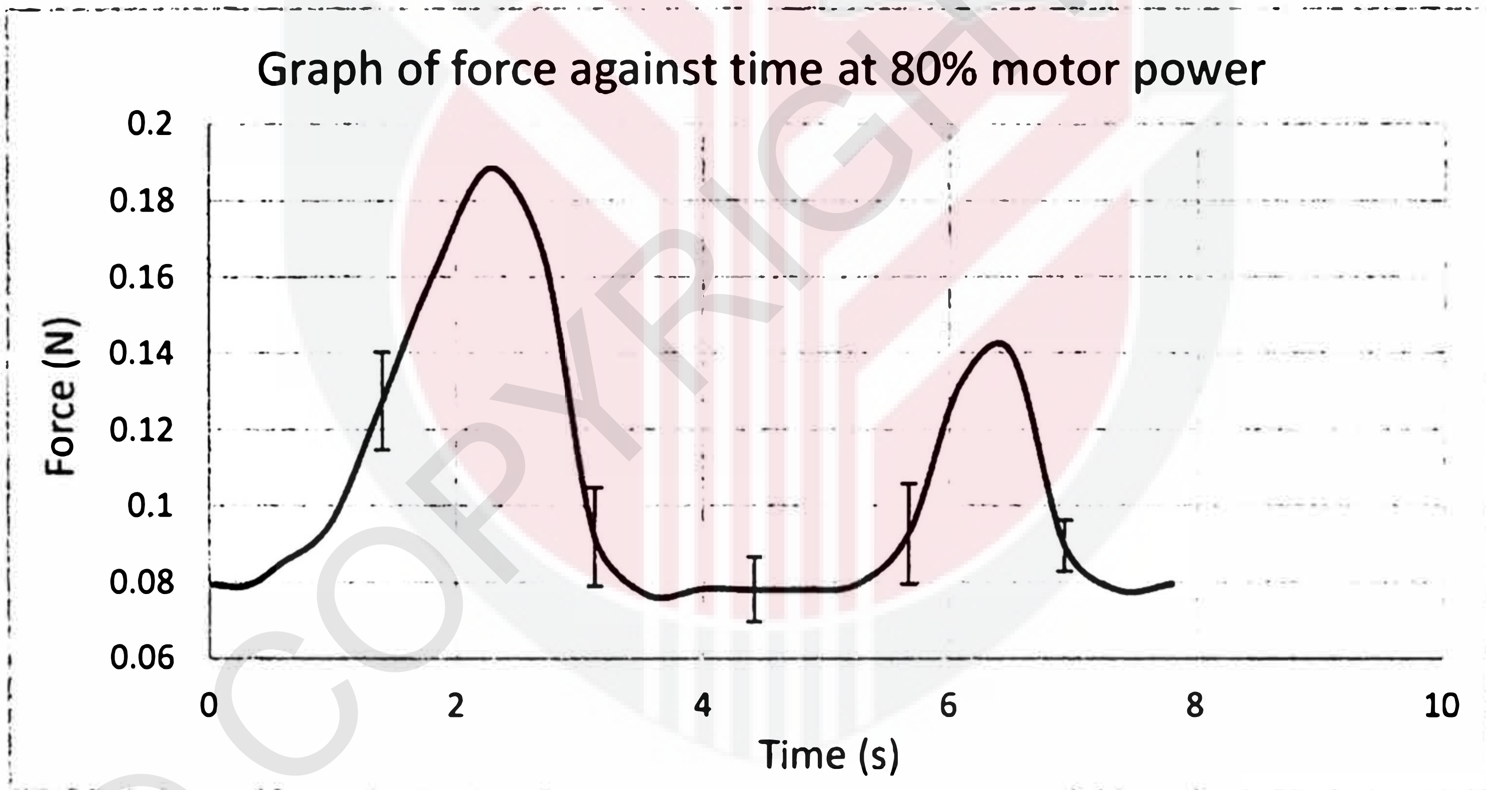


Figure 4.13: Graph of force against time at 80% motor power level under cyclic compression

Figure 4.14 shows the stress response of ice cream under cyclic compression at all motor power levels. It is observed that the overall stress response of the ice cream samples have similar trends. However, ice cream sample at 10% motor power level has maximum stress response of the second cycle that are slightly higher than the first cycle. In regards to the error that have occurred in stress relaxation compression, there is a likelihood that motor power level at 10% is not stable in performing the uniaxial press. Therefore, troubleshoot on the motor rotation is required in order to ensure the consistency of power output that leads to a more accurate result.

However, the graphs generated are sufficient in providing important information such as stress at peak, irrecoverable work, strain and irrecoverable strain. Textural properties of ice cream can be derived from the curves generated by such a test to give hardness (the force at the first break in curve), cohesiveness (the positive force being applied under the first and second compressions) and springiness (the distance that the food recovers it height after previous compression).

From the results obtained in all experiments, it is recommended that uniaxial press is better to be performed at motor power level ranging from 30%-70% in order to achieve more accurate and consistent result at the current stage. However, results obtained from this LEGO device is still trustworthy based on the trending.

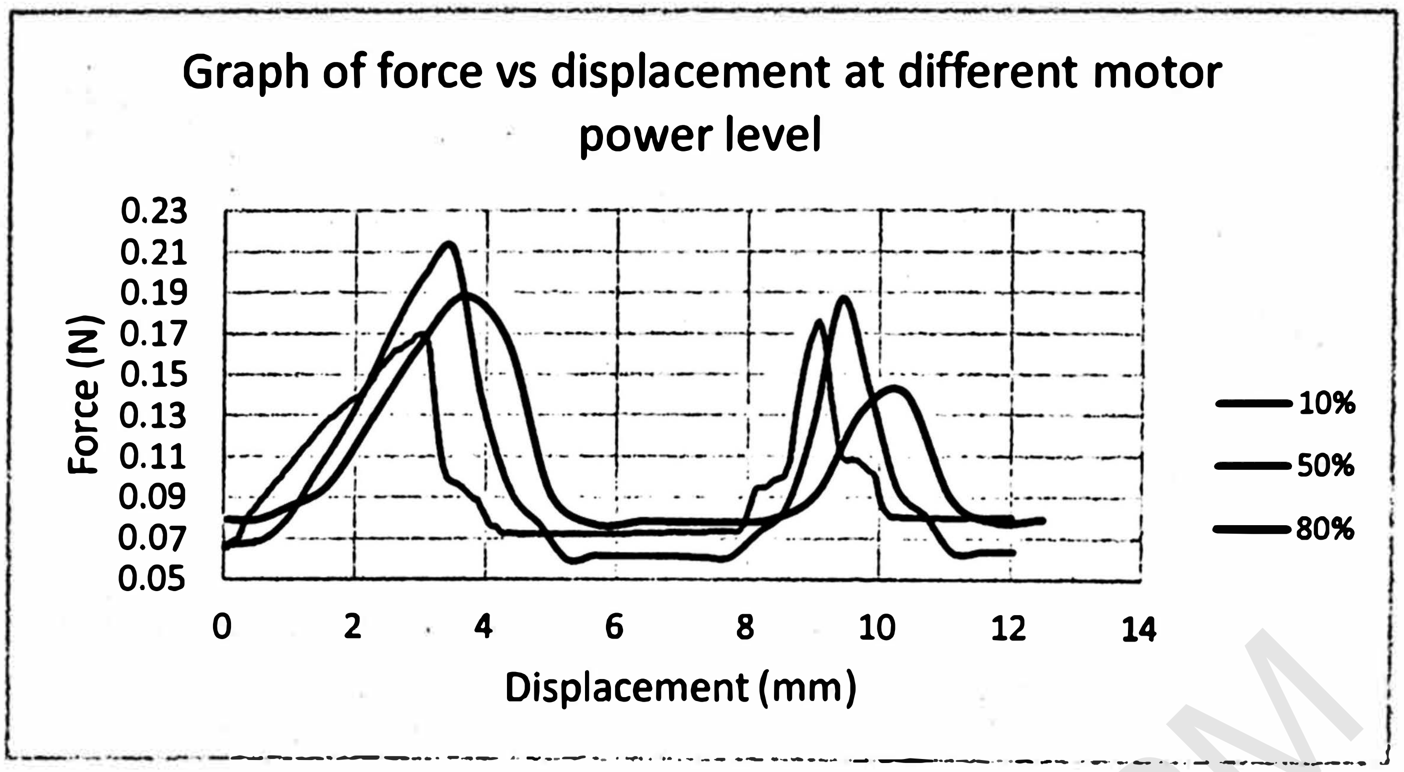


**Figure 4.14: Relationship between force against time at 10%, 50% and 80% motor power under cyclic compression**

# CHAPTER 5

# CONCLUSION AND RECOMMENDATION

## 5.1 Conclusion

The LEGO based measurement device presented in this work successfully in performing uniaxial press while synchronously measuring and collecting data. This measurement device has fulfilled the demanded requirement in offering a simple, cost effective, comprehensive, portable and flexible for the investigation of in-situ (low temperature) ice cream compression behavior. The setup is capable of performing uniaxial presses up to 10mm with velocities up to 14 mm/s. The use of external part for the force measurement allows the study of compression force up to 5 kg, which is sufficiently enough to study the mechanical behavior of food materials. The flexible experimental setup of LEGO device has provided the study of ice cream mechanical behavior in a controllable environment. Furthermore, MATLAB has provided a great functionality of the LEGO measurement device in performing the desirable action as well as to analyze the data collected through the use of toolboxes.

Ice cream is a viscoelastic material that exhibits both viscous and elastic characteristics when undergoing deformation at different stress level. The time-dependent behavior of ice cream results in the response of ice cream to deformation that may change over time. Uniaxial compression, stress relaxation compression and cyclic compression are shown to be useful for the characterization of mechanical behavior of ice cream.

## 5.2 Recommendation

The optimization of the existing LEGO device is needed due to the imperfections of some components. Highly controlled movement of the uniaxial compression is essentially needed in order to obtain the most accurate results. A stepper motor is recommended in controlling the speed of compression plate in a more stable and precise way. Besides, current LEGO device is only applicable in setting the motor power level of motor to drive the compression plate. In order to extend the versatility, use of contact type displacement sensor is recommended in providing an accurate strain measurement of the sample. The desired strain percent at a test speed can be achieved when conducting stress relaxation test. Furthermore, a MATLAB coding should also be developed in performing a series of mathematical calculations that will ease the procedure in analyzing the recording data from load cell. For example, stress-strain curve can be generated from the force vs time graph, provided with sufficient information. Furthermore, software such as Measurement & Automation Explorer (MAX) can be used for motion control configuration. Last but not least, sample preparation should be carried out in controllable environment in order to avoid any change in ice cream microstructure prior to the experiments.

## REFERENCES


[1] H. Douglas Goff and R. W. Hartel, *Ice cream*. 2013.

[2] C. Clarke, *The science of ice cream*. 2004.

[3] Canadean, "Consumer and Market Insights : Ice Cream Market in Malaysia Report scope," no. May, pp. 1–55, 2015.

[4] M. D. Eisner, H. Wildmoser, and E. J. Windhab, "Air cell microstructuring in a high viscous ice cream matrix," *Colloids Surfaces A Physicochem. Eng. Asp.*, vol. 263, no. 1–3 SPEC. ISS., pp. 390–399, 2005.

[5] R. T. Marshall, H. D. Goff, and R. W. Hartel, *Ice Cream*. 2003.

[6] M. R. Muse and R. W. Hartel, "Ice Cream Structural Elements that Affect Melting Rate and Hardness," *J. Dairy Sci.*, vol. 87, no. 1, pp. 1–10, 2004.

[7] H. D. Goff, "Colloidal aspects of ice cream - A review," *Int. Dairy J.*, vol. 7, no. 6–7, pp. 363–373, 1997.

[8] K. L. K. Cook and R. W. Hartel, "Mechanisms of ice crystallization in ice cream production," *Compr. Rev. Food Sci. Food Saf.*, vol. 9, no. 2, pp. 213–222, 2010.

[9] S. ADAPA, K. A. SCHMIDT, I. J. JEON, T. J. HERALD, and R. A. FLORES, "Mechanisms of Ice Crystallization and Recrystallization in Ice Cream: a Review," *Food Rev. Int.*, vol. 16, no. 3, pp. 259–271, 2000.

[10] X. E., Z. J. Pei, and K. A. Schmidt, "Ice cream: Foam formation and stabilization-a review," *Food Rev. Int.*, vol. 26, no. 2, pp. 122–137, 2010.

[11] R. P. Sofjan and R. W. Hartel, "Effects of overrun on structural and physical characteristics of ice cream," *Int. Dairy J.*, vol. 14, no. 3, pp. 255–262, 2004.

[12] E. da Silva Junior and S. C. da S. Lannes*, "Effect of different sweetener blends and fat types on ice cream properties," *Ciência e Tecnol. Aliment.*, vol. 31, no. 1, pp. 217–220, 2011.

[13] S. Bolliger, H. D. Goff, and B. W. Tharp, "Correlation between colloidal properties of ice cream mix and ice cream," *Int. Dairy J.*, vol. 10, pp. 303–309, 2000.

[14] G. Bylund, "Dairy Processing Handbook," *Tetra Pak Process. Syst.*, vol. G3, pp. 331–352, 1995.

[15] K. Zerfiridis, "of Yogurt Ice Cream from Sheep ' s Milk," vol. 55, no. 3, pp. 703–707, 1984.

[16] D. D. Hamann, Z. Junhua, C. R. Daubert, E. A. Foegedtng, and K. C. Diehl, "Analysis of compression, tension and torsion for testing food gel fracture properties," *J. Texture Stud.*, vol. 37, no. 6, pp. 620–639, 2006.

[17] D. Saha and S. Bhattacharya, "Hydrocolloids as thickening and gelling agents in food: A critical review," *J. Food Sci. Technol.*, vol. 47, no. 6, pp. 587–597, 2010.

[18] S. . S. K.E. Matak, S.E. Duncan, J.H. Wilson, C.R. Hackney, "Physical and Sensory Measurements of Dipping Characteristics of Lactose-Hydrolyzed Ice Cream," pp. 30–55.

[19] S. Y. Pon, W. J. Lee, and G. H. Chong, "Textural and rheological properties of stevia ice cream," *Int. Food Res. J.*, vol. 22, no. 4, pp. 1544–1549, 2015.

[20] H. D. Goff, B. Freslon, M. E. Sahagian, T. D. Hauber, a P. Stone, and D. W. Stanley, "Structural development in ice cream -- Dynamic rheological measurements," *J. Texture. Stud.*, vol. 26, pp. 517–536, 1995.

[21] A. Casarotto, K. Lundgren, and E. Wolfang, "Effects of Composition and Flavour on Viscoelastic Properities of Ice Cream," *Strength Cond.*, pp. 0–63, 2015.

[22] W. Canet, C. Fernández, and M. Dolores, "Some Objective Instrumental Methods for Evaluating the Texture of Solid Potato Tissue ( Solanum tuberosum L .)," 2009.

[23] M. Mancini, M. Moresi, and R. Rancini, "Uniaxial compression and stress relaxation tests on alginate gels," *J. Texture Stud.*, vol. 30, no. 0, pp. 639–657, 1999.

[24] H. J. Qi and M. C. Boyce, "Stress-Strain Behavior of Thermoplastic Polyurethane," *Mech. Mater.*, no. July, pp. 1–51, 2004.

[25] Zwick Roell, "Testing Systems Testing systems for texture analysis , viscosity measurement and packaging testing Intelligent Testing," *Nd.*

[26] R. Di Monaco, S. Cavella, and P. Masi, "Predicting sensory cohesiveness, hardness and springiness of solid foods from instrumental measurements," *J. Texture Stud.*, vol. 39, no. 2, pp. 129–149, 2008.

[27] F. J. C. Del Vecchio, J. M. L. Reis, and H. S. Da Costa Mattos, "Elasto-viscoplastic behaviour of polyester polymer mortars under monotonic and cyclic compression," *Polym. Test.*, vol. 35, pp. 62–72, 2014.

[28] "Compression Testing Machine." Fuel Instruments & Engineers Pvt. Ltd.

[29] "What is texture analysis?," *Brookfeild engineering*. Brookfield Engineering.

[30] L. C. Gerber, A. Calasanz-Kaiser, L. Hyman, K. Voitiuk, U. Patil, and I. H. Riedel-Kruse, "Liquid-handling Lego robots and experiments for STEM education and research," *PLoS Biol.*, vol. 15, no. 3, pp. 1–9, 2017.

[31] M. Li, Q. Tang, Z. Yan, and C. Science, "Using LEGO to Learn Engineering Design," 2017.

[32] D. M. Oyen, "Growing bones with Lego | University of Cambridge." [Online]. Available: http://www.cam.ac.uk/research/news/growing-bones-with-lego. [Accessed: 23-Dec-2017].

[33] R. Moser, *A Toy Brick Tensometer for Electromechanical Characterization of Elastomers*. 2015.

[34] G. S. Mittal, M. Zhang, and S. Barbut, “Products to Measure Viscolasticity,” vol. 4, no. 519, pp. 91–107, 1992.

[35] H. Singh, A. Rockall, C. R. Martin, O. K. Chung, and G. L. Lookhart, “The Analysis of Stress Relaxation Data of Some Viscoelastic Foods Using a Texture Analyzer,” *J. Texture Stud.*, vol. 37, no. 4, pp. 383–392, 2006.

## APPENDICES

```
%% Clear Variables and Open FUTEK USB DLL Assembly

clear variables;
pause('on');

%Net.addAssdownembly requires the full file path to access private .dll files
%such as the FUTEK USB DLL.
%With the current folder set as where both this script and the .dll file
%are located, the which() function returns the full file path.

%The included copy of FUTEK_USB_DLL.dll has been compiled for either 32 bit
%or 64 bit platforms. If you are running MATLAB 32 bit use only the 32 bit
%.dll file and if you are using MATLAB 64 bit use only the 64 bit .dll
%file.

%Full .dll file API available here:
http://www.futek.com/files/docs/API/FUTEK_USB_DLL/webframe.html

%Requires .Net 4.0 and Windows
NET.addAssembly(which('FUTEK_USB_DLL.dll'));
import FUTEK_USB_DLL.*
import FUTEK_USB_DLL.USB_DLL.*

%Serial Number in ' ' for your Instrument or USB Output Kit
serialNumber = '492848';

%% Initialize Variables

instr = USB_DLL();
%============USER INPUT==========================%
processType = input('Please enter the type of test to \n proceed(down, up, uniaxial,
relaxation, steprelaxation or cyclic)\n','s');



if strcmpi('uniaxial',processType)


    %input--------------------------------------------------%
    motorRate = input('insert motor power(%)(0-100)\n');
    samples = 1000; %input('insert number of sample\n');
    datainterval = input ('time interval of data point\n');
    RUNTIME = input('insert runtime\n');
    threshold = input('set threshold value(kg):\n');
    %------------------------------------------------------
```

```
elseif strcmpi('relaxation',processType)
    %input--------------------------------------------------%
    motorRate = input('insert motor power(%)(0-100)\n');
    samples = 1000; %input('insert number of sample\n');
    datainterval = input ('time interval of data point\n');
    RUNTIME = input('insert runtime\n');
    RELAXTIME = input('Time taken for relaxation\n');
    threshold = input('set threshold value(kg):\n');
    %-----------------------------------------------------%

elseif strcmpi('steprelaxation',processType)
    %input--------------------------------------------------%
    motorRate = input('insert motor power(%)(0-100)\n');
    samples = 1000; %input('insert number of sample\n');
    datainterval = input ('time interval of data point\n');
    RUNTIME = input('insert runtime\n');
    RELAXTIME = input('Time taken for relaxation\n');
    step = input('number of steps\n');
    threshold = input('set threshold value(kg):\n');
    %-----------------------------------------------------%

elseif strcmpi('cyclic',processType)
    %input--------------------------------------------------%
    motorRate = input('insert motor power(%)(0-100)\n');
    samples = 1000; %input('insert number of sample\n');
    datainterval = input ('time interval of data point\n');
    RUNTIME = input('insert runtime\n');
    cycle = input('number of cycle\n');
    threshold = input('set threshold value(kg):\n');

    %-----------------------------------------------------%

elseif strcmpi('down',processType)

    %input--------------------------------------------------%
    motorRate = 50;
    samples = 1000; %input('insert number of sample\n');
    datainterval = 0.001;
    RUNTIME = 100;
    threshold = input('insert threshold value(kg), start with 0 first:\n');
    %-----------------------------------------------------%
        %-----------------------------------------------------%
```

```
elseif strcmpi('up',processType)

      %input-----------------------------------------------%
      motorRate =100;
      samples = 1000; %input('insert number of sample\n');
      datainterval = 0.001;
      RUNTIME = 50;
      threshold = 0.1;
      %-----------------------------------------------------%

else
   disp('invalid input')
end
%==========================================%

deviceHandle = '';
deviceStatus = 0;
deviceStatusChr = '';
temp = 0;
offsetValue = 0;
fullScaleValue = 0;
fullScaleLoad = 0;
decimalPoint = 0;
normalData = 0;
calculatedReading = 0;
unitCode = 0;
unitChr = '';
unitCodeData = {'atm'; 'bar'; 'dyn'; 'ft-H20'; 'ft-lb'; 'g'; 'g-cm'; 'g-mm'; 'in-H20'; 'in-lb';
   'in-oz'; 'kdyn'; 'kg'; 'kg-cm'; 'kg/cm2'; 'kg-m'; 'klbs'; 'kN'; 'kPa'; 'kpsi';
   'lbs'; 'Mdyn'; 'mmHG'; 'mN-m'; 'MPa'; 'MT'; 'N'; 'N-cm'; 'N-m'; 'N-mm';
   'oz'; 'psi'; 'Pa'; 'T'; 'mV/V'; '涣'; 'mA'; 'A'; 'mm'; 'cm';
   'dm'; 'm'; 'km'; 'in'; 'ft'; 'yd'; 'mi'; '痢'; 'mg'; 'LT';
   'mbar'; '?C'; '?F'; 'K'; '?Ra'; 'kN-m'; 'g-m'; 'nV'; '猩'; 'mV';
   'V'; 'kV'; 'NONE'};
calculatedTable = cell(samples,4);

%==========================================LEGO
PART==========================================%
%LEGO Setup
mylego = legoev3('usb'); %connect ev3 via usb
mymotor = motor(mylego,'A'); %Large motor
mytouch1 = touchSensor(mylego,1); % 'killswitch' sensor at the bottom part
mytouch3 = touchSensor(mylego,3); % 'killswitch' sensor at the top part

%==============================================================
                    %
```

```
%% Open Connection and Begin Data Capture Run
%Intializes the connection to instrument with the specified Serial Number.
%Fetches Device Status to determine if connection is successful or returns
%the error code and exits
instr.Open_Device_Connection(serialNumber);
deviceStatus = instr.DeviceStatus();
if deviceStatus == 0
   disp('Pass')
else
   deviceStatusChr = num2str(deviceStatus);
   disp(['Device Error  \n disconnect Futek usb \n' deviceStatusChr])
   return;
end

%Fetches the device handle needed to retrieve stored values used in load
%calculation
deviceHandle = instr.DeviceHandle();

%--------------------- Set motor speed ---------------------
mymotor.Speed = motorRate;
start(mymotor)

a=figure;
grid on
tic

%Begin loop to collect samples


%UNIAXIAL COMPRESSION TEST------------------------------------------------%

if strcmpi('uniaxial',processType) %UNIAXIAL COMPRESSION TEST

   uniaxial

savefig(a,'uniaxial_compression.fig')
f = openfig('uniaxial_compression.fig');
L = findobj(f, 'type', 'line');
x_data = get(L, 'xdata');
y_data = get(L, 'ydata');

%---------------------------------------------------------------------%
%%RELAXATION TEST------------------------------------------%
elseif strcmpi('relaxation',processType) %RELAXATION TEST

   relaxation
```

```
savefig(a,'relaxation.fig')
f = openfig('relaxation.fig');
L = findobj(f, 'type', 'line');
x_data = get(L, 'xdata');
y_data = get(L, 'ydata');

%-------------------------------------------------------%



%%STEPRELAXATION TEST-------------------------------------%
elseif strcmpi('steprelaxation',processType) %RELAXATION TEST

   for i=1:step

   steprelaxation
   end

   motorRate=100;

   up

savefig(a,'relaxation.fig')
f = openfig('relaxation.fig');
L = findobj(f, 'type', 'line');
x_data = get(L, 'xdata');
y_data = get(L, 'ydata');

%-------------------------------------------------------%
%CYCLIC COMPRESSION TEST-----------------------------------%
elseif strcmpi('cyclic',processType) %CYCLIC COMPRESSION TEST

    for i=1:cycle
   uniaxial
    end

savefig(a,'cyclic_compression.fig')
f = openfig('cyclic_compression.fig');
L = findobj(f, 'type', 'line');
x_data = get(L, 'xdata');
y_data = get(L, 'ydata');

%-------------------------------------------------------%
%PLATE MOVES DOWN------------------------------------------%
elseif strcmpi('down',processType)

    down

%-------------------------------------------------------%
```

```
%PLATE MOVES UP------------------------------------------%
else strcmpi('up',processType)

   up

%--------------------------------------------------------------------%
end



%% Close Connection

% Close the connection to properly disconnect device and allow access by
% other programs, otherwise you must disconnect drive from USB port.
instr.Close_Device_Connection(deviceHandle);
```

Appendix 1: MATLAB coding in performing different type of compression tests

```
clc;    % Clear the command window.
close all;  % Close all figures (except those of imtool.)
imtool close all;  % Close all imtool figures.
clear;  % Erase all existing variables.
workspace;  % Make sure the workspace panel is showing.
fontSize = 22;

promptMessage = sprintf('Please choose a video');
button = questdlg(promptMessage, 'Select video', 'Continue', 'Cancel', 'Continue');
if strcmp(button, 'Continue')
        [baseFileName, folderName, FilterIndex] = uigetfile('*.mp4');
        if ~isequal(baseFileName, 0)
                movieFullFileName = fullfile(folderName, baseFileName);
        else
                return;
        end
else
        return;
end

        videoObject = VideoReader(movieFullFileName);
        % Determine how many frames there are.
        numberOfFrames = videoObject.NumberOfFrames;
   Framerate= videoObject.FrameRate;
        vidHeight = videoObject.Height;
        vidWidth = videoObject.Width;

        numberOfFramesWritten = 0;
        % Prepare a figure to show the images in the upper half of the screen.
        figure;
        %         screenSize = get(0, 'ScreenSize');
        % Enlarge figure to full screen.
        set(gcf, 'units','normalized','outerposition',[0 0 1 1]);

        % Ask user if they want to write the individual frames out to disk.
        promptMessage = sprintf('Do you want to save the individual frames out to
individual disk files?');
        button = questdlg(promptMessage, 'Save individual frames?', 'Yes', 'No', 'Yes');
        if strcmp(button, 'Yes')
                writeToDisk = true;
```

```
		% Extract out the various parts of the filename.
		[folder, baseFileName, extentions] = fileparts(movieFullFileName);
		% Make up a special new output subfolder for all the separate
		% movie frames that we're going to extract and save to disk.
		% (Don't worry - windows can handle forward slashes in the folder name.)
		folder = pwd;   % Make it a subfolder of the folder where this m-file lives.
		outputFolder = sprintf('%s/Movie Frames from %s', folder, baseFileName);
		% Create the folder if it doesn't exist already.
		if ~exist(outputFolder, 'dir')
			mkdir(outputFolder);
		end
	else
		writeToDisk = false;
	end

	% Loop through the movie, writing all frames out.
	% Each frame will be in a separate file with unique name.
	meanGrayLevels = zeros(numberOfFrames, 1);
	meanRedLevels = zeros(numberOfFrames, 1);
	meanGreenLevels = zeros(numberOfFrames, 1);
	meanBlueLevels = zeros(numberOfFrames, 1);
	for frame = 1 : numberOfFrames
		% Extract the frame from the movie structure.
		thisFrame = read(videoObject, frame);

		% Display it
		hImage = subplot(2, 2, 3);
		image(thisFrame);
		caption = sprintf('Frame %4d of %d.', frame, numberOfFrames);
		title(caption, 'FontSize', fontSize);
		drawnow; % Force it to refresh the window.

		% Write the image array to the output file, if requested.
		if writeToDisk
			% Construct an output image file name.
			outputBaseFileName = sprintf('Frame %4.4d.png', frame);
			outputFullFileName = fullfile(outputFolder, outputBaseFileName);

			% Stamp the name and frame number onto the image.
			% At this point it's just going into the overlay,
			% not actually getting written into the pixel values.
			text(5, 15, outputBaseFileName, 'FontSize', 20);
```

```
                    % Extract the image with the text "burned into" it.
                    frameWithText = getframe(gca);
                    % frameWithText.cdata is the image with the text
                    % actually written into the pixel values.
                    % Write it out to disk.
                    imwrite(frameWithText.cdata, outputFullFileName, 'png');
          end

          % Calculate the mean gray level.
          grayImage = rgb2gray(thisFrame);
          meanGrayLevels(frame) = mean(grayImage(:));

          % Calculate the mean R, G, and B levels.
          meanRedLevels(frame) = mean(mean(thisFrame(:, :, 1)));
          meanGreenLevels(frame) = mean(mean(thisFrame(:, :, 2)));
          meanBlueLevels(frame) = mean(mean(thisFrame(:, :, 3)));

          % Plot the mean gray levels.
          hPlot = subplot(2, 1, 1);
          hold off;
          plot(meanGrayLevels, 'k-', 'LineWidth', 2);
          hold on;
          plot(meanRedLevels, 'r-');
          plot(meanGreenLevels, 'g-');
          plot(meanBlueLevels, 'b-');
          grid on;

          % Put title back because plot() erases the existing title.
          title('Mean Gray Levels', 'FontSize', fontSize);
          if frame == 1
                    xlabel('Frame Number');
                    ylabel('Gray Level');
                    % Get size data later for preallocation if we read
                    % the movie back in from disk.
                    [rows, columns, numberOfColorChannels] = size(thisFrame);
          End
          % Update user with the progress.  Display in the command window.
          if writeToDisk
          progressIndication = sprintf('Wrote frame %4d of %d.', frame,
numberOfFrames);
          else
          progressIndication = sprintf('Processed frame %4d of %d.', frame,
numberOfFrames);
          end
```

```
            disp(progressIndication);
            % Increment frame count (should eventually = numberOfFrames
            % unless an error happens).
            numberOfFramesWritten = numberOfFramesWritten + 1;

            % Now let's do the differencing
            alpha = 0.5;
            if frame == 1
                Background = thisFrame;
            else
                % Change background slightly at each frame
                % Background(t+1)=(1-alpha)*I+alpha*Background
                Background = (1-alpha)* thisFrame + alpha * Background;
            end

            differenceImage = thisFrame - uint8(Background);
            % Threshold with Otsu method.
            grayImage = rgb2gray(differenceImage); % Convert to gray level
            thresholdLevel = graythresh(grayImage); % Get threshold.
            binaryImage = im2bw( grayImage, thresholdLevel); % Do the binarization
            % Plot the binary image.
            subplot(2, 2, 4);
            imshow(binaryImage);
            title('Binarized Difference Image', 'FontSize', fontSize);
  end

        % Alert user that we're done.
        if writeToDisk
            finishedMessage = sprintf('Done!  It wrote %d frames to folder\n"%s"',
numberOfFramesWritten, outputFolder);
        else
            finishedMessage = sprintf('Done!  It processed %d frames of\n"%s"',
numberOfFramesWritten, movieFullFileName);
        end
        disp(finishedMessage); % Write to command window.
        uiwait(msgbox(finishedMessage)); % Also pop up a message box.

inputvideo=vision.VideoFileReader(movieFullFileName); %Read Frame from video
vid1=vision.VideoPlayer; %Play video
while~isDone(inputvideo)
frame1=step(inputvideo);
step(vid1,frame1);
pause(0.005);
end
```

```
imwrite(frame1,'D:\referenceimage.jpg','jpg');
release(inputvideo);
release(vid1);
referenceimage=imread('D:\referenceimage.jpg');

vid2=vision.VideoFileReader(movieFullFileName);
X=zeros(2,numberOfFrames);
Y=zeros(2,numberOfFrames);
Z=zeros;

prompt = {'Enter the final frame number:'};
dlg_title = 'Input';
answer = inputdlg(prompt, dlg_title);
k=str2double(answer{1});

for i=(2:k) %must start exactly when the plate moves down
frame=step(vid2);
frame2=((im2double(frame))-(im2double(referenceimage)));
frame1=im2bw(frame2,0.4);
[labelimage]=bwlabel(frame1);
stats=regionprops(labelimage,'basic');
BB=stats.BoundingBox;
X(i)=BB(1);
Y(i)=BB(2);
Dist=((X(2)-X(k))^2+(Y(2)-Y(k))^2)^(1/2);
Z(i)=Dist;
S=strel('disk',6);
frame3=imclose(frame1,S);
step(vid1,frame1);
pause(0.05);
end
M=median(Z);
N=M/1000;
Speed=(N)/(k/Framerate);
release(vid1)
msg = cell(2,1);
msg{1} = sprintf('The displacement is %5f mm.\n',N');
msg{2} = sprintf('The speed is %5f mm/s.\n',Speed');
msgbox(msg)
```

Appendix 2: MATLAB coding for speed estimation of compression plate